Upper layer circulation of the Nordic seas as inferred from the spatial distribution of heat and freshwater content and potential energy

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The spatial distribution of heat and freshwater content and potential energy of a several hundred metre thick surface layer are computed for the Nordic seas and adjacent parts of the northern North Atlantic and the Arctic Ocean using a total of almost 100 000 hydrographic stations. The fields clearly show the major features of the area's circulation, with warm salty water in the eastern part and fresher, colder water in the western part. Comparisons with published estimates show that the potential energy field, representing the baroclinic part of the flow, accounts for about 30 % of the total flow but roughly 100 % of the flow of Polar Water in the northern part of the East Greenland Current, about 50 % of the total flow in the Norwegian Atlantic Current, and just a small fraction of the flow in the eastern part of Fram Strait. This suggests that the barotropic circulation is quite important in many parts of the Nordic seas. The barotropic circulation is also clearly seen by its effects on the integrated fields with isolines following deep bathymetric contours. We speculate that the barotropic circulation in combination with topographic obstacles, like the Greenland–Scotland Ridge and the ridge system in the Jan Mayen area, may have large impact on the spreading of freshwater and heat in the Nordic seas.

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The Meridional Overturning Cell (MOC) is a modern term for the deep vertical circulation in the North Atlantic. The MOC is ultimately driven by thermohaline processes at the sea surface, producing dense water, the North Atlantic Deep Water (NADW), that is filling up large parts of the abyss of the world's oceans. The production of deep water is a continuous process with contributions from vast areas making surface water denser. The finishing touch and the actual sinking of dense water from the sea surface, however, occurs in limited areas in the Labrador Sea and in the Nordic seas/Arctic Ocean. The mean rate of NADW production in the Labrador Sea has been estimated to be of about the same magnitude as the flow of dense water over the Greenland–Iceland–Scotland Ridge (e.g. Maurizen & Häkkinen 1999). In terms of production of NADW, the northern source seems to be the greater because the flow of dense water from the Nordic seas is reinforced south of the sill due to entrainment of ambient water (Dickson et al. 1990).

The upper layers of the Nordic seas, north of the Greenland–Iceland–Scotland Ridge and south of the Arctic Ocean, are dominated in the east by salty, relatively warm Atlantic Water entering across the ridge. In the west, the upper layers are dominated by rather fresh and cold Polar Water and
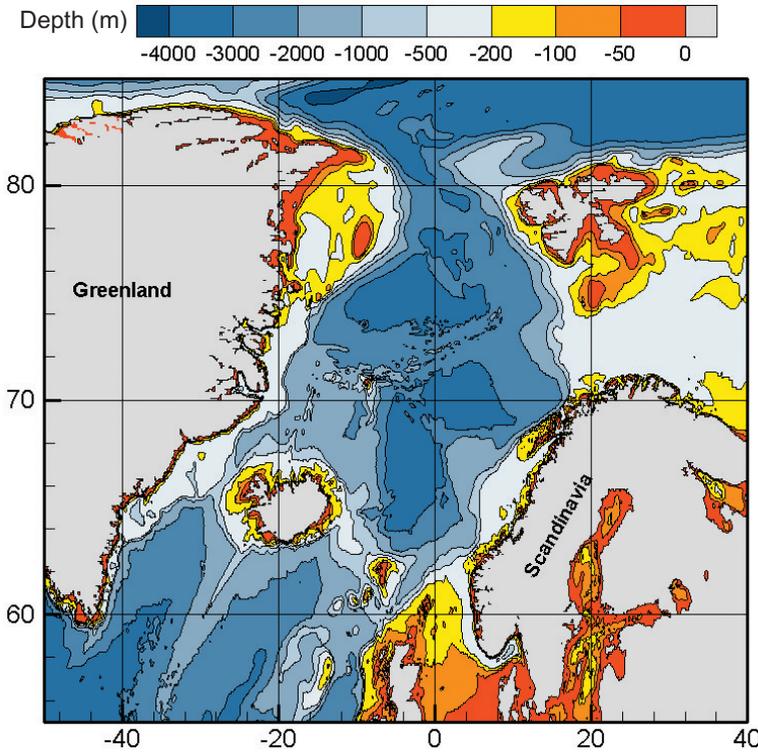
Depth (m)

-4000 -3000 -2000 -1000 -500 -200 -100 -50 0

Fig. 1. Bathymetric map of the Nordic seas.

sea ice exported from the Arctic Ocean and sea ice regionally produced by freezing in winter. Below these water masses, the basins are filled with water of nearly uniform temperature and salinity, created by cooling and slight freshening of Atlantic Water in the Nordic seas and the Arctic Ocean. Most of the inflowing Atlantic Water is transformed into deep water. However, some of it mixes with fresher water from the Arctic Ocean and freshwater supplied by runoff along the coasts, becoming part of a cyclonic shallow estuarine type of circulation along the periphery of the Nordic seas.

