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Formation of Barents Sea Branch Water in the northeastern Barents Sea and St. Anna Trough

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Summary

The Barents Sea throughflow accounts for approximately half of the Atlantic Water advection to the Arctic Ocean. Within the Barents Sea, the Atlantic Water undergoes considerable modifications before entering the Arctic Ocean through the St. Anna Trough. While the inflow area in the south-western Barents Sea is regularly monitored, oceanographic data from the outflow area to the northeast are scarce. Here, we use CTD (Conductivity, Temperature, and Depth) data from August/September 2008 to describe in detail the water masses present in the downstream area of the Barents Sea, their spatial distribution and transformations. We find that the Barents Sea Branch Water consists of both locally formed Cold Deep Water and modified Atlantic Water. While the Cold Deep Water represents a temperature and salinity minimum, the Atlantic component is identified by both temperature and salinity increasing with depth. As opposed to earlier reports, we find that the densest part of the Barents Sea Branch Water is more saline than the Fram Strait Branch Water observed within the St. Anna Trough. Despite the recent warming of the Barents Sea, locally formed bottom water observed in the St. Anna Trough matches the potential density at 2000 meter depth in the Arctic Ocean.

Introduction

The production of cold, dense water at high latitude shelves plays an important role in the thermohaline circulation of the world's oceans (Meincke et al. 1997). In recent decades, a temperature increase in the Atlantic Water flow towards the Arctic Ocean has been observed (Polyakov et al. 2005), and the temperature signal has been propagating downstream into the interior Arctic Ocean (Dmitrenko et al. 2008). The Barents Sea is the largest shelf sea adjacent to the Arctic Ocean. It accounts for a substantial part of the dense water that is formed within the Arctic (Martin and Cavalieri 1989). A portion of the recent Arctic climatic changes has been attributed to a multi-decadal oscillation within the North Atlantic (Sutton and Hodson 2005). The temperature variability in the Barents Sea is closely linked to this oscillation. The thermohaline response to the temperature changes remains uncertain. Better knowledge of the formation, characteristics and subsequent export of dense water masses from the Barents Sea to the Arctic Ocean is therefore necessary. Several processes contribute to the modifications of the Atlantic Water within the Barents Sea. These processes include freshwater input from river runoff, sea-ice melting and net precipitation, wind and tidal mixing and atmospheric cooling and sea-ice formation. The Barents Sea Branch Water, which is the downstream end product of these wide-ranging modification processes, is commonly identified as an intermediate temperature and salinity minimum in the Θ-S space (e.g. Schauer et al. 2002). Our results challenge this traditional view.

Materials and Methods

A total of 142 CTD-profiles covering the northeastern Barents Sea and the St. Anna Trough were obtained during two cruises in August/September 2008. Although the merged data set spans a period of three weeks, we consider it to be synoptic due to our focus on the water masses below the pycnocline. In general, the St. Anna Trough is sparsely sampled, whereas the area between Novaya Zemlya and Franz Josef Land is more densely sampled. However, based on the CTD measurements, we calculated an internal Rossby radius of approximately 1.5 km. Hence, most mesoscale features are not resolved by the CTD sampling.

Results and Discussion

Based on the hydrographic properties, we identify the three main sub-pycnocline water masses within the northeastern Barents Sea and the St. Anna Trough: Atlantic Water advected through the Barents Sea, Cold Deep Water locally formed through ice-freezing processes, and Atlantic Water from the part of the Fram Strait Branch Water that circulates within the St. Anna Trough. Here, we focus on the modification and fate of the Atlantic Water flowing through the Barents Sea feeding into the Barents Sea Branch Water.

Mixing between the three water masses can be inferred from the Θ-S diagrams from sections A, B and C (Fig. 1). Identifying the dominating mixing processes is, however, not straightforward. A calculation of both the synoptic and geostrophic gradient Richardson numbers based on the CTD data revealed values of O(10), which is one order of magnitude larger than the critical value of 1, which is a necessary condition for turbulence. Although this estimate is conservative due to the resolution of our data (both vertically and horizontally), we conclude that the geostrophic vertical velocity shear alone, which is consistent with direct current measurements in section B in 1991 (figure 6 in Gammelsrød et al. 2009), is likely not sufficiently strong to induce turbulent mixing. We also found indications of interleaving in the frontal area between the Atlantic Water and the Cold Deep Water, which represents another possible source of mixing. However, the spacing between the CTD stations is too coarse to resolve such a process properly. Furthermore, we found presence of double diffusive "staircases" in the northeastern Barents Sea. Hence, our results suggest that double diffusive processes contribute to the vertical heat fluxes in the less energetic flow regime in the north-eastern parts of the Barents Sea, while turbulent mixing probably plays a role in the more energetic flow pattern further downstream, although the current dataset cannot substantiate any firm conclusions but rather give some indications in terms of mixing processes.

