The East Greenland Current studied with CFCs and released sulphur hexafluoride

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Abstract

The distribution and evolution of water masses along the East Greenland Current (EGC) from south of the Fram Strait to the Denmark Strait were investigated using chlorofluorocarbons (CFCs) and the released tracer sulphur hexafluoride (SF_6) together with hydrographic data. Water masses contributing to the Denmark Strait overflow, and to some extent also contributions to the Iceland-Scotland overflow, are discussed from observations in 1999. Special emphasis is put on the advection and mixing of Greenland Sea Arctic Intermediate Water (GSAIW), which could be effectively traced thanks to the release of sulphur hexafluoride in the Greenland Sea Gyre in 1996. By means of the dispersion of the tracer, Greenland Sea Arctic Intermediate Water was followed down to the Denmark Strait Sill as well as close to the Faroe-Shetland Channel. The results indicate that this water mass can contribute to both overflows within 3 years from leaving the Greenland Sea. The transformation of Greenland Sea Arctic Intermediate Water was dominated by water from the Arctic Ocean, especially by isopycnal mixing with upper Polar Deep Water (uPDW) but, to a less extent, also by Canadian Basin Deep Water. A mixture of Greenland Sea Arctic Intermediate Water and upper Polar Deep Water was lifted 500 m on its way through southwestern Iceland Sea, to a depth shallow enough to let it reach the sill of the Denmark Strait from where it can be incorporated in the densest layer of the overflow. The observations show contributions to the Denmark Strait overflow from both the East Greenland Current and the Iceland Sea.

Keywords: Tracers; Overflow; Intermediate water masses; Deep-water masses; Chlorofluorocarbons; Sulphur hexafluoride; Nordic Seas; East Greenland Current; Greenland Sea; Denmark Strait

1. Introduction

The Nordic Seas, the generic term for the Greenland, Iceland and Norwegian seas, are important in the global thermohaline circulation, as they are a region where the ocean loses heat to the atmosphere and surface water loses enough buoyancy to convect away from the surface. The less dense portion of the descended water can flow south and across the Greenland-Scotland Ridge into the North Atlantic, where it makes up a considerable part of North Atlantic Deep Water. The importance of this process for the global thermohaline circulation has drawn large attention to the Nordic Seas and to the water masses and mechanisms that create the overflow water. Different sources of the overflow are reported (Swift et al., 1980; Smethie and Swift, 1989; Strass et al., 1993; Buch et al., 1996; Mauritzen, 1996; Jónsson, 1999; Rudels et al., 1999a, 2002; Fogelqvist et al., 2003) and there is still debate on the importance of different regions, water masses and processes. These divergent opinions can partly be explained by a variable composition of the overflow and recent reports on ongoing decadal changes (Dickson et al., 2002; Rudels et al., 2003).

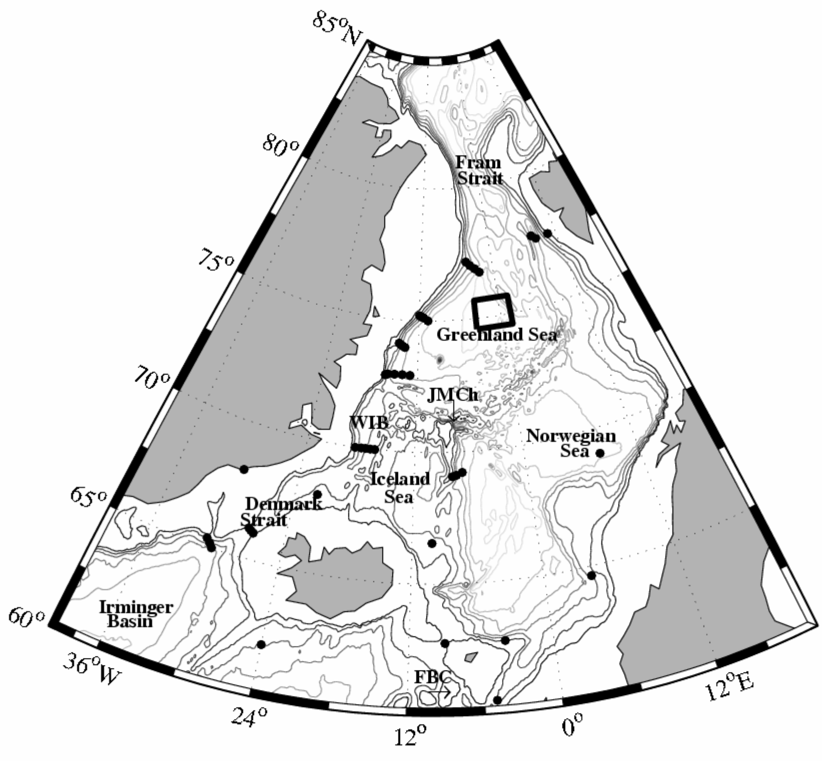

Fig. 1. Bathymetric map of the Nordic Seas with every 500 m represented by an isoline. The dots mark the locations of the stations sampled during the cruise with R/V Marion Dufresne in 1999. The black rectangle marks the area where 320 kg of SF_6 was injected in 1996. The compound was injected at a defined density level, σ_θ 28.049 kg m^{-3}, with an average depth of 330 m. (Abbreviations: JMCh – Jan Mayen Channel, WIB – West Iceland Basin, FBC – Faroe Bank Channel.)

Our investigations took part in summer 1999, mainly in the East Greenland Current (EGC) from 77°N to south of the Denmark Strait (Fig. 1). A major task was to map the compound sulphur hexafluoride (SF_6), which was released in the central Greenland Sea 3 years earlier (Fig. 1) as part of the EU/MAST III project European Sub-polar Ocean Programme, phase 2 (ESOP-2), dedicated to investigate the thermohaline circulation in the Greenland Sea (Messias et al., 1999). Additional results from the tracer experiment are presented by Watson et al. (1999) and Gascard et al. (2002). Sulphur hexafluoride has been utilised as a deliberately released tracer in a range of studies (see the review by Watson and Ledwell, 2000). In addition to this, SF_6 has recently been used as a transient tracer (Law and Watson, 2001; Tanhua et al., 2004) in the same way as the chlorofluorocarbons (CFCs), which gives the potential to make age estimates of water masses (Smethie and Swift, 1989; Smethie, 1993; Wallace et al., 1994) thanks to a time-dependent atmospheric source.

1.1. Methods

All data are from the period July 25th to September 6th 1999, collected from R/V Marion Dufresne during the GINS project. The hydrography data were collected with a SeaBird 911+ CTD equipped with a dissolved-oxygen sensor. Water samples were collected in Niskin bottles of 12 l (General Oceanics) mounted on a SeaBird rosette.

The determination of SF_6 was performed by analysis with gas chromatography with electron capture detection (ECD) coupled to a purge and trap pre-treatment system. The instrument and procedure is described by Olsson (2001) and Tanhua et al. (2004). For CFC analysis a similar purge and trap technique was used, as described by Fogelqvist (1999). The precision of tracer analysis and sampling procedure during the cruise was investigated by analysing up to 10 water samples taken from different Niskin bottles closed at the same depth. Tests were performed on water without released SF_6 and taken from two different depths, 400 and 800 m. The standard deviation was, for CFC-12 2.0%, for CFC-11 1.6% and for SF_6 1.5%. Throughout the cruise, sampling from the Niskin bottles started with SF_6 immediately followed by the CFCs. Calibration gas prepared at Brookhaven National Laboratory (Happell and Wallace, 1997) and cross-calibrated against gas prepared at Scripps Institute of Oceanography (USA) to the SIO-98 scale was used for the standardisation of the CFCs. The standardisation of sulphur hexafluoride was performed using gas calibrated against standards from Plymouth Marine Laboratory (UK) that in turn was calibrated against standards from University of Heidelberg (Germany).

Tracer ages for water masses can be obtained from CFC-11 and -12 by using their atmospheric history (Walker et al., 2000) and solubility (Warner and Weiss, 1985). A certain concentration in the seawater should then, by a first approximation, correspond to a certain time of formation, i.e. when the water mass was last in contact with the atmosphere. This concept can be greatly refined to get a better estimate of the 'true age' of a water mass, especially for the case when a range of tracers has been measured (Waugh et al., 2003). The purpose of this work is however to trace the changes in water mass composition along the East Greenland Current, and the CFC-age concept will only give an estimate of the relative age of the various water masses involved. The saturation of CFC-11 and CFC-12 in the surface ocean often deviates from 100% and is frequently reported to be around 80% in the Greenland Sea during winter (Bullister and Weiss, 1983; Rhein, 1991; Anderson et al., 2000) when dense water masses are formed. Even if the uptake of CFCs is generally greatly overestimated by assuming that surface water is saturated with CFCs (England et al., 1994), the calculated CFC ages in Table 1 are based on 100% saturation since numbers close to this was observed in some regions during this study. The CFC ages in the text are however, given as an interval containing the values received for both 80% and 100% saturation and for both CFC-11 and -12. For CFC ages of more than 20 years, 80% saturation will on average lower the estimates by only 2 years. On more recently ventilated water masses, an offset in saturation will however have a large impact on the numbers due to the small annual changes in atmospheric concentrations since the late 1980s. This also makes low age estimates much more uncertain and CFC ages estimated to be 10 years or less should more correctly be referred to as recently ventilated. This is, however, not true for SF_6 that has a rapidly increasing atmospheric concentration, and thus allows dating of water masses ventilated also during the last few years. More thorough investigations of the uncertainty and validity of the apparent tracer ages for different time periods are presented by Waugh et al. (2003) and Tanhua et al. (2004). It should also be mentioned that since almost all water masses are exposed to mixing, the tracer ages are affected due to resulting changes in CFC concentration and the reported tracer ages should be seen as an approximate and relative measure.

