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Mid-winter anomaly of sea ice in the Western Nansen Basin in 2010s

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Abstract. In this paper we review our earlier predictions of progressive “atlantification” of the Nansen Basin, meaning further eastward advance of the sub-polar structural water type along the Atlantic Water pathway. Fast and persistent reduction of sea ice area in the Western Nansen Basin in mid-winter after 2012 confirms the validity of our basic concept and gives some confidence for making cautious projection of future hydrographic and ice conditions in the Eastern Atlantic sector of the Arctic Ocean.

1. Introduction

Rapidly decaying sea ice cover in the Arctic Ocean is among the most visible indicators of the ongoing climate change. After the record minimum (in September, 2012), the ice area at the peak of seasonal decline is remaining significantly less than the average one over the period of relatively stable ice regime between 1979 and 2000 (Fig. 1a). The largest retreat of the consolidated ice edge (defined here by 50% ice concentration) in summer is occurring in the Pacific sector (90°E – 90°W) of the Arctic Ocean, where northward shift reaches 1000 miles. In the Eastern Atlantic sector (0° - 90°E) the retreat of the consolidated ice edge is substantially less, about 200 miles. No visible changes of ice cover happened in the Western Atlantic sector (90°W – 0°) or in the segment of the Pacific sector adjoining the Canadian Arctic archipelago. Spatial pattern of the ice cover changes in mid-winter is remarkably non-uniform. The only region where there are visible changes, compared to the 1979-2000 winter mean, is the Eastern Atlantic sector, including the Barents Sea and the Western Nansen Basin (WNB) between Svalbard and Franz Joseph Land (Fig. 1b). On the basis of statistical analysis of time series, in [1] concluded that the currently observed decrease of ice area in the Barents Sea was preconditioned by the reduction of ice import from the central basin in the 1990-2000s. Consequent weakening of density stratification enhanced vertical mixing down to intermediate Atlantic origin water (AW). Excessive heat input from the AW to the upper mixed layer (UML) led to further reduction of sea ice, thus closing the positive feedback loop. This explanation essentially renders the one suggested by [2] for accelerated ice decay in the WNB. Specific components contributing to the positive feedback loop on seasonal time scale were introduced and discussed in [2,3]. In this paper, we evaluate the main conclusions of the cited papers in view of the most recent changes in the WNB ice conditions and present a consistent picture of the present day state of the ice cover and water mass structure in the WNB. In Section 2, we focus on the characteristic features of the sea ice anomaly in the WNB in mid-winter, considering it to be the precursor of radical future changes in oceanographic regime of the Eastern Atlantic sector of the Arctic Ocean. In the subsequent three sections we distinguish and discuss key factors, which joint action led to the persistent reemergence of this anomaly in 2010s. General conclusions and broader outlook finalize the paper.

