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Internal overflow in the Nordic Seas and the cold reservoir in the northern Norwegian Basin

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ABSTRACT

Based on hydrographic data collected in 2014 in the area around Jan Mayen, the waters flowing out from the Greenland Sea to the Norwegian Sea through the Jan Mayen Channel (JMCh) and their potential contribution to the Greenland-Scotland Ridge overflow are investigated. The results show that only the waters flowing along the southern periphery of the Greenland Sea can enter the Norwegian Sea through the JMCh. These waters are composed of low-salinity water in the upper layer, slightly saline Return Atlantic Water in the middle layer, and the Greenland Sea Arctic Intermediate Water in the lower layer of the Jan Mayen Current. The depths of these waters increase by approximately 150–200 m upon entering the Norwegian Sea, forming an internal overflow within the Nordic Seas. The density range of waters entering the Norwegian Sea through this internal overflow is between $\sigma_\theta = 28.02$ and $28.06\ \mathrm{kg\ m^{-3}}$. These waters accumulate below 330 m with an east-west extent exceeding 160 km, forming a large, cold reservoir in the Norwegian Basin. In 2014, the cold reservoir water properties were highly consistent with the properties of the dense water located between 550 and 1000 m in the Faroe-Shetland Channel (FSC), which suggests that the cold reservoir may be an important source of the overflow water through the Faroese Channels, and could play a role in stabilizing and sustaining continuous overflows.

1. Introduction

The Nordic Seas are composed of the Greenland, Iceland and Norwegian Seas. The dense waters formed by deep convection during winter flow southward and spill over the Greenland-Scotland Ridge (GSR) as dense overflows (Aagaard et al., 1985; Dickson and Brown, 1994; Hansen and Østerhus, 2000). Various circulation schemes have been presented, including those by Mauritzen (1996), who suggested that the Atlantic Water (AW) in the Norwegian Atlantic Current becomes dense due to heat loss and is transported to the overflow regions at shallow and intermediate depths as boundary currents surrounding the Iceland and Greenland Seas and through the loops in the Arctic Ocean, and by Eldevik et al. (2009), who suggested an overturning loop from the Atlantic inflow to overflow just within the Norwegian Sea.

The GSR overflows occur in three distinct pathways: through the Denmark Strait, over the Iceland-Faroe Ridge and in the Faroe Bank Channel (FBC). The Faroe-Shetland Channel (FSC) and its continuation, the FBC, are together known as the Faroese Channels (Hansen and Østerhus, 2000). Dense waters flow from the FSC to the FBC, forming the eastern overflow into the deep North Atlantic Ocean (Mauritzen et al., 2005; Ullgren et al., 2014; Hansen et al., 2016). The volume transport of this eastern overflow is estimated to be 2.2 Sv (Hansen et al., 2016), contributing 1/3 of the total volume transport of overflows from the Nordic Seas and 1/4 (when entrained water is included) of the North Atlantic Deep Water (Dickson and Brown, 1994). The overflow water properties in the Faroese Channels exhibit temporal variability due to changes in source waters and their relative proportions (Turrell et al., 1999; Hansen and Østerhus, 2000; Ullgren et al., 2014). Previous studies suggest that the overflow water through the Faroese Channels is mainly fed by water masses such as the Modified East Icelandic Water, Norwegian Sea Arctic Intermediate Water and Norwegian Sea Deep Water (Mauritzen et al., 2005; Ullgren et al., 2014; Hansen et al., 2016). In addition, tracer experiments indicate that the Greenland Sea Arctic Intermediate Water (GSAIW) can enter the Norwegian Sea through the Jan Mayen Channel (JMCh) and eventually appear in the FSC (Olsson et al., 2005a; Messias et al., 2008).

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The driving mechanism for the GSR overflow is well established; that is, the thermohaline processes in the Nordic Seas (e.g. deep convection) lead to dense water accumulation, which favors a positive pressure gradient across the Greenland-Scotland Ridge to the North Atlantic. Constrained by hydraulic control, i.e. narrowing in width and density gradients, water is driven to spill over the ridge (Hansen and Østerhus, 2000; Nikolopoulos et al., 2003; Girton et al., 2006; Käse et al., 2009; Sandø et al., 2012). In this sense, the Nordic Seas are considered to be a dense water reservoir (Serra et al., 2010; Yang and Pratt, 2013). The large storage capacity of the Nordic Seas makes it possible to continuously feed the GSR overflows and support them with a buffer capacity against external influences. Although the climate of the Nordic Seas region has changed significantly in past decades, there has been no discernible change in the overflow volume transport (Olsen et al., 2008; Serra et al., 2010; Jochumsen et al., 2012, 2017; Hansen et al., 2016).

As a region of strong deep convection, the Greenland Sea has attracted attention. Convection in the gyre transforms surface water into dense intermediate and deep water (Voet et al., 2010). The GSAIW is suggested to be one of the sources to the Norwegian Sea Arctic Intermediate Water (Jeansson et al., 2017), which is thought to be the main source of the eastern part of the GSR overflows (Fogelqvist et al., 2003; Mauritzen et al., 2005; Eldevik et al., 2009). Using the tracer sulphur hexafluoride (SF_6) released into the center of the Greenland Sea in 1996 (Watson et al., 1999), Olsson et al. (2005a) found that the GSAIW passes through the JMCh, flows southward along the Jan Mayen Ridge, and finally appears in the Faroese Channels. Then the question arose, can any other Greenland Sea waters, in addition to the GSAIW, flow onwards into the Norwegian Sea and eventually contribute to the GSR overflow?

Eddy activity caused by current instabilities at the Arctic Front on the Mohn Ridge has been suggested to induce the strong exchange of water masses (Budéus and Ronski, 2009) by allowing the Greenland Sea water to flow into the Norwegian Sea (Blindheim, 1990; Blindheim and Rey, 2004). However, no consensus has been reached on the pathway of Greenland Sea water into the Norwegian Sea. The main objectives of this study are: to investigate which Greenland Sea waters enter the Norwegian Sea and the details of these waters when flowing through the JMCh; to clarify the status of these waters after entering the Norwegian Sea; and to explore whether these waters contribute to the GSR overflow.

2. Geography and general circulation of the Nordic Seas

2.1. Bathymetric features

The main bathymetric features in the Nordic Seas are shown in Fig. 1. The Nordic Seas are divided into several basins by ridges. The Greenland Sea is separated from the Iceland Sea and the Norwegian Sea by the western Jan Mayen Fracture Zone and the Mohn Ridge, respectively. The Norwegian Sea is partly separated from the Iceland Sea by the Jan Mayen Ridge to the west. The Norwegian Sea is composed of two basins, the Norwegian Basin and Lofoten Basin, which are separated from each other by the eastern Jan Mayen Fracture Zone and Vøring Plateau. The Norwegian Basin is the largest and deepest basin in the Nordic Seas, with an average depth between 3200 and 3600 m and a maximum depth exceeding 3800 m (Bourke et al., 1992; Blindheim and Østerhus, 2005).

2.2. Circulation and water masses

In the upper layer (upper several hundred meters), the Norwegian Atlantic Current carries warm and saline water northward whereas the East Greenland Current (EGC), carries relatively cold and fresh water from the Arctic Ocean southward (see Fig. 1). Greatly influenced by topography and the local wind field, the Norwegian Atlantic Current forms recirculation in the Nordic Seas, which interacts with the EGC current system in a complex way and forms several different water masses. Major water masses in the study area are listed in Table 1.

Generally, the regional circulation in the interior of the Nordic Seas is cyclonic. The EGC flows southwards along the Greenland coast. In the Jan Mayen Fracture zone, part of the EGC turns east to form the Jan Mayen Current (JMC) (Bourke et al., 1992; Blindheim and Østerhus, 2005). Waters on the eastern margin of the Greenland Sea flow northeastwards along the western side of the Mohn Ridge, eventually joining with the recirculating waters of the West Spitsbergen Current.

The northward flowing Norwegian Atlantic Current enters the Norwegian Sea in the south and turns northwest toward Jan Mayen when approaching the Vøring Plateau. Near Jan Mayen, the largest portion flows northeast along the eastern side of the Mohn Ridge, while the remainder is deflected westward in the northern Norwegian Basin towards the Jan Mayen Ridge. Some of the latter waters flow over the Jan Mayen Ridge and join the cyclonic gyre in the eastern Iceland Sea (Blindheim and Østerhus, 2005; Mork et al., 2014), while the remainder form the AW recirculation in the Norwegian Basin (Eldevik et al., 2009).