As mentioned above, SF_6 can as well be used as a transient tracer by utilising its atmospheric history (Maiss and Brenninkmeijer, 1998) and solubility (Bullister et al., 2002), but in the Nordic Seas, this use is limited due to the released SF_6. In this work, SF_6 is used mainly as a marker for Greenland Sea Arctic Intermediate Water (GSAIW). For recently ventilated water masses, exclusively containing SF_6 from the atmosphere, a derived age is also given (Table 1). To obtain the contribution from the released tracer, the input of SF_6 from the atmosphere has to be taken into account and the observed values have to be reduced accordingly. The contribution of atmospheric SF_6 to a water mass can be estimated from its CFC-12 content. This comparison is important in water samples with SF_6 concentrations of about 2 fmol kg^{-1} or less, where this is the only way to decide if there is a contribution from the release or only from the atmosphere.

In an attempt to quantify the fraction of the different water masses within the EGC, Optimum Multiparameter (OMP) analysis was conducted on the data, following Tomczak and Large (1989) and Karstensen and Tomczak (2000). OMP analysis is based on a simple model of linear mixing assuming that all water mass properties are affected by the same mixing processes, and it is thus possible to determine the spatial distribution of the water masses through a system of linear equations (Tomczak and Large, 1989; Karstensen and Tomczak, 2000). Prior to the analysis, each water mass is defined by describing it with one or two source water types, which represent the purest form of the water mass. In this work, all water masses have been described by only one water type, each chosen as an extreme found in this actual data set, and the variations around these points in the parameter space. The definitions will hence to some extent differ from those made in previous studies, although these previous definitions do not contain this set of parameters. The definitions used are presented in Table 1, which corresponds to the source water matrix, **G**, which also includes the equation of mass conservation. Every column in the matrix corresponds to one of the used parameters. The equation system can be written as $\mathbf{G}x-\mathbf{d}=\mathbf{R}$, where **x** is a vector containing the relative contribution of the water types to the sample, **d** is a vector with observed data and **R** is a vector of the residual of the fit. The solution is found by minimising the residual of the linear fit to all the used parameters, individually for each data point, in a nonnegative least-square sense. The analysis used was limited to the potential density anomaly interval $28.00 \leq \sigma_\theta \leq 28.07$ kg m^{-3} in order to focus on intermediate and deep waters. The observational parameters used in the analysis were salinity, potential temperature, oxygen, SF_6, CFC-12 and CFC-11 in addition to the mass conservation equation. Each parameter has a specific weight according to its environmental variability and instrumental precision. The weight for each parameter was calculated following Tomczak and Large (1989) by dividing the variance of each parameter within the source water matrix **G**, with the largest variance of the respective parameter in the source region. In addition to this mass conservation was weighted equal to the highest of the other parameters. One exception is SF_6, which was given a low weight by the calculation due to the large variance within GSAIW as a result of the release, that was given a weight close to those of the CFCs. This was chosen to get similar weights for all tracers and due to the special interest in GSAIW marked by SF_6. The applied weights were 29 for potential temperature, salinity and mass conservation, 4 for oxygen, 11 and 13 for CFC-12 and CFC-11 respectively, and 10 for SF_6. The actual numbers are those resulting from the calculation and they should be evaluated only in relation to each other. The number of parameters that was measured in each point controls how many water masses that can be resolved simultaneously. In this study this restricted it us to five water masses and hence it was not possible to include all observed water masses in each analysis and a subset was chosen on each section. An additional OMP analysis was made for the less dense water at the sill. In this analysis, the same parameters and weights were used but the density interval was set to σ_θ 27.80-28.0 kg m^{-3} and a different set of water masses was included.

The results certainly depend on the definitions chosen for the source waters. In addition, the well-defined sources might change with time due to environmental conditions. This uncertainty is limited though by the fact that all the definitions used are based on observations taken within a few weeks and that it would definitely take less than 3 years for one of the water masses, and SF_6, to be transported from the northern to the southern border of the area of investigation. The time-dependent parameters, the CFCs and SF_6, make the situation more complex but the short transport times imply that this would not be critical for the CFCs. Initially, the SF_6 concentration in the Greenland Sea was patchy, but the tracer was well contained in the gyre of the Greenland Sea (Messias et al., 1999). It was estimated that almost 90% of the released tracer remained in the gyre 19 months after the release, where it was homogenized. The SF_6 content at different locations inside the Greenland Sea had a standard deviation of 21% after 19 months, and only 11% 6 months later (Messias et al., 1999), suggesting also that the source properties for SF_6 in GSAIW are relatively well defined.

Table 1
Characteristic properties and CFC ages of the water masses found in the East Greenland Current during the investigation.

Water mass	Section	Depth	Pot. temp	Salinity	σ_θ	σ_1	$\sigma_{2.5}$	SF_6	Oxygen	CFC-12	CFC-11	SF_6 age	CFC age	
													CFC-12	CFC-11
		m	°C		kg m^{-3}	kg m^{-3}	kg m^{-3}	fmol kg^{-1}	µmol kg^{-1}	pmol kg^{-1}	pmol kg^{-1}	y	y	y
PIW	66	343	-0.22	34.533	27.741			1.8	328	2.9	5.7	2	12	14
RAW	74	116	2.78	34.997	27.904			0.8	312	2.5	5.4	11	11	11
ISAIW	70	198	-0.31	34.832	27.987			1.7	343	3.0	6.8	3	11	11
AAW	77	909	-0.08	34.885	28.018	32.733		0.39[a]	298	1.0	2.3	[a]	28	27
GSAIW	77	805	-0.67	34.879	28.041	32.774		8.6[a]	311	1.9	3.7	[a]	21	23
uPDW	77	1307	-0.45	34.907	28.054	32.780		1.1[a]	297	0.71	1.7	[a]	31	29
CBDW	77	1499	-0.70	34.916	28.073	32.806		n.d.	295	0.39	0.89	-	35	33
EBDW	77	1922	-0.91	34.915	28.081		39.737	n.d.	297	0.20	0.49	-	40	37
GSDW	73	2635	-1.12	34.901	28.079		39.751	0.26[b]	304	0.41	0.78	[a]	35	34

The three columns for σ_θ are for different reference pressures given in hbar, i.e., the following depths, 0, 1000 and 2500 m.
n.d. stands for “not detected” in the samples where the [SF_6] was below the limit of detection.
[a] There is a contribution from the tracer release and not only from the atmosphere, i.e., a portion of intermediate water from the Greenland Sea Gyre.
[b] An elevated level was observed originating from the tracer release but spread this deep due to some accidental injection discrepancy.

2. Description of the area

The Nordic Seas are simply the seas between Greenland and Norway. In the north these are bounded by the Fram Strait (Fig. 1), with a sill depth of 2600 m allowing exchange of deepwater between the Nordic Seas and the Arctic Ocean, and in the northeast by the Barents Sea that is too shallow to be a passage for deepwater. The southern border of the region, the Greenland-Scotland Ridge, is relatively shallow but is penetrated by two channels where the bulk of dense water to the North Atlantic passes; the Faroe Bank Channel (sill depth 850 m) and the Denmark Strait (620 m). The dense outflow from the Nordic Seas to the North Atlantic exits in about equal parts as Denmark Strait Overflow Water (DSOW) and Iceland-Scotland Overflow Water, west and east of Iceland respectively (Dickson and Brown, 1994; Hansen and Østerhus, 2000).

