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Exchange of warming deep waters across Fram Strait

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ABSTRACT

Current meters measured temperature and velocity on 12 moorings from 1997 to 2014 in the deep Fram Strait between Svalbard and Greenland at the only deep passage from the Nordic Seas to the Arctic Ocean. The sill depth in Fram Strait is 2545 m. The observed temperatures vary between the colder Greenland Sea Deep Water and the warmer Eurasian Basin Deep Water. Both end members show a linear warming trend of 0.11 ± 0.02 °C/decade (GSDW) and 0.05 ± 0.01 °C/decade (EBDW) in agreement with the deep water warming observed in the basins to the north and south. At the current warming rates, GSDW and EBDW will reach the same temperature of -0.71 °C in 2020. The deep water on the approximately 40 km wide plateau near the sill in Fram Strait is a mixture of the two end members with both contributing similar amounts. This water mass is continuously formed by mixing in Fram Strait and subsequently exported out of Fram Strait. Individual measurements are approximately normally distributed around the average of the two end members. Meridionally, the mixing is confined to the plateau region. Measurements less than 20 km to the north and south have properties much closer to the properties in the respective basins (Eurasian Basin and Greenland Sea) than to the mixed water on the plateau. The temperature distribution around Fram Strait indicates that the mean flow cannot be responsible for the deep water exchange across the sill. Rather, a coherence analysis shows that energetic mesoscale flows with periods of approximately 1–2 weeks advect the deep water masses across Fram Strait. These flows appear to be barotropically forced by upper ocean mesoscale variability. We conclude that these mesoscale flows make Fram Strait a hot spot of deep water mixing in the Arctic Mediterranean. The fate of the mixed water is not clear, but after the 1990s, it does not reflect the properties of Norwegian Sea Deep Water. We propose that it currently mostly fills the deep Greenland Sea.

1. Introduction

The deep ocean circulation of the Nordic Seas and the Arctic Ocean is isolated from the World Ocean below 800 m (sill depth of the Faroe Bank Channel). The region between the west coast of Svalbard and the east coast of Greenland is known as Fram Strait (Fig. 1). The eastern side of Fram Strait is a wide flat area of about 2500 m depth. Here we consider this plateau in Fram Strait to be the area away from the continental slopes roughly encompassed by the 2300 m and 2700 m isobaths. The sill with a depth of 2545 m according to the International Bathymetric Chart of the Arctic Ocean (IBCAO, Jakobsson et al., 2012) is located just east of 0°E and south of 79°N. The Greenland Sea is located to the south of Fram Strait while the Eurasian Basin of the Arctic Ocean is to the north and both are deep (> 3000 m) basins. The waters at depths of more than 2000 m in these basins are known as Greenland Sea Deep Water (GSDW) and Eurasian Basin Deep Water (EBDW) respectively (Aagaard et al., 1985; Swift and Koltermann, 1988; Somavilla et al., 2013). The Norwegian Sea is further to the south east of Fram Strait and contains Norwegian Sea Deep Water (NSDW) at depths >2000 m. Swift and Koltermann (1988) found water in the Norwegian Sea with similar temperature-salinity characteristics to what they had measured in Fram Strait. Based on this, they hypothesized that mixing in the deep Fram Strait could be the origin of Norwegian Sea Deep Water.

Changes in the frequency and water mass percentage of different water masses flowing through the deep Fram Strait have been studied from repeated east–west CTD sections along 78°50′N (Langehaug and Falck, 2012). This analysis was based on constant temperature–salinity end member definitions derived from observational studies in the 1980s (Swift and Koltermann, 1988). Specifically, no changes in the end member properties were considered in the analysis of Langehaug and Falck (2012). As a result of

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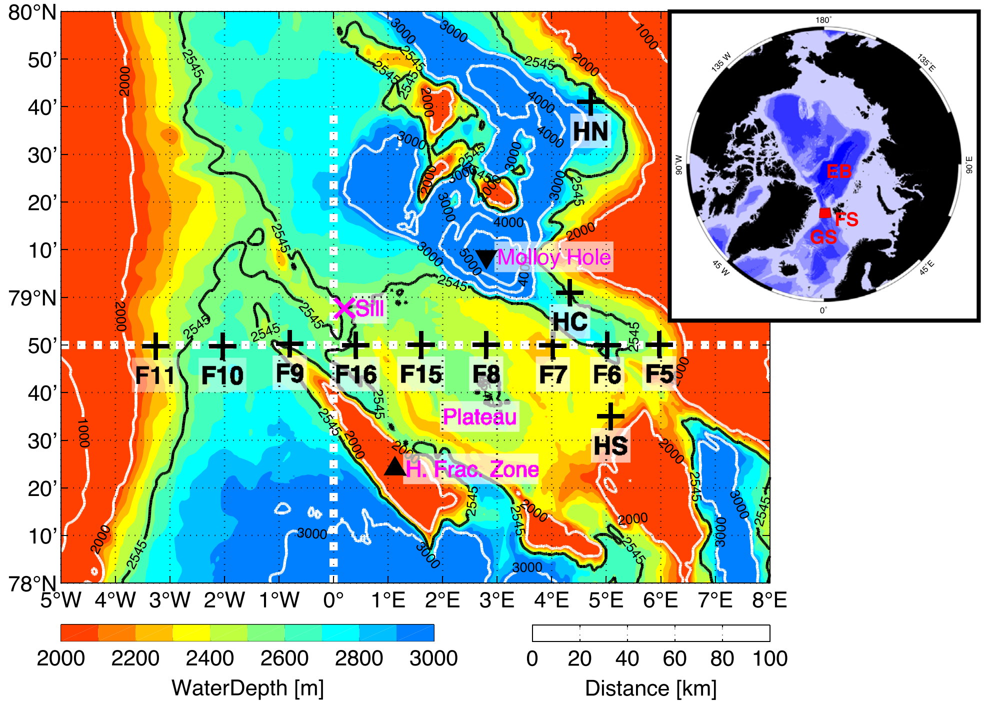

