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Spreading of overflow water from the Greenland to the Labrador Sea

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[1] In 1996, about 320 kg of SF_6 were introduced in the center of the Greenland Sea gyre. We use this signal together with the CFC distribution to follow the spreading of Greenland gyre water from the Denmark Strait through the Irminger Basin and the Labrador Sea to the Grand Banks. In the summer of 2003 Denmark Strait Overflow Water tagged with deliberately released SF_6 could be traced throughout the Irminger Basin to the central Labrador Sea, confirming that water with potential density of 28.045 contributes to the Denmark Strait Overflow. The upper limit of the transfer time from the central Greenland Sea to the Labrador Sea was found to be 7 years. This study suggests that roughly 4 kg of excess SF_6 has been transported over the Denmark Strait and confirm earlier reported transport through the Faroe Bank Channel. These results should be considered when using SF_6 as a transient tracer. **Citation:** Tanhua, T., K. Bulsiewicz, and M. Rhein (2005), Spreading of overflow water from the Greenland to the Labrador Sea, *Geophys. Res. Lett.*, *32*, L10605, doi:10.1029/2005GL022700.

1. Introduction

[2] In the last years, the suite of transient tracers have been augmented by sulphur hexafluoride [*Law and Watson*, 2001; *Tanhua et al.*, 2004]. In contrast to the constant or slowly decreasing atmospheric concentrations of the chlorofluorocarbon (CFC) components CFC-11 and CFC-12, SF_6 exhibits an almost linear increase in the current atmosphere (Figure 1). This fact makes SF_6 particularly useful for studies of recently ventilated water masses. In addition of being a promising transient tracer, SF_6 has been used as a deliberately released tracer. In 1996, about 320 kg of SF_6 was introduced in the center of the Greenland Sea gyre on the 28.049 potential density surface located at about 300 m depth [*Watson et al.*, 1999]. The SF_6 tagged water was only slowly leaving the gyre and part of the water was then advected southward with the East Greenland Current [*Olsson et al.*, 2005a]. Measurements have found the arrival of excess SF_6 in the Iceland Sea in 1998 and on the Denmark Strait sill in 1999 [*Johannessen et al.*, 2004], and a study in the Iceland Sea in 2002 (E. Jeansson, personal communication, 2004) found roughly 1.2 fmol kg^{-1} of deliberately released SF_6, i.e. excess SF_6, in the potential density interval 28.045 and 28.06. From there the tracer can be incorporated in the Denmark Strait Overflow Water (DSOW) and spread to the western subpolar North Atlantic with the Deep Western Boundary Current (DWBC). This pathway has however been questioned because of the high density at which the SF_6 was released in the Greenland Sea. Here we present CFC-12 and SF_6 data from Denmark Strait, Irminger Basin, Labrador Sea and along the western continental margin south to the Grand Banks that are evidence of the presence of excess SF_6 in the DSOW. The data were collected on the R/V Meteor during June 2003 (cruise M59/1) and September 2003 (cruise M59/3), and on the R/V Poseidon (cruise P301) in August 2003 (Figure 2).

2. Methods

[3] Samples for CFC-11 and CFC-12 measurements during M59/1 were sampled in glass-ampoules that were flame sealed on board for later analysis in the Bremen lab with purge-and-trap sample extraction and gas-chromatographic separation with electron capture detection (ECD) [*Bulsiewicz et al.*, 1998]. The estimated precision of the measurements is about 1%. During M59/3, CFCs were measured on board with the same method. CFC samples from the Denmark Strait collected during P301 were sampled in 100 ml glass bottles that were capped under water (Reston Chlorofluorocarbon Laboratory, Collection and Preservation of Water Samples for Chlorofluorocarbon Analysis in Glass Bottles with Foil-lined Caps, available at http://water.usgs.gov/lab/cfc/sampling/newmethod.htm). Comparing CFC samples measured on board with samples stored for 7 months tested this sampling method, and the CFC-12 concentrations were found to agree within 0.03 pmol kg^{-1}.