The JMCh to the northeast of Jan Mayen, with a width of ~20 km and a sill depth of ~2200 m, connects the Greenland and Norwegian Seas. Moorings deployed in the JMCh indicated that there is a steady deep flow from the Greenland Sea to the Norwegian Sea with an approximate velocity of 0.07–0.08 m/s (Swift and Koltermann, 1988; Sælen, 1990). Subsequent tracer experiments and numerical model results suggest that the intermediate water from the Greenland Sea can also enter the Norwegian Sea through the JMCh (Olsson et al., 2005a; Messias et al., 2008). Thus, the JMCh can be considered as a regular and direct route for Greenland Sea water entering the Norwegian Sea. However, we note that the deep-water flow in the JMCh can reverse at times, as observed between November 1992 and July 1993 (Østerhus and Gammelsrød, 1999).

3. Data

The Ocean University of China and the Institute of Marine Research in Bergen, Norway carried out a joint cruise on the ship STALBAS during September–October 2014 to investigate the possible water exchange among the basins of the Nordic Seas around Jan Mayen. Hydrographic profiles from a total of 75 CTD (Conductivity-Temperature-Depth) stations were collected using the SBE-19plus V2 instrument (Fig. 1). The sensors were calibrated in the National Center of Ocean Standards and Metrology (NCOSM) in Tianjin, China, and the accuracy of the CTD measurement was 0.001 °C for temperature, 0.003 for salinity and 0.1% of full-scale range for pressure. The data were quality controlled and spikes and obvious erroneous data have been removed. With a high spatial resolution, these data allow us to describe detailed spatial differences in water masses.

In addition to the above main stations, we also used data collected around Jan Mayen and in the Norwegian Sea on the ship STALBAS in June 2015 using the same SBE-19plus V2 instrument. The sensors were also calibrated by the NCOSM and returned the same accuracy as in the 2014 campaign. By comparing the 2014 and 2015 data sets (see Fig. 9), we aimed to identify changes, if any, in the water mass properties of the outflow from the Greenland Sea to the Norwegian Sea.

Finally, we used the stations in the GSR overflow areas obtained from the ICES Dataset on Ocean Hydrography (The International Council for the Exploration of the Sea, Copenhagen. 2014, http://www.ices.dk) to examine the possible contribution of the outflowing waters from the Greenland Sea to the overflows through the FSC. Ten CTD profiles taken along a section in the FSC (shown in Fig. 10) during September 2014 on the ship FRV Scotia (chief scientist A. Gallego) by Marine Scotland Science (United Kingdom) were used. The sensors have been calibrated using in situ water samples, and temperature and salinity data have been screened by the data originator for spikes and

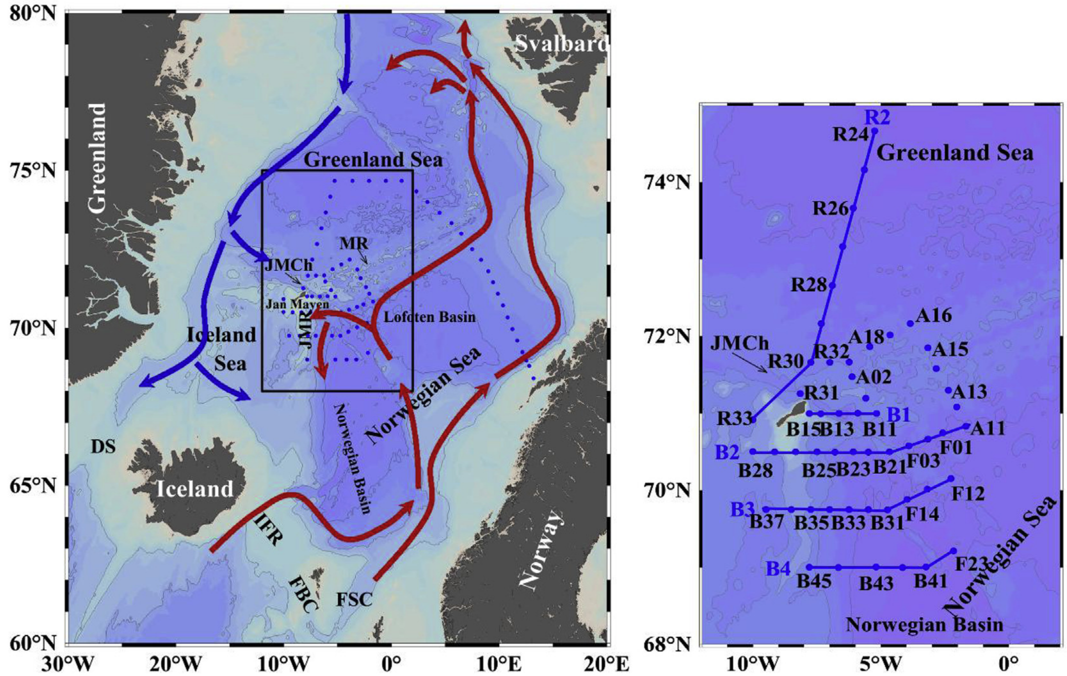

Fig. 1. Left: Map of the Nordic Seas showing bathymetry and the two main current systems, with all stations occupied in September–October 2014 denoted by blue dots. Depths are contoured at 1000 m, 2000 m and 3000 m. The black rectangle indicates the study region. The warm Norwegian Atlantic Current and the cold East Greenland Current (EGC) are depicted by red and blue arrows, respectively. The EGC bifurcates to the east at the Jan Mayen Fracture Zone to become the Jan Mayen Current (JMC) and farther south to the Iceland Sea to form the East Icelandic Current (EIC). Abbreviations: JMCh = Jan Mayen Channel; MR = Mohn Ridge; JMR = Jan Mayen Ridge; DS = Denmark Strait; IFR = Iceland-Faroe Ridge; FSC = Faroe-Shetland Channel; FBC = Faroe Bank Channel. The FBC, IFR and DS constitute the GSR. Right: CTD stations and sections of the cruise in the study region. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Major water masses in this study (Defined by potential temperature and salinity).

Water mass	Potential temperature (°C)	Salinity
Arctic Surface Water This water is formed from Polar Water (see below). After entering the Nordic Seas, surface Polar Water is warmed through summer heating to form the Arctic Surface Water (Swift and Aagaard, 1981)	$\theta > 0$ °C for $34.4 < S < 34.7$ [a] $\theta > 2$ °C for $34.7 < S < 34.9$ [a]	$34.4 < S < 34.9$ [a]
Atlantic Water This water has its origin in the Norwegian Atlantic Current	$\theta > 3$ °C [b]	$S > 35.0$ [b]
Greenland Sea Arctic Intermediate Water The water is formed by convection during cold winters. It appears as a clearly identified salinity minimum, and sometimes also a temperature minimum below 1000 m in the Greenland Sea.	-0.9 °C $< \theta <$ -0.5 °C [c]	$34.9 < S < 34.91$ [d]
Norwegian Sea Arctic Intermediate Water This water mass is defined as a salinity minimum with temperatures between -0.5 °C and 0.5 °C in the Norwegian Sea (Fogelqvist et al., 2003), that has been advected from the Greenland and Iceland Seas.	-0.5 °C $< \theta <$ 0.5 °C [c]	$34.87 < S < 34.90$ [c]
Polar Water This water is carried into the Nordic Seas from the Arctic Ocean by the East Greenland Current.	$\theta < 0$ °C [a]	$S < 34.4$ [a]
Return Atlantic Water This water appears as a warm core of the East Greenland Current. It is thought to be formed from both the Recirculating Atlantic Water from recirculation of the West Spitsbergen Current south of the Fram Strait and the Arctic Atlantic Water after recirculating in the Arctic Ocean.	0 °C $< \theta <$ 2 °C [c]	$34.9 < S < 35$ [c]

[a] Swift and Aagaard (1981).
[b] Mauritzen (1996).
[c] Fogelqvist et al. (2003).
[d] This study.

