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Intermediate water from the Greenland Sea in the Faroe Bank Channel: spreading of released sulphur hexafluoride

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Abstract

The Faroe Bank Channel is the deepest passage for dense water leaving the Nordic Seas into the North Atlantic. The contribution to this part of the Greenland-Scotland Overflow by intermediate water from the Greenland Sea is investigated by the tracer sulphur hexafluoride (SF_6) that was released into the central Greenland Sea in summer 1996. Continuous monitoring has since traced it around the Nordic Seas and into the connecting areas. It was observed for the first time close to the Faroe Islands in early 1999, indicating a transport time from the Greenland Sea of around 2.5 years. This study estimates that approximately 16 kg of SF_6 had passed the Faroe Bank Channel by the end of 2002, that is 5% of the total amount released. Both the arrival time and the amount of exported SF_6 deduced from the observations are consistent with the results from a numerical ocean model simulating the tracer release and spreading.

Keywords: Tracers; Overflow; Intermediate water masses; Thermohaline circulation; Sulphur hexafluoride; Nordic Seas; Greenland Sea; Faroe Bank Channel

1. Introduction

The Nordic Seas are of great climatic importance as they are the northern terminus of the oceanic conveyor belt (e.g. Broecker, 1991). The

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relatively high salinity of the warm Atlantic water that enters the Nordic Seas is a crucial ingredient in the formation of the deep-water masses, which return as dense water from the Nordic Seas into the North Atlantic, where they again mix and transform into North Atlantic Deep Water.

The circulation pattern in the Nordic Seas (Fig. 1a) involves the north-flowing Norwegian Atlantic Current (NwAC) and Faroe Current (FC), which together carry ~7 Sv (1 Sverdrup = $10^6\,m^3\,s^{-1}$) of Atlantic water into the Nordic Seas. A much smaller inflow of Atlantic water, the North

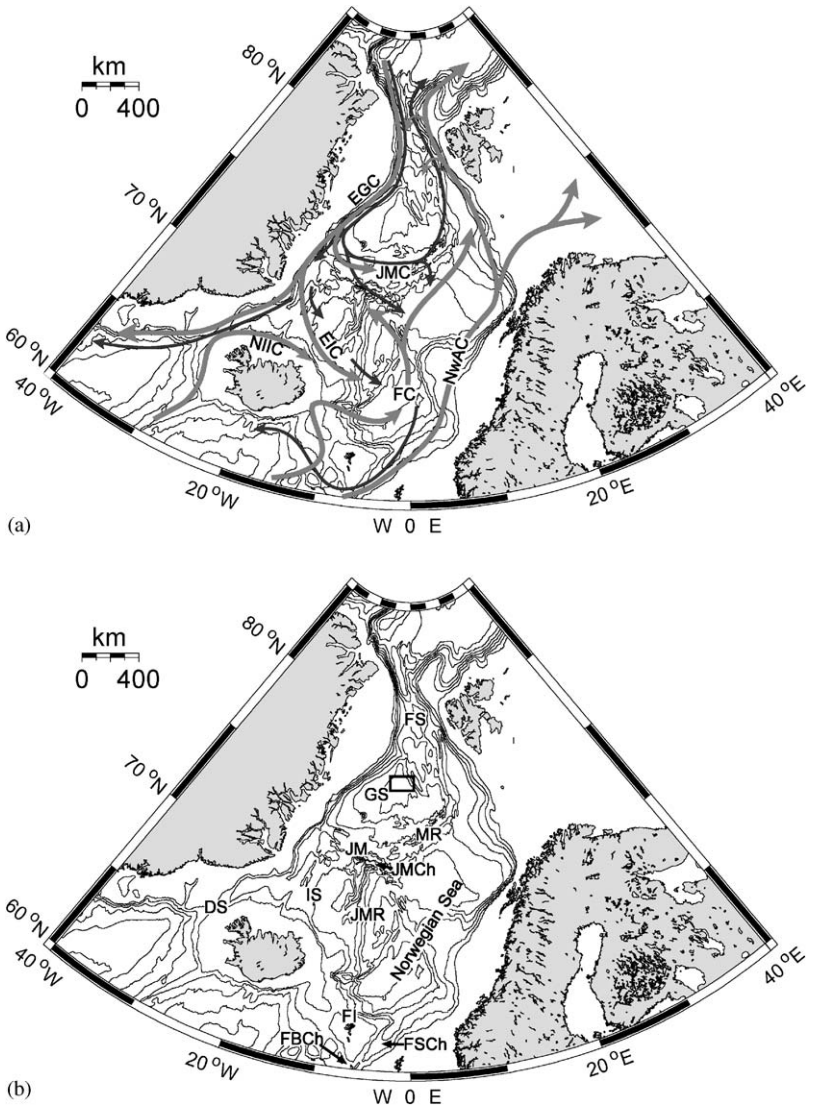

Fig. 1. (a) Main features of the surface currents (thick grey arrows) and intermediate-deep water currents (thin black arrows) in the Nordic Seas. The acronyms used are: EGC—East Greenland Current, EIC—East Icelandic Current, FC—Faroe Current, JMC—Jan Mayen Current, NIIC—North Icelandic Irminger Current, NwAC—Norwegian Atlantic Current. (b) A map of the Nordic Seas with some key geographic features indicated with the following acronyms: DS—Denmark Strait, FBCh—Faroe Bank Channel, FI—Faroe Islands, FS—Fram Strait, FSCh—Faroe Shetland Channel, GS—Greenland Sea, IS—Iceland Sea, JM—Jan Mayen, JMCh—Jan Mayen Channel, JMR—Jan Mayen Ridge, MR—Mohns Ridge.

Icelandic Irminger Current (NIIC) enters northwest of Iceland. The main outflow is the East Greenland Current (EGC), which flows to the south along the Greenland continental margin and can be divided into a shallow and a deep fraction of about the same magnitude (~3 Sv) (Hansen and Østerhus, 2000). There is also energetic circulation within the Nordic Seas. Cold surface water is deflected from the EGC to the east both at about 72°N by the Jan Mayen Current (JMC) as well as into the Iceland Sea. Intermediate and deep water of the Greenland Sea pass over the Mohns Ridge and through the Jan Mayen Channel into the Norwegian Sea (e.g. Østerhus and Gammelsrød, 1999) and intermediate water enters the southern Norwegian Sea from the Iceland Sea through the East Iceland Current (EIC).