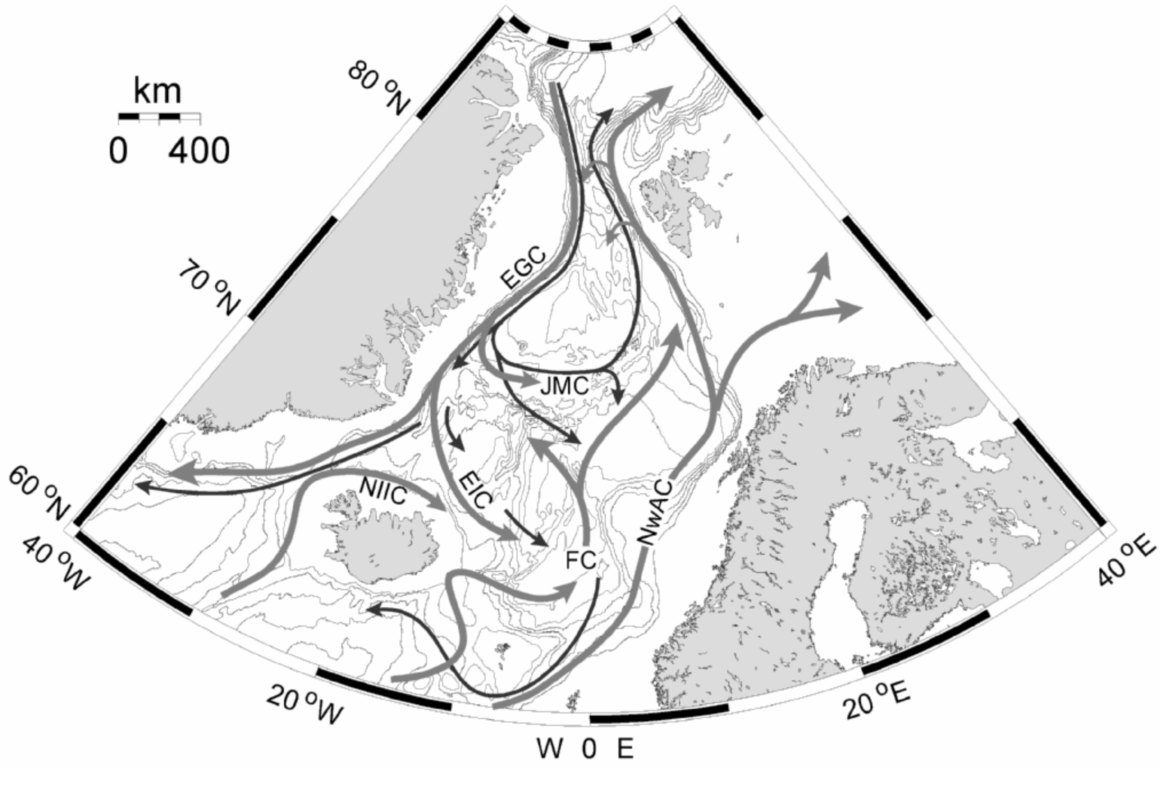

Fig. 2. Major currents in the Nordic Seas. Light grey arrows indicate cold surface currents, dark grey arrows indicate warm surface currents and black arrows indicate deep currents. (Abbreviations: EGC - East Greenland Current, JMC – Jan Mayen Current, EIC – East Icelandic Current, NIIC – North Icelandic Irminger Current, FC – Faroe Current, NwAC – Norwegian Atlantic Current.)

The dense outflow is replaced by warm and saline Atlantic water from the south (Fig. 2). One branch of Atlantic water enters the Barents Sea while another, the West Spitsbergen Current, continues north towards Fram Strait where a smaller part enters the Arctic Ocean, and the rest turns west close to the Fram Strait or over the Boreas Basin. This westwardly flowing Return Atlantic Current, consisting of Re-circulating Atlantic Water (RAW; Bourke et al., 1988), joins the East Greenland Current (EGC) along the continental slope of Greenland. The two branches of Atlantic water that enter the Arctic Ocean, through the Barents Sea and the Fram Strait, respectively, are modified on their route and are mixed together to form Arctic Atlantic Water (AAW; Rudels et al., 1999b). Another fraction of the Barents Sea branch forms the upper Polar Deep Water (uPDW) in the Arctic Ocean (Rudels et al., 1999b).

In addition to the inflow of Atlantic surface water from the south, cold and fresh Polar Surface Water enters from the Arctic Ocean and constitutes a thin surface layer in the EGC above the RAW, separated by the Polar Front from the warmer and more saline water further east. The EGC is also supplied with AAW and uPDW through western Fram Strait and below these, two additional deepwater masses enter from the Arctic Ocean. Canadian Basin Deep Water (CBDW; Aagaard et al., 1985; Rudels, 1986; Anderson et al., 1994; Rudels et al., 1999b) is the densest water that can leave the Canadian Basin over the Lomonosov Ridge into the Eurasian Basin. The deepwater from the Nansen and Amundsen basins, the Eurasian Basin Deep Water (EBDW; Aagaard et al., 1985; Rudels, 1986; Smethie et al., 1988; Swift and Koltermann, 1988) is colder than the CBDW and flows below this into the Nordic Seas. Branches leave the East Greenland Current as the Jan Mayen Current at the Jan Mayen Fracture Zone and as the East Icelandic Current in the Iceland Sea (Fig. 2).

The two regions of the Nordic Seas directly influenced by surface inflow of Polar and Atlantic water are denoted the Polar and Atlantic domain respectively. The region between these two domains is referred to as the Arctic domain (Swift and Aagaard, 1981) and includes the Greenland Basin, the southern Boreas Basin and the central Iceland Sea and is delimited in east and west by the Arctic and the Polar Front respectively. The surface water is dense in the Arctic domain with the result that the vertical stability of the water column is low and this can produce thick, dense, nearly homogeneous, mixed-layers by winter cooling and mixing. Most of the water currently formed at the surface in this domain is not dense enough to form deep and bottom waters, and is thus to be found at intermediate depths in summer. This water mass, known as Arctic Intermediate Water (AIW), is formed and modified mainly in the central Greenland Sea and the central and north-eastern Iceland Sea (Swift and Aagaard, 1981; Blindheim, 1990; Malmberg and Jónsson, 1997). It has been concluded that AIW is the major water mass exported from the Greenland Sea Gyre (Mauritzen, 1996) and here AIW of this origin is denoted Greenland Sea Arctic Intermediate Water (GSAIW), while the type formed by local wintertime convection in the Iceland Sea (Swift et al., 1980) is called Iceland Sea Arctic Intermediate Water (ISAIW). The latter is the water mass described by Swift and Aagaard (1981) as upper Arctic Intermediate Water. The main formation of deepwater inside the Nordic Seas takes place in the Greenland Basin and the product is known as

Greenland Sea Deep Water (GSDW; Nansen, 1906; Helland-Hansen and Nansen, 1909; Clarke et al., 1990).

3. Observations of water masses

All observations were made during the R/V Marion Dufresne cruise at the positions shown in Fig. 1, where the sections along the eastern slope of Greenland from the Fram Strait to the Denmark Strait are the focus of this study. Special emphasis is put on mixing and propagation of the intermediate water masses, but also upper and deeper water masses are described. The northernmost section was located at the Greenland Fracture Zone between the Boreas Basin and the Greenland Basin. Three more sections were sampled in the Greenland Sea, extending from the continental slope of Greenland into the Greenland Basin, the southernmost of them close to the Jan Mayen Fracture Zone. In the West Iceland Basin a section was sampled along 70°N from the slope of Greenland to the Kolbeinsey Ridge and at the sill of the Denmark Strait, a three-station section was sampled where the Irminger Current introduced clearly different properties into the upper layers with the high-salinity Atlantic water. Additional results from the cruise are available in the work by Lacan and Jeandel (2004) presenting neodymium and hydrography data from some of the locations.

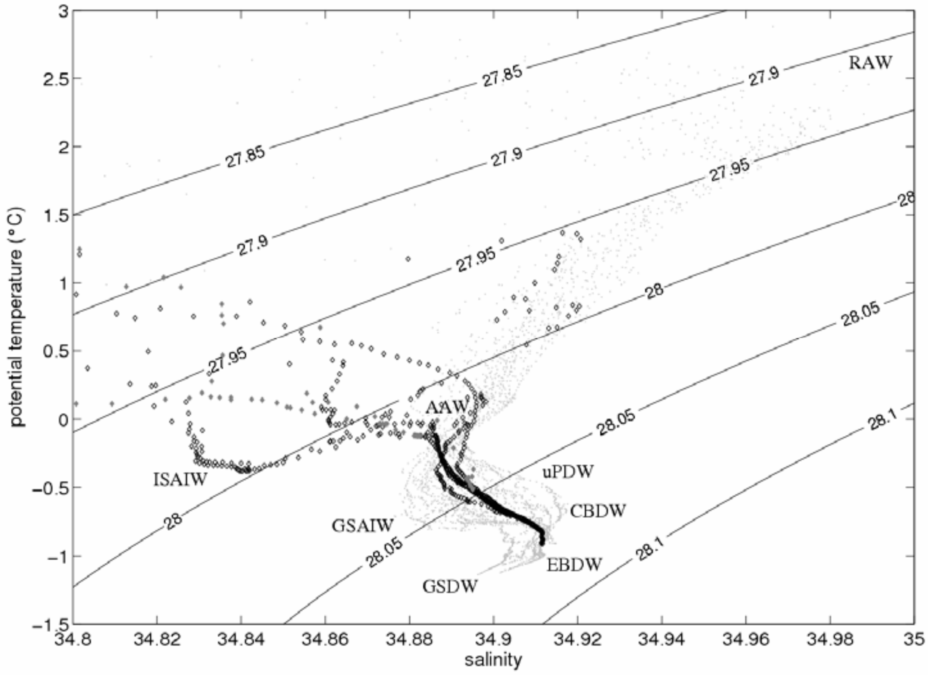

Fig. 3. Potential temperature vs. salinity (θ-S) for all stations sampled in the EGC from 77°N to 66°N. Grey dots mark properties observed in the Greenland Sea (73-77°N) while black open diamonds mark properties observed in the Iceland Sea at 70°N and grey filled diamonds marks those observed in the Denmark Strait. The observed water masses are marked after the properties given in Table 1.