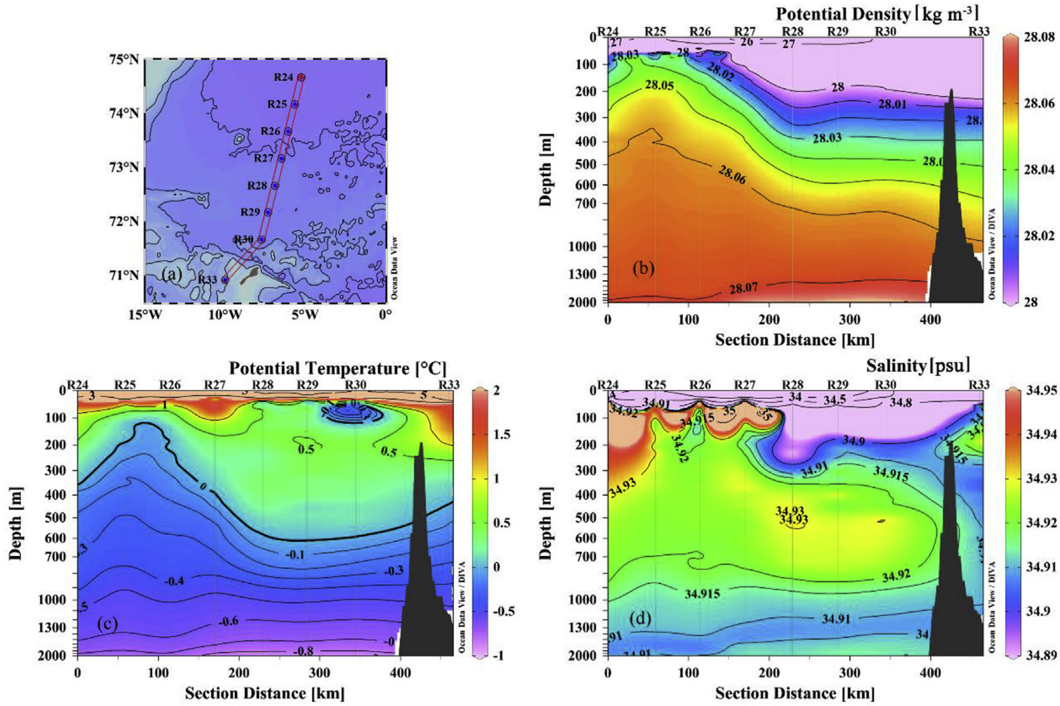

Fig. 2. Potential temperature, salinity and potential density in section R2 from the central to southern Greenland Sea.

other erroneous values.

4. Results and discussion

4.1. Water mass structure in the Greenland Sea and Jan Mayen Channel

Section R2 from the central gyre to the southern edge of the Greenland Sea (Fig. 2) shows that the waters in the central and marginal areas were quite different. The surface of the Greenland Sea was characterized by the Arctic Surface Water in a layer ~50 m thick. A cold and low-salinity core in the subsurface layer of the southern Greenland Sea (stations R28, R29 and R30) was found in the upper 200 m, occupying a large area in the southern part of the basin (Fig. 2c and d). This water originated from the previously ice-covered Polar Water (Bourke et al., 1992). It was found at station R30, with a core density between 27.97 and 27.98 and temperature and salinity at approximately 80 m being −0.36 °C and 34.812, respectively.

The depth of water with a salinity higher than 34.91 varied greatly throughout the Greenland Sea, being below 300 m at the edge of the basin while just below the surface layer at only 30 m in the central gyre. The water with temperatures up to 2.0 °C in the subsurface layer of the central Greenland Sea had a salinity of over 35.0, indicating that it originated from the AW recirculation south of the Fram Strait. The temperature of the deeper water (with a salinity over 34.91) in the Greenland Sea decreased with depth and was generally lower than 0 °C. This water was likely formed by the intrusion of AW into the interior of the Greenland Sea (Budéus and Ronski, 2009) and was redistributed by winter convection. The salinity of water at 300–800 m in the JMC at the edge of the basin was between 34.92 and 34.93, slightly higher than that of the central Greenland Sea. Named the Return Atlantic Water (RAAW), this water layer was 500–700 m thick, characterized by temperatures above 0 °C in the EGC (Håvik et al., 2017), and likely mixed with the waters from the Greenland Sea interior along its route.

The layer with a clearly identified salinity minimum below 1000 m denoted the GSAIW. The relatively warm, saline Atlantic-derived water recirculates in the Greenland Sea. When it is cooled in winter, convection can be induced (Aagaard and Carmack, 1989; Clarke et al., 1990; Ronski and Budéus, 2005; Rudels et al., 2012). This kind of convection in the Greenland Sea occurs in the form of plumes (Aagaard and Carmack, 1989; Paluszkiewicz et al., 1994); as the fluid parcel reaches the depth corresponding to its density, it spreads towards the rim in deep layers (Rudels et al., 2005). As seen in Fig. 2b, the density of the upper waters in the central Greenland Sea was very high (greater than 28.05 kg m^{-3} at 100 m). Upon losing heat, these waters can easily convect to form the GSAIW. The GSAIW had shifted from a mode with a more notable contribution of polar waters in the early 1990s into a more Atlantic-dominated mode in the late 2000s (Rudels et al., 2012; Jeansson et al., 2017). Latarius and Quadfasel (2016) reported that its redistribution during winter can reach depths of more than 1500 m. In our data, the core of the GSAIW, represented by the salinity minimum, was located at 1500–1800 m. Another type of convection that occurs in the Greenland Sea is "cabbeling convection", usually appearing at the intersection of cold and warm water masses where two water masses mix to form a new water mass with a density higher than the density of either mixing water masses (McDougall, 1984). Cabbeling convection plays an important role in the transformation of water masses in the Greenland Basin, e.g., increasing the water volume in the intermediate layer (Kasajima and Johannessen, 2009).

Based on the principle of potential vorticity conservation, the change in potential vorticity caused by topography will steer the current to flow along the channel (Hogg, 1983). The flow in the channel is in geostrophic balance and is mostly eastward, i.e., towards the Norwegian Sea, based upon previous studies (Swift and Koltermann, 1988; Sælen, 1990; Olsson et al., 2005a; Messias et al., 2008). With relatively similar water properties, stations in section B1 (Fig. 3), located in the southern JMCh, generally represented the features of the outflowing waters. The temperature of these waters varied greatly with depth. The temperatures above 500 m were greater than 0 °C. Near surface (50–60 m) temperatures exceeded 3–5 °C. The subsurface layer of approximately 100–200 m (e.g., stations B12 and B14) was occupied by relatively cold water (reaching as low as 0.01 °C), beneath which was slightly warmer water whose main component was the RAAW. Waters with a temperature range of −0.5 to 0 °C below 500 m had characteristics similar to those found in the southern Greenland Sea. These

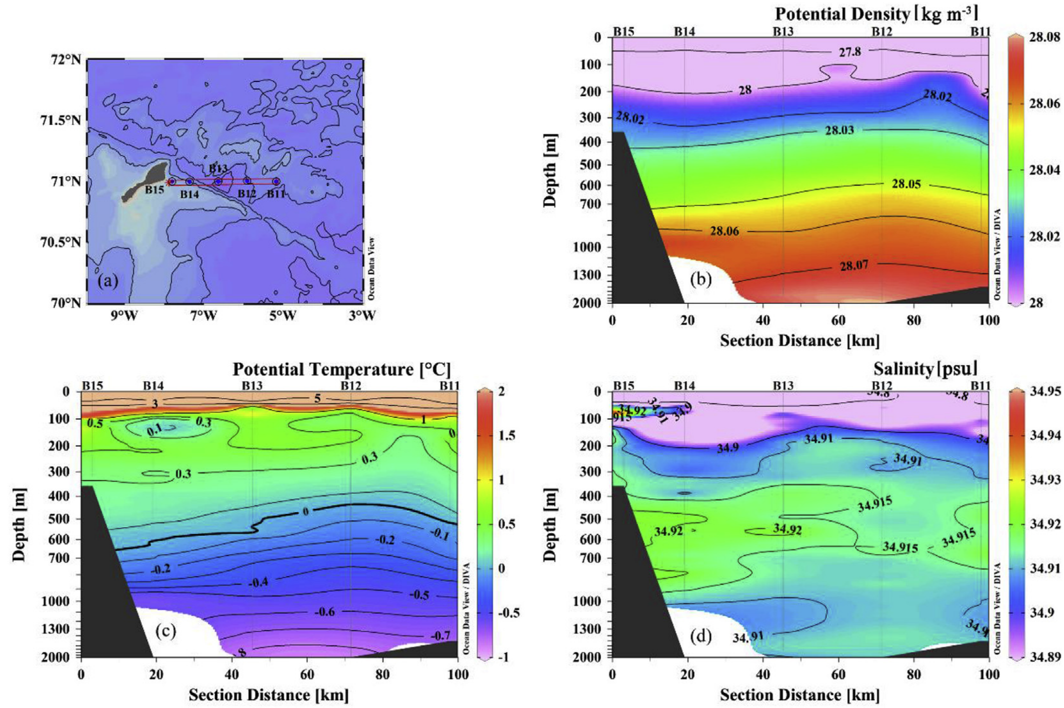

Fig. 3. Same as Fig. 2, but for section B1 in the JMCh.

waters are suggested to originate from the deeper waters below the AW in the West Spitsbergen Current which recirculate in or south of the Fram Strait and move south with the EGC (Bourke et al., 1992; Rudels et al., 2005); however, these waters may have an alternative source: the waters formed by earlier convection, which are modified by recirculation and mixing in the interior basin.

