GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 6, 1298, doi:10.1029/2002GL016441, 2003

Arctic Ocean variability derived from historical observations

Igor Polyakov,[1] David Walsh,[1] Igor Dmitrenko,[1] Roger L. Colony,[1]
and Leonid A. Timokhov[2]

Received 11 October 2002; accepted 21 February 2003; published 22 March 2003.

[1] This study has been motivated by reports of extra ordinary change in the Arctic Ocean observed in recent decades. Most of these observations are based on synoptic measurements, while evaluation of anomalies requires an understanding of the underlying long-term variability. Historical climatologies give reference means, and while these datasets are a reliable source of the mean Atlantic Layer temperature, they significantly underestimate variability. Using historical data, we calculated statistical parameters for selected Arctic Ocean regions. They demonstrate a high level of Atlantic Layer temperature variability in the Nansen Basin and sea-surface salinity fluctuations on the Siberian shelf and the Amundsen Basin. These estimates suggest strong limitations on our ability to define amplitudes of anomalies by comparing recent synoptic measurements with climatologies, especially for regions characterized by strong variability. *INDEX TERMS:* 4207 Oceanography: General: Arctic and Antarctic oceanography; 4215 Oceanography: General: Climate and interannual variability (3309); 4536 Oceanography: Physical: Hydrography. **Citation:** Polyakov, I., D. Walsh, I. Dmitrenko, R. L. Colony, and L. A. Timokhov, Arctic Ocean variability derived from historical observations, *Geophys. Res. Lett.*, *30*(6), 1298, doi:10.1029/2002GL016441, 2003.

1. Introduction

[2] Extreme amplification of the polar vortex in the late 1980s and early 1990s triggered significant changes in the Arctic Ocean water temperature and salinity. The first evidence of warming in the subsurface Atlantic Layer (AL) was found in the Nansen Basin in 1990 [*Quadfasel et al.*, 1991] (for geographical notations see Figure 1). Positive AL Core Temperature (150–800m, ALCT) anomalies of up to 1°C were carried along the continental margin into the Arctic Ocean interior [*Carmack et al.*, 1995] (see also SCICEX websitehttp://arcss.colorado.edu/data/arcss.html). Increased transport of water caused a displacement towards the Canadian Basin of the Pacific-Atlantic water boundary [*Carmack et al.*, 1995; *McLaughlin et al.*, 1996]. Year-long mooring observations on the slope off the Novosibirskiye Islands in 1995–96 showed generally warmer ALCT, by about 1°C, compared with climatologies, with abrupt "cooling" events (by up to 0.5–1.0°C) [*Woodgate et al.*, 2001]. Modeling experiments also suggest that the AL warming in the 1990s was episodic in character [*Karcher et al.*, 2002].

[3] *Steele and Boyd* [1998] found a retreat of fresh surface waters and loss of the cold halocline layer from the Eurasian Basin in the 1990s, and linked this water-mass change to a shift in atmospheric winds and ice motion. *Johnson and Polyakov* [2001] advocated two mechanisms for the Eurasian Basin salinification: eastward diversion of Russian rivers, and increased brine formation due to enhanced ice production in the Laptev Sea, which is subsequently advected to the central Eurasian Basin. In contrast, near-surface observations in the Canadian Basin in the 1990s showed strong freshening [*McPhee et al.*, 1998].

[4] Russian historical data [see, e.g., *Gorshkov*, 1980; *Treshnikov*, 1985] were used in the above studies as reference data to define thermohaline anomalies. However, recent measurements are generally based on "snapshot" CTD profiles, and reliable evaluation of anomalies requires an accurate knowledge not only of climatic means, but also of variability. The *Environmental Working Group* (*EWG*) [1997] Atlas is the only climatology providing measures of water temperature and salinity variability. The goal of the paper is to estimate background variability derived from these historical observations for future comparison with recently observed anomalies.

2. Data

[5] The data used in this study consist of temperature and salinity measurements from Russian winter surveys of the central Arctic Ocean between 1973–79, and 40 years of summer and winter observations in the Laptev Sea.