It is evident that the hydrographic state of the Nordic seas might be sensitive to changes in the import of Atlantic and Polar waters, as well as to changes in air—sea interaction and ice production and melting. An increased eastward deflection of cool and relatively fresh Polar Water from the Iceland Sea might be of large importance for the freshening of inflowing Atlantic Water and might thereby be deleterious for deep water production. Such an increased deflection might be caused, for example, by changes of the wind field over the Nordic seas (Stigebrandt 1985; Blind-

heim et al. 2000).

The aim of this paper is to give an alternative description of the essential features of the mean circulation of water, heat and salt in the Nordic seas and in the vicinity of the inflow regions using vertically integrated quantities for the surface layers instead of the commonly used fields of T, S, and ρ at different levels. For this, we use historic hydrographic data. The paper starts by briefly defining freshwater height, heat content and profile potential energy. These quantities have earlier proved to be powerful diagnostic variables for analyses of circulation and dynamics of surface waters. In previous work we have analysed the circulation and dynamics of the Skagerrak (Gustafsson & Stigebrandt 1996; Gustafsson 1999). However, in the Skagerrak the stratification is almost completely dominated by salinity so the heat content has an insignificant impact on the dynamics. In large parts of the Nordic seas, salinity and temperature are of equal significance for the stratification and dynamics, which makes the analysis more elaborate. A discussion follows the presentation of the results.

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Fig. 2. The number of profiles deeper than 200 m per 1° × 0.5° square. Only squares with more than five observations are considered.
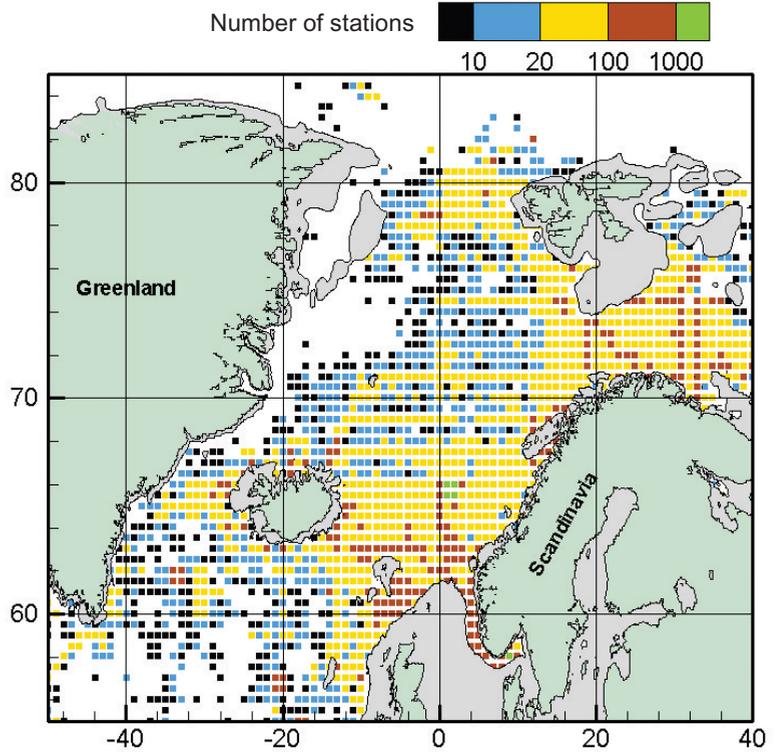
Methods

To the lowest order, the Nordic seas are supplied with warm and salty Atlantic Water and cold and fresh Arctic surface water. These water masses are modified by mixing with each other and by heat and water exchange with the atmosphere. Freshwater supply from the European continent, carried by the Norwegian coastal current, may also be of some importance if mixed into the Norwegian Atlantic Current. The deep water of the Nordic seas is quite homogeneous in comparison with the variations of the temperature and salinity of the surface waters. It is therefore useful to describe the variations of heat and freshwater content of water closer to the sea surface using the deep water as reference. We have calculated fields of the vertically integrated quantities: freshwater content F, heat content H, and potential energy P relative to a reference water $\rho_{ref} = \rho(S_{ref}, T_{ref})$ using NODC station data up to 1998 for the Nordic seas. The definitions used here are:

$$F = \int_0^D \frac{S_{ref} - S}{S_{ref}} \, dz \qquad (1)$$

$$H = \rho_{ref} C_P \int_0^D T - T_{ref} \, dz \qquad (2)$$

$$P = g \int_0^D \frac{\rho_{ref} - \rho}{\rho_{ref}} \, z \, dz \qquad (3)$$

For the computations we use $S_{ref} = 34.9$ and $T_{ref} = -0.9$ °C. These values are close to the deep water properties in the Nordic seas.