The salinity features were significantly different from those of temperature. As seen from Fig. 3d, the JMCh waters were well stratified. Except for the extremely low-salinity surface water, salinities above 200 m primarily ranged between 34.85 and 34.90. Taking the temperature characteristics into consideration, we can deduce that this water comes from the JMC. This water was still characterized by temperature and salinity minima in the subsurface layer, but the values were slightly higher than those observed upstream. The water between 300 and 1000 m had a salinity range of 34.91–34.92. Compared to the intermediate water in the southern Greenland Sea, this water had lower salinity, indicating that it mainly originated from the JMC but was slightly modified by mixing with the surrounding waters on its route to the JMCh. The salinity minimum below 1000 m indicated the presence of the GSAIW, which intruded as a wedge between the warmer RAAW and deeper waters from the Arctic Ocean (Rudels et al., 2005). The depth of the salinity minimum in this survey was between 1100 and 1300 m.

The θ–S diagram for all stations in the southern JMCh (see Fig. 1 for locations) were quite similar (Fig. 4a). Generally, water characteristics throughout most of the water column were similar to those of the JMC, e.g., stations R30 and R32 (Fig. 4b). For station R31, which was located at the northern entrance to the channel, the waters of the subsurface and intermediate layers flowed out along the JMCh (Fig. 4b). However, there was a distinct water layer found in the density range $28.0 < \sigma_\theta < 28.03\ \mathrm{kg\ m^{-3}}$ with a cold, fresh core ($-0.1 < \theta < 0.4$ °C, $34.88 < S < 34.91$) at station R31, which was

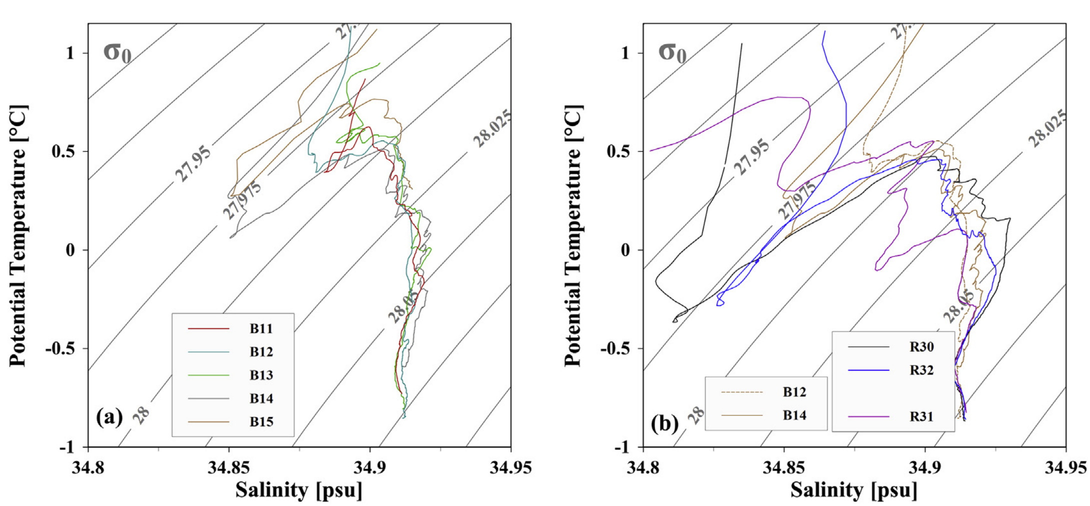

Fig. 4. θ–S diagram of the stations in the Jan Mayen Channel (a) and upstream of the channel (b). The θ–S characteristics of the stations in the JMCh are relatively similar. For the sake of clarity, only stations B12 and B14 are shown in (b) for comparison with other stations in the southern Greenland Sea.

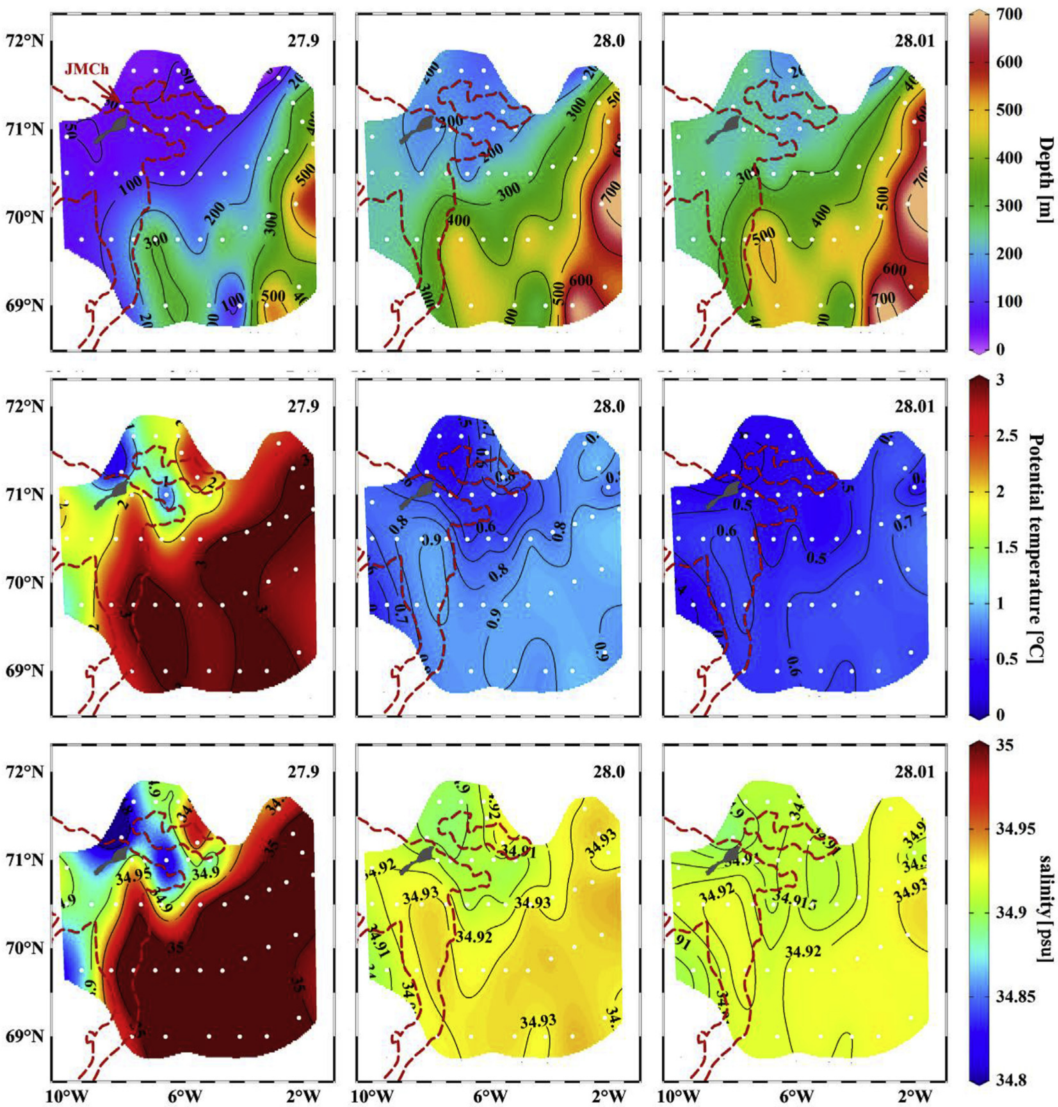

Fig. 5. The depth (upper panels), potential temperature (middle panels) and salinity (lower panels) of the densities σ_θ = 27.9, 28.0 and 28.01 kg m^{-3}. The 1500 m isobath indicated in dark red dashed lines is added to indicate the location of the JMCh. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

not present in any other stations. One possible explanation is that this water might be a cold eddy that was separated from the JMC and trapped by the topography after entering the channel. Despite this unusual pattern, we can still conclude that the water flowing through the JMCh originates from the JMC. The waters above 1000 m were composed of polar waters in the upper layer, the RAAW in the middle layer and perhaps some convected water modified by recirculation or mixing in the interior Greenland Sea. Water below 1000 m was mainly related to convected water with its water properties consistent with those in the central Greenland Sea but at shallower depths. The result suggests that only the waters flowing along the southern periphery of the Greenland Sea flowed through the JMCh, which can be attributed to the effects of topography around Jan Mayen.