[6] Seven Russian winter aircraft surveys (1973–79) occupied 1034 oceanographic stations. These central Arctic Ocean surveys constitute the most complete set of arctic observations. For example, for the region northward of 80°N between 30–330°E, the number of oceanographic stations in the 1970s constitutes 64.5% of the total number of stations occupied during the 1950–80s [*EWG*, 1997]. The number of observations during these surveys was approximately the same from year to year, with some variation in the total area of observation. Nansen bottles were typically used to take water samples and to measure water temperature at standard levels (5, 10, 15, 20, 25, 30, 40, 50, 75, 100, 150, 200, 250, 300, 400, 500, 600, 750, 1000 m, and then by 500m intervals to the bottom). The accuracy of temperature and salinity measurements was estimated to be 0.01°C and 0.01, respectively [see, *Polyakov and Timokhov*, 1994, hereinafter referred to as P&T].

[7] An extensive archive of Laptev Sea temperature and salinity, extending from 1960–90, was produced by the Arctic and Antarctic Research Institute [*Dmitrenko et al.*, 2001]. These data are complemented with data from joint Russian-German summer (1993–95 and 1998–2000) and winter (1996, 1999) expeditions. Summer ship-based observations were made in August–September. Aircraft surveys

[1]International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, Alaska, USA.
[2]Arctic and Antarctic Research Institute, St. Petersburg, Russia.

0094-8276/03/2002GL016441

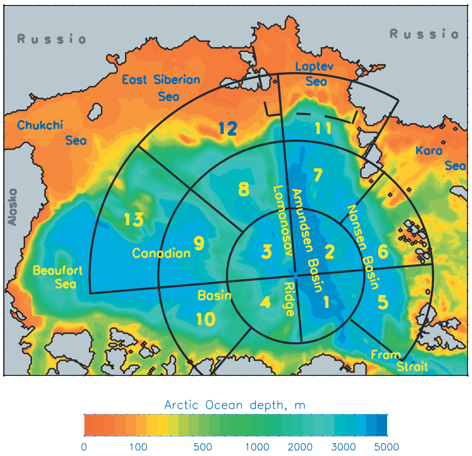

Figure 1. Map of the Arctic Ocean. Labeled regions are used for analysis of the water temperature and salinity from the 1970s. Dashed lines show the Laptev Sea region used for analysis of data from the 1950–90s.

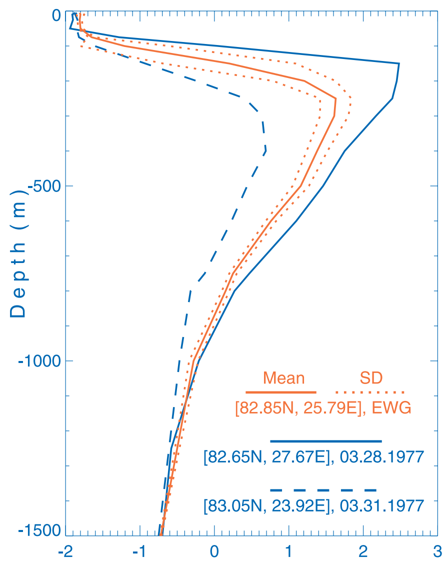

Figure 2. Vertical profiles of water temperature (°C) measured in 1977 in the Eurasian Basin northward Spitsbergen (blue) and from *EWG* [1997] climatology. Note the large 1977 temperature difference (>1.5°C) in the core of the Atlantic Water (150–300m).

were conducted during the winter (March–April). Nansen bottles were used prior to 1993 while in recent years CTD measurements were obtained having accuracies at least an order of magnitude greater than the bottle measurements. The total number of stations is 2088 for the winter season and 3350 for the summer season.

[8] The *EWG* [1997] climatology used in this study for comparison purposes contains 50-km gridded data at 23 levels, averaged for the period 1950–89 and by decade. Together with mean ocean temperature and salinity fields, the Atlas provides basic statistics such as water temperature and salinity standard deviations (σ).