Altogether there are four paths for cold overflow from the Nordic Seas to the deep North Atlantic; in addition to the one between Greenland and Iceland (the Denmark Strait), these exit between Iceland and the Faroe Islands, across the Wyville–Thomson Ridge, and through the Faroe Bank Channel (FBCh). The total overflow between Iceland and Scotland is of similar magnitude to that through the Denmark Strait, and the deepest exit is through the FBCh after passing the Faroe–Shetland Channel between the Faroe and Shetland Islands (Fig. 1b). The present volume flux through the FBCh, of water colder than 3 °C, has been estimated to be 1.9 Sv, but it is suggested that this flux has decreased by about 0.5 Sv during the last ~50 years (Hansen et al., 2001). The pure overflow, defined as water below 0.3 °C, is estimated to be 1.2 Sv (Hansen and Østerhus, 2000) and is estimated to have decreased as much as 2–4% annually during 1995–2000 and in total at least 20% during the last 50 years (Hansen et al., 2001). This latter definition of the overflow is used throughout this work. Results using a synoptic-forced numeric model (Nilsen et al., 2003) indicate substantial decadal variability in both the north-flowing and the south-flowing volume flux over the Greenland–Scotland Ridge. The overflow has most likely also decreased across the Iceland–Faroe Ridge and the Wyville–Thomson Ridge (Hansen et al., 2003). Time series also reveal a change in water properties of the FBCh overflow, which has become fresher (Turrell et al., 1999), mainly by an elevated incorporation of intermediate water due to a decrease in deepwater formation. Both the inflow and the overflow are thoroughly discussed by Hansen and Østerhus (2000).

To investigate the formation of water contributing to the overflows into the North Atlantic, a tracer release experiment was initiated in summer 1996 (see Watson et al., 1999). In total 320 kg of sulphur hexafluoride (SF_6) was injected into the central Greenland Sea Gyre (see Fig. 1b) at the density surface $\gamma_\theta = 28.049\,\mathrm{kg\,m^{-3}}$ at an average depth of about 300 m.[1] SF_6 is a compound that is almost entirely man-made (Harnisch and Eisenhauer, 1998), and it has been utilised as a deliberately released tracer in a range of oceanographic studies (Watson and Ledwell, 2000). In addition to this, SF_6 has been used as a transient tracer in recent investigations (Law and Watson, 2001; Tanhua et al., 2004) in the same way as the chlorofluorocarbons (CFCs).

The Greenland Sea tracer release has made it possible to follow intermediate water from the Greenland Sea around the Nordic Seas and into connecting areas. The spreading of the tracer has been monitored ever since the release, and the tracer is now found in most parts of the Nordic Seas and has also overflowed the Greenland–Scotland Ridge and entered the North Atlantic (Messias et al., submitted; Olsson et al., 2004).

2. Data and methods

2.1. Data collection

The data reported in this work have been collected mainly within the EU projects "European Subpolar Ocean Programme, phase 2" (ESOP-2) and "Tracer and Circulation in the Nordic Seas Region" (TRACTOR). The experiment with the release of SF_6 was performed in ESOP-2, which was dedicated to the investigation

[1]Often reported as $\sigma_\theta = 28.049$ with or without units, which is not consistent with the JPOTS standard (JPOTS Editorial Panel, 1991).

of the thermohaline circulation, mainly by studies in the Greenland Sea (Messias et al., 1999). One of the goals of the TRACTOR project has been to follow the SF_6 tracer as it spreads in time and space from the Greenland Sea to the surrounding basins. Further results from the experiment are presented elsewhere (Watson et al., 1999; Gascard et al., 2002; Olsson et al., 2004).

Samples have been collected around the Faroe Islands regularly since 1998, mainly north of the islands and in the FBCh (Fig. 1b). Information on the station activity in the FBCh is given in Table 1. Samples for SF_6 were collected with rosettes mounted on SeaBird CTDs, and temperature and salinity measurements accompany the samples. Most of the sampling sites are located on standard sections, which are occupied by R/V Magnus Heinason at least four times a year. From these cruises, a large number of CTD profiles have been acquired from the areas around the sampling sites. On each CTD station, a double set of water samples is collected at one depth and analysed by a salinometer for salinity calibration.

The determination of SF_6 was performed with a gas chromatograph with electron capture detection (ECD) coupled to a purge-and-trap pretreatment system (Law et al., 1994; Tanhua et al., 2004). The standard deviation of a set of samples from the same depth is less than 2%. The standardisation of SF_6 was performed with gas calibrated against standards from Plymouth Marine Laboratory (UK), which in turn were calibrated against standards from University of Heidelberg (Germany). The concentrations of all samples in this study were well above the detection limit of about 0.1 fmol kg^{-1}.

2.2. Calculations

The transient atmospheric source of SF_6 must be considered also in a deliberately released tracer experiment. The atmospheric background signal of SF_6 in a seawater sample can be estimated from the observed CFC concentrations. The atmospheric history is obtained from Walker et al. (2000) for the CFCs and from Maiss and Brenninkmeijer (1998) for SF_6. The solubility of the gases in oceanic surface water is computed by equations that are functions of potential temperature (θ) and salinity (S) (Warner and Weiss, 1985; Bu and Warner, 1995; Bullister et al., 2002). Time series for a typical upper water in the Greenland Sea are illustrated in Fig. 2a.

Mixing of water masses of different ages can result in apparent ages that are quite different for CFCs and SF_6 and hence make it problematic to calculate the atmospheric background. To minimise this uncertainty it is necessary to evaluate

Table 1
The sampled stations in the FBCh including timing, location and determined tracers

Year	Month	Ship	Positions[a]	Tracers[b]
1997	Aug	Aranda	61°20′N, 8°16′W; 61°22′N, 8°13′W; 61°25′N, 8°10′W; 61°28′N, 8°08′W & 61°30′N, 8°05′W	CFCs
1998	Nov	Magnus Heinason	V06	SF_6
1999	Feb	Magnus Heinason	V05 & V06	SF_6
	June	Magnus Heinason	V05 & V06	SF_6
2000	Feb	Magnus Heinason	V05 & V06	SF_6
	June	Magnus Heinason	V05 & V06	SF_6
2001	Feb	Magnus Heinason	V05 & V06	SF_6
	June	Håkon Mosby	V05, V06, 61°15′N, 8°01W; 61°18′N, 7°57′W & 61°21′N, 7°50′W	SF_6, CFCs
	Sep	Magnus Heinason	V05 & V06	SF_6
2002	Feb	Magnus Heinason	V05 & V06	SF_6
	June	Magnus Heinason	V05 & V06	SF_6
2003	Feb	Magnus Heinason	V05 & V06	SF_6

[a]The positions for V05 and V06 are 61°20′N, 07°53′W and 61°16′N, 08°00′W, respectively (see Fig. 4).
[b]In addition to the listed tracers T and S were determined on all cruises.