The fields are interpolated using means of F, H and P in 1° × 0.5° squares containing more than five stations. A total of about 96 300 hydrographic stations are employed in the analysis. Two different integration depths are used, $D = 200$ m and $D = 500$ m, where the integration to 500 m captures most of the Atlantic inflow and that to 200 m shows more details on the shelves. The reason for using fixed integration depths is that the integrals become heavily dependent on the water depth when this is shallower than the integration depth. We therefore only show data where the ocean

Fig. 3. (a, b) Linearly interpolated fields of heat content, (c, d) freshwater height, and (e, f) profile potential energy. The shelves are indicated with grey shading. The heat content is divided by ρC_P.

depth exceeds the integration depth. Fixed integration depths also makes the calculations less sensitive to small temporal and spatial variations in the deep water salinity and temperature that can corrupt the calculations.

The advantage of these integral quantities compared to the more used *T*, *S*, and ρ hydrographic fields is that *F* and *H* are conservative in the sense of vertical mixing and that *P* is directly related to the baroclinically driven geostrophic flow *Q* over the depth interval through the relation $Q = P/f$, where *f* is the Coriolis parameter. The baroclinic flow field should in the present context be interpreted as a rough measure of the baroclinic transport that is superimposed on an unknown barotropic flow field. Another aspect to have in mind is that the actual baroclinic flow mostly occurs at places with gradients in *P* (at density fronts). This means, for example, that areas with small horizontal gradients of *P* have quite weak baroclinic flow.

Results

The geographical distribution of the stations is shown in Fig. 2. The station density is generally very large, with more than 20 stations in each square over the central and eastern part of the area. The squares at weather ship M are exceptional with more than 1000 stations. The fields of *F*, *H* and *P* integrated to 200 and 500 m, respectively, are shown in Fig. 3. We tested whether the fields are biased by seasonally varying sampling frequency or by the limited number of measured profiles by calculating 3 months seasonal average fields (not shown). These fields indicate relatively small seasonal variations. The patterns are quite similar to the long-term average fields. Therefore, we conclude that the data material is sufficient to give representative average fields.

Basin circulation

The heat content fields integrated to 200 and 500 m (Fig. 3a, b) show the warm Norwegian Atlantic
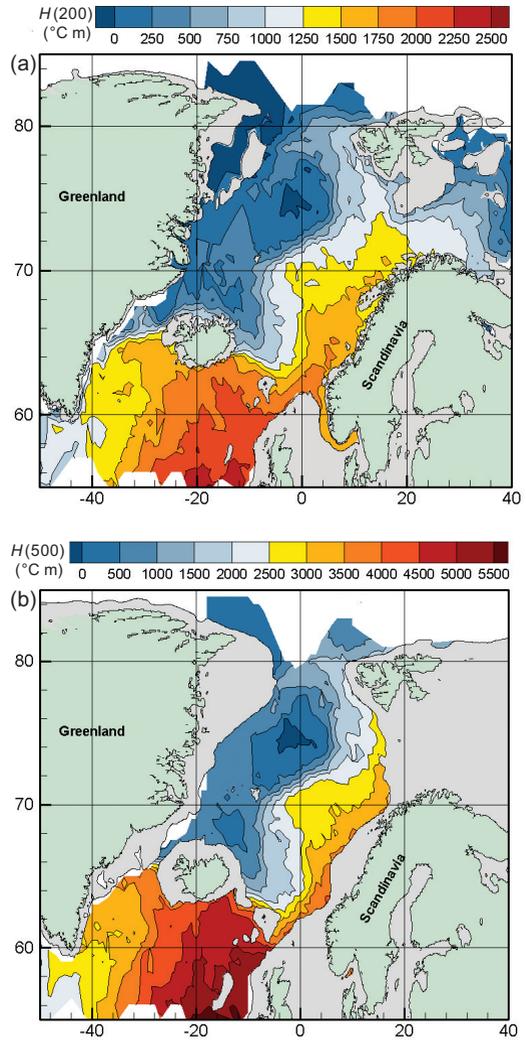
Current starting at the Scotland–Iceland Ridge. This current is saltier than the reference water and therefore gives a negative freshwater contribution to the Nordic seas (Fig. 3c, d). It is evident from the decreasing heat content over both 200 and 500 m that the Norwegian Atlantic Current cools gradually northwards. Along the western coast of Norway, the freshwater height increases slightly most probably due to mixing with fresher water from the Norwegian coastal current (barely visible near the Norwegian coast at this figure scale).

