

Fate of Early 2000s Arctic Warm Water Pulse

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The water mass structure of the Arctic Ocean is remarkable, for its intermediate (depth range ~150–900 m) layer is filled with warm (temperature >0°C) and salty water of Atlantic origin (usually called the Atlantic Water, AW). This water is carried into and through the Arctic Ocean by the pan-Arctic boundary current, which moves cyclonically along the basins' margins (Fig. 1). This system provides the largest input of water, heat, and salt into the Arctic Ocean; the total quantity of heat is substantial, enough to melt the Arctic sea ice cover several times over. By utilizing an extensive archive

of recently collected observational data, this study provides a cohesive picture of recent large-scale changes in the AW layer of the Arctic Ocean. These recent observations show the warm pulse of AW that entered the Arctic Ocean in the early 1990s finally reached the Canada Basin during the 2000s. The second warm pulse that entered the Arctic Ocean in the mid-2000s has moved through the Eurasian Basin and is en route downstream. One of the most intriguing results of these observations is the realization of the possibility of uptake of anomalous AW heat by overlying layers, with possible implications for an already-reduced Arctic ice cover.

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WARM PULSES OF THE ATLANTIC WATER LAYER ENTERING THE ARCTIC OCEAN.

The first evidence of a recent warming event in the AW layer of the Arctic Ocean was found in 1990 in the Nansen Basin. Positive temperature anomalies of up to 1°C, associated with this 1990s pulse of warm AW, moved downstream and reached the Makarov Basin by 1993. By the time this pulse reached the Canada Basin in the early 2000s the positive temperature anomalies were only up to 0.5°C.

Observations from 1997 to 2009 in Fram Strait, the entry point of AW into the Arctic, captured a second AW warm pulse from 2004 to 2007 that was first measured downstream in the eastern Eurasian Basin in 2004. Extensive observations made in 2007 under the auspices of the International Polar Year revealed temperature anomalies of up to 1°C along the AW pathway in an advection pattern similar to that observed in the 1990s. Moreover, a comparison of the AW temperatures from the 1990s and 2007 showed this second warming to be, on average, 0.2°C greater than the 1990s warming.

The speed of along-slope warming propagation can be estimated by the distinctive pattern of this warming event. According to these estimates, it took ~5 years for the warming to reach the Laptev Sea

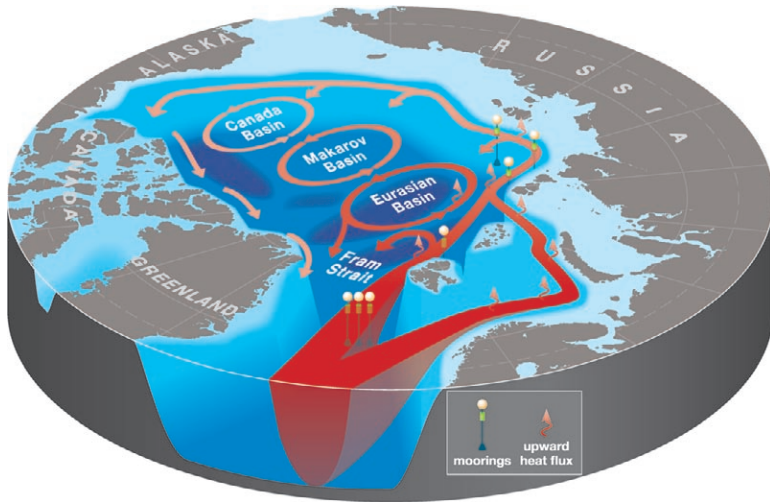


FIG. 1. Circulation of the intermediate Atlantic water of the Arctic Ocean shown by red and pink arrows. In the real ocean the flows likely follow topographic contours; the arrows show schematic pathways and do not reflect details of the flow. The observational data used in this study are from repeated oceanographic sections (series of temperature and salinity vertical profiles along lines) and moorings (freestanding devices moored to the seafloor). The submarine Lomonosov Ridge, running from Siberia to Greenland, separates the Makarov and Eurasian Basins. A deeper midocean ridge, the Nansen Gakkel ridge, roughly parallel to the Lomonosov Ridge, divides the Eurasian Basin into the Nansen Basin (near the Barents Sea) and the Amundsun Basin (along the Lomonosov Ridge)—both not marked.