While the temperature and salinity minimum associated with the Cold Deep Water is commonly interpreted as the core of the Barents Sea Branch Water (e.g. Schauer et al. 2002), we argue that the deeper and denser ($28.0 < \sigma_\Theta < 28.08$) temperature and salinity maximum constitutes a core of Atlantic origin. Moreover, geostrophic calculations and direct current measurements (Gammelrød et al., 2009) indicate that this relatively warm and saline core likely constitutes a substantial part of the Barents Sea Branch Water flow towards the Arctic Ocean.

In addition to the intermediate Cold Deep Water, a denser mode of the Cold Deep Water was observed just north off Novaya Zemlya (see black arrow in Fig. 1). A similar water mass was also observed at the very bottom (500 meter bottom depth) further north in the St. Anna Trough. The density of this Cold Deep Water ($\sigma_\Theta = 28.09$) matches the potential density at 2000 m depth in the Arctic Ocean.

To summarize, based on an extensive, near-synoptic array of CTD measurements, we find that both water masses formed locally through ice freezing and thermohaline convective processes as well as Atlantic Water modified through atmospheric cooling in the Barents Sea contribute directly to the Barents Sea Branch Water observed in the St. Anna Trough. As a consequence, the Barents Sea Branch Water displays a relatively wide range of densities ($28.0 < \sigma_\Theta < 28.09$), and has the potential to sink to great depths in the Polar Basin, thereby renewing the Arctic Ocean intermediate and deep water.

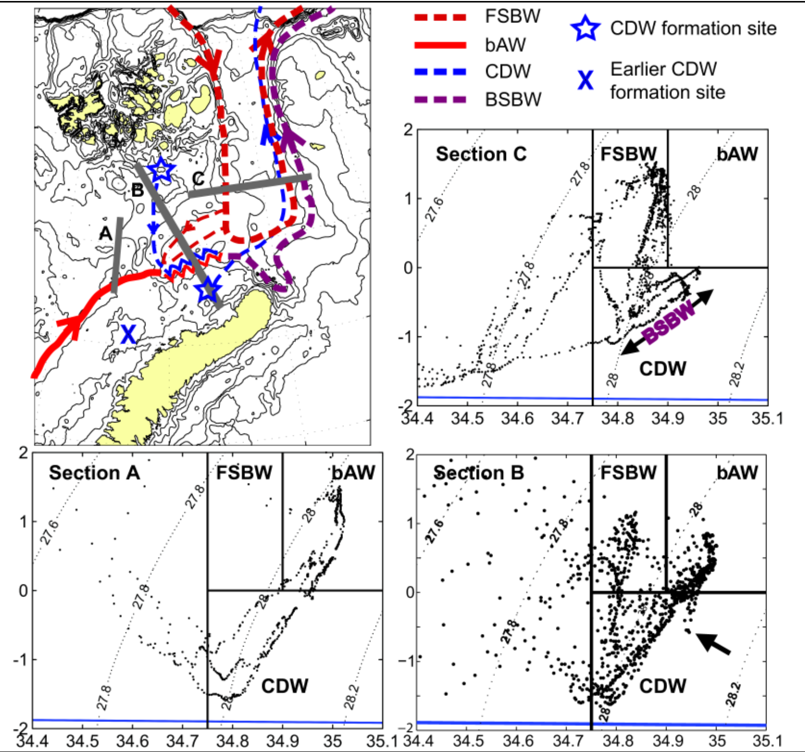

Figure 1. *Θ-S* diagrams for three sections: A (lower left), B (lower right) and C (upper right). Black lines indicate the bounds defining the different water masses; FSBW: Fram Strait Branch Water, bAW: Barents Atlantic Water, CDW: Cold Deep Water, BSBW: Barents Sea Branch Water. Gray lines show positions of the sections and coloured lines show the advection paths of the different water masses. Blue lines in the *Θ-S* diagrams show the freezing temperature.

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