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Variations of the Faroe Bank Channel overflow

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ABSTRACT

The Faroe Bank Channel is the deepest passage across the Greenland-Scotland Ridge which separates the Arctic Mediterranean from the rest of the World Ocean. Through this channel there is a continuous flow of cold overflow water of major importance for the formation of North Atlantic Deep Water and hence the global thermohaline circulation. Using results from CTD cruises acquired by the Faroese Fisheries Laboratory (Fiskirannsóknarstovan) since the early eighties, we discuss temporal variations of the temperature in the overflow water. We find statistically significant evidence for a reduction in the outflow of the coldest water (< -0.5°C) through the decade 1988-1997. This supports other evidence of changes in deep convection in the Greenland Sea and indicates a major reduction in the total deep-water formation in the Arctic Mediterranean. The reduction of the coldest overflow seems, however, to be compensated by increased overflow of slightly warmer intermediate water. We also report evidence for non-stationary behaviour of the overflow tongue after exiting the channel involving formation of cold boluses and discuss this in relation to observed rapid variations of the extent of the overflow water in the channel.

Keywords: Overflow variations, thermohaline circulation, Faroe Bank Channel, Arctic Mediterranean.

INTRODUCTION

The Faroe Bank Channel is a narrow channel between the Faroe Bank and the Faroe Plateau. In continuation of the Faroe-Shetland Channel, it forms the deepest passage across the Greenland-Scotland Ridge (Fig. 1) and is therefore an important route for the exchange of intermediate and deep water across the ridge.

The oceanic areas north of the Greenland-Scotland Ridge consist of the Nordic Seas (the Norwegian Sea, the Iceland Sea and the Greenland Sea) as well as the Arctic Ocean and are collectively known as the Arctic Mediterranean. The ridge separates this region from the rest of the World Ocean and blocks exchanges below the depth of the Faroe Bank Channel sill at about 840 m. Above this level, Atlantic water flows towards the northeast over the ridge into the Arctic Mediterranean where it is modified by cooling, dilution and freezing. These processes separate the water into two components, a low-salinity surface component which leaves the Arctic Mediterranean in the East Greenland Current and through the Canadian Archipelago, and a more saline component which sinks to intermediate (500 – 1000 m depth) or deep levels and has to pass over the ridge to enter the Atlantic. This deep outflow of cold water is termed “overflow” and has been observed to occur through the Denmark Strait and across the Iceland-Faroe Ridge and the Wyville-Thomson Ridge as well as through the Faroe Bank Channel.

Dedicated to Professor Unnsteinn Stefánsson in honour of his contributions to oceonography and education.

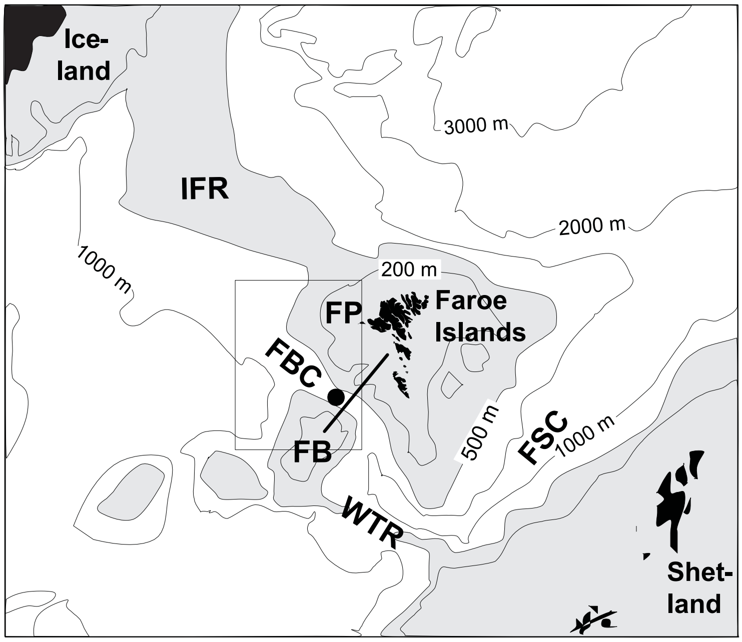

Figure 1. The Faroe Bank Channel (FBC) separates the Faroe Bank (FB) from the Faroe Plateau (FP). It is a continuation of the Faroe-Shetland Channel (FSC). Areas shallower than 500 m are hatched and include the Iceland-Faroe Ridge (IFR) as well as the Wyville Thomson Ridge (WTR). The standard section is shown as a thick line between the Faroe Bank and the Faroe Plateau. The rectangle shows the region studied during cruise 8720 (Fig. 9). The black circle indicates the location of a moored ADCP (Fig. 3) on the sill of the channel.