3. Variability From Historical Observations

[9] Figure 2 shows vertical profiles of water temperature measured in winter 1977 at two locations (60km apart) in the Eurasian Basin near Spitsbergen. The deviation of the temperature in 1977 from the *EWG* [1997] climatology, also shown in the figure, is striking: in the AL core (150–300m), the difference exceeds 1°C, exceeding the σ given in *EWG* [1997] Atlas by a factor of 3. These ALCT anomalies are of the same magnitude as the anomalies found in the 1990s. Strong positive and negative ALCT anomalies measured in 1977 were also found at several nearby locations, suggesting the spatial variability apparent in Figure 2 is not a result of measurement error.

[10] We speculate that the reason for the "suppressed" variability given by *EWG* [1997] is the multi-stage quality control procedure used. At the first stage this procedure eliminates data with anomalies exceeding three σ; at the next stage means and σ's are re-computed for the reduced data, and anomalies exceeding two σ are eliminated. Data reduced for the second time are used to calculate means and standard deviations given by the *EWG* [1997]. This approach may lead to a substantial underestimate of σ, thereby reducing the utility of the dataset.

[11] These considerations led us to further analyze Arctic Ocean variability apparent in the data. Figure 3 demonstrates ALCT and SSS variability in the 1970s. The largest ALCT variability is seen close to Fram Strait, diminishing along the Nansen Basin slope towards the Laptev Sea (Figures 3). The σ and ALCT anomalies are maximum in the Eurasian Basin, while for the Canadian Basin historical data from the 1970s show smaller variations (Figure 4). Note also that the ALCT σ from Region 5 may be directly compared with that from *EWG* [1997] shown in Figure 2.

[12] Figure 3 also demonstrates that the Laptev-East Siberian seas shelf is a source of strong SSS variations.

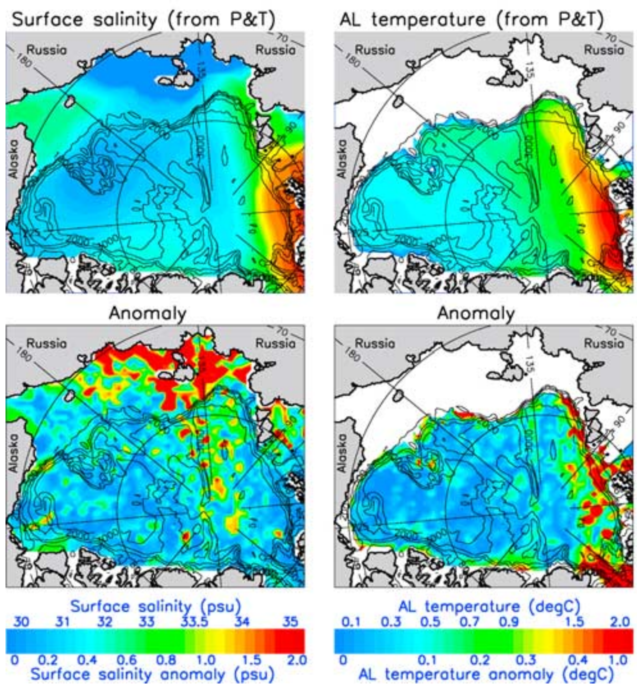

Figure 3. Surface salinity (left) and AL core temperature (°C, right) from Russian surveys in the 1970s (P&T) Top: climatological mean fields. Bottom: difference (sign is omitted) between instantaneous values and climatological means.