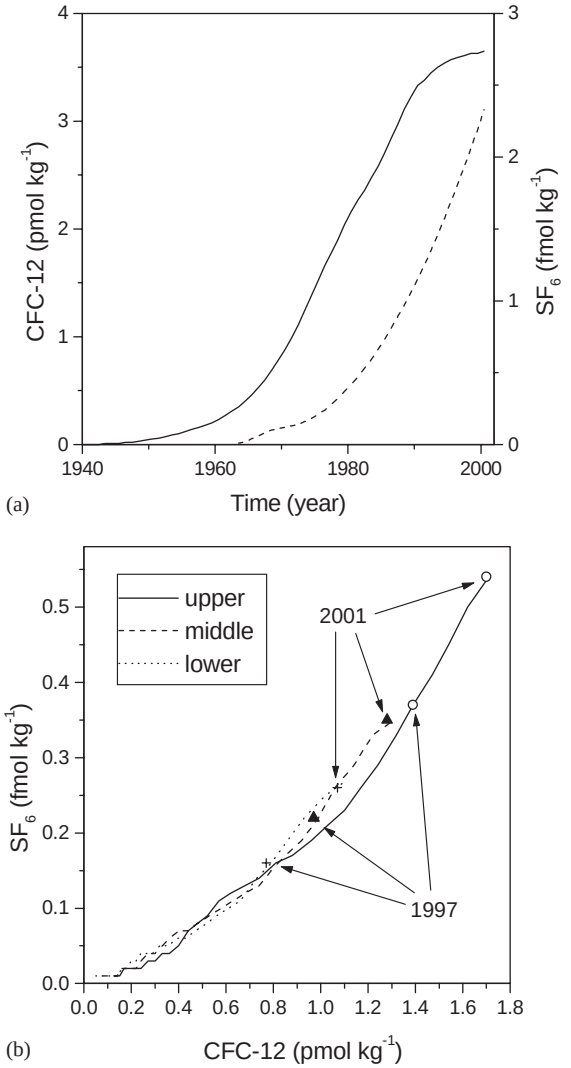

Fig. 2. Graphs showing correlation of transient tracer concentrations in seawater. (a) Functions of CFC-12 (solid line) and SF_6 (dashed line) versus time in a surface water of $S = 34.89$ and $T = -0.7\,^{\circ}C$ in equilibrium with the atmosphere. (b) Function of CFC-12 versus SF6 in the different water types resulting from mixing of the source waters according to Table 2 and Eq. (1). The relationship in the years 1997 and 2001 in the three water types are indicated (o = upper, ▲ = middle, + = lower).

which source waters are mixed. From the cruises where CFCs were available (see Table 1), the overflow water in the FBCh was divided into three different types, upper, middle and lower, based on the properties of the observed samples (average θ and S are shown in Table 2). The next step was an attempt to determine the mixing histories of these water types. All three water types have evidently a portion of water from the Greenland Sea (Greenland Sea Arctic Intermediate Water, GSAIW), as shown by the elevated levels of SF_6. The other contributing water masses are believed to be: Norwegian Sea Deep Water (NSDW), Northeast Atlantic Water (NEAW) and Modified East Icelandic Water (MEIW) (Fogelqvist et al., 2003). The water mass commonly defined as Norwegian Sea Arctic Intermediate Water (NSAIW), believed to be a major contributor to the Iceland–Scotland Overflow Water (Hansen and Østerhus, 2000; Fogelqvist et al., 2003), is not included here since it is to a large extent made-up from what is called GSAIW (Blindheim, 1990) herein. This name is used to make it clear that this is the water mass containing the tracer from the Greenland Sea. The properties of GSAIW differ slightly from those of NSAIW, which is affected by NSDW situated underneath, with mixing between these two occurring in the boundary layer. This can be the reason why this study gives a larger portion of NSDW in the overflow compared to Fogelqvist et al. (2003), who use NSAIW as source water instead of GSAIW. The properties of the intermediate water from the Greenland Sea containing the released tracer are taken from observations made during the ESOP-2 project, 3–4 months after the release (Tanhua and Olsson, unpublished data), and the properties of the other involved water masses are obtained from Fogelqvist et al. (2003).

The temporal evolution of the concentrations of CFC-12 and SF_6 in the four source waters was computed from the solubility and θ and S data and the assumption of equilibrium with the atmosphere. Furthermore, as the time from contact with the atmosphere to their appearance in the FBCh varies between the source waters, this has to be considered when the background concentration is computed. The observed CFC-12 concentration in GSAIW is comparable to a time delay of 15 years from ventilation to observation. This does not mean that the "age" of the water mass is 15 years since an eventual under-saturation is also

Table 2
Properties of the three different water types in the FBCh as follows: potential temperature, salinity and fractions of the four source waters

			Source waters			
Water types in FBCh	Θ °C	Salinity	GSAIW, fractions	NSDW, fractions	MEIW, fractions	NEAW, fractions
Upper	−0.016	34.900	0.35	0.50	0.10	0.048
Middle	−0.482	34.902	0.20	0.72	0.060	0.023
Lower	−0.638	34.907	0.11	0.83	0.040	0.020

The following acronyms are used: GSAIW—Greenland Sea Arctic Intermediate Water, NSDW—Norwegian Sea Deep Water, MEIW—Modified East Icelandic Water, NEAW—North East Atlantic Water.
The properties of the source waters are taken from Fogelqvist et al. (2003) except for those of GSAIW which are taken from observations during ESOP-2.

included here. If a 2-year transit time from the Greenland Sea to the FBCh is used (which agrees well with the tracer observations) we get a total time delay of 17 years for GSAIW. The observed CFC-12 concentration in NSDW is comparable to a time delay of 31 years, which together with a transit time of 1 year gives a total delay of 32 years. MEIW and NEAW are saturated with respect to CFC-12, but a delay time of 1 year is used. Thus, the time evolution in the three water types of the FBCh is computed by adding together the contributions by the different source waters and taking the time delay into consideration according to Eq. (1):

$$X^{\mathrm{wt}}_{\mathrm{year}=i} = f^{\mathrm{GSAIW}}\, X^{\mathrm{GSAIW}}_{\mathrm{year}=i-17} + f^{\mathrm{NSDW}}\, X^{\mathrm{NSDW}}_{\mathrm{year}=i-32} + f^{\mathrm{NEAW}}\, X^{\mathrm{NEAW}}_{\mathrm{year}=i-1} + f^{\mathrm{MEIW}}\, X^{\mathrm{MEIW}}_{\mathrm{year}=i-1}. \quad (1)$$

Here X represents the concentration of any tracer and f the fraction of source water contributing to the water type (wt). The fractions of the four source waters are computed to fit θ, S and CFCs (Table 2) observed in the three water types. When the background for a given year i is computed, the concentration of the tracer in the source water is taken for the year i minus the transit time as indicated by the subscripts for any of the source waters given by the superscripts. The results of the computations are shown in Fig. 2b. For comparison the computed relationships for 1997 and 2001 in the three water types are indicated. No direct comparison with observations can be made since there are none made with only background SF_6.