slope from the Fram Strait region (Fig. 2), suggesting a speed of $\sim 1.5 \text{ cm s}^{-1}$. Repeat oceanographic sections (vertical profiles of temperature and salinity collected at closely spaced stations along a line) as a part of an oceanographic network deployed in the late 1990s/early 2000s documented the ongoing large-scale warming of the Eurasian Basin, which culminated in 2006–08 (Figs. 2 and 3). Furthermore, observations suggest that the warm anomaly propagated further eastward, toward the Canada Basin (Fig. 2). For example, 2009 observations from the northern side of the Northwind Ridge in the Canada Basin showed AW temperatures were higher than those observed in the same area in 2008. However, attribution of this warm anomaly to the AW pulse of the mid-2000s requires data collection in 2010 and beyond.

RETREAT OF AW WARMING OF THE 2000s. Observations from 2008–09 suggest that the recent warm surge has passed its peak in the Eurasian Basin. Stronger cooling of $\geq 1.5^\circ\text{C}$ is found in the western Nansen Basin, near the origin of AW for the Arctic Ocean interior. Weaker cooling of $\sim 0.5^\circ\text{C}$ or even less

was documented further downstream from Fram Strait, in the eastern Eurasian Basin (Figs. 2 and 3).

Although the data are sparse, there are implications that along-slope advection of the water temperature anomaly is not the whole story. A point-to-point comparison of the available temperature records (Figs. 2 and 3) suggests an almost synchronous reduction of the warm anomaly from the Fram Strait and the Eurasian Basin regions. It suggests that cooling is not caused by the influx of colder AW, because it would require an unrealistically rapid propagation of water from Fram Strait along the slope downstream. Instead, it raises the possibility that some other, nonadvective processes may modulate temperature changes in these regions. For example, satellite records showed a 3.7% sea ice–extent decline since the early 1980s. These changes culminated in a record-breaking ice minimum during the summer of 2007. We suggest local atmosphere–ocean and shelf–basin interactions influenced by anomalous openings in ice cover likely play an

important role in ventilating the ocean’s interior. The observed changes may also be tied to changes in AW pathways. Such hypotheses provide new perspectives on the increasing role of these interactions under changing high-latitude marine climate.

SPREAD OF AW HEAT UPWARD. What impacts do the observed AW warm pulses have on the upward flux of AW heat? How does the uptake of AW heat by overlying layers evolve as the anomalously warm pulses shift from their warming to cooling phase? The AW is believed to be effectively insulated from the pack ice by a ~ 30 – 50 -m cap of fresh, cold surface water and a strong pycnocline in which salinity increases from values of $S \sim 33$ psu (effectively equivalent to parts per thousand) or lower to $S \sim 34.5$ psu at a depth of 150–300 m. The decrease of AW temperature with distance from Fram Strait implies that AW heat must be lost as the AW spreads. Most of this heat is spread laterally by advection, eddy stirring, or double diffusive processes, but some portion may also be lost upward, to the overlying halocline waters. New repeated temperature and salinity measurements in