The observation of cold water at depth between the Faroes and the Faroe Bank is not recent (Knudsen 1911), but the importance of the channel for the global thermohaline circulation was only realized after the seminal paper by Cooper (1955) which has inspired a series of observational (Hermann 1959; Tait 1958, 1961; Crease 1965; Sætre 1967; Borenäs and Lundberg 1988; Saunders 1990, 1992) as well as theoretical (Crease 1965; Rydberg 1980; Borenäs and Lundberg 1988; Johnson and Sanford 1992) studies. These studies all document the persistent occurrence of cold water in the deeper parts of the Faroe Bank Channel, as exemplified by Figure 2. This water flows northwestwards in a strong current with average velocities exceeding 1 m s^{-1} in the core, at about 100 m above the bottom (Fig. 3).

In modern terminology, the cold water in the depths of the Faroe Bank Channel mainly consists of two water masses, Norwegian Sea Deep Water (NSDW) deriving from the depths of the Greenland Sea and the Arctic Ocean (Aagaard *et al*. 1985; Swift and Koltermann 1988) and Norwegian Sea Arctic Intermediate Water (NSAIW; Blindheim and Ådlandsvik 1995) in a fairly even mixture (Fogelquist *et al*. submitted for publication). The flux of overflow water through the Faroe Bank Channel has been estimated by a number of authors (Crease 1965; Borenäs and Lundberg 1988; Saunders 1990; Hansen *et al*. 1998) to be close to 2 Sv (1 Sv = 10^6 m^3 s^{-1}). With the generally accepted number of 5-6 Sv for the total overflow across the Greenland-Scotland Ridge (Dickson and Brown 1994), this implies that the Faroe Bank Channel carries about one third of the total.

In the highly energetic deep overflow, changes occur on a wide range of time scales and this study is an attempt to investigate these variations using CTD observations acquired by the Faroese Fisheries Laboratory since the mid-seventies. A number of studies have indicated long-term changes in the deep-water formation processes of the Arctic Mediterranean (*e.g*. Schlosser *et al*. 1991; Meincke *et al*. 1997) and the primary motive for this study was to check whether the available CTD data gave any indications of such changes. Furthermore, the observations give useful information on the average water mass distribution across the channel as well as on rapid temporal variations.

MATERIAL AND METHODS

The data used in this work was obtained from CTD observations acquired by the Faroese

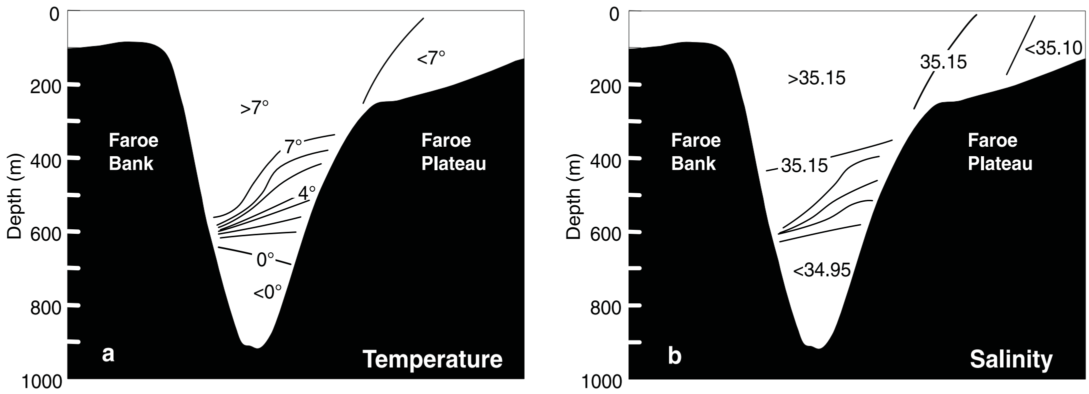

Figure 2. Temperature (a) and salinity (b) on a CTD section acquired in February 1993 by R/V Magnus Heinason. Section location is shown as the line on Figure 1.

