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One more step toward a warmer Arctic

Igor V. Polyakov,[1] Agnieszka Beszczynska,[2] Eddy C. Carmack,[3] Igor A. Dmitrenko,[1]
Eberhard Fahrbach,[2] Ivan E. Frolov,[4] Rüdiger Gerdes,[2] Edmond Hansen,[5] Jürgen Holfort,[5]
Vladimir V. Ivanov,[1] Mark A. Johnson,[6] Michael Karcher,[2,7] Frank Kauker,[2,7]
James Morison,[8] Kjell A. Orvik,[9] Ursula Schauer,[2] Harper L. Simmons,[1]
Øystein Skagseth,[9] Vladimir T. Sokolov,[4] Michael Steele,[8] Leonid A. Timokhov,[4]
David Walsh,[10] and John E. Walsh[1]

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[1] This study was motivated by a strong warming signal seen in mooring-based and oceanographic survey data collected in 2004 in the Eurasian Basin of the Arctic Ocean. The source of this and earlier Arctic Ocean changes lies in interactions between polar and sub-polar basins. Evidence suggests such changes are abrupt, or pulse-like, taking the form of propagating anomalies that can be traced to higher-latitudes. For example, an anomaly found in 2004 in the eastern Eurasian Basin took ∼1.5 years to propagate from the Norwegian Sea to the Fram Strait region, and additional ∼4.5–5 years to reach the Laptev Sea slope. While the causes of the observed changes will require further investigation, our conclusions are consistent with prevailing ideas suggesting the Arctic Ocean is in transition towards a new, warmer state. **Citation:** Polyakov, I. V., et al. (2005), One more step toward a warmer Arctic, *Geophys. Res. Lett.*, *32*, L17605, doi:10.1029/2005GL023740.

1. Introduction

[2] The warm (temperature > 0°C) and salty intermediate (150–900 m) Atlantic Water (AW) plays a special role in the thermal balance of the Arctic Ocean. It enters the Norwegian Sea and flows northward as the Norwegian Atlantic Current (Figure 1). About one third of this flow continues east on the Barents Sea shelf, while the larger portion, the West Spitsbergen Current, flows toward Spitsbergen [*Schauer et al.*, 2004]. Both branches lose heat to the atmosphere until their upper parts merge with and subduct below the colder and fresher Arctic surface water in the Arctic Ocean. The warm and saline core of the Fram Strait branch is preserved at intermediate levels while the Barents Sea branch, crossing the shallow shelf, undergoes further cooling, freezing/melting and mixing with continental run-off. Finally both branches rejoin in the northern Kara Sea and flow cyclonically along the basin margins [*Rudels et al.*, 1994] (Figure 1). Isolated from drifting ice and the atmosphere by a surface layer, the AW carries significant quantities of heat. Maximum (2–3°C) AW temperatures are found in the Nansen Basin, while in the Canadian Basin the AW temperature has, until recently, remained near 0.5°C, but is now warming above 1°C [*Shimada et al.*, 2004]. This AW temperature decrease during transit provides evidence that some fraction of AW heat may be lost along the AW pathways.

[3] The first evidence of warming in the AW layer was found in the Nansen Basin in 1990 [*Quadfasel et al.*, 1991]. Positive AW temperature anomalies of up to 1°C relative to the *Environmental Working Group* (*EWG*) [1997] climatology were found in the Makarov Basin in 1993, centered over the Lomonosov and Mendeleyev Ridges [*Carmack et al.*, 1995; *Swift et al.*, 1997; *Steele and Boyd*, 1998; *Morison et al.*, 1998]. Increased transport caused a displacement of the Pacific-Atlantic water boundary towards the Canadian Basin [*McLaughlin et al.*, 1996; *Morison et al.*, 1998]. Both observations [*Woodgate et al.*, 2001] and modeling [*Karcher et al.*, 2003] indicate the variable nature of the AW flow, with abrupt cooling/warming events. This sustained warming of the AW layer stopped in the late 1990s [*Boyd et al.*, 2002], but remnants of this warming have recently arrived in the Canada Basin [*Shimada et al.*, 2004].