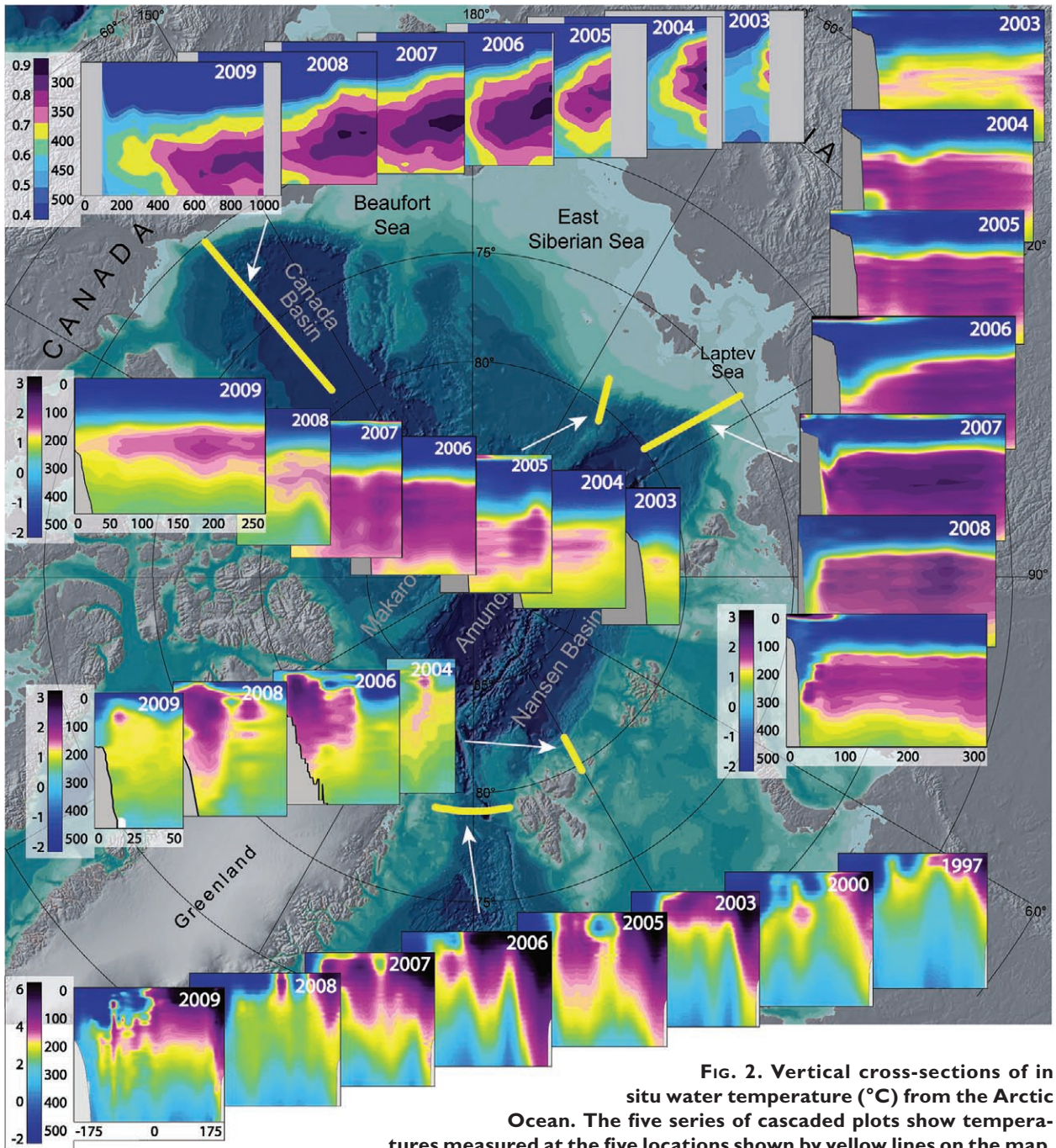


FIG. 2. Vertical cross-sections of in situ water temperature (°C) from the Arctic Ocean. The five series of cascaded plots show temperatures measured at the five locations shown by yellow lines on the map.

In each section, the horizontal axis shows distance from the southern end of the section (km) and the vertical axis shows depth (m). Note that the horizontal scale and temperature scale vary from one cascaded section to another. Warming in the Eurasian Basin is associated with the warm AW pulse, which entered the polar basin in the 2000s; in contrast, the warm anomaly in the Canada Basin is related to an earlier pulse of warm water, which entered the Arctic Ocean interior through Fram Strait in the early 1990s.

the halocline and just below the upper mixed layer (referred to here as the overlying layer, OL) from several cross-isobath sections spanning 43° to 185°E show consistently higher temperatures in the OL in

eastern sections than in the western sections. Since the AW layer is the closest source of heat, this leads us to suggest significant upward heat flux from the AW to the OL during the transit along the slope.