The potential energy (Fig. 3e, f) is related to the baroclinic geostrophic transport through the relationship given in the preceding section. The

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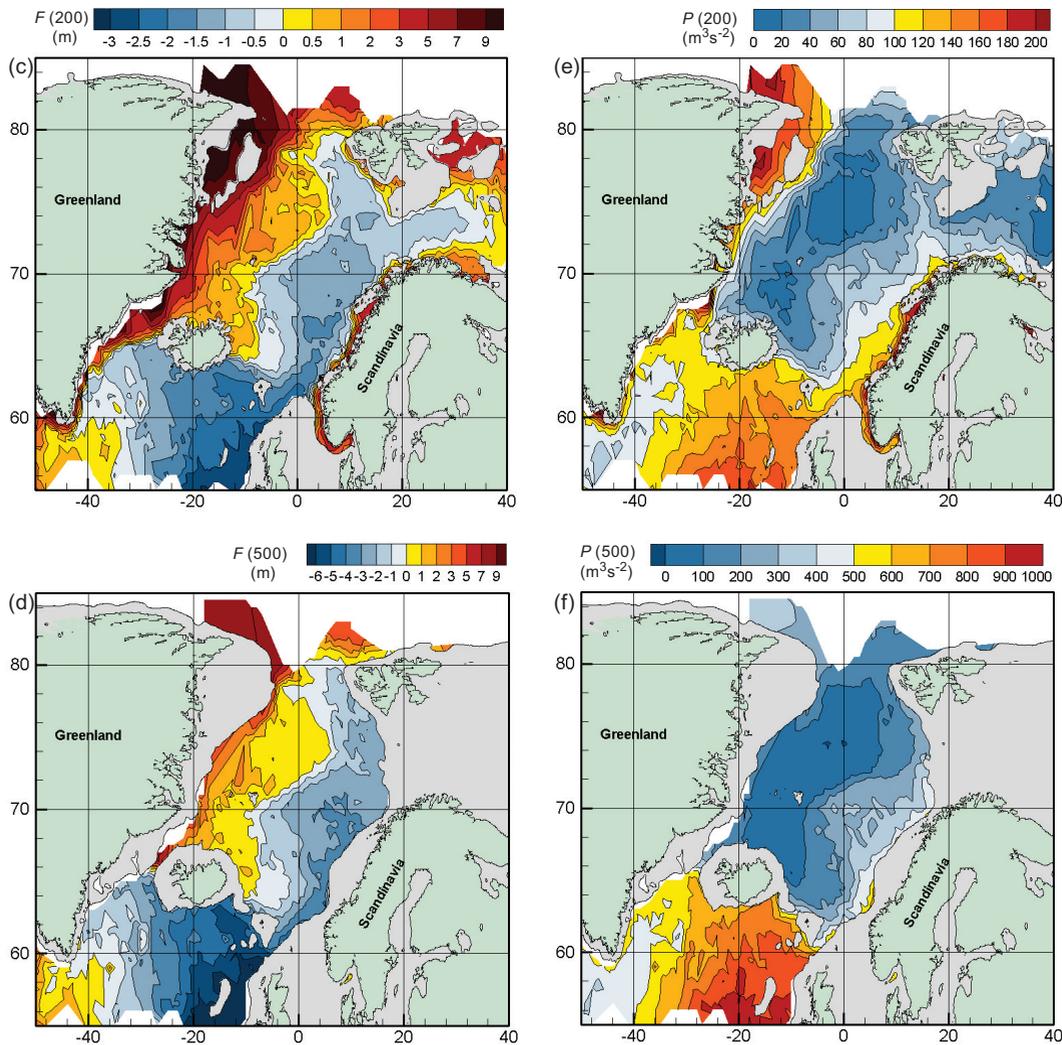
P field in Fig. 3f (with reference to 500 m depth) indicates a northward flow west of Norway of about 4 - 5 Sv. This includes transports of Atlantic Water in the Norwegian Atlantic Current, water of Arctic origin outside this and also Atlantic Water that has recirculated in the Norwegian Basin. The baroclinic flow of "new" Atlantic Water is perhaps less than 4 Sv and therefore substantially less than the estimate of 8 Sv for the total Atlantic inflow (Hansen & Østerhus 2000). If the latter figure is reasonably correct, a large part (>50 %) of the flow in the Norwegian Atlantic Current should be barotropic. The baroclinic transport in the Norwegian Atlantic Current changes only little until reaching the latitudes of northern Norway, where