2. Data

[4] The McLane Mooring Profiler (MMP, 78°27′N, 125°40′E) was used at the eastern Eurasian Basin (EEB) mooring. This instrument is capable of profiling along a mooring line at a speed of ∼25 cm/s, with a sampling period of 0.5s. The MMP measures temperature, salinity, and velocity. Accuracy of temperature sensor is 0.002°C. Water temperature and salinity from Fram Strait (78°50′N, 78°845′E, instrument depth ∼250 m) and Svinoy (62°48′N, 4°06′E, instrument depth ∼300 m) moorings were measured using Aanderaa current meters, with a temperature resolution of 0.01°C and accuracy of 0.05°C. Data were recorded every hour at Svinoy and every two hours in Fram Strait. The raw data were despiked, low-pass filtered with a cut-off period of 40h and averaged over 6h intervals. Due to instrument failure on the Fram Strait mooring, the original time series does not cover the periods 1999–2000 and 2001–2002. The missing data were reconstructed based on the high

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[1] International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, Alaska, USA.
[2] Alfred-Wegener Institut fur Polar- und Meeresforschung, Bremerhaven, Germany.
[3] Department of Fisheries and Oceans, Sydney, British Columbia, Canada.
[4] Arctic and Antarctic Research Institute, St. Petersburg, Russia.
[5] Norwegian Polar Institute, Tromsø, Norway.
[6] Institute of Marine Science, University of Alaska Fairbanks, Fairbanks, Alaska, USA.
[7] O.A.Sys – Ocean Atmosphere Systems GbR, Hamburg, Germany.
[8] Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle, Washington, USA.
[9] Bjerknes Centre for Climate Research, GI/UB, Bergen, Norway.
[10] Naval Research Laboratory, Washington, D. C., USA.

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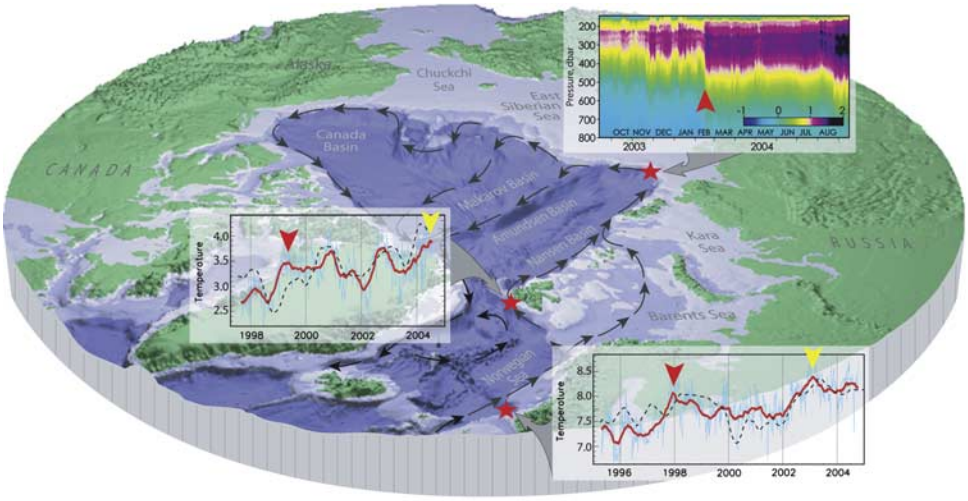

Figure 1. Propagation of warm temperature anomalies into the Arctic Ocean. Large red and yellow arrows indicate two pulses of warm AW. The pathways of AW are shown schematically by black arrows. Red stars show locations of moorings. (Top) Depth–time diagram of water temperature (°C) from the EEB mooring. (Middle and bottom) Time series of water temperature (°C) from Fram Strait and Svinoy moorings. Blue lines show weekly averaged temperature, red lines show six-month running mean temperature. Simulated [*Karcher et al.*, 2003] de-seasoned six-month running mean water temperature anomalies are shown by black dashed lines.

correlation ($R > 0.85$) observed with the neighbouring instrument at the same depth on a mooring 7 km to the east.