For each sample, one of the three water types was chosen to be the most representative, decided by its θ and S properties. The corresponding water mass fraction (see Table 2) and year are put into Eq. (1), and the resulting background concentration is subtracted from the observed concentration of each sample.

3. Results

A typical water mass distribution on a section crossing the FBCh is illustrated by an example in Fig. 3. The deepest part of the channel is always occupied by dense overflow water on its way into the Atlantic Ocean, passing the section from the southeast to the northwest, and usually water with density exceeding $\gamma_\theta = 28.049\,\mathrm{kg\ m^{-3}}$ (the release density) dominates the bottom layer (Fig. 4). Thus, all of the 23 CTD profiles acquired at the deepest standard station, V06, in the period 1998–2001 reached or exceeded this density at the deepest measurement. Unfortunately, the SF_6 samples have not always reached this layer, but on most cruises, this has been the case.

All water below about 600 m had $\gamma_\theta > 28\,\mathrm{kg\,m^{-3}}$, and showed increasing SF_6 concentrations from at least year 2000 (Fig. 5). However, the SF_6 concentration does not show a continuous increase with time, but the variability is to some extent reflected in the variability in water

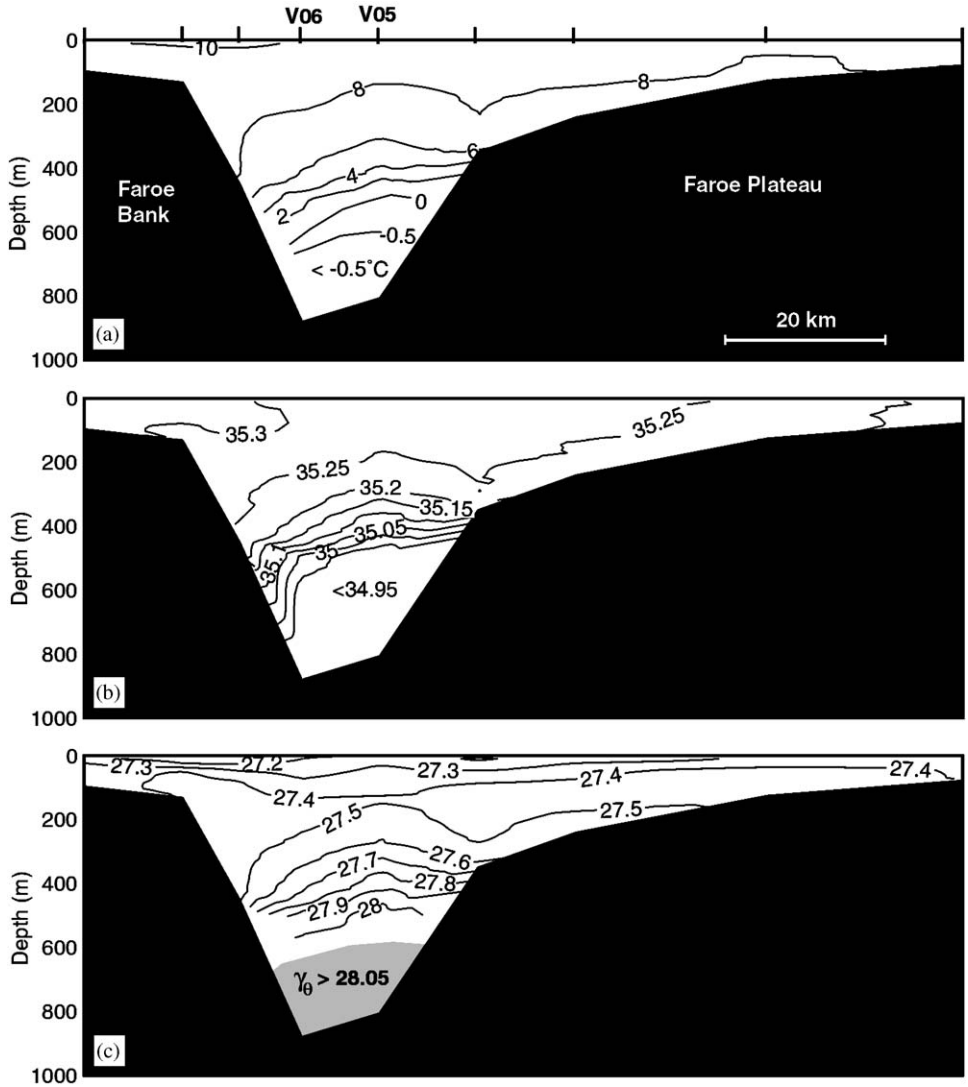

Fig. 3. (a) Potential temperature in °C, (b) salinity, and (c) potential density γ_θ in kg m^{-3} on a section across the FBCh in June 2000. Station locations are shown in Fig. 4. The positions of the two standard stations, V05 and V06, from which most of the SF_6 samples derive, are indicated.

properties. The water shallower than about 500 m (not shown) has had less relative increase in SF_6 concentration (1.4 fmol kg^{-1} at 300 m already in June 1999) and this signal is of atmospheric origin only.

When the measured SF_6 concentrations are corrected for the background and all data below 600 m are plotted versus time, a clearer pattern is seen (Fig. 6). In the autumn of 1998 the SF_6 concentration is close to the background values, after which it increases almost linearly until spring/summer 2000. After this the excess concentration varies around 0.9 ± 0.1 fmol kg^{-1}, except for the last observations in 2002 when it had once again increased. On some occasions the concentrations show larger variations, mainly a result of the presence of water that was not well represented by any of the three water types, e.g. more saline water