[4] The determination of SF_6 was performed by analysis with gas chromatography with electron capture detection coupled to a purge and trap pre-treatment system. The instrument and procedure is from *Tanhua et al.* [2004], with the following modifications; After purge of the water, the analyte is trapped in a 1/16″, large ID Carboxen-1000 cold-trap kept at −60°C. After thermal desorption the sample is separated from interfering compounds on a 3 m., 1/8″ column packed with mol-sieve 5A. The sample is refocused on a 1/32″ Carboxen-1000 packed micro-trap kept at −130°C, from where it is thermally desorbed onto a Porabond Q PLOT column (0.32 mm ID × 30 m) kept isothermally at 100°C and with detection on an ECD. The analytical precision of the method is determined to 2.4%, the detection limit is estimated to 0.05 fmol kg^{-1} (~0.15 ppt) during this study. The SF_6 were calibrated against a calibrated air standard prepared at CMDL, Boulder, CO. Samples for SF_6 measurements collected in the Denmark Strait from R/V Poseidon was sampled the same

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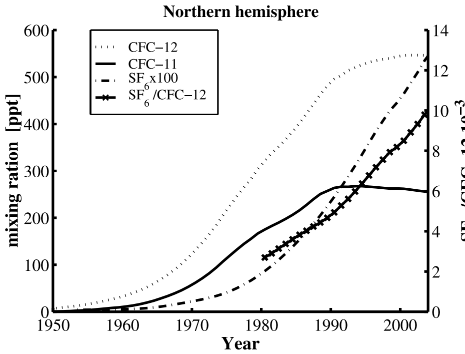

Figure 1. The northern hemisphere atmospheric concentrations of CFC-12, CFC-11 and SF_6 [*Walker et al.*, 2000; *Maiss and Brenninkmeijer*, 1998], updated with CFC data from the AGAGE network and from NOAA, CMDL for SF_6.

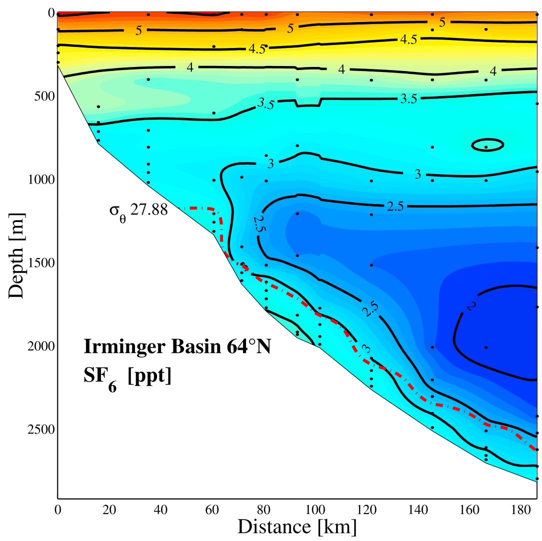

Figure 3. Section of SF_6 at 64°N. The red dashed line is the potential density 27.88, marking the upper limit for Denmark Strait Overflow Water (DSOW).

way but stored up-side down submerged in seawater prior to analysis on-shore, 2.5–3 months later.