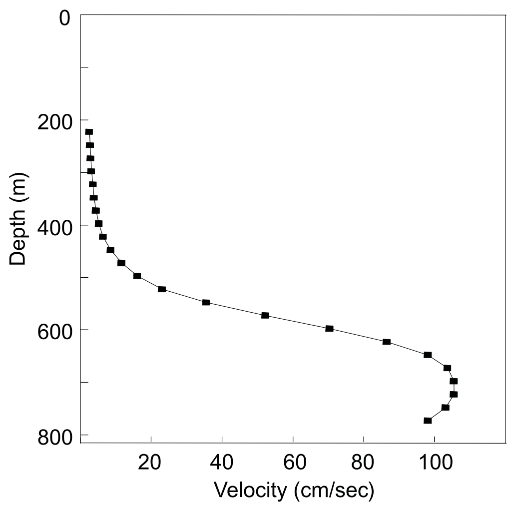

Figure 3. Vectorially averaged current velocity towards 304° from a moored ADCP deployed on the sill of the Faroe Bank Channel from June 1996 to May 1997. From Hansen et al. *(1998).*

research vessel *Magnus Heinason* on 54 cruises in the period 1982-1997. One of these cruises (cruise 8720 in July 1987) was a special survey which included a dense net of stations in the area where the overflow from the Faroe Bank Channel exits the channel. All the other cruises include at least one of a set of standard stations in the channel. The standard section was established in 1988 (Fig. 1) and included nine standard stations crossing the Faroe Bank Channel, four of these with bottom depths of more than 300 m and two stations (V05 and V06) deeper than 700 m.

In Figure 4, these stations are shown together with detailed topography along the section. The standard section is located a few miles southeast of the narrowest cross-section, which is also indicated in Figure 4. For the overflow through

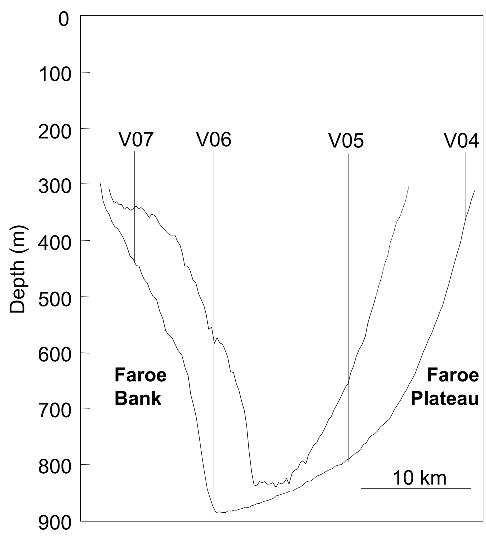

Figure 4. Bottom topography (continuous trace) along the CTD standard section (shown on Figure 1) with the location of four standard stations V04, V05, V06 and V07. Broken line shows bottom topography on a section crossing the channel in the sill area (through the black circle on Figure 1).

TABLE 1

Occupations of standard stations V01 to V09 on cruises that include stations V05 or V06 by R/V Magnus Heinason in the period 1982-1997. Cruises are identified by four-digit cruise numbers.