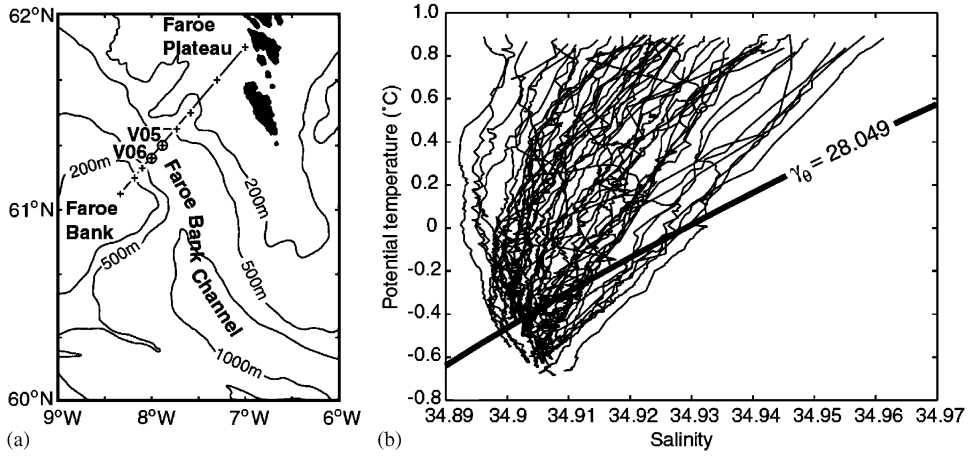

Fig. 4. Map of the FBCh (a), showing the standard CTD stations and θ–S diagram (b) from CTD profiles acquired in the vicinity of standard stations V05 and V06 in the period 1998–2001. In (b), the $\gamma_\theta = 28.049\,\mathrm{kg\,m^{-3}}$ isopycnal is identified. The overflow passes the section from the southeast to the northwest and also the additional sampled stations are located along this section but at slightly different positions than those shown.

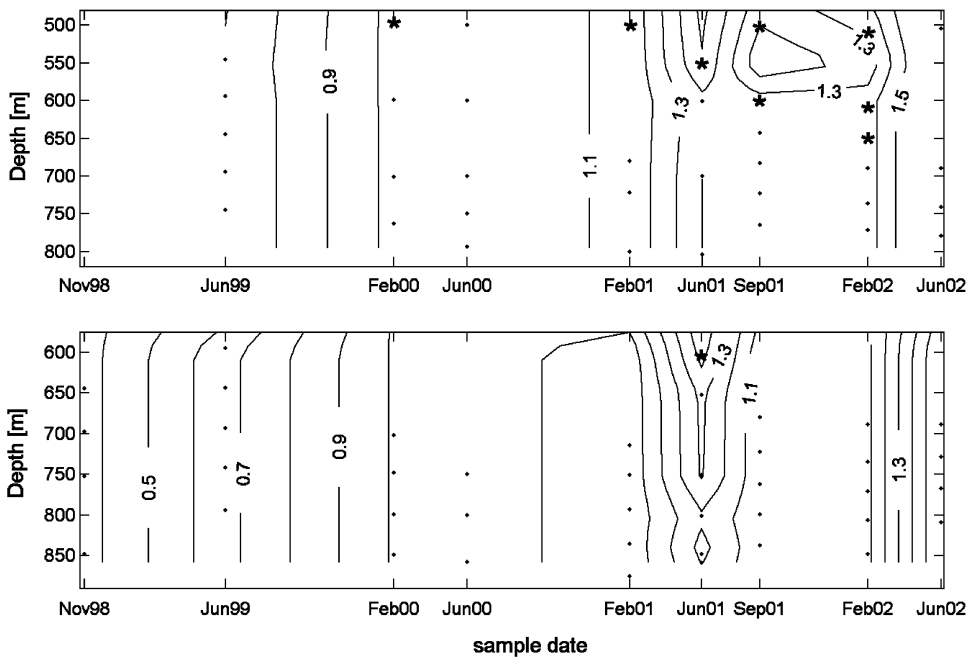

Fig. 5. Observed SF_6 concentration in $\mathrm{fmol\,kg^{-1}}$ versus time in the FBCh at (a) V05 and (b) V06. The depth interval was chosen to include all observations of overflow water, which are shown by dots, while observations from outside the overflow ($>0.3\,^\circ\mathrm{C}$) are marked by asterisks.

and hence containing a larger portion of NEAW. The reason for the increase in June 2002 (Fig. 6) is not known but might indicate that the overflow is supplied by more than one pathway, and that the transit time of the second caused it to appear 4 years later. Alternatively the overflow could have a

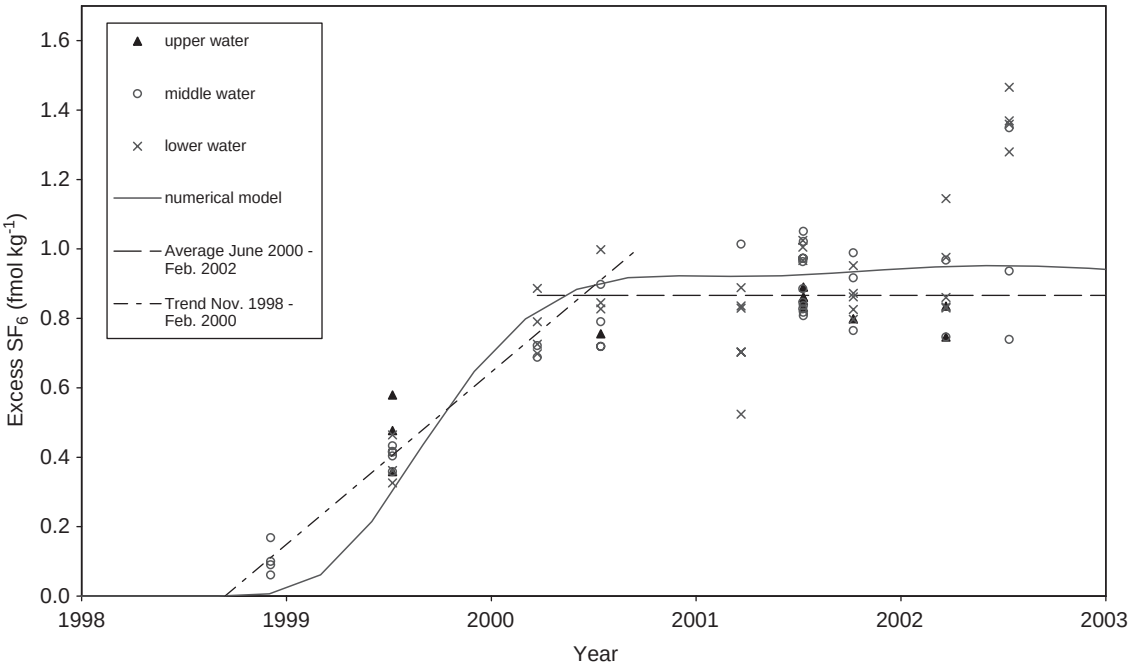

Fig. 6. The time evolution of excess SF_6 in the FBCh based on observations (markers) and model (solid line), in units of fmol kg^{-1}. All observations with $\theta < 0.3\,^{\circ}C$, taken between November 1998 and June 2002 are included. Also shown are lines representing the average estimated excess of the constant phase utilised to give the estimated outflow as well as the increasing trend during the build-up phase.

quite different composition with a larger fraction of water originating in the Greenland Sea.