the current splits into two branches taking different routes to the Arctic Ocean, one through the Barents Sea and the other through Fram Strait. Further, by comparing with the freshwater height field we see that much of the baroclinic potential energy gradient north of Norway is due to the fresh Norwegian coastal current. Blindheim (1989) estimates a transport of some 0.7 Sv in the Norwegian Coastal Current at this latitude. The profile potential energy close to the northern Norwegian coast is approximately 100 m^3s^{-2}, corresponding to a baroclinic transport of some 0.7 Sv, which therefore fits well with Blindheim's estimate. The northward branch of the Norwegian Atlantic current extending to Fram Strait

is clearly seen in the H and F fields, but the potential energy is weak. The flow towards the Arctic Ocean should therefore be mostly barotropic, which also has been observed by direct current measurements in Fram Strait (Fahrbach et al. 2001). Due to the shallowness of the Barents Sea this branch cannot get enough profile potential energy to sustain a purely baroclinic transport, which is why the transport across the Barents Sea must be partly barotropic and/or wind-driven. Indeed, a current meter section in the western Barents Sea during September–October 1978 (Blindheim 1989) shows a barotropic component of about 2 cm/sec, which adds up to a flow of about 1.3 Sv over the section. Further to the east, cooling of the warm Atlantic Water is quite rapid, while freshwater height remains approximately constant, indicating atmospheric cooling and only minor horizontal mixing.

The East Greenland Current (EGC) is a prominent feature in the freshwater height field (Fig. 3c). The core of EGC seems to be confined to the shelf with rapidly changing freshwater height across the shelf slope. However, weak (but still significant) signals of eastbound flows in terms of freshwater are found between the EGC and Jan Mayen and north of Iceland. The former is coherent with the Jan Mayen current and the well known eastward ice drift called "Isodden". The latter is known as the East Icelandic Current (EIC). Both these eastward flows represent leakage of relatively fresh water from the EGC, which has a large potential to influence the thermohaline forcing of the entire Nordic seas. It is likely that the strength of the flow is related to large-scale atmospheric circulation patterns like the NAO (Blindheim et al. 2000). The F-field therefore indicates that the entire freshwater load carried by the EGC does not leave the Nordic seas, but rather some fraction recirculates within the basin. Areas of weak stratification are evident as areas with small profile potential energy. These are the areas most likely for deep convection and ventilation of deep water. Especially in Fig. 3e, where the integration is performed to 200 m, we see that the whole central part of Greenland Sea and a central portion of the Iceland Sea have mean profile potential energy of less than 20 m^3s^{-2}.

The inflow of warm and salty Atlantic Water

There are strong fronts in both F and H across the Greenland–Scotland Ridge indicating that the major part of the warm inflow follows the fronts and the ridge before moving northwards in the Norwegian Sea. Such an eastward flowing core, with a transport of about 4 Sv, is observed in recent current measurements north of the Faroes (Hansen et al. 1999). The across-front drop in potential energy over the Greenland–Scotland Ridge is about 500 m^3s^{-2} (from 700 to 200 m^3s^{-2}), which represents a flow of about 4 Sv and thus fits nicely with the observations. A prerequisite for such close coincidence is that the current is mostly baroclinic, which indeed is seen in the current measurements where the flow field has a well-developed baroclinic structure.