The evolution of the water masses along their pathway in the East Greenland Current across the mentioned sections is discussed. Their characteristics are presented as numbers in Table 1 and in the potential temperature-salinity space in Fig. 3 and in the CFC-12-salinity space in Fig. 4. In the following description, the water masses are divided into three classes depending on their density and what depth interval they occupy. Due to the special interest for the Greenland Sea Arctic Intermediate Water and the released tracer this water mass is discussed in a separate section after the evolution of the other water masses has been described. It should be mentioned that all observations are snapshot sections across the flow and do not provide any information on the actual volume transports since no current data are used in this analysis. The results presented are thus somewhat biased by the actual position and depth sampled.

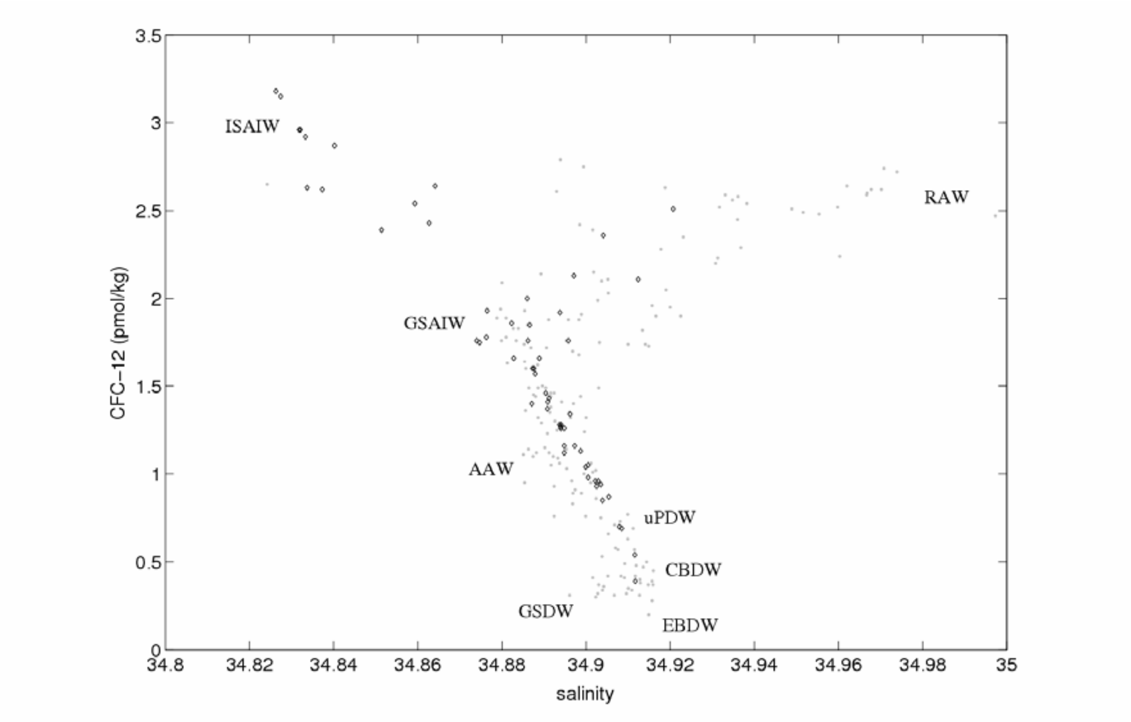

Fig. 4. CFC-12 concentration vs. salinity for all stations sampled in the EGC from 77°N to 66°N. Grey dots mark properties observed in the Greenland Sea (73-77°N) while black diamonds mark properties observed in the Iceland Sea (66-70°N). The observed water masses are marked after the properties given in Table 1.

3.1. Upper waters

Polar Intermediate Water (PIW) is characterised by minimum in temperature and salinity and high CFC content (Table 1) and the CFC age based on 80 % saturation as well as the SF_6 age was 2-3 years. PIW is believed to originate in the halocline of the Arctic Ocean (Rudels et al., 2002) but the occurrence during this survey was most prominent in the Denmark Strait west of the North Icelandic Irminger Current, particularly over the Greenland slope, but spread in a thin layer across the strait. PIW might have been present over the Greenland shelf further north, but lack of sampling prevents any conclusions. PIW was observed below the Polar Surface Water only at those stations where this, instead of Recirculating Atlantic Water, was situated above Iceland Sea Arctic Intermediate Water (ISAIW). In addition to the presence at the sill, PIW was incorporated in the low-salinity lid of the overflow plume further downstream.

The Recirculating Atlantic Water (RAW) is present in the East Greenland Current as a shallow salinity-maximum layer (Fig. 3). In the Greenland Sea, it was spread in a layer across the EGC as well as into the gyre. The best-preserved core was observed in the Greenland Basin well east of the Polar Front, where no mixing with Polar water takes place and the CFC age was 0-11 years, the higher age agreeing with that derived from SF_6 (Table 1). This is a surprisingly high age since RAW leaves the surface close to Fram Strait. The core maintained its tracer levels on the path by the Greenland Sea and this shows that it was not affected by any admixture of Arctic Atlantic Water, although the deeper layers of RAW probably were. A large fraction of RAW seemed to be deflected eastwards by the circulation of the Greenland Sea or the Jan Mayen Current, and in the West Iceland Basin remnants of RAW were only present over the slope of Greenland (Fig. 3). This is a much more limited extension of RAW compared to what was observed here 1 year earlier (Rudels et al., 2002). This is likely due to an increased supply of ISAIW from the east, occupying the same depth and density interval. Inter-annual variations in the extent of RAW and ISAIW in the Iceland Sea are discussed by Rudels et al. (2003). The vertical position of RAW was shallow enough to let it flow over the shelf and this might explain the sparse observations in the West Iceland Basin as well as the very low presence at the sill of the Denmark Strait. This may further be an effect of intense diapycnal mixing close to the strait as suggested by Rudels et al. (2002) and the high abundance of PIW and ISAIW.

3.2. Intermediate waters

Iceland Sea Arctic Intermediate Water (ISAIW) appeared in the West Iceland Basin as a low-salinity temperature minimum (Fig. 3) accompanied by a maximum in CFCs (Fig. 4) and SF_6, indicating ventilation during the last few years (CFC age 0-11 years, SF_6 0-3 years). ISAIW was most apparent in the eastern part of the basin and isopycnally spread to the west, where it was observed with higher salinity and temperature and reduced levels of CFCs and oxygen, probably mainly caused by mixing with Recirculating Atlantic Water (RAW) but to some extent also with Arctic Atlantic Water. The appearance of ISAIW into the EGC made the clear cores of these two Atlantic-originating water masses more or less disappear. There is large inter-annual variability in the extent of ISAIW, that was more dominating in this region in 1999 than, e.g. in 1998 (Rudels et al., 2002) and 1997 (Tanhua et al. unpublished data). At the sill, ISAIW was abundant in the western half, below the Polar Intermediate Water as a potential contributor to the overflow and it was also present in the plume of the Denmark Strait overflow south of the sill.

Arctic Atlantic Water (AAW) flows south from the Arctic Ocean within the EGC, below the more saline RAW. It showed a CFC age of 25-28 years and was mainly identified by an intermediate CFC minimum (Fig. 4) and hence easily distinguished also from the less saline fraction of RAW which has considerably higher levels of CFCs. From the CFC concentrations it can be concluded that AAW has a relatively long residence time in the Arctic Ocean after being ventilated in the Norwegian Sea. The definition used here, as a CFC minimum, gives a slightly colder, denser AAW than defined by Rudels et al. (1999b). A straight comparison is hard to make due to the different definitions, but one explanation might be that the less dense part is intensely mixed with RAW, and the CFC-minimum of AAW is hence mainly preserved in the deeper layers. Since CFCs are not included in the earlier definitions of AAW this is difficult to evaluate. Rudels et al. (1999b) also suggest that AAW only passes Fram Strait occasionally, from where it mixes extensively with RAW and is hence seldom found as a distinct water mass south of Fram Strait. The identification of AAW in this study was mainly possible thanks to its low CFC concentrations.

AAW was present from the northernmost section, where it was seen around 900-m depth closely outside the border of the Greenland Sea Gyre, down to the Denmark Strait Sill. It was most distinct in the north and on its way south, following the slope of Greenland, it became more saline, probably by mixing with the deeper layer of RAW, and more difficult to observe. The AAW fractions given by the OMP analysis (Fig. 6) are not directly comparable since it is not the same water parcel that is followed southwards and the lateral extension of the sections varies (Fig. 5). The relatively low abundance of AAW at 73°N might result from passage of the core outside of the surveyed section. Similarly, part of the fraction interpreted as AAW at 70°N might be a mixture of RAW and ISAIW since RAW was not included as a source-water mass at this section. An increase in the fractions of less dense water masses, like AAW, from 70°N to the sill is however expected since the bulk of the denser water masses are deflected north of the sill. Results from OMP analysis indicate that AAW made up a large portion of the water in the deeper part of the sill, but outside the high-density core (Fig. 7). These layers are composed by many water masses and lacks distinct characteristics. There is a possibility that another water mass with properties similar to those of AAW is introduced in the Iceland Sea but the presence of AAW can also easily be underestimated, both due to its vague characters and due to the possibility that the main pathway might be over the continental shelf (Mauritzen, 1996) where no sampling took place.