3. Propagation of Warm Anomalies Into the Arctic Ocean

[5] Recent observations show that another pulse of anomalously warm AW has entered the Arctic Ocean. Mooring observations in the EEB carried out in 2002–04 showed that modest variations in the earlier part of the record were dramatically exceeded by two abrupt warming events in February and late August of 2004 (Figure 1). The AW temperature increase lasted eight months, until the end of the available record, and reached 0.8°C, comparable with the anomaly found in the Eurasian Basin in the 1990s [*Quadfasel et al.*, 1991]. This recent warming is associated with substantial increase in AW layer thickness and a corresponding 60–70% increase in water column heat content (with freezing point taken as a reference temperature). Attendant observations carried out in three consecutive summers provide evidence that this anomaly occupies the entire area of the EEB continental slope covered by the oceanographic surveys (Figure 2).

[6] The source of this and earlier changes observed in the Arctic Ocean over recent decades lies in interactions between polar and sub-polar basins. Several observational sites are maintained along the path of the AW from the North Atlantic to the Arctic Ocean. One is the Svinoy section located west of Norway at about 63°N crossing the eastern branch of the Norwegian Atlantic Current, the major conduit between the Atlantic and the Arctic Ocean [*Orvik et al.*, 2001]. The second site is Fram Strait, where the Fram Strait branch of the AW inflow is monitored [*Schauer et al.*, 2004] (Figure 1). Temperature records from both sites exhibit several warming events superimposed on a background warming trend (Figure 1). This evolution of water temperature is related to the atmospheric processes: an amplified north-south oriented dipole in sea-level pressure over the Atlantic in the 1980–90s caused enhanced westerly winds, which drove warmer water from the North Atlantic into the Norwegian Sea and from there into the Arctic Ocean [*Skagseth*, 2004; *Karcher et al.*, 2003]. This likely enhanced the inflow of warmer water, resulting in higher temperatures along AW pathways (Figure 1).

[7] A distinct pattern of two warming events observed at Svinoy in 1997–98 and 2002–03 allows the propagation of the anomalies to be traced to higher-latitude regions (Figure 1, see also Figure S1 from auxiliary material[1]). For example, lagged correlations (*R*) of two-year-long portions of the Svinoy and Fram Strait records identified the best match between the 1997 peak from the Svinoy record and the 1999 peak from the Fram Strait record (compare $R = 0.92$ for these two peaks and $R = 0.78$ for the second-best match between 1997 peak from Svinoy and 2002 peak from Fram Strait records, Figure S1). This anomaly was found later, in 2004, in the EEB (also identified by the lagged correlations) so it took ~1.5 years for the anomaly to reach the Fram Strait region and an additional ~4.5–5 years to reach the Laptev Sea slope. These estimates suggest an anomaly speed of about 3.8 cm/s for the first segment (Svinoy to Fram Strait) and ~1.5 cm/s for the second segment (Fram Strait to the Laptev Sea). The estimate for the first segment agrees well with previous computations of advection time for the 1983–84 warm anomaly, which traveled northward from the Svinoy section with a speed of ~3.6 cm/s [*Furevik*, 2001], for the Great Salinity Anomaly [*Dickson et al.*, 1988], and for sea-surface temperature anomalies propagating along the Norwegian coast [*Furevik*, 2000]. Results from the coupled ice–ocean NAOSIM model agree with the observational estimates [*Karcher et al.*, 2003]. For example, the best fit between simulated time series of water temperature from Svinoy and Fram Strait is found at a 1.5 year lag ($R = 0.68$) whereas for the

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL023740.