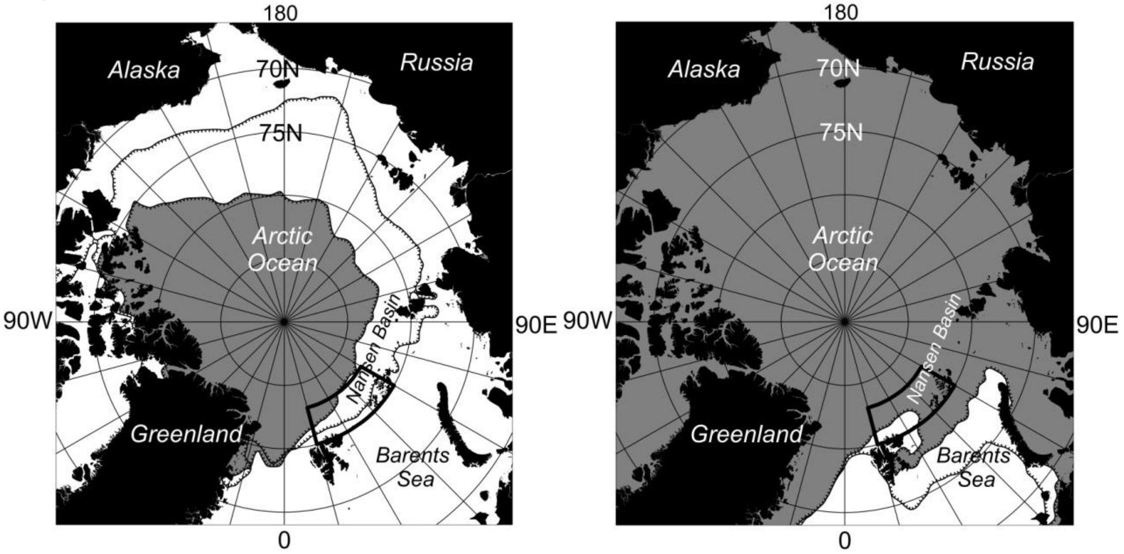

Figure 1. The mean boundary of 50 % ice concentration: (a) in September 1980-2000 (black line) and in September 2012-2016 (dashed); (b) in February 1980-2000 (black line) and in September 2012-2016 (dashed). WNB location (80-83ºN, 15-60ºE) is highlighted by the black polygon

2. Ice anomaly in the Western Nansen Basin in 2010s

Following the approach used in [2] we define the WNB within the boundaries 80-83°N, 15-60°E (Fig. 1). Presented in Figure 2 time series of ice area in the WNB is basically the time extension of graph in [3: Fig. 4] for the interval between 2012 and 2017. Extremely deep (up to four sample standard deviations=SSD) negative anomaly of ice area emerges in February 2012 and persists until the end of the record. The September time series also shows enhanced negative anomalies in 2012 and 2013, compared to the time interval between 1979 and 2011. However, in the most recent three years, the value of the negative anomaly at the peak of seasonal ice minimum either stays close to one SSD from the average, or the sign changes to positive. As was hypothesized by [3] low ice concentration (or thinner ice) zone in mid-winter is stretched along the AW flow north-east of Svalbard. This rather speculative, at that time, presumption was fully confirmed by satellite data during the next years [2]. Evolution of ice conditions in the WNB, during the extreme development of negative anomaly from December to February for the consecutive years 2011-2014, was described in detail by [2]. It was particularly shown that steady occurrence of the ice anomaly for the 1.5 – 2 months in mid-winter may not be explained by dynamical (wind) forcing alone. Additional thermodynamic forcing in mid-winter can only be provided by the oceanic heat, because to the north of the Polar Circle the heat balance at the ocean surface in the winter season is steady negative. The phenomenological concept explaining the origin of the winter ice anomaly in the WNB was initially formulated by [3]. In [3] this concept was extended to a self-consistent work hypothesis supported by statistical analysis, simple 1D model calculations, and output of a 3-dimensional hydrodynamic model. The principal possibility of deep (reaching the AW layer) convection development in the WNB causing intensive bottom ice melting was demonstrated under the present day conditions characterized by the depleted ice cover, warmer/saltier UML and warmer/saltier AW. In [4] the seasonal evolution of the vertical thermohaline structure in the WNB was scrutinized on the basis of oceanic reanalysis data MERCATOR [5; http://bulletin.mercator-ocean.fr]. The contribution of vertical thermohaline convection in delivering heat and salt to the ocean surface and sea ice was explicitly elucidated. In the next sections, we will point out and describe the drivers in charge of the formation and maintenance of the observed negative ice anomaly in the WNB, and substantiate the proposed explanation why this anomaly emerged in this specific place and time.