Cruise *V07*	*Start* *V08*	*End* *V09*	*V01*	*V02*	*V03*	*V04*	*V05*	*V06*		
8202	82/05/05-82/05/05					+				
8407	84/05/12-84/05/12					+		+	+	
8805	88/03/06-88/03/07	+	+	+	+	+	+	+	+	+
8826	88/05/25-88/05/25					+				
8838	88/06/24-88/06/25	+	+	+	+	+	+	+	+	+
8936	89/05/20-89/05/21		+	+	+	+	+	+	+	+
8952	89/07/10-89/07/10	+	+	+	+	+	+	+	+	+
8988	89/11/23-89/11/24	+	+	+	+	+	+	+	+	+
9068	90/08/20-90/08/20	+	+	+	+	+	+	+	+	+
9088	90/11/11-90/11/11	+	+		+	+		+	+	+
9124	91/03/14-91/03/16	+	+	+	+	+	+	+	+	+
9140	91/05/28-91/05/25	+	+	+	+	+	+	+	+	+
9152	91/07/06-91/07/04						+			
9164	91/09/01-91/09/02	+	+	+	+	+	+	+	+	+
9188	91/11/27-91/11/26	+	+	+	+	+	+	+	+	+
9220	92/03/14-92/03/15	+	+	+	+	+	+	+	+	+
9240	92/05/22-92/05/23	+	+	+	+	+	+	+	+	+
9244	92/06/05-92/06/05					+	+			
9256	92/07/24-92/07/24	+	+	+	+	+	+	+	+	+
9272	92/11/04-92/11/03	+	+	+	+	+	+	+	+	+
9312	93/02/08-93/02/08	+	+	+	+	+	+	+	+	+
9340	93/05/17-93/05/17	+	+	+	+	+	+	+	+	+
9344	93/06/09-93/06/15	+	+	+	+	+	+			
9348	93/07/05-93/07/04						+			
9356	93/08/13-93/08/14	+	+	+	+	+	+	+	+	+
9368	93/09/26-93/09/26	+	+	+	+	+	+	+	+	+
9404	94/02/02-94/02/01	+	+	+	+	+	+	+	+	+
9412	94/03/08-94/03/08	+	+	+	+	+	+	+		
9416	94/03/20-94/03/20	+	+	+	+	+	+	+		
9428	94/04/10-94/04/11				+	+				
9432	94/04/26-94/04/26				+	+				
9436	94/04/29-94/04/30	+	+	+	+	+	+	+	+	+
9440	94/05/18-94/05/17	+	+	+	+	+	+	+	+	+
9452	94/07/02-94/07/03				+	+	+			
9464	94/08/19-94/08/20	+	+	+	+	+	+	+	+	+
9484	94/10/24-94/10/25	+	+	+	+	+	+	+	+	+
9508	95/02/18-95/02/19	+	+	+	+	+	+	+	+	+
9532	95/05/05-95/05/07						+			
9568	95/11/12-95/11/11					+	+			
9608	96/02/18-96/02/19	+	+	+	+	+	+	+	+	+
9620	96/03/28-96/03/26						+			
9632	96/05/05-96/05/05	+	+	+	+	+	+	+	+	+
9648	96/07/02-96/06/30	+	+	+	+	+	+	+		
9660	96/09/03-96/09/02	+	+	+	+	+	+	+	+	+
9668	96/09/06-96/09/08					+				
9688	96/11/10-96/11/09	+	+	+	+	+	+	+	+	+
9708	97/02/13-97/02/14	+	+	+	+	+	+	+	+	+
9724	97/04/06-97/04/07	+	+	+	+	+	+	+	+	
9740	97/05/24-97/05/25	+	+	+	+	+	+	+	+	+
9748	97/06/16-97/06/16	+	+	+	+	+	+	+	+	+
9752	97/06/30-97/06/28						+			
9764	97/09/02-97/09/01	+	+	+	+	+	+	+	+	+
9792	97/11/06-97/11/07	+		+	+	+	+	+	+	+

the channel, the two stations V05 and V06 are of most interest and Table 1 lists all cruises which include either of these stations. Most of the cruises are from the 1988-1997 period, when regular occupation of the standard section has been carried out. However, we also include two previous cruises with observations at V05.

Observations have been made using two different Neil Brown Mark III CTD's, an E.G.&G. Mark V CTD and two different Seabird 911+ CTD's. In later years, water has been sampled on each profile for onshore salinity calibration. Earlier observations have less accurate salinities, but in this work we only use salinity peripherally.

RESULTS FROM STANDARD STATIONS

A noteworthy feature of Figure 2 is the pinching of isolines on the Faroe Bank side of the channel. This is typical as documented in Figure 5, which shows the average temperature distribution across the channel based upon 37 cruises from Table 1 which included observations on the four deepest standard stations. On the average, the vertical distance between two isotherms increases northeastwards and Figure 6 shows the vertical distance between the 5°C and the 0°C