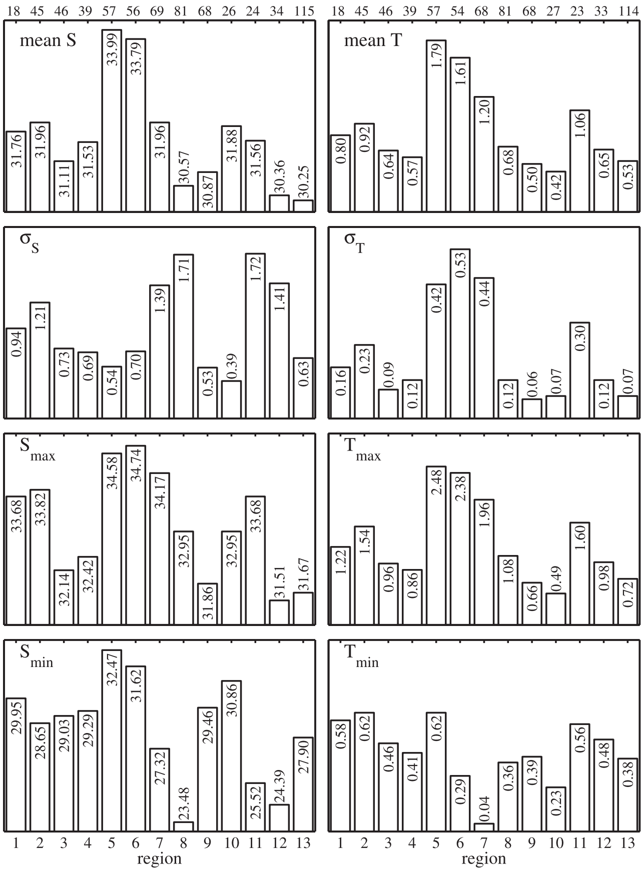

Figure 4. AL core temperature (T, °C) and surface salinity (S) means (top), their σ (second top), maxima (third top), and minima (bottom) for 13 regions of the Arctic Ocean (depth >300m) shown in Figure 1. Numbers above the top panels denote the number of measurements used for analysis.

Figure 5 corroborates this finding, showing statistical estimates of means and σ, and indicating the Lena River as the major source of summer and winter patches of fresh water. Centers of strong winter salinification are often associated with leads and polynyas, where brine formation due to enhanced ice production occurs. These SSS anomalies are advected eastward to the East Siberian Sea and northward to the Amundsen Basin interior roughly following the Lomonosov Ridge (Figure 3, left bottom). This pathway of fresh Laptev Sea waters entering the interior Arctic Ocean in the vicinity of the Lomonosov Ridge was also found using observations from the 1990s [*Guay et al.*, 2001].

[13] Most ALCT anomalies exceeding three σ are located along the slope north of Spitsbergen, Severnaya Zemlya, and Novosibirskiye Islands, and (unexpectedly) over the Gakkel Ridge at approximately 85°N. Similarly large SSS anomalies (σ > 3) occur north of Spitsbergen and Novosibirskiye Islands and over the same Gakkel Ridge site. No strong anomalies were found off Severnaya Zemlya, while large SSS perturbations are seen over the Chukchi Cap.

4. Discussion

[14] Substantial changes have occurred in the Arctic region over the last few decades. Shifts in atmospheric circulation patterns have resulted in increased transport and temperature of Atlantic waters entering the Arctic via Fram Strait [*Rudels et al.*, 2000]. This intrusion of warm water from the North Atlantic found its way to the Arctic Ocean interior along the continental margins of the Eurasian and Canadian basins. According to these observations, the Atlantic water was nearly 1°C warmer compared with climatological data. Salinification in the Eurasian Basin and freshening by as much as several salinity units were observed in the Canadian Basin.

[15] Most of these estimates are based on synoptic measurements, hence reliable anomaly estimates require knowledge of the means and standard deviations derived from historical data. We found that these data allow the maximum temperature of the AL to be computed quite accurately (see Appendix). The *EWG* [1997] climatology provides statistical estimates of variability, but our analysis shows that the *EWG* [1997] dataset considerably underestimates variability. Using Russian historical data we calculated basic statistical parameters for selected Arctic Ocean regions. The estimates of σ demonstrate a high level