Figure 3 provides additional intriguing data for our analysis. The data show (within available temporal resolution) apparently synchronous warming of the AW and the OL at 125°E. This is consistent with a rapid communication of heat between the AW and the OL. Heat budget estimates based on these measurements yield $\sim 3\text{--}4 \text{ W m}^{-2}$ for the early 2000s and up to $\sim 6 \text{ W m}^{-2}$ for the peak year of 2007. Thus, these observations suggest that the recent warming of AW in the Eurasian Basin may have facilitated greater upward transfer of AW heat. Available estimates based on numerical modeling using coupled ice–ocean regional models suggest that the decrease in ice thickness in the Eurasian Basin over recent decades of $\sim 30 \text{ cm}$ resultant from increases in AW ocean heat flux was comparable to the decrease of ice thickness due to atmospheric thermodynamic forcing. The implication is that AW warming helped precondition the arctic sea ice for the extreme ice loss observed in recent years.

Microstructure observations showed, however, that halocline mixing in the Arctic interior is very weak, $\sim 1 \text{ W m}^{-2}$ or less, but that mixing in the Laptev Sea is higher, with episodic peaks of $\sim 4\text{--}8 \text{ W m}^{-2}$. We do not yet understand how to reconcile these estimates. How much of this heat flux reaches the surface and impacts Arctic ice remains an open question, and presents a target for future research.

SUBPOLAR BASINS AS A SOURCE FOR HIGH-LATITUDE CHANGES.

Interactions between polar and subpolar basins drive extreme change throughout the oceanic system. Observations carried out since 2003 documented the recent, steady warming of the eastern Norwegian Sea. These regional changes of water temperature are related to the enhanced supply of warmer water from the North Atlantic into the Norwegian Sea and northward into the Arctic Ocean, resulting in higher temperatures along AW pathways. Data from the West Spitsbergen Current showed that intensive AW warming culminated in 2006 with AW temperature anomalies (relative to 2000–07 summer mean) up to 1.2°C in the vicinity of Svalbard. The magnitude and timing of this warm anomaly are confirmed by data from a free-standing device moored to the sea floor (a “mooring”) in Fram Strait (Fig. 3) operated by European scientists since the mid-1990s, which also showed an increased transport of warm ($T > 4^\circ\text{C}$) water in 2006 and 2007. These mooring data show that the yearly-averaged volume transport of