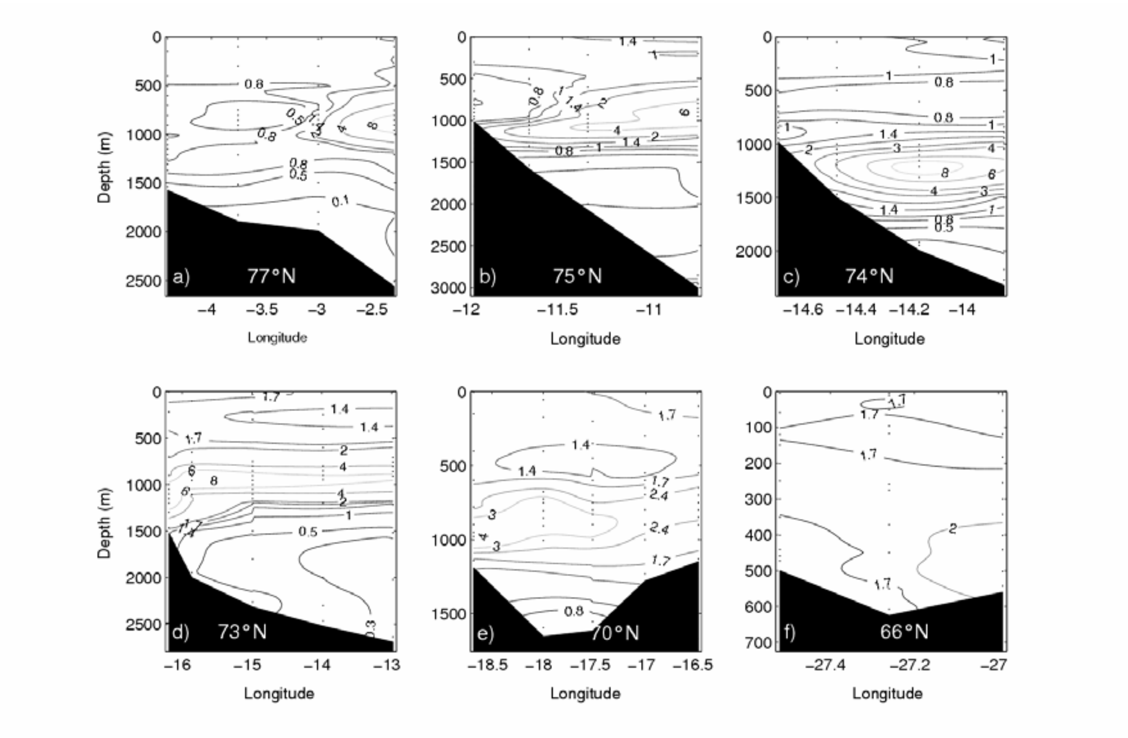

Fig. 5. Sections showing SF_6 in fmol kg^{-1} at (a) 77°N, (b) 75°N, (c) 74°N, (d) 73°N, (e) 70°N and (f) 66°N. The dots show the positions where water samples were taken for the tracer.

The upper Polar Deep Water (uPDW) occupies a similar density interval as Greenland Sea Arctic Intermediate Water (GSAIW). As a result of the presence of GSAIW, uPDW was normally found in a layer between GSAIW and Canadian Basin Deep Water (CBDW) in the EGC (Fig. 3) and hence mainly in the denser part of the interval earlier defined (Rudels et al., 1999b). The CFC age of this water mass was found to be 27-31 years. In the north, uPDW was more abundant in the west and the bulk was freshened by isopycnic mixing with GSAIW within the Greenland Sea but

mixing with CBDW was also important. The OMP analysis (Fig. 6) shows a trend of decreasing uPDW on the way through the Greenland Sea as if it was pushed westwards by GSAIW and was hence not covered by the sampling, but it was again more abundant in the deep layers of the West Iceland Basin. The densest water observed in the Denmark Strait was a mixture of uPDW and GSAIW and the OMP analysis estimated that uPDW was most important of the two (Fig. 7). That uPDW constituted a larger fraction in the Iceland Sea than in the Greenland Sea can to some extent be an effect that uPDW was passing too high up the slope to be caught on the northerly sections, but also resulting from the fact that large volumes of water observed further north are deflected from the EGC into the Greenland Sea or further south. Current meter data from 75°N in the EGC indicate that of a total summer transport of 11 Sv (1 Sv = 10^6 m^3 s^{-1}), 8 Sv continue south while the rest re-circulates in the gyre (Woodgate et al., 1999). During winter the southward transport is believed to be the same but the re-circulating part to be up to 30 Sv.

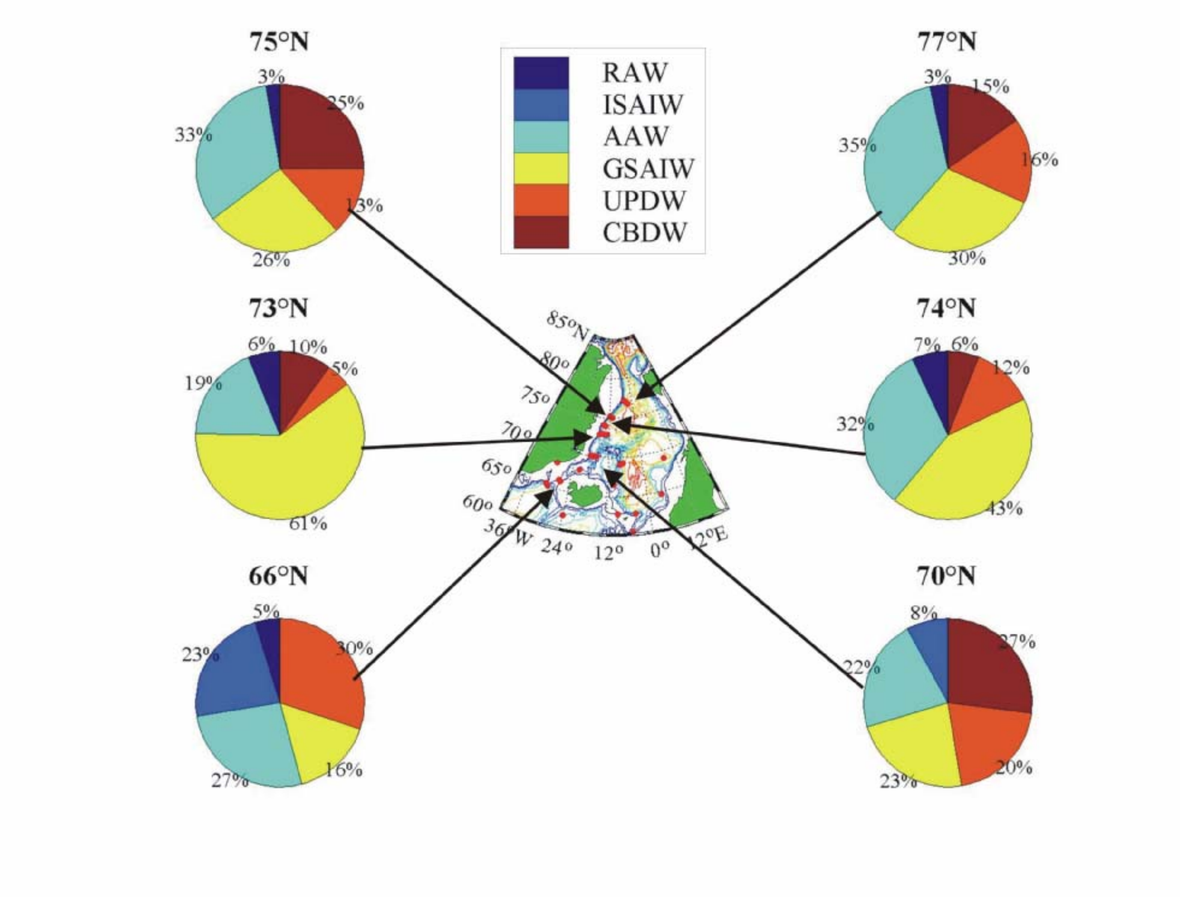

Fig. 6 Water-mass fractions at each section in the EGC from 77°N to 66°N as received from the OMP analysis described in section 2, i.e., the σ_0 interval 28.00-28.07 kg m^{-3}. Note that only five of the six water masses are included in the analysis of each section; for the four sections in the Greenland Sea these are RAW, AAW, GSAIW, uPDW and CBDW, but in the Iceland Sea, ISAIW replaced RAW, respectively, CBDW on the 70°N- and the 66°N-section. Rather than using an average of the water mass fractions from all data points derived from the OMP analysis, the data are gridded over the section and the density range and the fractions are integrated over the intermediate water column. In this way, the results are less biased due to differences in sampling resolution. It should be clarified that the resulting fractions are not representative for the occurrence over the whole section because many water masses are also present outside the density range of the analysis.

The Greenland Sea Arctic Intermediate Water is discussed thoroughly in section 3.4.

3.3. Deepwaters

By comparing the definitions for deepwater masses of Arctic Ocean origin (Rudels et al., 1999b) with the characteristics found during this work (Table 1), it is evident that all were altered by mixing with Greenland Sea Arctic Intermediate Water (GSAIW) and Greenland Sea Deep Water (GSDW). Since the salinity of Arctic deepwater is higher than that of both water masses from the

Greenland Sea, the mixing is seen as a freshening compared to the values found in the Arctic Ocean (salinities higher than 34.92 for both Canadian Basin and Eurasian Basin Deep Water).