4.2. The internal overflow and its path

The waters outflowing from the Greenland Sea entered the Norwegian Sea through the JMCh. We need to trace these waters to better interpret their flow into and subsequent spreading within the Norwegian Sea.

A change in the depth of an isopycnal surface implies a change in the density profile and thus the pressure field, while a change in the temperature/salinity composition of the isopycnal surfaces implies a change in water properties (Rossby et al., 2009). Therefore, we used isopycnal surfaces to trace the waters outflowing through the JMCh. In the outflow, the upper waters with low-temperature and low-salinity (σ_θ < 28.0 kg m^{-3}, depth < 200 m) underwent the greatest modifications (Fig. 5). The low-salinity waters (S < 34.91), with a density σ_θ < 27.9 kg m^{-3}, can discernibly reach approximately 70.5°N where they met the warm, saline AW, and the original characteristics became untraceable (Fig. 5). Below this layer, the original characteristics of waters lighter than 28.01 kg m^{-3} remained intact within the JMCh but were greatly modified upon reaching the northern Norwegian Basin (Fig. 5). The waters flowing into the interior Norwegian Sea can be observed in layers with densities greater than 28.01 kg m^{-3} (depth > 200 m). We divided the layers into two parts and separately considered their contributions to the Norwegian Sea. The upper and lower waters were represented by the density ranges of σ_θ = 28.02–28.04 kg m^{-3} (Fig. 6) and σ_θ = 28.05–28.06 kg m^{-3} (Fig. 7), respectively. Notably, different water masses may be present on the same isopycnal surface. Therefore, it is necessary to ascertain the temperature and salinity range of the water we are interested in for each isopycnal surface before

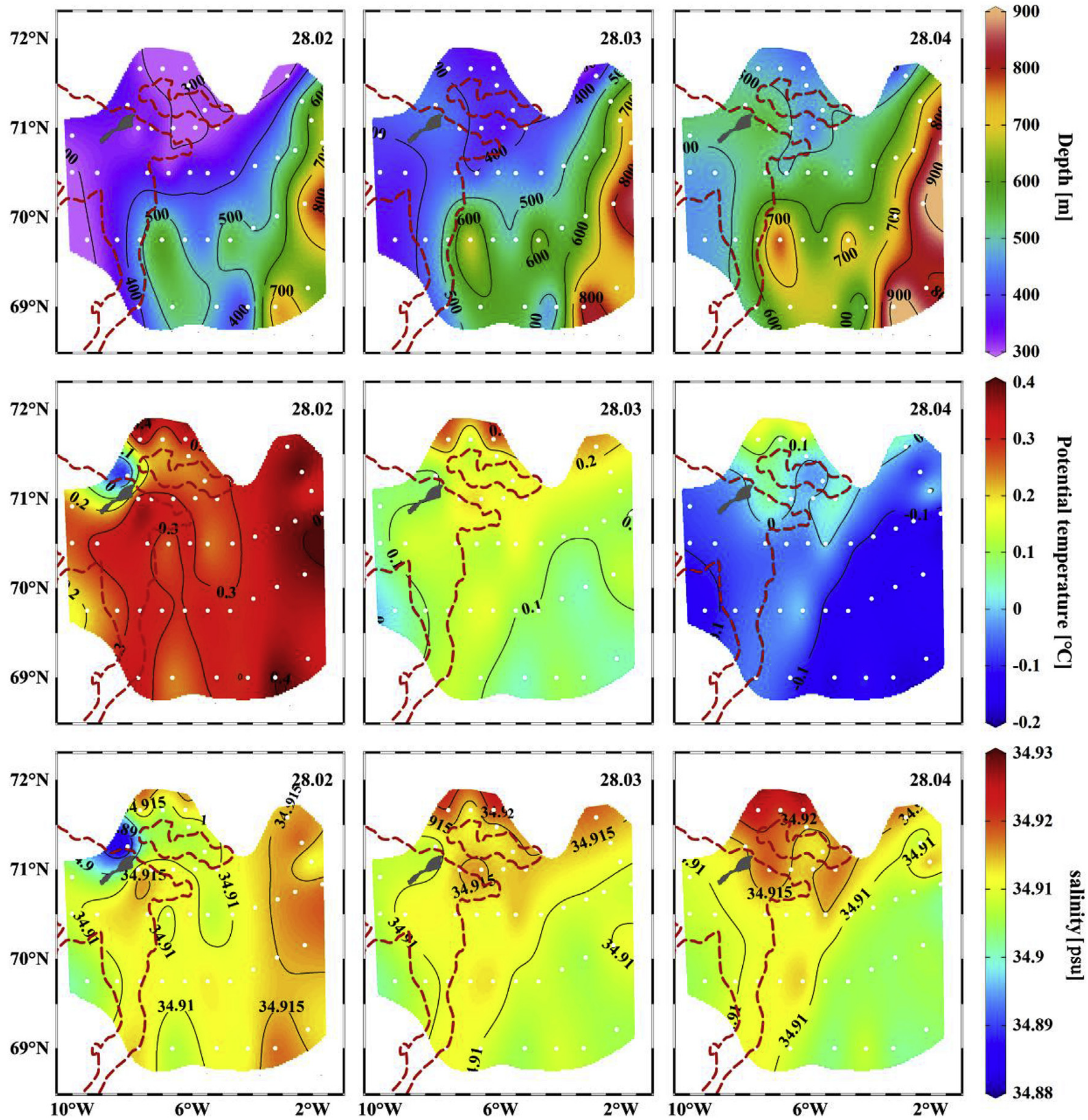

Fig. 6. Same as Fig. 5 but for the densities σ_θ = 28.02, 28.03 and 28.04 kg m^{-3}.

determining its geographic extension. Distinguishing different water masses on an isopycnal surface requires careful analysis of the temperature, salinity structure, and the criteria for ascertaining water masses on each isopycnal surface are different. For the above reasons, spatial distributions of isopycnic depth, potential temperature and salinity are shown to better examine the extension of different water masses.

The salinities of the waters flowing out of the JMCh at densities of 28.02, 28.03 and 28.04 kg m^{-3} were generally less than 34.92, and mostly between 34.91 and 34.915; the corresponding temperatures were greater than 0 °C (Fig. 6). The waters with salinities between 34.91 and 34.915 over the Jan Mayen Ridge in the western Norwegian Basin were consistent with those in the JMCh, indicating that the waters in the density range of 28.02–28.04 kg m^{-3} within depths shallower than 500 m in the JMCh, extended southward, mainly along the western Norwegian Basin. The waters in the eastern part of the Norwegian Basin were not directly related to those flowing out of the JMCh during the survey period, which can be deduced from the former's greater depth and lower salinity (less than 34.91). These waters will be discussed in the Section 4.3.1.

Isopycnals deepened from the Greenland Sea to the Norwegian Sea, indicating that the same water masses would be found at greater depth following the path as they flowed into the Norwegian Sea. The depth of the 28.02 kg m^{-3} isopycnal surface increased from 340 m in the JMCh to 560 m in the western Norwegian Basin; the isopycnal surfaces of σ_θ = 28.03 and 28.04 kg m^{-3} increased from 420 m and 550 m to 680 m and 780 m, respectively (Fig. 6).

The isopycnal surfaces of σ_θ = 28.05 and 28.06 kg m^{-3} indicated the distribution of waters below 0 °C (Fig. 7). On these isopycnal surfaces, the waters which occupied a large area from the western edge to the middle part of the northern Norwegian Basin were consistent with the waters in the JMCh. The eastern part of the basin was dominated by waters with a salinity below 34.91. The salinity of waters in the Norwegian Sea on the 28.07 kg m^{-3} isopycnal surface was generally lower than 34.91, which was fresher than waters in the JMCh.