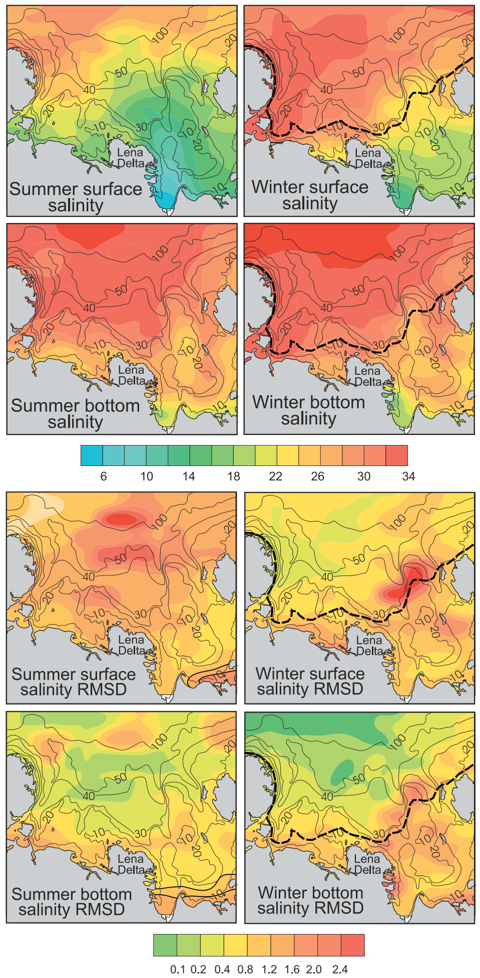

Figure 5. Laptev Sea mean summer and winter salinity (top four panels) and σ (bottom four panels) from oceanographic surveys in the 1950–90s. The bathymetry contours (m) are shown by black lines. Dashed line shows the location of fast ice edge often associated with polynyas and leads.

of ALCT variability in the Nansen Basin, and SSS fluctuations on the Siberian shelf spreading into the Amundsen Basin. If we accept these statistical estimates, they place strong constraints on our ability to define long-term means, and hence the magnitudes of ALCT and SSS anomalies computed using synoptic measurements from the 1990s referenced to means from climatologies. This is because climatologies are computed from data which do not adequately represent all phases of Arctic variability, so calculation of means, and consequently, anomalies, is problematic. This difficulty is aggravated in regions having large spatial and/or temporal variability such as the Nansen Basin (ALCT) or the Amundsen Basin (SSS). Limited our analysis to observations from the 1970s only, our computed water temperature and salinity σ may be underestimated. Further research is necessary to get better understanding of variability of the Arctic waters.

Appendix A: Robustness of Analyses

[16] The coarse resolution of the historical data places strong constraints on our ability to resolve fine-scale features, although the quantitative effect on resolution of low-mode features such as the magnitude and depth of the temperature maximum is not clear. In order to evaluate the limitations of the data in a quantitative way, we performed a simple "experiment," in which data from a standard high-resolution CTD cast were sub-sampled at depths corresponding to the standard levels in the historical data, after which statistics were computed for the sub-sampled data and compared with values computed for the full data set. Modern high-resolution CTD profiles of temperature and salinity from the 1994 Arctic Ocean Section [*Swift et al.*, 1997] are used. While much detail is lost by subsampling, the major features of the water column remain practically intact: a surface mixed layer, a shallow temperature maximum associated with Bering Sea inflow, and the deeper ALCT. We find that the 50–100m depth resolution of the subsampled data in the vicinity of the AL core allows the ALCT to be computed quite accurately (with a 0.98 correlation between time series of subsampled and unsubsampled ALCT), but the precise depth of the temperature maximum cannot be accurately deduced from the sub-sampled data.

[17] Sensitivity of our statistical estimates (Figure 4) to box location, size, and procedure for estimating σ (means for regions, or local values from P&T; one-stage method versus multi-stage method) was also evaluated. This analysis shows robustness of regional estimates for the ALCT and SSS statistics. For example, averaged over the 13 regions, the difference between ALCT means and σ calculated for "standard" regions (Figure 1) and for reduced-size regions (by 1° and 2° from each latitudinal and longitudinal side, respectively) is 0.04°C and 0.03°C. The average difference in σ calculated by taking means from regions and from P&T is 0.05°C. Comparison of σ calculated using one-stage and multi-stage [*EWG*, 1997] procedures, shows that, on average, the relative error *R* (%) for estimating water temperature and salinity standard deviation (σ_T, σ_S) is about 30–40%. These estimates are spatially averaged and depend substantially on geographical location and depth. For example, estimates for σ_T show $R \sim 20\%$ at 100m and $R > 70\%$ at 500m. Estimates of *R* for σ_S are somewhat less sensitive to the choice of procedure, varying from 16% at 25m to 47% at 500m.

[18] **Acknowledgments.** This research is a part of ongoing NSF-funded IARC Program "Nansen and Amundsen Basins Observational System" (NABOS). We thank the Frontier Research System for Global Change for financial support. We also thank T. Weingartner for his comments.