4. Discussion

4.1. Time evolution

As illustrated in Fig. 6, the SF_6 signal from the tracer release did not appear in the FBCh until winter 1998–99, which is slightly more than 2 years after the tracer was released in the Greenland Sea Gyre (summer of 1996). This should then reflect the transit time of a water parcel, at the density level of the release, from the central Greenland Sea to the FBCh. The build-up time, from fall 1998 to spring/summer 2000, is ~1.5 years and should be the result of mixing both within the Greenland Sea and during the transit to the FBCh. Observations indicate that the SF_6 signal was homogeneously mixed ($\pm 10\%$) in the Greenland Sea Gyre after 1.5–2 years (Messias et al., 1999). The level in the Greenland Sea has continued to decrease ever since although at a slower rate.

The escape from the central Greenland Sea presumably occurs both directly and indirectly; to the west diffusive mixing probably dominates the spread into the EGC bordering the Greenland Sea, while advection likely plays a larger role in the exiting to the east through the Jan Mayen Channel and into the Norwegian Sea. The close to stable excess tracer signal in the FBCh could be a combination of mixing of water taking two routes from the Greenland Sea, one more directly and one e.g. passing further into the Norwegian Basin. It should be noted that the strength and relative importance of the different flow paths are not constant in time. The essential role of the JMC in the simulated tracer spreading presented in Section 4.3 underlines this. Also, it is becoming more and more evident that the variability of the atmospheric forcing has an impact on the Nordic Seas current regimes, the FBCh region included (e.g. Nilsen et al., 2003).

4.2. Transport estimates

The concentration evolution in the FBCh combined with the literature values of the volume fluxes in different depth layers (e.g. Hansen et al., 2001) gives an estimate of the SF_6 transport. The volume flux below the 0.3 °C isotherm shows a seasonal signal with highest values in fall and lowest in spring and a decreasing trend of 2–4% per year from 1996 to 2000 (Hansen et al., 2001). The mean flux in 2000 was ~1.2 Sv, which would give a mean transport of SF_6 during the phase of constant excess (~0.9 fmol kg^{-1}) of ~5 kg SF_6 per year. Adding together the annual transports from the fall 1998 to the winter of 2002/2003 would give a total transport of 1.5 years × 5 kg per year/2 (during the build up phase) plus 2.5 years × 5 kg per year (during the constant phase), or 16 kg. This is ~5% of the SF_6 released in the central Greenland Sea. This means that although the concentrations are low, significant amounts of the tracer are exported thanks to the large fluxes and this indicates that the importance of different regions can hence be easily underestimated. It is assumed that the amount of tracer exported above the 0.3 °C isotherm is insignificant since the water properties indicate that very little water from the Greenland Sea is included here. The 0.3 °C limit is defined to include NSDW and NSAIW and hence GSAIW (see Hansen et al., 2003).

4.3. Comparison with a numerical ocean model

Further understanding of the pathways of SF_6 within the Nordic Seas and subsequent export through the FBCh may be gained from a numerical ocean model. For this purpose, we use an advective–diffusive model of tracer transport and mixing within the intermediate waters of the Nordic Seas (Eldevik et al., 2005). The model was originally set up by Straneo et al. (2003) to describe the spreading of Labrador Sea Water. The stationary horizontal velocity field prescribed should ideally be based on in situ observations (which is the case for the Labrador Sea study), but adequate current data are not available for the Nordic Seas. Eldevik et al. (2005) deduce their flow field (on a 10 km × 10 km grid) from the output of the high resolution (20 km) general circulation model (GCM) of Hátún et al. (2005). The GCM is a version of the Miami Isopycnic Coordinate Ocean Model (MICOM, Bleck et al., 1992) covering the North Atlantic and the Nordic Seas for the period 1951–2000. This regional set-up, as well as its corresponding global (and coarser) versions focused on the Arctic Mediterranean, should be state of the art for GCM systems covering the Nordic Seas. The GCM's spreading of active (Furevik et al., 2002) and passive (Gao et al., 2004) tracers and Atlantic–Nordic Seas exchanges (Nilsen et al., 2003; Hátún et al., 2005) have all been evaluated favourably against observations.

The velocity field used by the advection–diffusion model is the average of the GCM horizontal velocity over the intermediate water (IW) column. The IW is here defined to be the water between 500 and 1500 m depth (where the ocean depth is less than 1500 m, the average velocities are weighted consistent with the reduced thickness). The SF_6 is generally observed in the IW part of the water column in the Nordic Seas (cf. Messias et al., submitted). For the case at hand, the mean 1997–2000 GCM flow field is used. The corresponding streamlines of the advective–diffusive solver are displayed in Fig. 7, where the black rectangle centred at 1.5°W, 75.25°N is the August 1996 release site. It does show the general IW patterns of Fig. 1a, but there are features more emphasized in the model current field. Particularly, the streamlines following the JMC, then diverting into the Norwegian Sea east of Jan Mayen, are more important contributors to the export of the simulated IW towards the FBCh than those of the deep EGC. Note that the model domain does not really include the FBCh. The southern open boundary is the slightly upstream Faroe–Shetland Channel. Comparing the observed and modelled tracer concentration at the two different sites should nevertheless be consistent. What leaves the Nordic Seas through the Faroe–Shetland Channel is exported to the Atlantic predominantly through the FBCh (about 90%), with the flow over the Wyville–Thomson Ridge closing the budget (cf. Hansen and Østerhus, 2000).

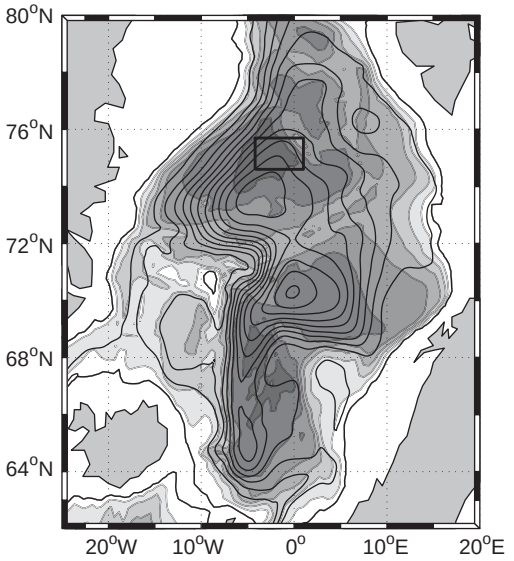

Fig. 7. The model domain and IW streamlines. The contour interval corresponds to 0.5 Sv. The greyscales show the topography at 500 m intervals and the rectangle marks the site of the tracer release.