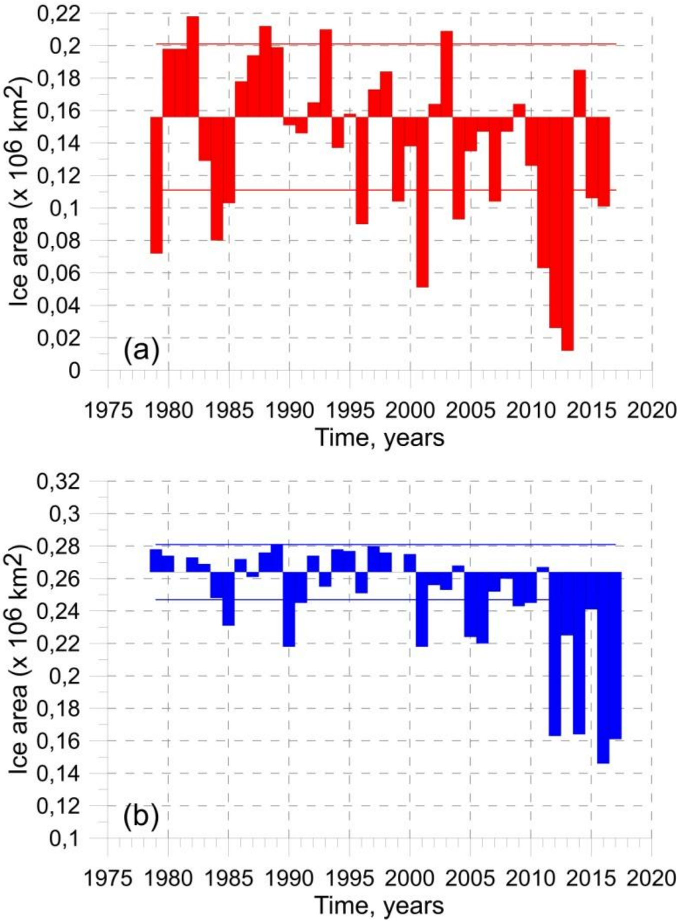

Figure 2. Time series of the ice area ($x10^6$ km^2) in the WNB in September (a) and in February (b). One sample standard deviation (SSD) is shown by solid lines

3. Sea ice decline on the pan-Arctic scale

It is generally acknowledged that the overall decline of the Arctic sea ice, and the transition to seasonal ice cover over the Arctic Ocean margins triggered progressive changes in the Arctic environment. Despite the fact that the transition to the present day state of the Arctic sea ice started back in 1990s [6,7], the decline of the sea ice extent in the WNB had not been distinct until the mid-2000s [3]. Even when the total sea ice area in the Arctic Ocean decreased abruptly in September, 2007, the retreat of the ice edge in the Eastern Atlantic sector was relatively moderate, 150-200 km on average as compared to 600-800 km in the Pacific sector. Significant change of the ice conditions in the WNB commenced after 2007. The probable reason behind this delay is the typical pattern of the large-scale ice circulation in the Arctic Ocean. The main elements of this pattern include ice transport from the Siberian shelf to the Fram Strait (the so-called Transpolar Drift) and the anticyclonic Beaufort Gyre in the Canadian Basin [8]. Due to continuous replenishment of ice in the Transpolar Drift by the newly forming ice, the WNB and the northern part of the Barents Sea appear to be permanently covered by consolidated perennial ice. Substantial replacement of the multiyear ice with seasonal ice after 2007 altered this stable regime since thinner young ice is less resistant to external dynamic and thermodynamic forcing. Faster deterioration of seasonal the ice led to the formation of vast areas with low ice concentration and/or open water by the end of summer. As a consequence of this overall shift in the state of pan-Arctic sea ice cover, decrease of ice extent in the Eastern Atlantic sector in the summer 2012 was comparable with the decrease in the Pacific sector, and in the following years sometimes exceeded it. At some point on time line, (basing on Fig.3, we assume that this happened in 2012) the ice import to the WNB from the central basin was critically reduced, causing a less amount of fresh water by the end of the melt season and consistent salinity increase in the UML.