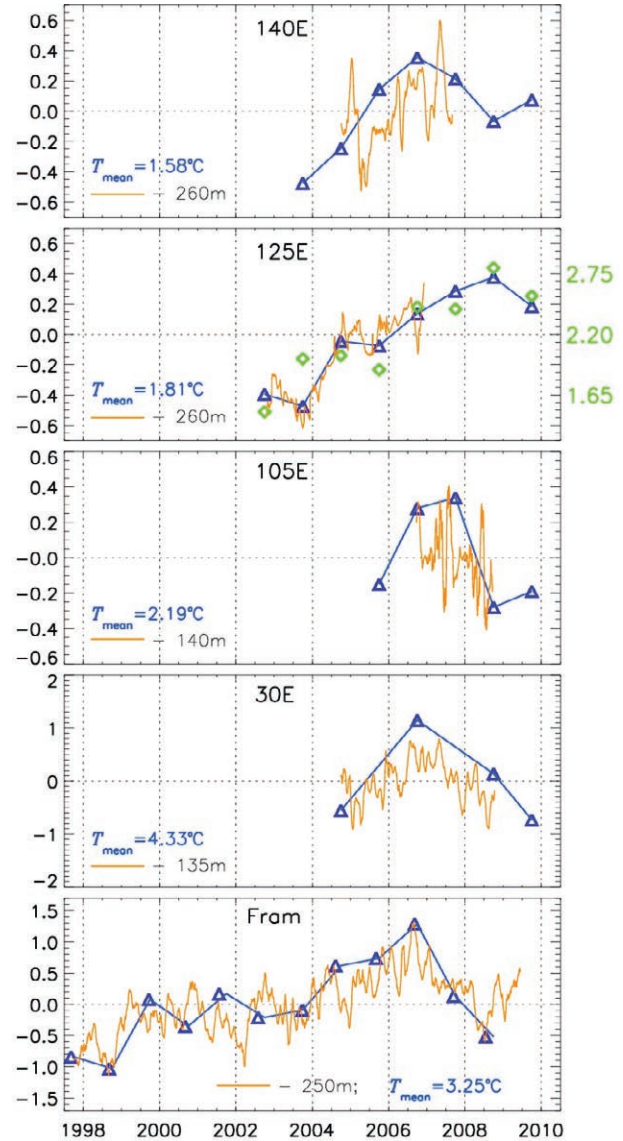


FIG. 3. Time series of Atlantic Water (AW) temperature anomalies ($^\circ\text{C}$) relative to the time-series means from oceanographic sections (blue) and mooring observations (yellow) and heat content density of the layer overlying the AW ($\sim 50\text{--}125\text{-m}$ depth range, MJ m^{-3} , green).

water with $T > 4^\circ\text{C}$ was 80% higher in 2006 than the long-term (2002–08) mean. Oceanographic surveys and mooring observations demonstrate that the temperature peak in 2006 was followed by cooling, with a temperature decrease of $\sim 1^\circ\text{C}$ (Fig. 3). This cooling likely contributed to the 2008–09 reduction of the warm AW pulse from the eastern Eurasian Basin (Fig. 2). However, a recent 2009 oceanographic investigation in Fram Strait carried out by European scientists has reported a new warm anomaly (Fig. 2).

These findings suggest that a third pulse of warm water will soon enter the Arctic Ocean.

CONCLUSIONS. Long-term observations have provided critical information about the evolution of a remarkable warm pulse of AW from its entrance at Fram Strait into the eastern Arctic Ocean and its decay along its pathway into the ocean interior. These observations also raise the tantalizing possibility of uptake of anomalous AW heat by overlying layers, with possible implications for an already-reduced Arctic ice cover—a fundamental issue for modern-day polar climatology. Coherent changes in local atmospheric and oceanic thermodynamic forcing and multiyear ice coverage suggest a plausible role of anomalous oceanic heat in recent changes of the Arctic ice cover. There are also some indications of an increasing role for both local atmosphere–ocean and shelf–basin interactions.

Detection and documentation of the current anomalous state of the Arctic Ocean is possible only thanks to concerted international observational efforts. Observations were provided by the Canada/U.S. Beaufort Gyre Exploration Project; the Canadian ArcticNet; the international Arctic/Subarctic Ocean Fluxes (ASOF) program; European Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies (DAMOCLES); the integrated Arctic Ocean Observing System (iAOOS)—Norway; and the Nansen and Amundsen Basins Observational System (NABOS), part of the Study of Environmental Arctic Change (SEARCH) program, plus several regional national programs. Between these programs, a combination of repeated oceanographic sections and moorings positioned along the AW path (Figs. 1 and 2) and maintained since the mid-1990s/early 2000s provided a unique opportunity to trace development of the 2000s warm AW pulse. This synthesis, resulting from data provided by interconnected Arctic Ocean field programs, demonstrates an important value-added property: each field program complements the others in a synergistic manner. For example, recent observations from upstream locations give some predictive power about the future thermal state of the downstream waters.


Many questions still exist, explanations for which remain currently obscure and will require further development of the observational network. Understanding the key factors that influence the upward transfer of intermediate-depth ocean heat to the surface layer and bottom of the sea ice and synchronous cooling

of the AW layer remain central research questions. Despite recent advancements, our knowledge about the boundary current remains poor. Addressing these and other questions requires a carefully orchestrated combination of sustained observations and advanced modeling. There is a community-wide effort to develop a sustained Arctic Observing Network (AON). This will be critical for developing reliable forecasts of the future state of the Arctic ice cap and the inclusion of AW pulses in global or regional Earth system models used for climate predictions.

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