There is also a frontal structure seen in all three quantities in between the Reykjanes Ridge, part of the Mid-Atlantic Ridge and the Rockall Plateau, implying that the major northward flow occurs in this area. Indeed, drifter observations in the area by Otto & van Aken (1996) show the strongest north-eastward flow just westward of the 2000 m isobath at the Rockall Plateau. How this flow crosses the Greenland–Scotland Ridge seems to be quite complicated and is not yet well understood (Hansen & Østerhus 2000), but according to our integrated fields a substantial part crosses the ridge close to Iceland, where it turns and follows the ridge eastward. This should imply that a large part of the inflowing Atlantic Water originates from the frontal region, and is a mixture of warm and salty water in the east and cool and rather fresh water in the west. There is, however, a well known warmer and saltier northward flowing core following the Scottish slope at relatively shallow depth (Hansen & Østerhus 2000). A current meter section between Shetland and the Faroes shows a highly barotropic transport of about 3 Sv for this branch (Hansen et al. 1999). This flow is manifested as a narrow tongue in all three integrated quantities at the southeastern side of the Faroe–Shetland Channel. The change in potential energy across this tongue is only about 20 m^3s^{-2} (from the 200 m field), which is far too small to explain the entire flow. Our results are therefore consistent with the current measurements that showed speeds above 10 cm s^{-1} close to the bottom (Hansen et al. 1999).

There is also a tendency to enhanced potential energy and heat content south-west of Iceland. This is likely a manifestation of the inflow west of Iceland known as the Irminger Current. This current is highly variable (Kristmannsson 1998) and drifter studies showed that it is probably fed

from south along the western side of the Rey-kjanes Ridge (Krauss 1995).

In general, the branching of the North Atlantic Current evident in the integrated fields and other observations shows that the topographic steering of the North Atlantic circulation is immense even for current systems near the surface.

The inflow of cold and relatively fresh water from the Arctic Ocean

The front between Arctic Ocean surface water and water of Atlantic origin is quite evident in the freshwater distribution in Fram Strait. The more saline Atlantic Water follows the Svalbard islands while the Arctic outflow is focused on the Greenland side. The potential energy front that probably regulates the flow rate of Polar Water (Stigebrandt 1981) is naturally most prominent in Fig. 3e since it is a shallow phenomenon. The potential energy jump across the front is approximately 160 $m^3 s^{-2}$, which should correspond to a geostrophic flow of some 1.2 Sv. This corresponds well with Foldvik, et al. (1988), who estimated the outflow of Polar Water to 1 Sv from a current meter section along 79° N. The total transport along the section was estimated to about 3 Sv, including a significant barotropic component with deep currents in the range 2-3 cm s^{-1}.

Recirculation of low salinity water

The fields of integral quantities show clearly the well known patterns of circulation of the different water masses in the Nordic seas and also reveal interesting aspects of less studied features. The 200 and 500 m F-fields indicate that low salinity water from the East Greenland Current (EGC) spreads eastward along the Greenland–Scotland Ridge; see Blindheim et al. (2000), who discuss influence of this water at station M. This may be seen even more clearly in a close-up of the fresh-water height for individual stations (not shown). The eastward leakage of water from the EGC might be due to a topographic blocking effect in Denmark Strait that prevents the entire EGC from passing through the strait. A similar effect is seen north of Jan Mayen. We suggest that such a blocking may be of crucial importance for the general circulation in the Nordic seas by its influence on the mean salinity.

Discussion

The eastward leakage, by the East Icelandic Current, of water of relatively low salinity from the EGC freshens the inflowing Atlantic Water. If the leakage from the EGC increases, the salinity of the deep water of the Nordic seas may eventually decrease. The resulting decreased density contrast between the deep water of the Nordic seas and the Atlantic Water could lead to a decrease in the baroclinic component of the flow of Atlantic Water into the Nordic seas. Eventually the density contrast could even change sign and an estuarine type of circulation, like in the Arctic Ocean, could be established. This was discussed by Stigebrandt (1985), who considered increased occurrence of southerly winds over the western Nordic seas, spreading fresher water eastwards, as a likely trigger of estuarine circulation. We expect that also barotropic circulation might influence the leakage from the EGC.

The fields of F, H and P are largely parallel to topographic contours (see Fig. 1), indicating that the topographic steering of the upper ocean circulation in the area is strong. The steering is a result of the strong barotropic circulation with, for example, mean currents around 15 cm s^{-1} along the western slope of the Greenland Sea (Fahrbach et al. 1995). The barotropic circulation adds to the buoyancy driven transport and carries water properties from the coast into the deep basins at places where the isobaths leave the coast (e.g. the relatively shallow area between Jan Mayen and Greenland). However, the strong constraint put on the circulation by topography also seems to prevent efficient exchange across the ridges.

We conclude this paper with some questions that we think merit further investigations: (1) How large is the eastward leakage from the EGC and how much is due to barotropic circulation? (2) What is the general role of topographic steering for spreading freshwater and heat in the Nordic seas? (3) How good are estimates of the inflow of Atlantic Water using the mean potential energy and how large is the variability? These and other questions will be addressed in a forthcoming paper.

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