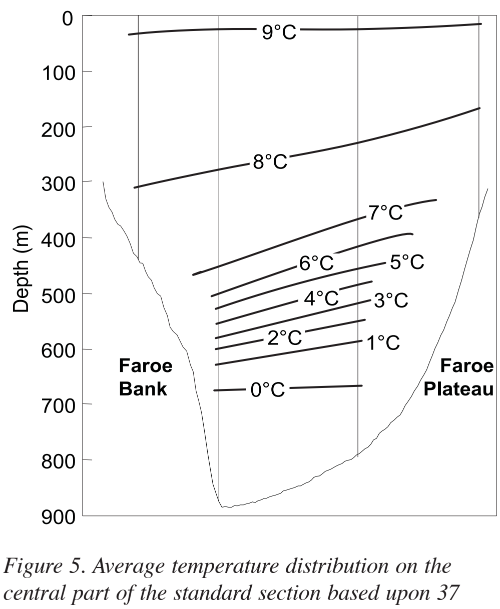

Figure 5. Average temperature distribution on the central part of the standard section based upon 37 cruises (Table 1).

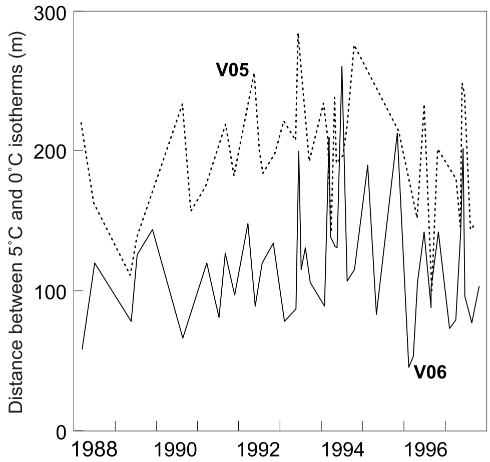

Figure 6. The vertical distance between the 5°C isotherm and the 0°C isotherm at standard stations V05 and V06 (Fig. 4) respectively as observed in the period 1988-1997.

isotherms at station V05 and V06, respectively, using observations from the 1988-1997 period. With one exception, the distance was consistently higher at V05 (average distance 193 m) than at V06 (average distance 118 m). This is also reflected in the slope of the isolines as demonstrated in Table 2. On the average, the 5°C isotherm was 77 m deeper at V06 than at V05, but for the 0°C isotherm the average depth difference between V05 and V06 had been reduced to 6 m.

To illustrate the temporal change of temperature, Figure 7 shows the depth of three different isotherms at V06, plotted against time for the 1988-1997 period. The 3°C isotherm does not exhibit any obvious trend, the 0°C isotherm has perhaps a slight increase during the period, while the -0.5°C isotherm seems to have an increasing trend. These conclusions are verified in Table 3 which lists average depths of the isotherms at V05 and V06 at different times. For water at 0°C and warmer, the isotherms do not show any significant change between the two five-year periods, but the -0.5°C isotherm at V06 descended by 62 m and a statistical test (t-test) indicated that this change was significant at the 0.01 level. A different way to consider this change is by a regression analysis of the depth of the isotherm versus time. This analysis indi-

TABLE 2

Difference in average depth of various isotherms between standard stations V05 and V06 (V06 - V05) for the period 1982-1997.

Isotherm:	5°C	4°C	3°C	2°C	1°C	0°C
Depth:	77 m	64 m	54 m	38 m	25 m	6 m

TABLE 3

Depths of various isotherms (in meters) at stations V05 and V06 for two cruises in 1982 and 1984 and for two five-year periods as well as the difference between the two five-year periods ("Change"). For the five-year periods depths are reported as average ± standard error (number of values). !! indicates that the change from the 1988-1992 period to the 1993-1997 period was statistically significant at the 0.01 level.

Station	*Period*	*5°C*	*4°C*	*3°C*	*2°C*	*1°C*	*0°C*	*-0.5°C*
V05	May 1982	390	436	456	480	527	624	686
V05	May 1984	410	446	488	528	540	624	
V05	1988-1992	464±11(17)	490±12(17)	519±12(17)	554±11(17)	586±11(16)	641±11(14)	
V05	1993-1997	454±8 (28)	483±8 (28)	509±8 (28)	542±9 (28)	581±8 (27)	650±10(25)	
V05	Change	-10	-7	-10	-12	-5	+9	
V06	1988-1992	538±12(15)	553±13(15)	571±14(15)	587±14(15)	610±14(15)	645±13(15)	681±21(8)
V06	1993-1997	533±9 (31)	548±8 (31)	564±8 (31)	582±8 (31)	606±8 (31)	657±8 (31)	743±14(12)
V06	Change	-5	-5	-7	-5	-4	+12	+62 !!

cated an annual depth increase of the -0.5°C isotherm by 10 m with a standard error of 3 m, which again is significantly different from zero. At station V05 this isotherm was not sampled sufficiently often to allow a comparison between the five-year periods.