3. Results and Discussion

[5] The DSOW is the densest water mass found in the subpolar North Atlantic. It is found at the continental slope and is characterized by densities higher than 27.88 and by high transient tracer concentrations, since part of this water mass originates from recently ventilated water, evident in the SF_6 distribution (Figure 3). We present the tracer concentrations in units of mixing ratio, calculated from the known temperature and salinity dependent solubility of the tracers [*Warner and Weiss*, 1985; *Bullister et al.*, 2002]. In this way the concentrations are directly comparable with the atmospheric history of the tracers and are independent of the temperature and salinity of the sample. The estimated excess SF_6 is then calculated back to mass units for the mass transport calculations. The sources of the elevated SF_6 signal in the DSOW can be twofold: a) the rapid atmospheric increase during the last decades and b) contributions from the deliberately released SF_6 in the Greenland Sea Gyre in 1996. In order to distinguish the two sources, we discuss SF_6/CFC ratios. Since no CFCs were deliberately released, the SF_6 tagged water from the Greenland Sea should exhibit higher ratios than untagged water. Here we present CFC-12 data, since the precision of CFC-12 is somewhat better for offline samples, but the CFC-11 data confirm within their uncertainty the results presented. Figure 4 presents the SF_6/CFC-12 ratios vs. CFC concentration for the six sections from Denmark Strait and the Irminger Basin, where there is a strong signal of DSOW along the Greenland slope. The samples within the DSOW have ratios which are significantly higher than the contemporary atmospheric ratio of 9.8 10^{-3}. The geographical location of the anomaly high ratios are indicated by red dots in Figure 2.

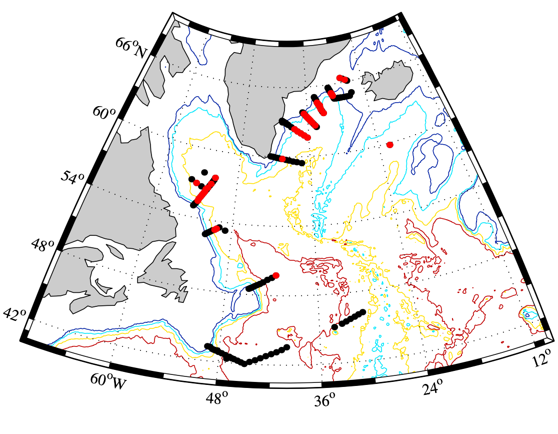

Figure 2. Map of the station net during M59/1, M59/3 and P301 during the summer of 2003. Stations marked with red are stations with a SF_6/CFC-12 ratio above 9.8 10^{-3} in the overflow water.

[6] The DSOW is known to be made up of several water masses originating in the Nordic Seas and the Arctic Ocean, all with different properties and apparent ages [cf. *Swift et al.*, 1980; *Strass et al.*, 1993; *Rudels et al.*, 2005]. The observed tracer field in the Irminger Basin was simulated by assuming mixing of up to three water masses with various temperature, salinity and ventilation time (i.e. tracer signature), all with densities consistent with DSOW. It is assumed that the SF_6 and CFC-12 are equally (100%) saturated at formation. A ratio as high as 9.0 10^{-3} could be obtained for CFC-12 concentrations corresponding to that of DSOW in the Irminger Basin (~320 ppt) in a scenario where recently ventilated, low temperature and low salinity water (representing Polar Intermediate Water) mixes with an old water mass (~40 years) with temperature of −0.7 and salinity of 34.91 (representing Arctic Ocean Deep Water) in equal amounts. There is however no mixing scenario that can produce SF_6/CFC-12 ratios higher than contemporary atmospheric ratio. Furthermore, the highest SF_6/CFC-12 ratios in the DSOW are found at the highest densities, whereas the maximum of the CFC-12 concentrations is shifted to lower densities (Figure 5). This is consistent with the notion that the densest part of the DSOW is not as recently ventilated as the less dense part [cf. *Swift et al.*, 1980]. To conclude, an additional source of SF_6 is needed to