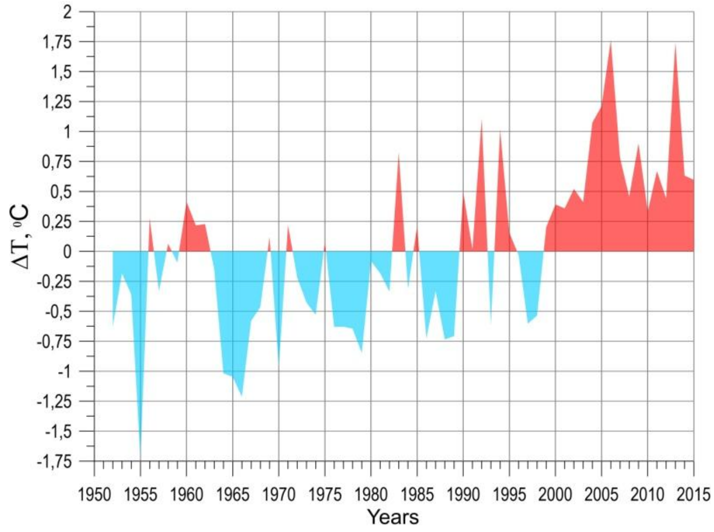

Figure 3. Spatially averaged temperature anomaly from 1950-2010 mean in the AW core in Fram Strait. Spatial averaging is done for the area 78-80°N, 5-10°E.

4. Atlantic Water warming in Fram Strait

Atlantic Water (AW) is the major advective heat source which substantially makes up the Arctic Ocean heat budget [9]. The temperature increase in the AW branch entering the Arctic Ocean through the Fram Strait has been observed since in 1990s [10]. The first warming pulse with a temperature peak about 1°C above the climate norm of 1950-1990 was documented in mid-1990s. After a short term cooling, a stronger pulse (up to 1.75°C above climate norm) occurred in the mid-2000s [11]. Later on, the AW temperature permanently remained within the range of .5 – 1.5°C above the climate norm [12]. A steady shift to the warmer state of the AW inflow disturbed the existing balance at the lower ice surface due to the increased heat flux from below [13]. According to estimations by [7], an increase in the average vertical heat flux from the AW from conventional 2 W/m^2 [14] to 4 W/m^2 would be enough to provide the observed thinning of the Arctic sea ice in the 2000s. However, it is important to underline that the higher temperature of the AW layer does not guarantee increased heat impact on the sea ice, because almost everywhere in the Arctic Ocean the AW is isolated from the ocean surface and sea ice by high gradient transition layers. In this sense, the WNB is a very specific region, because at its western margin the AW reaches the ocean surface. On the transit across the WNB the AW progressively loses heat and salt from its upper part gradually transforming into the Arctic Intermediate Water mass [15]. Besides direct heat loss to the air, this transformation process includes cooling and freshening through ice melt and horizontal mixing with the surrounding polar water. General decay of the Arctic sea ice over 1990-2000s (as described in the previous section) slowed down the AW transformation in the WNB because of the reduced amount of ice subject to melting along the AW pathway. Enhanced heat uptake and intensified vertical mixing during extended periods of open water in summer additionally slowed down the AW cooling and freshening in its upper part, thus preconditioning farther eastern spreading of relatively warm and salty water close to the ocean surface.

5. Seasonal cycling of the AW temperature in the WNB

An outstanding feature of the AW in the Eastern Atlantic sector of the Arctic Ocean is the trong seasonal cycle of temperature. This regularity was initially revealed in the WNB from the mooring-based observations [16] and traced along the AW flow as far as the eastern Laptev Sea [17, 18]. Seasonal oscillations of temperature in the inflowing AW in the Fram Strait [10] backed up the hypothesis that a large portion of the seasonal temperature variability observed in the Eastern Atlantic sector originates in the Nordic Seas where the AW reaches the ocean surface [16]. In the framework of this concept the phase of seasonal signal is shifted forward in time along the AW pathway with increasing time leg, while the amplitude decays at about the same rate as the mean temperature contrast between the AW warm core and the surrounding water. Available observations and modeling results promptly support the advective nature of seasonal signal in the WNB [19,20], while in the Eastern Nansen Basin other factors may also contribute to the observed temperature oscillations [17,18,21]. With respect to the AW heat impact on sea ice in the WNB the phase of seasonal temperature cycling is of primary importance. On the mid-WNB meridian, the temperature maximum is achieved in the end of fall - early winter (November –December, see Fig. 2 in [4]), when the UML rapidly cools down due to intensive heat exchange with colder air. Subsequent buoyancy loss in the UML favors turbulent entrainment of the underlying pycnocline waters [22] and weakening of the vertical density gradient between the UML and AW, thus providing favorable prerequisite conditions for development of vertical convection.