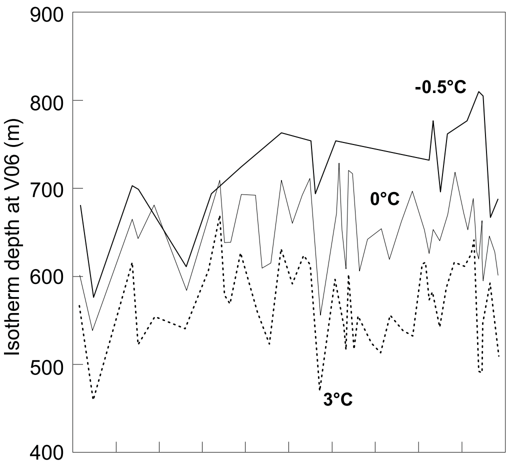

Figure 7. The depth of three different isotherms at standard station V06 (Fig. 4) as observed in the period 1988-1997. The coldest isotherms have not been sampled on all of the cruises.

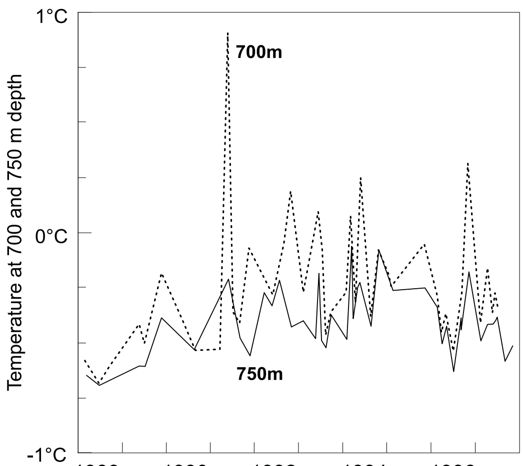

Figure 8. Temperature at two different depths on standard station V06 (Fig. 4) as observed in the period 1988-1997.

TABLE 4.

Temperature at fixed depths at station V05 and V06 for two cruises in 1982 and 1984 and averaged over two different five-year periods.For the five-year periods temperatures are reported as average ± standard error (number of values). ! indicates that the change from the 1988-1992 period to the 1993-1997 period is statistically significant at the 0.05 level.

Period	*Temperature at 700 m on V05*	*Temperature at 700 m on V06*	*Temperature at 750 m on V06*
May 1982	-0.581		
May 1984	-0.274		
1988-1992	-0.164±0.082 (14)	-0.264±0.101 (15)	-0.459±0.046 (13)
1993-1997	-0.082±0.088 (27)	-0.229±0.044 (30)	-0.379±0.026 (29)
Change	+0.082	+0.035	+0.080 !

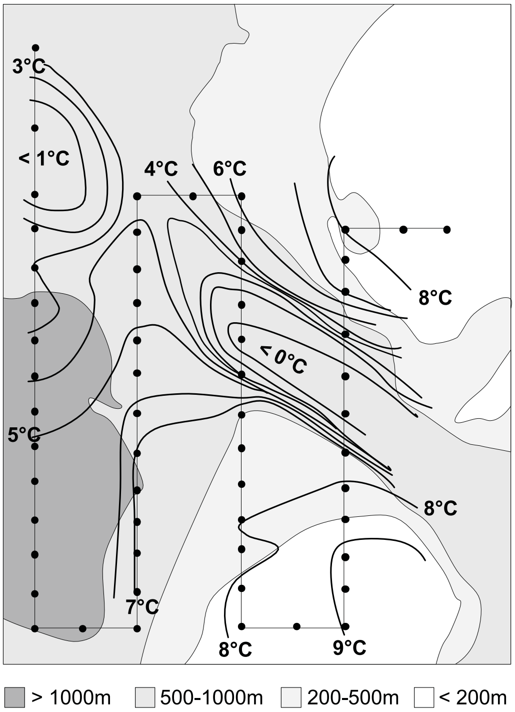

Figure 9. Temperature 50 m above bottom in the exit area of the Faroe Bank Channel overflow as observed by R/V Magnus Heinason *in July 1987. The area is shown as a rectangle on Figure 1. Black circles on thin line show CTD stations and cruise track. Bottom depth is indicated by hatching.*