Fig. 1. Map of the bathymetry around the Fram Strait sill from IBCAO version 3.0 (Jakobsson et al., 2012). Only water depths from 2000 m to 3000 m are shown in color to highlight the bathymetric features relevant for the bottom water. Based on this topographic data set, the sill is 2545 m deep and located just east of 0°E and south of 79°N; its isobath is also drawn as a thick black line. The Høvgaard Fracture Zone (1165 m depth) and the Molloy Hole (5573 m depth) are the shallowest and deepest points in the deep Fram Strait, respectively. A distance scale bar is given in the bottom right. The median locations of the deep moorings considered in this study are marked by black crosses: F5–11 and F15/16 along 78°50′N and the three Hausgarten moorings (HS, HC, HN) in the eastern Fram Strait. The extents of the zonal (along 78°50′N) and the meridional (along 0°E) CTD sections are marked by white dashed lines. The inset in the top right corner shows the whole Arctic. The extent of the main map is shown as a red polygon in relation to the Fram Strait ("FS") as well as the Greenland Sea ("GS") to the south and the Eurasian Basin ("EB") to the north. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

this the analysis concludes that GSDW completely disappeared from Fram Strait throughout the 2000s (Langehaug and Falck, 2012). However, repeated CTD stations in the Greenland Sea show that GSDW has been warming at a (for deep waters rapid) pace of ≈ 0.14 °C/decade (Somavilla et al., 2013) from values of − 1 °C in the 1990s to > − 0.8 °C in the late 2000s for $\theta_{2.5}$ (potential temperature relative to 2500 dbar) around 2500 m depth which is close to the sill depth of Fram Strait. Following the halt of deep convection in the Greenland Sea in the early 1990s (Schlosser et al., 1991; Rhein, 1991; Meincke et al., 1992), the warming of the deep Greenland Sea is explained by the continuous inflow of the warmer EBDW to the Greenland Sea across Fram Strait (Aagaard et al., 1991; Somavilla et al., 2013). That is, the Greenland Sea has a heat source, but no longer a heat sink and therefore is in a non-stationary state and warms.

The exchange of deep water across Fram Strait required to account for the warming (and increase in salinity) of the Greenland Sea was estimated as 0.4 Sv ($1\ \mathrm{Sv}=10^6\ \mathrm{m^3/s}$) (Somavilla et al., 2013). However, there should not be an associated net volume flux across Fram Strait (at least not unless there are huge and unrealistic vertical displacements of isopyncals below ≈ 2000 m in the Arctic Ocean to the north and the Nordic Seas to the south) which implies a balancing northward transport of 0.4 Sv. The exchange could also be achieved solely by eddy diffusion across Fram Strait and no steady mean currents are required in order to explain the warming of the deep Greenland Sea. Tracer release experiments in a coarse resolution numerical model (Marsh et al., 2008) showed that the flow across Fram Strait was inhibited below 2100 m in the 1990s, but there was an indication of exchange and the propagation of Greenland Sea Deep Water into the Eurasian Basin in the 2010s (Y. Aksenov personal communication). Gridded velocities from a multi-year mooring array across Fram Strait imply a mean meridional flow in the deep Fram Strait with flow to the north in the east and to the south in the west (Beszczynska-Möller et al., 2012). However, that depiction also corresponds to a mean net southward volume transport of 1.4 Sv below 1500 m, contrary to the expectation of zero mean net meridional transport. This is due to the sparse horizontal coverage of the moorings in Fram Strait. The Rossby radius of about 8 km in Fram Strait (Zhao et al., 2015) and bottom topographic features such as submarine valleys are not sufficiently resolved. In the upper water column of the eastern Fram Strait, the West Spitsbergen Current (WSC) transports warm Atlantic origin water northwards and the boundary current is barotropically unstable (Teigen et al., 2010) thereby generating eddies in the Fram Strait with a mostly barotropic structure. The resulting barotropic eddy field was described both from in situ and remote sensing observations (e.g. Johannessen et al., 1987; Manley et al., 1987). This Atlantic Water inflow to the Arctic Ocean has been observed to have warmed by 0.6 °C/decade above 1000 m throughout the late 1990s and 2000s (Beszczynska-Möller et al., 2012). We note, however, that this is a distinct process unrelated to the evolution of the deep waters in Fram Strait as discussed in the present study.

Straits and sills separating oceanic basins throughout the World Ocean have received considerable attention because they influence the interface height of isopycnals in the basins. If the horizontal density gradient across the sill is large, energetic flows result downstream of the sill that mix and entrain waters thereby transforming water masses. Examples are Denmark Strait (Nikolopoulos et al., 2003), the Strait of Gibraltar (Price and O'Neil Baringer, 1994), and the Samoan Passage in the deep Pacific (Alford et al., 2013). What are then the gradients across the deep Fram Strait and the associated flow structure? How is the exchange of the deep waters across Fram Strait achieved and where does the