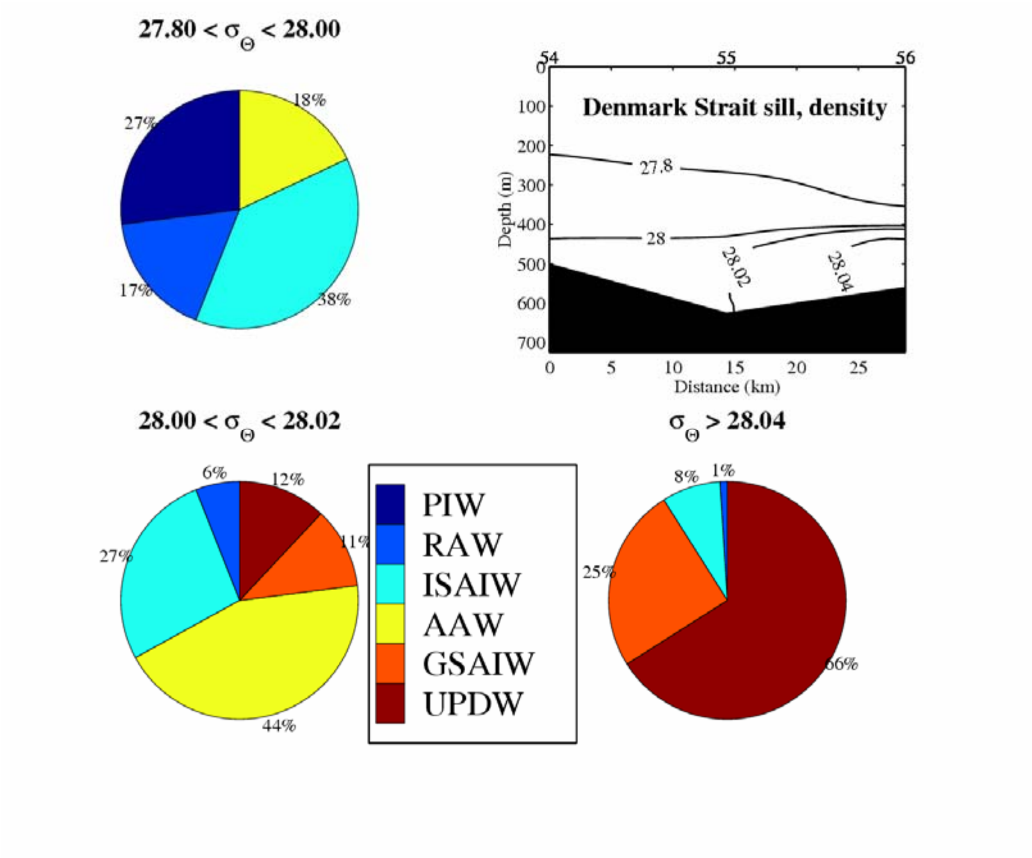

Fig. 7 The fractional composition of different water masses as deduced from the OMP analysis for three density intervals at the Denmark Strait Sill. The numbers are the average percentage fraction derived from the OMP analysis on all samples inside each interval. Different OMP analyses were applied for the various density intervals due to the presence of various water masses. For the σ_θ interval 27.80-28.00 kg m^{-3} PIW, RAW, ISAIW and AAW are included, whereas for the other two layers ISAIW, RAW, AAW, GSAIW and UPDW are included. The σ_θ range 28.02-28.04 kg m^{-3} is not included anywhere because no samples were taken in this interval. The density on the two westernmost stations was too low and in the east this range was occupying a very thin layer. The area between the isopycnals 28.02 and 28.04 kg m^{-3} in the figure is actually between two stations.

Canadian Basin Deep Water (CBDW) is the most saline deepwater in the Nordic Seas. The CFC age was 32-36 years and it was identified as a deep salinity-maximum layer located around 1500 m depth all the way south to the West Iceland Basin. Further into the Greenland Basin, CBDW was less saline as an effect of the strong dominance of lower-salinity GSAIW and GSDW. Further west towards the Greenland Shelf, CBDW was overlain by uPDW, thus inhibiting extensive freshening by admixture of GSAIW. On its south-flow through the Greenland Sea, it became colder and slightly less saline while the tracer content was less affected by the mixing, and at 73°N, it constituted a homogenous layer across the whole section. Although a core of CBDW flowed almost unchanged from the Greenland Sea to the West Iceland Basin, the bulk was mixed. The less dense part was mixed with GSAIW and could not easily be traced at 70°N. The denser part became colder by mixing with Eurasian Basin Deep Water and a small portion of GSDW, and higher up the slope, it was mainly mixed with uPDW.

Eurasian Basin Deep Water (EBDW) is the densest water from the Arctic Ocean in the EGC and differs mainly from CBDW by lower temperature and higher CFC age, in the Greenland Sea 35-40 years during this study. This can be compared with the CFC age of EBDW in the Arctic Ocean of 25-30 years reported by Bönisch and Schlosser (1995). The core of EBDW followed the 2000-m-isobath along the slope of Greenland throughout the Greenland Sea. On its way south, it was mixed with GSDW, hence becoming colder, fresher and with increased content of CFCs. Higher up the slope, EBDW possessed its highest salinity and was warmer, mainly from a lack of mixing with GSDW and possibly partly due to mixing with CBDW. The densest portion of the Arctic Ocean deepwater was recirculated in the Greenland Sea but the deepwater of the West Iceland Basin consisted of a mixture of EBDW and CBDW somewhat freshened on its way south. Almost undiluted EBDW close to the Denmark Strait Sill has been reported in some years (Buch et al., 1996).

Greenland Sea Deep Water (GSDW) was found only in the deep part of the Greenland Sea, from 2000 m downward. It was clearly colder, less saline and had higher levels of oxygen compared to deepwater from the Arctic Ocean and the CFC age was 33-35 years. Due to the low rate of deep convection in the Greenland Sea since around 1980 (Rhein, 1991; Bönisch and Schlosser, 1995; Bönisch et al., 1997), observations of the deepwater in the central Greenland Sea has shown a constant CFC-11 concentration around 0.75 pmol kg^{-1} from 1982 (Bullister and Weiss, 1983) and through 1997 (Olsson, 2001) and the values observed in 1999 were very close to this (Table 1). Traditionally, GSDW is recognised by higher CFCs than deepwater from the Arctic Ocean, but in this study, they were lower than those observed in CBDW. Since no sampling took part in the interior of the Greenland Basin, differences from what is normally found (Smethie et al., 1988; Clarke et al., 1990; Bönisch and Schlosser, 1995) is expected as a result of mixing. No GSDW was found in the West Iceland Basin since it is located too deep to cross the Jan Mayen Fracture Zone into the Iceland Sea.

3.4. Greenland Sea Arctic Intermediate Water

Greenland Sea Arctic Intermediate Water (GSAIW) could be traced even in small portions thanks to the released SF_6, which was a good indicator of this water mass. In addition to the high content of released tracer (Fig. 5), GSAIW is characterised by minimum in salinity (Fig. 3) and relatively high levels of oxygen. The maxima in released SF_6 were found at slightly higher density than the salinity minima of GSAIW, although both were well associated with the core. The observed CFC age of 17-23 years indicates that it resides inside the Greenland Sea Gyre for a long period after formation and that only a fraction of the rather homogenous layer gets ventilated each year. The long residence time in the Greenland Sea Gyre, was also indicated by the still high levels of tracer here, 3 years after the release. This was clearly seen on the two northernmost sections (Fig. 5a and b) where the core of GSAIW, with clearly elevated concentration of SF_6, was present in the east, close to the Polar Front and inside the gyre. Above the slope in the EGC, a smaller portion of GSAIW was present with an increasing admixture towards Greenland (Fig. 5a). The highest SF_6 concentration (Fig. 8) was observed at 74°N in a layer of GSAIW situated outside the gyre around 1200 m depth, continuing all the way to the slope (Fig. 5c). At this cross section, the EGC transported a large volume of GSAIW that had been advected from the Greenland Sea, while further to the north, only smaller amounts were entraining the bulk of water of Arctic origin. Heading south through the Greenland Sea, GSAIW was isopycnally spread, and at 73°N, it occupied a continuous layer all the way to the slope, where the core was located (Fig. 5d). The contribution of GSAIW in the EGC was as expected larger at 73°N than further north, due to additional supply from the Greenland Sea. Isopycnic mixing was observed throughout the Greenland Sea, affecting the bulk of GSAIW as it propagated south (see Fig. 3) and most of the mixing occurred with upper Polar Deep Water (uPDW) but to a considerable extent also with Canadian Basin Deep Water (CBDW), while mixing with overlying water masses was observed much less. The general picture shows that the presence of uPDW, with density similar to that of GSAIW (Table 1), normally resulted in strong, isopycnic mixing and lower levels of SF_6, while the slightly denser layer, in which the slower diapycnic mixing with CBDW dominated, retained its SF_6 content better.