The depth of each isopycnal also changed. The isopycnal surfaces of σ_θ = 28.05 and 28.06 kg m^{-3} increased from 660 m and 890 m to 910 m and 970 m, respectively. The depth of the 28.07 kg m^{-3} isopycnal surface was generally greater than 1200 m, deeper than the water depth of the FSC, which is the main source of the overflow in the

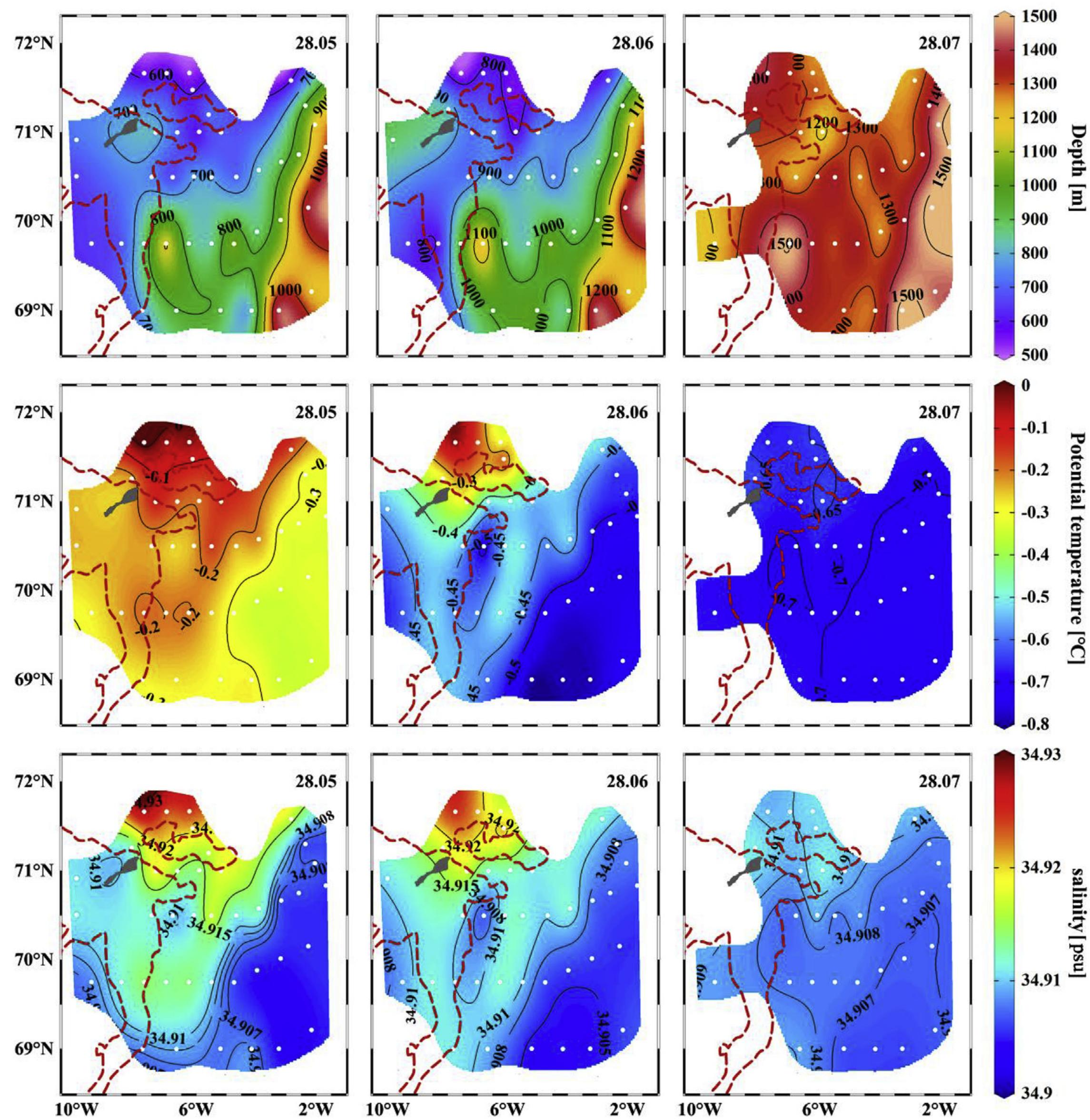

Fig. 7. Same as Fig. 5 but for the densities σ_θ = 28.05, 28.06 and 28.07 kg m^{-3}.

FBC (about 850 m) (Hansen and Østerhus, 2000).

Bourke et al. (1993) questioned the importance of the JMCh in transporting deep water from the Greenland Sea to the Norwegian Sea, but they were discussing waters deeper than 2000 m. For the upper waters shown in our study, the JMCh is very important for carrying Greenland Sea water to the Norwegian Sea. As described above, the existence of the JMCh allows the Greenland Sea water to flow into the Norwegian Sea. Generally, the waters from the Greenland Sea sank by 150–200 m during this process. This is because the waters in the Greenland Sea are denser than the waters in other basins so these waters will sink into the layer corresponding to their density (Blindheim, 1990). The behavior of dense waters outflowing through the JMCh and their significant deepening is very similar to the overflows that occur over the GSR. Therefore, we introduce the term "internal overflow" of the Nordic Seas for this flow. Likewise, this flow occurs along the deepest passage through the Mohn Ridge.

4.3. The cold reservoir in the Norwegian Basin

The four sections carried out in the northern Norwegian Basin can help to describe the status of the Greenland Sea water after entering the Norwegian Sea. Section B1 is shown in Fig. 3. The other three sections B2, B3 and B4 are presented in Fig. 8. The AW was located under the 50-m thick surface waters in the northern Norwegian Basin (Fig. 8). The depths of the AW reached 600 m in the eastern Norwegian Basin and decreased to the northwest and west, with a shallow depth of 300 m comprised by the AW recirculation in the western Norwegian Basin.

The dense waters outflowing through the JMCh accumulated below 330 m in the western part of the Norwegian Basin and can be traced down to 1140 m. With an east-west width of over 160 km, this area formed a large storage for the JMCh outflow. The salinities of these waters were generally between 34.91 and 34.915, while the temperatures decrease with depth. Because the temperature was generally below ~0.5 °C, we introduce "cold reservoir" to describe these water masses in the Norwegian Basin. The cold reservoir was located beneath the AW and its recirculating water in the Norwegian Basin. There was a transition zone between the cold reservoir waters and the waters above. However, the reservoir core still preserved the characteristics of waters that outflowed through the JMCh.

4.3.1. Time variability in the internal overflow and the cold reservoir

The water outflowing through the JMCh during the survey period

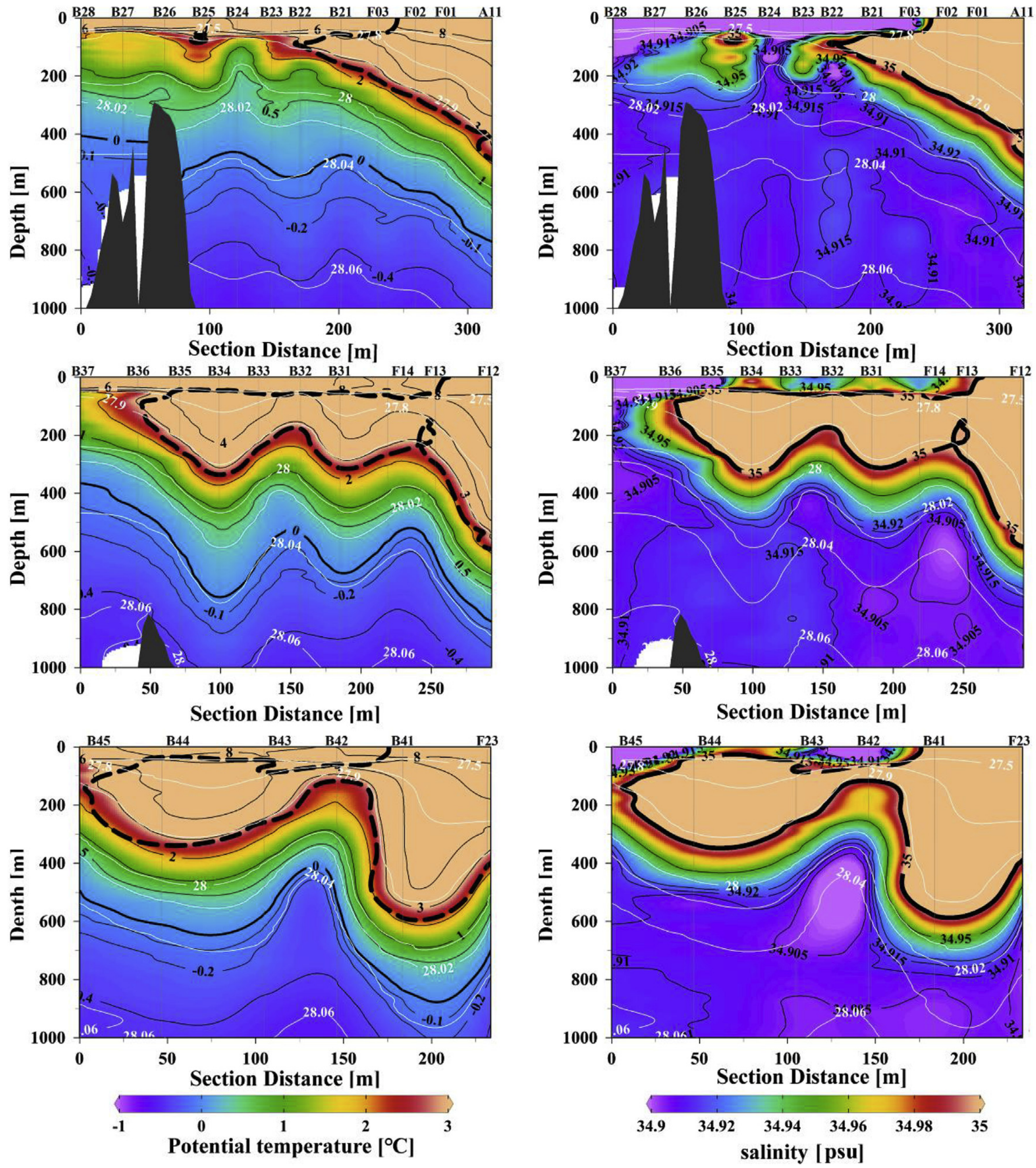

Fig. 8. Potential temperature (left) and salinity (right) in sections B2 (top panels), B3 (middle panels), and B4 (lower panels) in the northern Norwegian Basin. The overlaid solid white lines represent isopycnals; the dashed, thick black lines in the temperature panels are associated with the 35.0 isohaline (the thick black lines in the salinity panels) for each specific section.