References

Carmack, E. C., R. W. Macdonald, R. G. Perkin, F. A. McLaughlin, and R. J. Pearson, Evidence for warming of Atlantic water in the southern Canadian Basin of the Arctic Ocean: Results from the Larsen-93 expedition, *Geophys. Res. Lett.*, *22*, 1061–1064, 1995.

Dmitrenko, I. A., S. A. Kirillov, V. A. Gribanov, and H. Kassens, Ice productivity in recurring on the Kara and Laptev sea shelf estimated from long-term hydrological observations, *Russ. Meteorol. Hydrol.*, *12*, 22–30, 2001.

Environmental Working Group (EWG), *Joint U.S.-Russian Atlas of the Arctic Ocean* [CD-ROM], Natl. Snow and Ice Data Cent., Boulder, Colo., 1997.

Gorshkov, S. G., *Atlas of Oceans: Arctic Ocean* (in Russian), 199 pp., Mil. Def., Moscow, 1980.

Guay, C. K. H., K. K. Falkner, R. D. Muench, M. Mensch, M. Frank, and R. Bayer, Wind-driven transport pathways for Eurasian Arctic river discharge, *J. Geophys. Res.*, *106*, 11,469–11,480, 2001.

Johnson, M. A., and I. V. Polyakov, The Laptev Sea as a source for recent Arctic Ocean salinity changes, *Geophys. Res. Lett.*, *28*, 2017–2020, 2001.

Karcher, M. J., R. Gerdes, F. Kauker, and C. Koberle, Arctic warming: Evolution and spreading of the 1990s warm event in the Nordic Seas and the Arctic Ocean, *J. Geophys. Res.*, *108*(C2), 3034, doi:10.1029/2001JC001265, 2002.

McLaughlin, F. A., E. C. Carmack, R. W. Macdonald, and J. K. B. Bishop, Physical and geochemical properties across the Atlantic/Pacific water mass front in the southern Canadian Basin, *J. Geophys. Res.*, *101*, 1183–1197, 1996.

McPhee, M. G., T. P. Stanton, J. H. Morison, and D. G. Martinson, Freshening of the upper ocean in the Arctic: Is perennial sea ice disappearing?, *Geophys. Res. Lett.*, *25*, 1729–1732, 1998.

Polyakov, I. V., and L. A. Timokhov, Mean fields of temperature and salinity of the Arctic Ocean, *Russ. Meteorol. Hydrol.*, *7*, 33–38, 1994.

Quadfasel, D. A., A. Sy, D. Wells, and A. Tunik, Warming in the Arctic, *Nature*, *350*, 385, 1991.

Rudels, B., R. Meyer, E. Fahrbach, V. Ivanov, S. Osterhus, D. Quadfasel, U. Schauer, V. Tverberg, and R. A. Woodgate, Water mass distribution in Fram Strait and over the Yermak Plateau in summer 1997, *Ann. Geophys.*, *18*, 687–705, 2000.

Steele, M., and T. Boyd, Retreat of the cold halocline layer in the Arctic Ocean, *J. Geophys. Res.*, *103*, 10,419–10,435, 1998.

Swift, J. H., E. P. Jones, K. Aagaard, E. C. Carmack, M. Hingston, R. W. Macdonald, F. A. McLaughlin, and R. G. Perkins, Waters of the Makarov and Canada basins, *Deep Sea Res.*, *44*, 1503–1529, 1997.

Treshnikov, A. F., *Atlas of the Arctic* (in Russian), 204 pp., Moscow, 1985.

Woodgate, R. A., K. Aagaard, R. D. Muench, J. Gunn, G. Bjork, B. Rudels, A. T. Roach, and U. Schauer, The Arctic Ocean boundary current along the Eurasian slope and the adjacent Lomonosov Ridge: Water mass properties, transports and transformations from moored instruments, *Deep Sea Res., Part I*, *48*, 1757–1792, 2001.

R. L. Colony, I. Dmitrenko, I. Polyakov, and D. Walsh, International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK 99775-7220, USA.

L. A. Timokhov, Arctic and Antarctic Research Institute, 38 Bering Str., St. Petersburg, 199397 Russia.