6. Vertical convection

Vertical convection - opposite directed motion of water with different density under gravitational forcing, is the most efficient mechanism which provides vertical mixing of waters around the World Ocean. Convection may develop due to the increase of density in the upper water layer as a result of cooling (thermal convection) or salinification (haline convection). Under conditions of permanent ice-cover, the room for thermal convection is very narrow since the temperature of surface water remains close to the freezing point all year round, making temperature contribution to density variations very small. In the ice covered seas, ocean-air heat loss is predominantly compensated by ice growth, release of brine into the water, and subsequent density increase. However, over most of the Arctic Ocean, the depth of haline convection is limited to a few tens of meters since the amount of brine released from the growing ice is insufficient to make the water dense enough for mixing up the underlying pycnocline. With the increasing seasonality of Arctic sea ice cover, this steady regime is changing and the most noticeable change occurs along the AW flow in the Nansen Basin [23].

7. Conclusions and broader perspective

In the 2010s gradual decay of the ice cover around the Arctic Ocean reached the tipping point when changing conditions at the surface started to notably affect physical processes in the underlying ocean waters. The first signs of oceanic response on shifted energy balance at the ocean-air interface expectedly emerged in the transition zones between subpolar and polar domains. Arctic warming hotspots, which origin is likely to be directly linked with the Arctic sea ice decline, were recently reported in the Chukchi - Beaufort Sea [24] and in the Barents Sea [1] where subpolar hydrographic regime changes to the polar one. Here we described another example of how the reduction of pan-Arctic sea ice cover initiated a positive feedback loop connecting the change of vertical thermohaline structure with regional ice decay in the Western Nansen Basin, where eastward-moving warm Atlantic Water collides with sea ice, drifting out from the central basin. This collision results in the AW cooling and freshening in its surfaced upper part due to ice melt. Under these conditions, which were typical for the second half of the 20th century, a compact region north of Svalbard (the so-called Whalers Bay) remained permanently ice free in winter because of steady sensible heat polynya, maintained by the AW heat. In the changing climate, the Arctic sea ice cover shrinks down, the share of seasonal ice increases while the ice itself becomes more thin, mobile and fragile. These changes on the pan-Arctic scale invoked regional response, namely: reduced ice import to the marginal transition zones (seas) from the central basin. In case of the WNB, breaking of earlier existed steady-state heat and salt balances in the UML, together with an increased heat and salt import with the AW inflow, reduced vertical density stratification, thus facilitating development of winter thermohaline convection along the AW pathway. Enhanced convection delivers additional heat and salt to the UML contributing to accelerated sea ice melt and/or impeding local ice formation. The strong seasonal cycle of temperature in the AW layer with the culmination at the mid-WNB meridian in early winter additionally facilitates convection development above the AW warm core. Satellite detectable outcome of this chain of events is an anomalously long duration of low ice concentration zone in the WNB in mid-winter, which is observed after 2012.