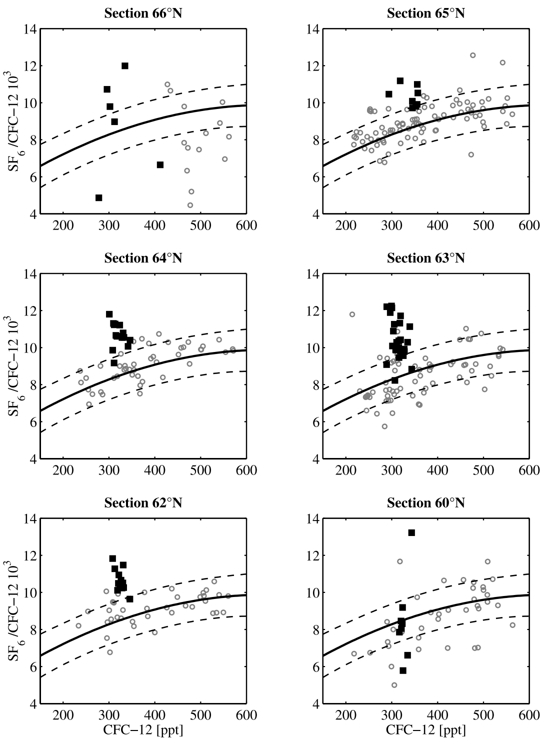

Figure 4. SF_6/CFC-12 ratio vs. CFC-12 concentration for the six sections in the Irminger Basin and across the Denmark Strait. Black squares denote samples in the DSOW (potential density >27.88) grey circles are samples from outside of this range. The quadratic fit to the non-DSOW samples (section 60–65°N) is marked with a thick black line together with the error estimates (50% confidence interval) as dashed lines.

explain the high ratios in the densest DSOW mode, i.e. water tagged with deliberately released SF_6 from the Greenland Sea. This means that water of at least 28.045 potential density has been transported over the sill. We assume that data points above the upper error limit of the fit in Figure 4 have a contribution of excess SF_6, corresponding to the difference between the measured ratio and the upper error limit, which is, incidentally, almost identical to the 2003 atmospheric ratio. The mean value of excess SF_6 for the sections 62°N to 65°N is 0.124 fmol kg^{-1}. The average DSOW flow at the sill is reported to be 3.35 Sv [*Macrander et al.*, 2005]. While the total transport increases downstream due to entrainment and mixing, the transport of waters colder than 2°C (≈27.88 potential density) decrease roughly by a factor of 2 [*Käse et al.*, 2003]. Using a flow of 1.7 Sv gives a total flux of 1.0 kg excess SF_6 y^{-1} over the Denmark Strait. These numbers can be compared with the result from *Olsson et al.* [2005b], who calculated 0.9 fmol kg^{-1} of excess SF_6 in the Faroe Bank Channel, which combined with a flow of 1.2 Sv gives an excess SF_6 flux of 5 kg y^{-1} with the Iceland Scotland Overflow Water (ISOW). The higher flux of excess SF_6 through the Faroe-Bank Channel is due the larger depths of this channel, water with potential density greater than 28.05 is normally found in the channel, which is the main pathway for excess SF_6 to the North Atlantic. It should also be noted that relatively high SF_6/CFC ratios were found in the ISOW in the Irminger Basin (CFC-12 under ~300 ppt), Figure 4. Measurements from one station in the Iceland Basin sampled from R/V Poseidon in 2003 indicates that about 0.5 fmol kg^{-1} excess SF_6 is present in the core of ISOW on the eastern flank of the Reykjanes Ridge, i.e. about half the amounts found in the Faroe Bank Channel. It is conceivable that this water mass carries a signal of excess SF_6 also in the Irminger Basin, even though that is not possible to verify with these data. This would make our flux estimate of excess SF_6 through the Denmark Strait to be a lower limit.

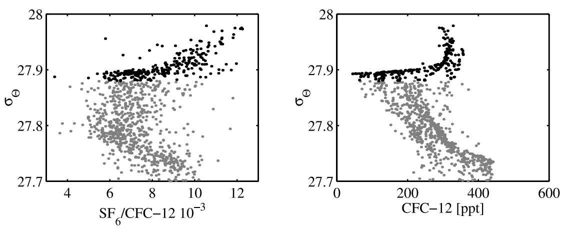

Figure 5. Density vs. SF_6/CFC-12 ratio (left), and density vs. CFC-12 concentration (right) for all the samples. Black dots denote samples in the DSOW (potential density >27.88); grey dots are samples outside of this range.