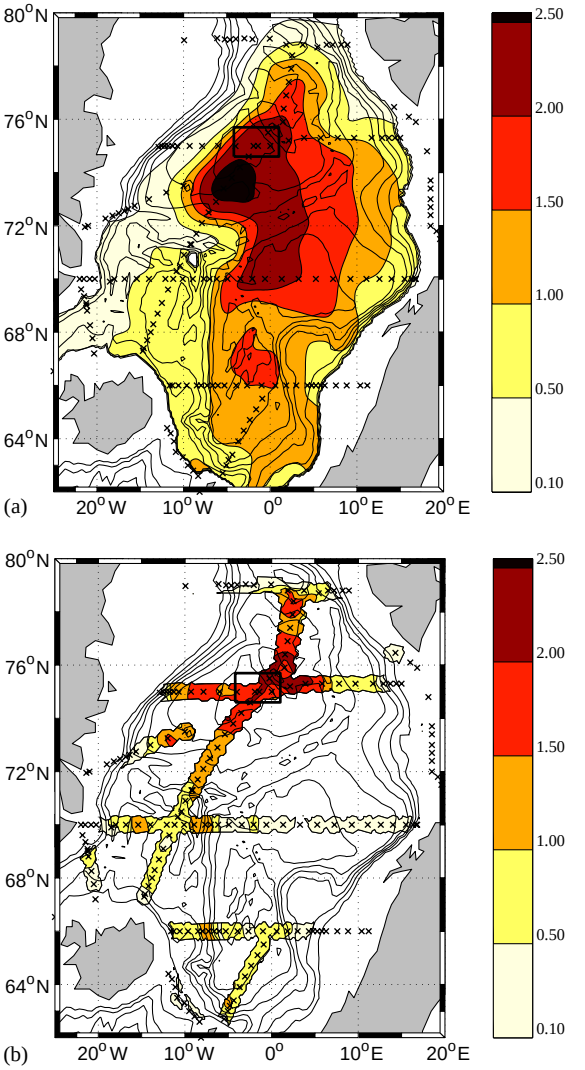

Fig. 8. (a) Modelled and (b) observed distributions of released SF_6 integrated over the water column (nmol m^{-2}) 6 years after the tracer release. The observed distribution was obtained subtracting the SF_6 estimated to be of atmospheric origin from the total observed and is from Messias et al. (submitted), where the spreading is presented in more detail. The rectangles in both figures mark the site of the tracer release.

The modelled outflows through the Denmark Strait (0.9 Sv) and the Faroe–Shetland Channel (1.7 Sv) are realistic. Corresponding observationally based estimates are 0.6 Sv (Girton et al., 2001) and 1.7 Sv (Hansen and Østerhus, 2000). There is no exchange between Iceland and the Faroes as the Iceland–Faroe Ridge is shallower than 500 m. The net IW inflow through the Fram Strait, in the conservative model being the sum of the Denmark Strait and Faroe–Shetland Channel fluxes, is thus 2.6 Sv. The model's Laplacian eddy diffusivity is assumed constant, and set to the nominal value 100 $m^2 s^{-1}$. Eldevik et al. (2005) also do simulations where they vary the magnitude of the diffusion, as well as the degree of anisotropy and spatial inhomogeneity, and find that the results are rather insensitive to this particular choice. The reader is referred to Eldevik et al. (2005) for further details on the model set-up and evaluation.

A snapshot from the numerical simulation of the SF_6 release and spreading is seen in Fig. 8a. From the release site, the tracer is advected along and mixed across the streamlines of Fig. 7 for 6 model years to produce the summer 2002 distribution in Fig. 8a. A synthesis of the corresponding in situ observations (column inventories), taken from Messias et al. (submitted) is shown in Fig. 8b. The crosses indicate the hydrographic stations. The agreement between model and field data is fair with respect to patterns and good on

concentrations. The observations support the model prediction of the importance of the pathway directly from the Greenland Sea to the Norwegian Sea via the JMC. Consistent high concentration anomalies are found roughly following the 2000 m isobath in Fig. 8b: from the north to the south-east of Jan Mayen, then to the western Norwegian Basin, and then to the north of the Faroes. The model seems to be off in the central Norwegian and Lofoten basins, where it predicts two high-concentration anomalies. This suggests that the model recirculation in the two basins (cf. Fig. 7) is somewhat too strong, although a similar pattern is present in the flow climatology of Nøst and Isachsen (2003).

The concentration of SF_6 in the FBCh predicted by the model is compared with the observations in Fig. 6. The model concentration, given in tracer mass per unit area, has been converted to mass per unit volume by dividing it by the thickness of the IW. There is a remarkable agreement in arrival time, build-up time, and 'end' concentration between the two. The modelled total export through FBCh by winter 2002/2003 is 15 kg, consistent with the 16 kg estimated from observations.

The comparison of the model results and the observations shows that the rather simple advective-diffusive model is quite skilful. The key component in reproducing the observed export of SF_6 is the direct pathway east of Jan Mayen from the Greenland Sea to the Norwegian Sea. It suggests that this 'shortcut' is more important than previously assumed (cf. Fig. 1a), at least as the IW circulation of the late 1990s and early 2000s is concerned.

4.4. Uncertainties

The uncertainties in estimating the tracer transport are the result of at least four different components, the actual observations, the background subtraction, the time evolution and the volume fluxes. The errors originating in sampling, analysis and calibration of the tracer data are only a few percent and insignificant compared to the total.

The largest uncertainty is associated with the establishment of the background-corrected SF_6 concentration. This is dependent on how well all the observed water samples fit into the defined water types and how representative and constant the source water compositions of these water types are. It is also dependent on the properties of the defined source waters, e.g. the assumed tracer saturation, and how variable they are.

The common variability in time and space affects the FBCh water types and the source waters as well as the sampled locations in the FBCh. The mean excess SF_6 for all samples in the FBCh between June 2000 and February 2002 is $0.9\,\mathrm{fmol\,kg^{-1}}$ with a standard deviation of $0.1\,\mathrm{fmol\,kg^{-1}}$. The variations are relatively small and hence we assume that it can be relatively representative for the last 30 months and for the whole FBCh.

How well the water types are able to represent the water samples is hard to tell. However, some estimates can be made from the observed CFC concentrations based on the ranges within each water type and differences between the water types. From this approach a rough estimate $0.1\,\mathrm{fmol\,kg^{-1}}$ is obtained. It might be higher for the more saline samples, e.g. above 34.91, although these are so few that they do not considerably affect the estimates.