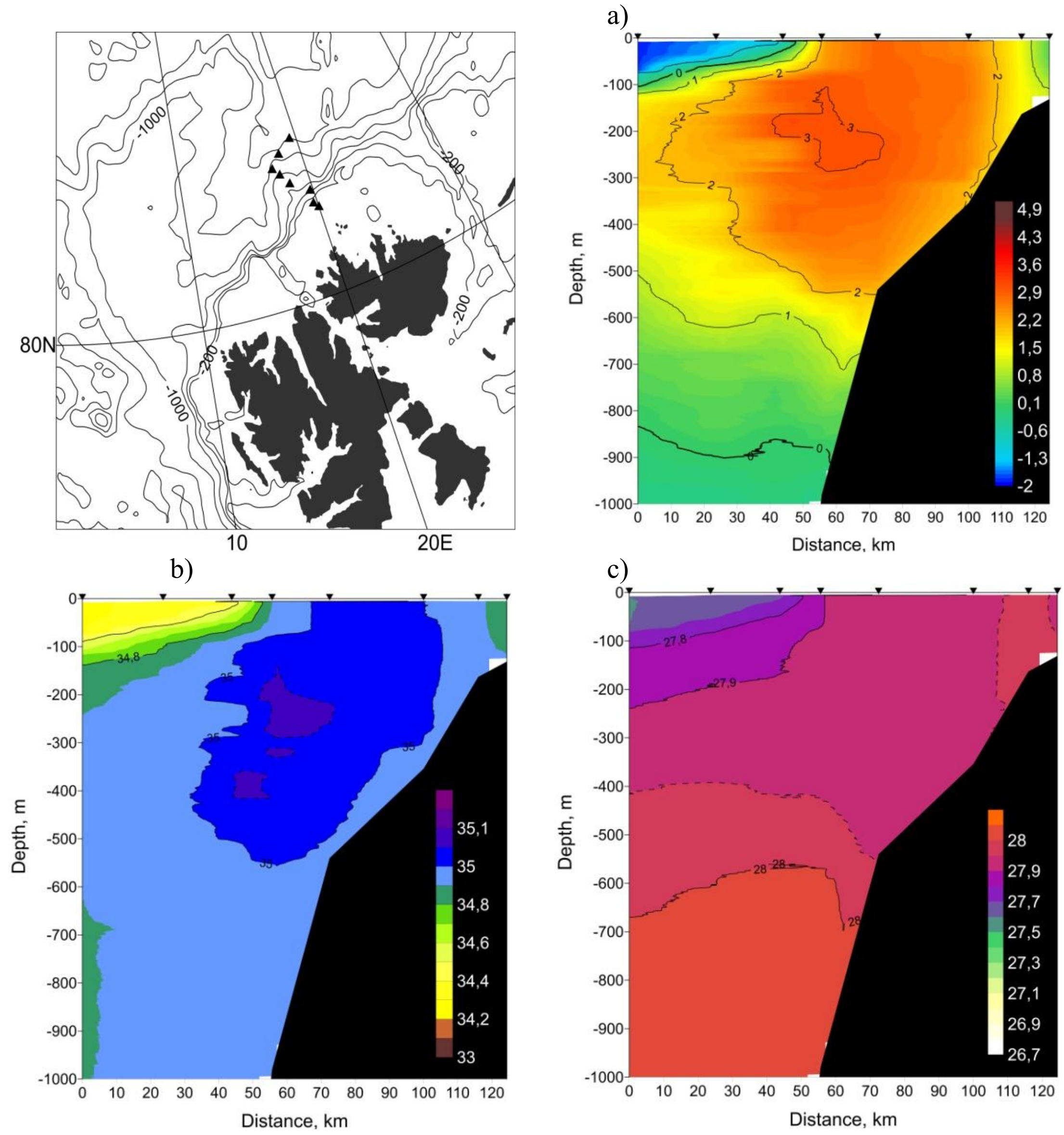

Figure 4. Vertical distribution of potential temperature, °C (a); salinity (b) and potential density anomaly, kg/m^3 (c) in January 2014 north-east of Svalbard (position of transect is shown on inset). Measurements were carried out on R/V/ "Helmer Hanssen".

In a broader perspective, provided that the predicted in the global climate models pace of global warming [25] keeps on, vast areas of the Eastern Atlantic sector may become ice free all year round with yet unclear consequences for regional weather and climate. If this happens, vertical water mass structure will shift to a subpolar type, which is characterized by deep reaching winter convective mixing. Corresponding changes may also be expected in the marine ecosystem with dominance of imported species from the south. We would not argue, that by now, the projection of such radical "atlantification" is rather speculative and should be considered with caution. However, an extremely fast (on the climate time scale) transition of the water mass structure in the WNB to a subpolar-wise type, along with anomalous ice reduction in mid-winter, points out that under favorable background conditions, positive feedbacks may substantially accelerate transition to a new mean state.

Acknowledgments

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