[7] The results from the measurements in the Labrador Sea and along the western continental margin south to the Grand Banks (WOCE section A2) are illustrated in Figure 6. The different shape of the fitted curve is mainly due to the different water masses with different apparent age and formation histories present in the two regions, and possibly also to less influence of excess SF_6 in the ISOW layer. As expected, there are lower ratios and CFC-12 concentrations for the overflow water in this region, consistent with the longer transport time from the area of formation. There is however still a tendency for the SF_6/CFC-12 ratios to be elevated in the DSOW layer, although not as pronounced as in the Irminger Basin. The ratios in the DSOW are generally lower than the contemporary atmospheric ratios, and it is

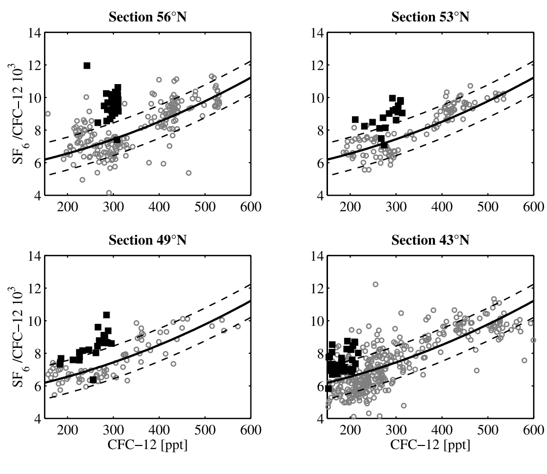

Figure 6. SF_6/CFC-12 ratio vs. CFC-12 concentration for four sections in the Labrador Sea and south to the Grand Banks. Black squares denote samples in the DSOW (potential density >27.88) grey circles are samples outside of this range. The quadratic fit to the non-DSOW samples is marked with a thick black line together with the error estimates (50% confidence interval) as dashed lines.

therefore not clear whether they are due to the presence of excess SF_6. We did however calculate the excess SF_6 the same way as for the Irminger Basin and found 0.13 fmol kg^{-1} for the stations at 56°N (the central Labrador Sea), i.e. similar to the mean value for the Irminger Basin. The excess SF_6 then decreases with distance from the Denmark Strait, and at the Grand Banks section there is no longer any trace of excess SF_6 within the analytical precision (the high ratios at low CFC-12 concentration reflects the increased uncertainty of the SF_6 measurements at low concentrations). It thus seems that the pulse of excess SF_6 has reached the central Labrador Sea in 2003, but has barely been exported out of the Labrador Sea. This result is consistent with the propagation time of a salinity anomaly from the Denmark Strait to the Grand Banks of 4 years (2 years to the Labrador Sea), reported by *Stramma et al.* [2004], assuming that the excess SF_6 reached the Denmark Strait in 1999. The dominating sources of error to the excess SF_6 transport estimate are the uncertainty of the time evolution of the tracer and the uncertainty of the DSOW volume transport. Lacking time series of tracer measurements, we assume a constant transport of excess SF_6 from 1999 to 2003 and a constant DSOW flow of 1.7 Sv. Our study sets the upper time limit for the transport from the central Greenland Sea to the Labrador Sea to 7 years, and suggests that roughly 4 ± 1 kg of excess SF_6 has been transported over the Denmark Strait into the Deep Western Boundary Current during the years 1999 to 2003 (~4 years and 1.0 kg y^{-1}). This amount together with the 18 kg excess SF_6 through the Faroe Bank Channel in the same time frame [*Olsson et al.*, 2005b] has to be accounted for when using SF_6 as a transient tracer in the overflow water masses from the Nordic Seas.

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