had a density range of σ_θ = 28.02–28.06 kg m^{-3} with salinities mainly between 34.91 and 34.915. We found this water appeared widely in sections B1, B2 and B3, with relatively limited expansion into the area covered by section B4. There was very little of this water appearing in section R located in the Lofoten Basin in the northernmost part of the survey area (not shown), indicating the water that outflowed out of the Greenland Sea did not reach that section. These waters outflowing through the JMCh flowed southward along the eastern side of the Jan Mayen Ridge, i.e., on the western side of the Norwegian Basin. This is consistent with Olsson et al. (2005a) who indicated that the direct pathway for spreading of the intermediate water in the Greenland Sea to the Norwegian Sea is through the JMCh and then along the eastern side of the Jan Mayen Ridge.

We further examined the data collected in the same region in June 2015. When comparing section S2, the representative section of 2015 in the JMCh (Fig. 9c), with section B1 of 2014 (Fig. 9b), we found that water properties had significantly changed. Waters with salinities less than 34.91 occupied depths below 300 m in the western part of the channel in June 2015. The waters flowing into the northern Norwegian Basin mostly had a salinity of less than 34.91 while traces of waters with salinities higher than 34.91 only reached section D (Fig. 9e), which is the southernmost area these low-salinity waters appeared in June 2015. This suggested that the salinity of the waters outflowing through the internal overflow within the Nordic Seas was variable and this would certainly lead to spatial differences in the salinity of the cold reservoir. The water with a salinity below 34.91 in the eastern part of the survey area in 2014 (Fig. 8) was supposed to originate from the waters outflowing from the Greenland Sea at an earlier time, although we cannot confirm a fresher water outflowing before our 2014 cruise. Water with a salinity higher than 34.91 observed in 2014 in the western

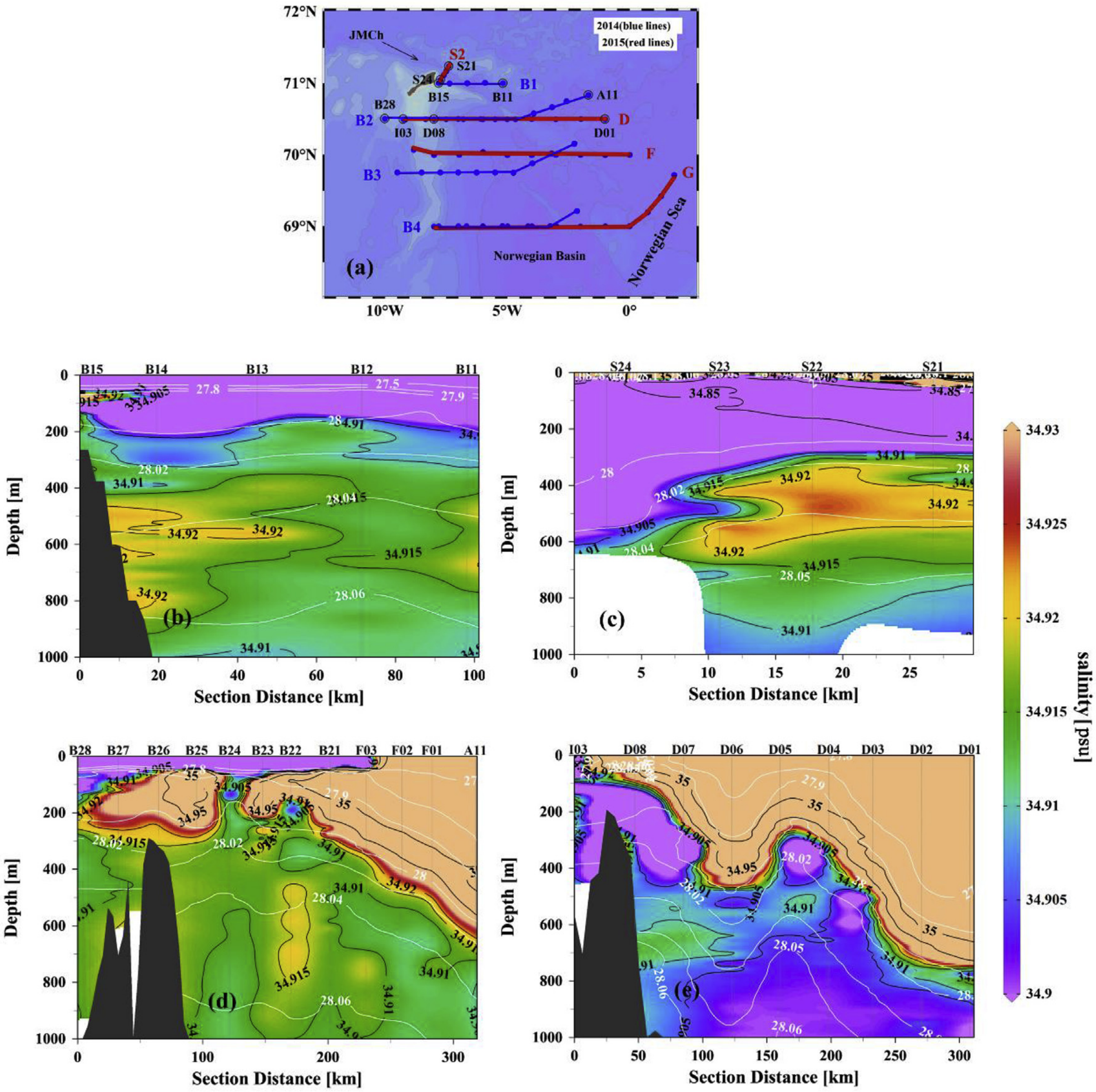

Fig. 9. Changes in the salinity of the outflowing water through the Jan Mayen Channel. (a) Locations of sections B1, B2, B3 and B4 in 2014 (blue lines) and their corresponding sections S2, D, F and G in 2015 (red lines). Salinity within the JMCh is shown in section B1 (b) and in section S2 (c). Salinity in the northern Norwegian Basin is shown in section B2 (d) and in section D (e). The overlaid solid white lines in (b–e) represent isopycnals. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Norwegian Basin likely flowed out recently.

Direct current observations indicated flow variations in the JMCh, at least in the bottom layer (Østerhus and Gammelsrød, 1999; Sælen, 1990). While the outflow via the JMCh is primarily density-driven, this flow may be enhanced by the wind stress. The numerical results of Eldevik et al. (2005) suggested that the spreading of the Greenland Sea water to the Norwegian Sea is much faster, and the internal circulation of the Greenland Sea may be spun up and offset to the south during a positive NAO period, the direct effect of which is to increase the wind-stress curl over the Nordic Seas on short time scales (months). There was a significant water mass transformation in the Greenland Sea during the past decades, with a new, less dense class of intermediate water starting forming since 1994 (Brakstad et al., 2019). Moreover, there was clearly observed variability in the convection depth in the Greenland Sea (Ronski and Budéus, 2005) and also a change in water properties of the GSAIW during the last decade (Jeansson et al., 2017), which likely affects the cold reservoir in the Norwegian Basin through the outflow via the JMCh. Given the lack of direct current meter measurements with high spatial resolution in this area, the variability at different time scales in the JMCh, and thus in the cold reservoir, is presently unresolved.