The OMP analysis shows an increasing presence of GSAIW southwards through the Greenland Sea (Fig. 6) while entering the Iceland Sea results in a much smaller fraction, an effect of that the bulk of GSAIW stays in the Greenland Sea circulation. In the West Iceland Basin, GSAIW was clearly warmer and more saline than in the Greenland Sea and consistent with this, there was a strong reduction in SF_6 (Fig. 8) and CFCs. The properties of the core indicate that it consisted to about 50% of GSAIW while the rest was uPDW and CBDW in about equal proportions. Compared to the almost pure core at 73°N, it was quite intensely mixed but since the 70°N-section had its maximal SF_6 concentration in the westernmost part, the core of GSAIW did perhaps pass further up the slope (Fig. 5e). It is also possible that the denser part of the GSAIW layer, carrying the bulk of released tracer, had been deflected eastwards from the EGC and this is strengthened by the fact that the whole layer of GSAIW was less dominant and thinner than at 73°N. Most plausibly, this deflection was carried out by the Jan Mayen Current in the recirculation of the Greenland Sea but potentially also further south by the East Icelandic Current (see Section 4.2.). The total fractions of GSAIW and uPDW at 70°N were of about the same order (Fig. 6).

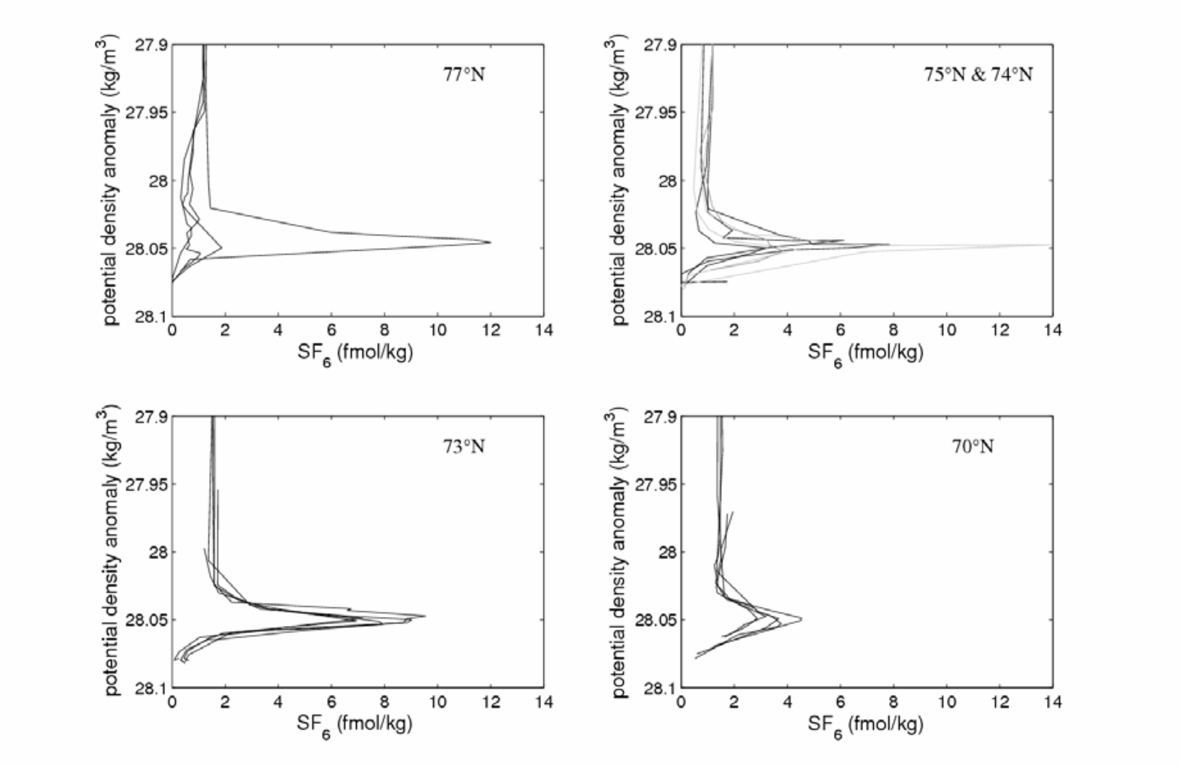

Fig. 8. Potential density anomaly (in σ_θ) vs. SF_6 concentration for stations on section 77°N (a), 75°N (black) and 74°N (grey) (b), 73°N (c) and 70°N (d).

At the sill of the Denmark Strait, the densest water was observed at the Icelandic slope and showed minimum in CFCs (1.15 pmol kg^{-1} of CFC-12) but maximum in SF_6 (2.5 fmol kg^{-1}, see Fig. 5f) and thus evidently contained the released tracer (Fig. 9). For comparison, if this water had been equilibrated with the atmosphere at the time of observation the concentration of SF_6 would have been lower (2.1 fmol kg^{-1}) while that of CFC-12 would have been considerably higher (3.6 pmol kg^{-1}). This dense core displayed properties very similar to those found in the SF_6-layer in the centre of the 70°N-section and the OMP analysis indicates that the parcel at the sill consisted to about 1/4 of GSAIW and 2/3 of uPDW (Fig. 7). It should be mentioned that the layer of GSAIW was lifted approximately 500 m from 70°N to the sill and the potential density anomaly (σ_θ=28.047 kg m^{-3}) showed that the SF_6-tagged GSAIW had been mixed mainly isopycnally along its transport from the central Greenland Sea, where it was released at σ_θ=28.049 kg m^{-3}, all the way south to the sill of the Denmark Strait.

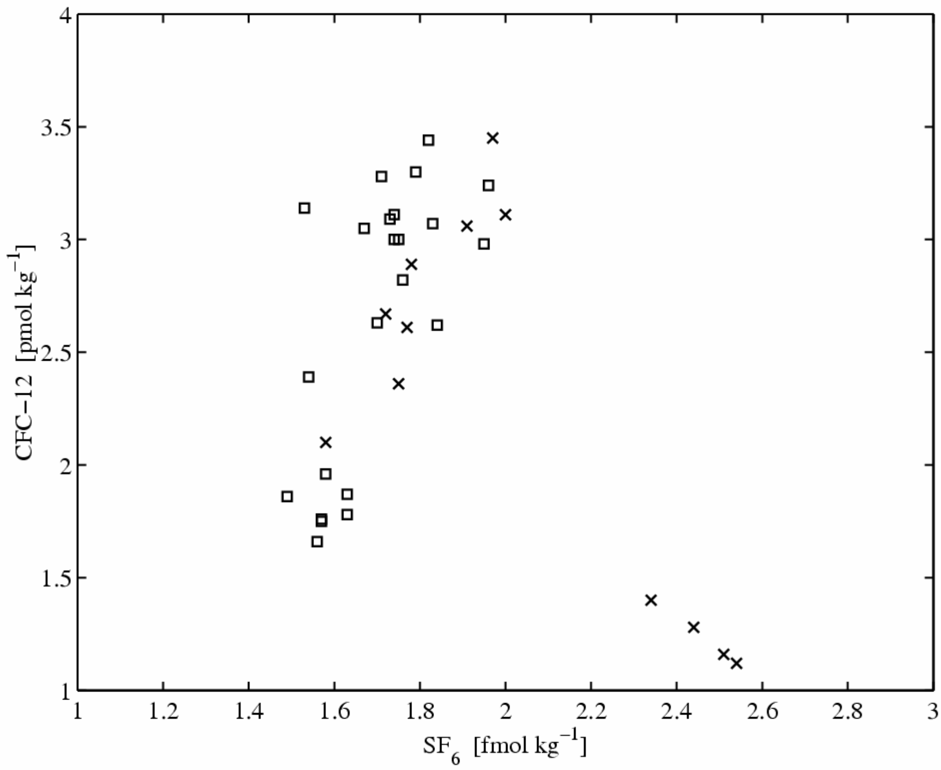

Fig. 9. The concentration of CFC-12 vs. the concentration of SF_6 for the three stations sampled in the Denmark Strait. The station furthest east is marked by crosses and the presence of released tracer is clearly shown by the maximal SF_6 concentration observed at minimal CFC concentration.

4. Contributions to the overflows

4.1. The Denmark Strait overflow

It is assumed that the water masses contributing to the Denmark Strait Overflow Water (DSOW) are those observed at a section positioned along the sill of the strait, from where they can continue south without topographic hindrance. The water masses identified at the sill below the North Icelandic Irminger Current were Polar Intermediate Water (PIW), Recirculating Atlantic Water (RAW), Iceland Sea Arctic Intermediate Water (ISAIW), Arctic Atlantic Water (AAW), Greenland Sea Arctic Intermediate Water (GSAIW) and upper Polar Deep Water (uPDW). Since the variability at the sill is very large, no attempts were made to quantify the contributions from different water masses to the overflow; instead, the lower part of the water column at the sill was divided into three different density layers and the composition of these three layers were estimated from OMP analysis (Fig. 7). How important each of these three layers is for the overflow is left out for other investigations. Since there were no samples taken in the σ_θ range 28.02-28.04 kg m^{-3} we lack information for a layer that is potentially important for the overflow. Since this work is based on observations from the EGC, contributions from closer by, e.g., the Iceland Sea, are not well investigated. The OMP analysis however reveals ISAIW to be the major contributor to the least dense layer investigated on the sill, but it is also incorporated in the denser parts (Fig. 7). This layer is also composed by AAW, RAW and PIW. The latter water mass is more abundant at even lower density, but σ_θ 27.80 kg m^{-3} is chosen as the low density limit of the analysis since it is commonly used to define DSOW south of the sill (Dickson and Brown, 1994; Hansen and Østerhus, 2000). It should be noted that only a small portion of the low-density layer is covered by the sampling, and it is likely that, e.g., the core of RAW is centred higher up on the Greenland shelf, and is thus underrepresented in the calculations.