The offset between the mixing proportions in Table 2 and the actual mixing history of each water type is dependent on a couple of things. The four selected source waters are those believed to contribute to the overflow (Hansen and Østerhus, 2000; Fogelqvist et al., 2003). The error from the mixing proportions is limited by the fact that no source water dominates the total SF_6 contribution: each one constitutes a fraction between 9% and 43%. This implies that a more than 20% change in any of the water masses is needed to give a markedly different background concentration. A direct comparison between the fraction of GSAIW and the SF_6 concentration cannot be made since the concentration in the Greenland Sea has been decreasing with time and was patchy to start with. Initially, part of the GSAIW passing the FBCh might have left the Greenland Sea before the experiment and be free of released tracer, which

makes a straightforward approach difficult. Based on the mean water mass composition of all overflow samples in this study, as deduced from the water types, the fraction of GSAIW in the overflow would be 17%. If this is true the 0.9 fmol kg^{-1} in the FBCh would have been about 5.5 fmol kg^{-1} in the Greenland Sea. As mentioned above this value has, however, been changing considerably with time although as an average it is reasonable compared to the observations (Messias et al., submitted).

An estimate of the extreme offset from the assumed SF_6 levels in the source waters can be done. The uncertainty is due mainly to the degree of saturation of the tracer. Since the same processes determine the uptake of CFCs and SF_6 from the atmosphere to the ocean it is assumed that these gases are saturated to the same degree in surface water. The saturation of SF_6 in the two recently ventilated water masses, MEIW and NEAW, is assumed to be 100% which is consistent with the saturation of CFCs observed by Fogelqvist et al.(2003). In the Greenland Sea however, the saturation for CFCs has been reported to be around 80% (Bullister and Weiss, 1983; Rhein, 1991; Anderson et al., 2000). Such an under-saturation implies that the actual atmospheric concentration was higher than the value directly obtained from the observed tracer concentration in the water, and compensation for an assumed degree of under-saturation hence gives a lower age estimate. Assuming a saturation of 80% in GSAIW instead of 100% results in a CFC age being 5 years lower and the corresponding SF_6 concentration, 5 years later but saturated to 80%, would be higher, e.g. 0.63 instead of 0.46 fmol kg^{-1}, an effect of the different temporal evolution of the two compounds (Fig. 2a). The alternative that GSAIW in the Greenland Sea would be newly ventilated and the observed relatively low concentration of CFCs was caused only by low saturation (65%), would give a corresponding SF_6 concentration of 1.15 instead of 0.46 fmol kg^{-1}. If any of these two scenarios are true, the excess SF_6 is over-estimated by between 0.02 and 0.24 fmol kg^{-1}. Although such an extremely low saturation as the latter has been observed in the Labrador Sea (Azetsu-Scott et al., 2003), it seems not to be a valid number in the Greenland Sea, and the numbers are only mentioned here for comparison. Only the first scenario of 80% saturation will be included in the uncertainty estimates, and this indicates an offset of less than 0.1 fmol kg^{-1}. The concentration of SF_6 in NSDW is not markedly off-set since observations both in 1997 and 2001 show levels close to those used as the source function, and the levels in MEIW and NEAW are at least not much underestimated since these are based on newly ventilated water with 100% saturation.

In summary, the mean excess SF_6 during the period of relatively constant level (years 2000–2002) would, with the mentioned uncertainties be somewhere between 0.6 and 1.1 fmol kg^{-1}.

When the uncertainty in flux of the released SF_6 through the FBCh is estimated, the uncertainty in the temporal evolution also has to be considered. This uncertainty appears mainly during two phases, the initial build-up and an eventual increase the last year. The arrival time of excess SF_6 in the FBCh occurred at the earliest around November 1998 and at least before June 1999. The build-up phase is estimated to be 1.5 years long but with an extreme start and end this could vary ± 6 months. This also means that the remaining time will be between 2.5 and 2.75 years. If, on the other hand, we assume that the last observation (which on average is 0.3 fmol kg^{-1} higher) is representative for the last 9 months (from immediately after the second last observation), we will have three scenarios of the time evolution. Applying the interval in concentration presented above, the total export would range between 10 and 23 kg.

4.5. Overflow export in the other regions

Additional outflow of SF_6 east of Iceland, i.e. across the Iceland–Faroe Ridge or the Wyville–Thomson Ridge is believed to be low since the major portion of water passing these is not dense enough to contain the released tracer. A smaller amount might exit over the Wyville–Thomson Ridge although the agreement between the observations and the model indicates that this should be of less importance since the modelled Faroe–Shetland Channel estimate is only slightly

higher than the observational FBCh estimate. No observation-based estimate of the export through the Denmark Strait has yet been made since no similar time series exists there although the first observation of the tracer at the western overflow has been reported by Olsson et al. (2004). The model estimate for the Denmark Strait is presented by Eldevik et al. (2005).

5. Conclusions

The first arrival of the released SF_6 in the FBCh is estimated to early 1999 based both on observations and on numerical modelling. This gives a transit time from the central Greenland Sea to the FBCh of about 2.5 years. The total transport of released SF_6 through the FBCh into the North Atlantic by the end of 2002 is calculated to be 16 kg from the observations and 15 kg based on the numerical model. This means that of the 320 kg released in the Greenland Sea in 1996, approximately 5% had passed through the FBCh 6.5 years later.

In the numerical model the main pathway of this water is the direct route of the JMC from the Greenland Sea into the Norwegian Sea. This is also consistent with repeated observations of the tracer on the eastern side of the Jan Mayen Ridge (e.g. Olsson et al., 2004). The EGC's main role during this period is to 'feed' tracer from the Greenland Sea to the Denmark Strait (Eldevik et al., 2005).

It has not been estimated how large a fraction of the overflow through the FBCh has been formed in the Greenland Sea although a considerable part of the tracer released there has exited the Nordic Seas through this passage. The transit can be accomplished in as short a time as 2.5 years or less. However, the transit time might be different for different portions and only a fraction of the intermediate water leaves the Greenland Sea each year which is seen in the well retained SF_6 concentration (Messias et al., submitted). A change in the ventilation of the Greenland Sea can hence be transferred to the surrounding basins rather quickly although its full effect is not seen until after some decades. Nevertheless, the Greenland Sea is seen to be important for the overflow through the FBCh and perhaps more comprehensive investigations of the tracer evolution in the Greenland Sea can give estimates also of the volume export of GSAIW within the overflows. The composition and changes of the overflow are of great importance in examining how it can be affected by climate change and hence also its role for the thermohaline circulation and the climate of Northern Europe.

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