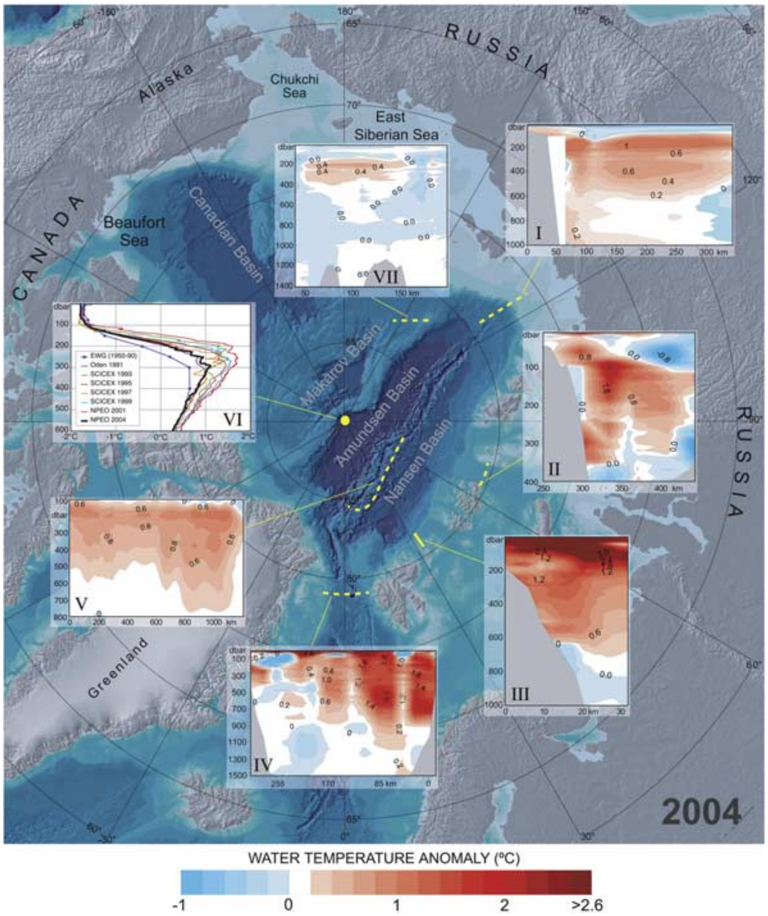

Figure 2. Evidence of a new warm anomaly entering the central Arctic Ocean. Numerals I–VI indicate temperature sections (°C) taken in 2004 (data are reduced by means taken from the 40-year mean *EWG* [1997] climatology). Numerals I, III, and IV indicate cross-sections occupied during IB *Kapitan Dranitsyn*, RV *Lance*, and FS *Polarstern* cruises respectively, numerals II and VII refer to sections carried out during SS *Akademik Fedorov* cruise, numeral V refers to a cross-section from the Russian manned drifting station *SP-32*, and numeral VI indicates a panel showing vertical profiles of temperature (°C) measured at the North Pole. Horizontal axes show distance in panels I–V and VII and temperature in panel VI.

Svinoy and EEB time series the lag is 7 years ($R = 0.54$). Half of the observed heat flux increase observed in 1999 in Fram Strait was due to increased temperatures in the inflowing water, while the other half was due to stronger flow [*Schauer et al.*, 2004]. This increase is comparable to the strength of warming observed in the Arctic Ocean in the 1990s [*Schauer et al.*, 2004], corroborating our previous conclusion based on the EEB data.

[8] The abrupt nature of these warming events is striking. The first temperature increase at the EEB slope of about 0.4°C in February 2004 happened in a single day, after which the AW layer equilibrated at a new warmer state for almost seven months, when another abrupt warming occurred. The measured along-slope current reduced dramatically, from 1.6 cm/s to less than 0.7 cm/s, after the warming reached the mooring site. In this, high-latitude basins seem to play the role of a trap for anomalies sent by the North Atlantic Ocean to its northern neighbor which is also supported by the earlier finding of the decay of propagation speed of the oceanic flow with higher latitude [*Swift et al.*, 1997] (because of the short length of the available record, caution is required in interpreting our data). Substantial changes in thermohaline structure at two other mooring sites also occurred within days. A plausible interpretation for these events is the passage of a sharp-edged front through the mooring location. It is unclear whether the mooring was on the edge of the current, and the temperature change shows a lateral shift in the position of the current, or whether the change represents the along-stream structure of the AW current. Future study will help to clarify the nature of propagating fronts in the Arctic Ocean. Regardless of the exact cause, the change is abrupt and persistent.