The middensity layer was the most heterogeneous of the three, and seemed to be a mixture of many water masses, with AAW and ISAIW being the dominating ones (Fig. 7).

The most saline and dense (σ_θ=28.047 kg m^{-3}) water at the sill was mainly composed by uPDW (2/3) with important admixture of GSAIW (1/4) and smaller portions of less dense water (Fig. 7). A small contribution of Canadian Basin Deep Water (CBDW) cannot be excluded but it was not included in the OMP analysis at the sill. In the slightly less dense range, σ_θ 28.02-28.04 kg m^{-3}, where observations were lacking, GSAIW is likely to be of high importance due to the density range it occupies (see Fig. 3).

No high-saline fraction was detected in the overflow south of the sill at this occasion, and this differs from other years (Tanhua and Olsson, unpublished data), and hence no excess SF_6 indicating presence of GSAIW. An inconsistency between a section on the sill and one south of it is not surprising considering the highly variable thickness of the overflow (Mann, 1969; Käse et al., 2003) and the high short-time variability in the flow at the sill (Aagaard and Malmberg, 1978). Although contrary opinions are presented (Bacon, 1998), most observations support that there is no inter-annual variability in the transport of DSOW (Dickson and Brown, 1994; Girton et al., 2001), although changes in the properties of the water are observed (Dickson et al., 2002). The overflow is further characterised both by narrow bottom jets (Girton et al., 2001; Jungclaus et al., 2001) and cyclonic and anti-cyclonic eddies (Bruce, 1995; Krauss and Käse, 1998; Jungclaus et al., 2001) that will highly influence the variability of the overflow and the results of snapshot observations. Furthermore, intense mixing and entrainment occurring immediately south of the sill (Käse et al., 2003) makes it difficult to identify any water masses in the overflow. A signal of enhanced SF_6 in the overflow would however be a good indication of GSAIW.

The contribution of GSAIW and uPDW to the Denmark Strait overflow disputes the hypothesis by Mauritzen (1996) that these are too dense to pass the Denmark Strait. These density layers were observed to be lifted 500 m on their route from the West Iceland Basin to the Denmark Strait and hence it became possible for these water masses to reach the North Atlantic. That the observed mixture of GSAIW and uPDW might be an important part in the overflow agrees with the findings of Rudels et al. (2002) although they discuss that this densest layer might get diapycnally mixed north of the sill. As obtained from the well-retained density of the SF_6-tagged patch at the sill this has not been the case for this water parcel. Buch et al. (1996) also suggest that deepwater from the Arctic Ocean is incorporated in the overflow and Strass et al. (1993) observed a possible source of DSOW to be formed by mixing of Arctic Intermediate Water in the EGC in western Greenland Sea. Mauritzen (1996) concludes that AAW is the dominating water mass in the overflow; in this study AAW was indeed observed as a contributor to DSOW although as one water mass among many. The high CFC content of the DSOW observed in the Irminger Basin during this study is consistent with earlier studies pointing out the importance of recently ventilated water (i.e. ISAIW) for the overflow (Swift et al., 1980; Swift and Aagaard, 1981; Smethie and Swift, 1989; Jónsson, 1999). The flow from the northeast to the strait is reported to be large and relatively constant over the year (Jónsson, 1999), although large inter-annual differences are observed (Jonsson and Valdimarsson, 2004), whereas the flow directly from the EGC shows larger annual variability and is thus not in accordance with the relatively constant formation of DSOW reported from investigations south of the sill. A flow from the east does, however, not necessarily mean solely transport of water of origin from the Iceland Sea, but could also imply large volumes coming from further north. The water mass properties observed by Jonsson and Valdimarsson (2004) northeast of the strait resemble those observed in 1999 at the sill as well as at 70°N. At both locations these layers contained released tracer and seemed to be a mixture of GSAIW and uPDW. This might indicate that this water originated further north. If so, it can either have been transported with the EGC all the way here, or it can have been mixed in the Greenland Sea and entered the Iceland Sea through the Jan Mayen Fracture Zone.

Of the water masses observed in the West Iceland Basin, only the deepest layers consisting of CBDW and Eurasian Basin Deep Water were observed to be too dense to exit through Denmark Strait. These waters must therefore turn eastward and continue along the Icelandic slope into the Central Iceland Sea. There might though have been a smaller portion of CBDW in the densest layer at the sill since this would be difficult to detect in the presence of uPDW.

4.2. The Iceland-Scotland overflow

In addition to the investigations along the east coast of Greenland, some stations sampled in the Iceland and Norwegian seas gave information on the possible contribution of Greenland Sea Arctic Intermediate Water (GSAIW) to the Iceland-Scotland overflow thanks to elevated SF_6 concentration.

SF_6-tagged GSAIW was observed at the eastern slope of the Jan Mayen Ridge in western Norwegian Basin (Fig. 1), in the path of the North East Icelandic Current, as well as northeast of the Faroe continental margin. At the last location, the density was clearly lower due to mixing with warmer and fresher water, and it was located at a depth similar to the bottom depth of the Faroe Bank Channel, indicating that GSAIW could be part of the dense layer of the Iceland-Scotland overflow.

These observations suggest two possible pathways for GSAIW from the Greenland Sea to the Faroe Bank Channel. The layer observed at the Jan Mayen Ridge had most likely flowed through the Jan Mayen Channel (Østerhus and Gammelsrød, 1999) north-east of Jan Mayen (Fig. 1), whereas that observed north-east of Iceland probably was transported with the East Icelandic Current (Fig. 2). A recent numerical-model simulation evaluated together with the spreading of the released tracer indicates that the main pathway from the Greenland Sea to the Faroe-Shetland Channel is by this eastern route (Eldevik et al., in press; Olsson et al., 2004).

5. Conclusions

The East Greenland Current is important in supplying dense water to the Denmark Strait; water masses that have the potential to form overflow water. No quantitative estimates of the contributions to the overflow can be made from this single cruise but indeed qualitative conclusions on which water masses that contribute to different parts of the overflow. The densest of these water masses, the upper Polar Deep Water formed in the Arctic Ocean can be found within the EGC south to the Denmark Strait. On its way, it is modified by extensive isopycnic mixing with Greenland Sea Arctic Intermediate Water. These two water masses seem to be the major constituents of the densest part of the western overflow from the Nordic Seas. In the West Iceland Basin the EGC is supplied with Iceland Sea Arctic Intermediate Water recently formed in the Iceland Sea. This water constitutes a large fraction of the fresher, less dense layer of the Denmark Strait Overflow Water, together with Polar Intermediate Water, Re-circulating Atlantic Water and Arctic Atlantic Water.

The middensity layer at the strait seemed to be a mixture of more or less all the abovementioned water masses but with Arctic Atlantic Water and Iceland Sea Arctic Intermediate Water incorporated to a larger extent at the time of these observations.

Large volumes of water from the EGC are deflected eastwards with the Jan Mayen Current, the East Icelandic Current as well as north of the Denmark Strait; the Greenland Sea Deep Water and the bulk of Eurasian Basin Deep Water are too dense to enter the Iceland Sea. The major part of the Canadian Basin Deep Water as well as the Eurasian Basin Deep Water entering the Iceland Sea, are located to deep to cross the sill of the Denmark Strait. Greenland Sea Arctic Intermediate Water and upper Polar Deep Water was however lifted to about half of the depth possessed at 70°N which made it possible to reach the sill.

Greenland Sea Arctic Intermediate Water did also spread eastwards, possibly by two different routes; through the Jan Mayen Channel and through the Iceland Sea. It was observed north of the Faroe Islands, not far from the Faroe-Shetland Channel, implying that it contributes also to the Iceland-Scotland overflow which is verified by a recent study by Olsson et al. (2004).

The deliberately released tracer sulphur hexafluoride proved to be potent in tracing the dispersion of a water mass. Entrainment and mixing into and within the East Greenland Current were possible to follow with the multivariate analysis technique Optimum Multiparameter analysis utilizing hydrographic and chemical tracers, where SF_6 clearly defined the Greenland Sea Arctic Intermediate Water. An obvious strength of SF_6 is the low fraction of the tracer-marked water mass needed to detect its presence in mixtures, although there is a transient SF_6 background in recently ventilated waters that could be compensated for by simultaneous measurements of CFCs.

Even if no SF_6 originating from the release in the Greenland Sea was observed south of the Greenland-Scotland Ridge, it was present both at the sill of Denmark Strait and close to the Faroe Bank Channel. This shows that intermediate water from the Greenland Sea Gyre could contribute to both overflows within 3 years time from leaving the formation region in the Greenland Sea.

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