4.4. Possible relationship between waters in the cold reservoir and the eastern overflow

As described above, the waters derived from the Greenland Sea accumulated in the Norwegian Basin and formed a cold reservoir with a large volume. Waters in this reservoir had densities lower than waters in the Greenland Sea at the same depth but higher than those in the North Atlantic and thus had the potential energy available for supplying the GSR overflows. The source of the Denmark Strait overflow is commonly thought to be the EGC (e.g. Olsson et al., 2005b; Tanhua et al., 2005; Jeansson et al., 2008) and a more eastern pathway from the Iceland Sea (e.g. Våge et al., 2011). The Iceland-Faroe Ridge is rather shallow for most of the waters in the cold reservoir. We focused on the eastern overflow to investigate possible relationship between the waters in the cold reservoir and the overflow water. Dense waters of the Nordic Seas pass through the FSC before overflowing at the FBC. With a depth

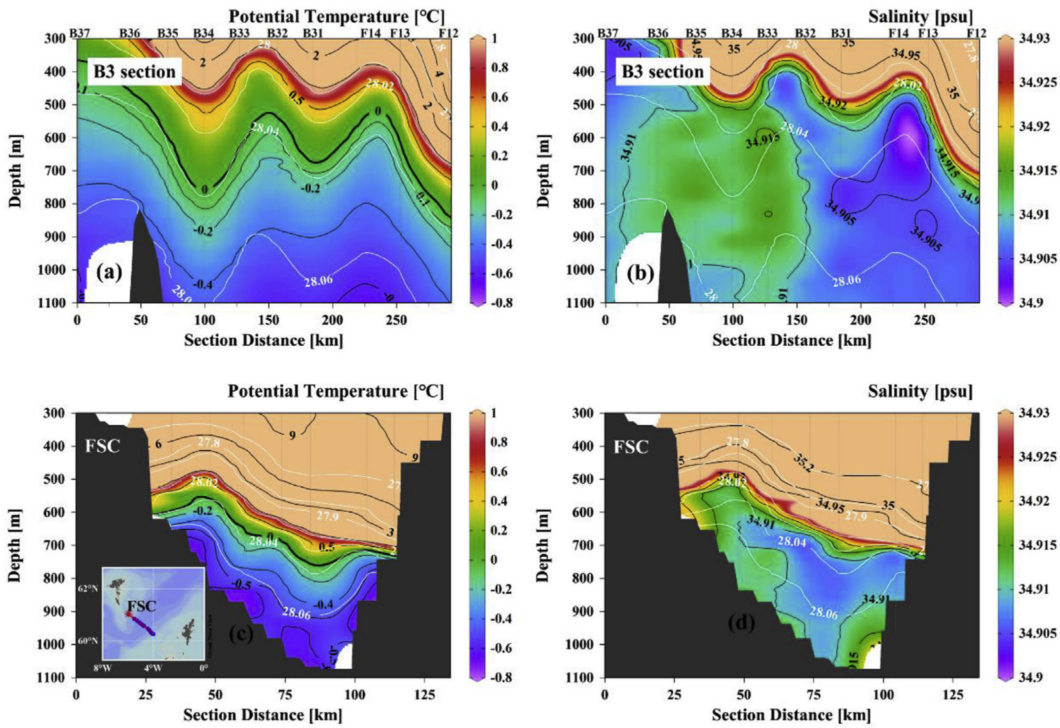

Fig. 10. Water properties of the cold reservoir in Norwegian Basin (represented by B3 section, upper panels) and the FSC overflow region (lower panels). Potential temperature (a) and salinity (b) in B3 section in the Norwegian Basin. Potential temperature (c) and salinity (d) in the FSC (section location shown on the inset map, see the Data section for more details). The overlaid white lines in (a–d) represent isopycnals.

of slightly more than 1000 m, the FSC is favourable for the spill-over of waters in the cold reservoir. Previous studies suggest the Norwegian Sea Arctic Intermediate Water can be as warm as 2.5 °C between 400 and 600 m in the FSC (Mauritzen et al., 2005). Its high temperature is caused by mixing with warmer water along its path, while its salinity minimum is maintained. Messias et al. (2008) indicated that the GSAIW from the Greenland Sea gyre can be found at 800 m, above the Norwegian Sea Deep Water from the Norwegian Sea, in the western part of the channel. Limited by the survey extension to the south, we examine the possible links between waters in the cold reservoir and the overflow through the Faroese Channels using data from the ICES Dataset on Ocean Hydrography in September 2014. As seen from the section in the FSC, the overflow waters, defined by densities greater than 27.8 kg m^{-3}, were generally located below 400 m under warm Atlantic inflowing waters. The waters with densities of 28.02–28.06 kg m^{-3}, salinities below 34.915 and temperatures below 0.5 °C resembled those in the cold reservoir (Fig. 10). These waters were below 550 m, with a lower boundary of ~1000 m. The waters outflowing through the JMCh and thus stored in the cold reservoir are a potential source for the overflow in the Faroese Channels. The pathway of these waters to the FSC is indicated to flow south along the Jan Mayen Ridge (Olsson et al., 2005a). This shortcut from the Greenland Sea to the Norwegian Sea is suggested to play a more pronounced role in feeding the FSC than the EGC during a positive NAO period (Eldevik et al., 2005), although there is a strong recirculation in the FSC (Mauritzen et al., 2005) and hence not all the waters represented in the FSC can flow into the overflow areas.

Direct measurements over an extended period of time (ideally at least a year) will be needed to determine the actual transport and its variability through the JMCh. Assuming a current speed of 0.08 m/s (as suggested by Sælen, 1990), an outflow thickness of 1000 m, and an average channel width of 20 km, the volume transport in the JMCh is estimated to be up to 1.6 Sv. Although the estimate of transport through the JMCh is a very rough approximation, we suggest that the waters outflowing through the internal overflow (and those stored in the cold reservoir) are an important contributor to the overflow of the Faroese Channels.

5. Conclusions

Based on the hydrographic survey conducted around Jan Mayen in September–October 2014, an investigation was carried out on the details of different Greenland Sea waters entering the Norwegian Sea through the JMCh, the extent to which these waters accumulated in the Norwegian Basin, and their possible contribution to the GSR overflows.

The existence of the JMCh allows the Greenland Sea water to enter the Norwegian Sea. As it does so, it deepens by 150–200 m, a process resembling those of the overflows in the GSR, and forms an internal overflow within the Nordic Seas. Waters outflowing via this internal overflow are mainly derived from the southern periphery of the Greenland Sea. These waters comprise low-salinity polar waters from the subsurface layer of the JMC, the slightly saline RAAW of the middle layer, and the GSAIW formed by winter convection.

Tracking water masses by examining temperature, salinity and depth on isopycnal surfaces, we find the waters that flow through the JMCh at densities $\sigma_\theta < 28.0$ kg m^{-3} are significantly modified and only appear in the northernmost Norwegian Basin where they meet the AW. The waters with densities greater than 28.01 kg m^{-3} (with depth > 200 m) expand southwards, retaining their original characteristics. The waters with densities between 28.02 and 28.06 kg m^{-3} are almost unchanged along their route. Expanding southward and eastward in the Norwegian Basin, the waters originating from the Greenland Sea accumulate beneath the AW and recirculating Atlantic-derived water in the western part of the basin, forming a cold reservoir with a maximum temperature of only ~0.5 °C. The cold reservoir has a large volume, with depths ranging from 330 m to 1140 m and an east-west extent of more than 160 km. Salinities in the cold reservoir are generally less than 34.915.

Comparing the waters in the FSC Channel with waters in the cold reservoir, we find that the two are consistent with each other within density ranges greater than 28.02 kg m^{-3}, indicating that the cold reservoir is a potential source of the overflow water through the Faroese Channels. The pathway is suggested to mainly flow south along the Jan Mayen Ridge (Olsson et al., 2005a) and is more pronounced in feeding the FSC than the EGC during a positive NAO period (Eldevik et al., 2005). It is reported that GSR overflows are rather stable (Hansen and Østerhus, 2000; Serra et al., 2010; Hansen et al., 2016). The outflow via the JMCh and the existence of the cold reservoir in the Norwegian Basin likely play a role in sustaining continuous overflows, similar to the flow through the Iceland Sea (Fogelqvist et al., 2003; Eldevik et al., 2005).

Our results show that the waters of the cold reservoir in the Norwegian Basin are from the Greenland Sea, with the main pathway being the JMCh. This explains the essential reason for the existence and maintenance for the cold reservoir, and indicates that the convection process that occurs in the central Greenland Sea can contribute to the GSR overflows via the Norwegian Basin. However, the exact transport through the JMCh and the extent of the cold reservoir are not clear because of the limited data. In the present study, we confirm the JMCh as a direct pathway for water outflowing from the Greenland Sea, but we are not sure whether this pathway is exclusive.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.dsr.2019.04.012.

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