[9] Mooring-based records and oceanographic surveys suggest that a new pulse of anomalously warm water entered the Arctic Ocean in 2004, complementing the anomaly observed in Fram Strait in 1999 and near the EEB slope in 2004 (Figures 1 and 2). Observations made in the Nansen Basin in 2004 provide evidence that the ocean was much warmer relative to the *EWG* [1997] climatology (Figure 2). Temperature anomalies of ~1°C were measured in 2004 in the Nansen Basin, including the Fram Strait region, the area over the Gakkel Ridge, and in the Saint Anna Trough (Figure 2), comparable with anomalies seen in the early 1990s. AW temperatures of 4.2°C measured east of Svalbard in 2004 were higher than has ever been recorded in the history of observations, including those from the anomalously warm 1990s. Combined with data on the previous warm anomaly, which entered the Arctic Ocean

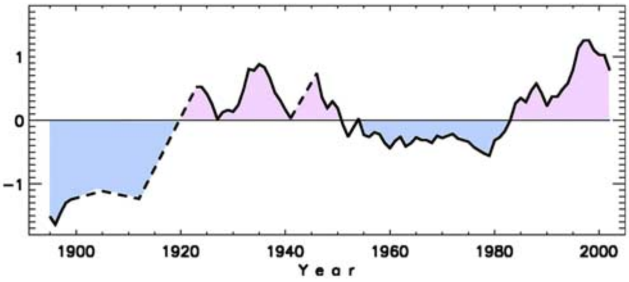

Figure 3. Long-term variability of temperature of the intermediate AW of the Arctic Ocean. Prolonged warm (red shade) and cold (blue shade) periods associated with phases of multi-decadal variability and a background warming trend are apparent from the record of 6-year running mean normalized AW temperature anomalies (dashed segments represent gaps in the record). Adapted from *Polyakov et al.* [2004].

through Fram Strait in 1999 and was captured in 2004 by the EEB mooring and attendant oceanographic survey (Figures 1 and 2), this information provides evidence that the Nansen Basin of the Arctic Ocean entered a new warm state. These two warm anomalies are progressing towards the Arctic Ocean interior, as indicated by measurements over the Siberian part of the Lomonosov Ridge, where in 2004 temperatures were higher than normal by 0.6°C, but still have not reached the North Pole observational site (Figure 2). Thus, observations suggest that the new anomalies will soon enter the central Arctic Ocean, leading to further warming of the polar basin.

4. Concluding Remark

[10] What remains obscure is the degree to which this warming may be due to long-term change or to multi-decadal fluctuations. Multi-decadal fluctuations with time scales of 50–80 years are known to be exceptionally strong in the Arctic [*Polyakov and Johnson*, 2000]. Through analysis of a vast collection of observational data it was shown that over the 20th century multi-decadal AW fluctuations are a dominant mode of variability (Figure 3). Associated with this variability, the AW temperature record shows two warmer periods in the 1930–40s and in recent decades, and two colder periods early in the 20th century and in the 1960–70s. While the causes of the observed variability will require further investigation, our analysis suggests that the Arctic Ocean is in transition towards a new, warmer state, with possible implications for already reduced Arctic ice cover, and potential impacts on processes occurring at lower latitudes.

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I. A. Dmitrenko, V. V. Ivanov, I. V. Polyakov, H. L. Simmons, and J. E. Walsh, International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK 99775-7220, USA. (igor@iarc.uaf.edu)

I. E. Frolov, V. T. Sokolov, and L. A. Timokhov, Arctic and Antarctic Research Institute, St. Petersburg, Russia, 199397.

D. Walsh, Naval Research Laboratory, Washington, DC 20375, USA.

M. A. Johnson, Institute of Marine Science, University of Alaska Fairbanks, Fairbanks, AK 99775-7220, USA.

E. C. Carmack, Department of Fisheries and Oceans, Sydney, B. C., Canada, V8L 4B2.

J. Morison and M. Steele, Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle, WA 98105, USA.

A. Beszczynska, E. Fahrbach, R. Gerdes, M. Karcher, F. Kauker, and U. Schauer, Alfred-Wegener Institut fur Polar- und Meeresforschung, Bremerhaven, D-27515, Germany.

E. Hansen and J. Holfort, Norwegian Polar Institute, N-9296 Tromsø, Norway.

K. A. Orvik and Ø. Skagseth, Bjerknes Centre for Climate Research, GI/UB, N-5007 Bergen, Norway.