A deepening of isotherms implies increased temperatures at fixed depths, and Figure 8 does indeed indicate a trend of this nature, both at 700 m and 750 m for station V06. In Table 4, the two five-year periods, 1988-1992 and 1993-1997 are again compared. Average temperatures were higher in the later period for 700 m at both V05 and V06 and for 750 m at V06, but only this last difference was found to be significant (at the 0.05 level). A regression analysis for this series gave an annual temperature increase at 750 m depth on V06 equal to 0.013 °C (with a standard error of 0.009°C).

RESULTS FROM SPECIAL SURVEY

The results from cruise 8720 in July 1987 allow a fairly detailed mapping of the overflow water in the area where it exits the Faroe Bank Channel. Figure 9 shows the temperature 50 meters above bottom in this area together with a detailed bottom topography. It is noted that the coldest water 50 m above bottom on the western boundary of the observational area did not fall below 0°C as compared to the Faroe Bank Channel itself where the deepest 50 meters always have been found to be below this value (Fig. 7). This indicates strong mixing of the overflow water in the area and is consistent with the observation by many authors that a pure form of the overflow water occurs only in the channel proper.

Furthermore, the cold bolus (< 1°C) observed on the western boundary of the observational area does not appear to have been connected to the overflow water on the Faroe Bank. With a stationary flow pattern, temperatures should increase with distance from the channel since the surrounding waters are much warmer. Disconnected cold boluses therefore indicate non-stationarity. The observations shown in Figure 9 were acquired during a period of two days and are not completely synoptic. However, that does not affect this conclusion since a stationary flow would appear the same on a synoptic and a non-synoptic survey. The most obvious interpretation is that the overflow current pulses and may release boluses of cold water which propagate away from the channel and are subject to intense mixing.

DISCUSSION

The statistically significant deepening of the -0.5°C isotherm indicates that the coldest part of the overflow water in the Faroe Bank Channel decreased in extent during the decade 1988 - 1997, especially in the first part of the period. Naturally, this conclusion requires comparable sampling throughout the period and positioning error is the most obvious candidate for a bias. However, with the introduction of GPS positioning accuracy has become better since the late eighties, and even the early cruises relied on LORAN C which was quite stable in Faroese waters. A check is provided by the observed bottom depth at the stations. Comparing bottom depths for stations on which the -0.5°C isotherm could be observed, the difference of the average for the two five-year periods was only 5 m.

Therefore, there appears to be no reason for assuming a systematic bias due to different positions in the two five-year periods. However, since there were only 8 observations of this isotherm in the first five-year period and 12 in the second, even the result of a statistical test must be questioned. Considering the two early occupations of V05, in 1982 and 1984 respectively, increases the significance somewhat since on both these occasions the 0°C isotherm and the -0.5°C isotherm were observed to be shallower or at the same level as the average for the first period.

Although not conclusive, there is therefore a case for a decreased extent of water colder than -0.5°C in the Faroe Bank Channel, taking place from the late 1980s to the mid-1990s, especially in the first part of that period. There is also some indication that the reduction may encompass water up to the 0°C isotherm, although to a smaller degree. The -0.5°C isotherm is commonly used as reference for the upper boundary of the Norwegian Sea Deep Water (NSDW) and we conclude that the influence of NSDW in the Faroe Bank Channel decreased from 1988 to 1997.

This conclusion is not unexpected. A number of studies have indicated a reduction of deep convection in the Greenland Sea (*e.g.* Schlosser *et al.* 1991; Meincke *et al.* 1997). Other deep-water formation processes might have compensated for this, but changes have been observed in the depths of the Norwegian Sea which are consistent with a reduced input of deep water (Østerhus *et al.* 1996). A similar conclusion may be drawn from an observed freshening in the Faroe-Shetland Channel by Turrell *et al.* (1999), who conclude that a change has occurred in the composition of the deep waters of the Faroe-Shetland Channel, *i.e.* that the percentage content of NSDW decreased from being 60% in the period 1970-1985 to 40% after 1990.

In the simplest terms, the deep water formation creates a density distribution at depth in the Arctic Mediterranean which drives a flow towards and through the Faroe Bank Channel. A reduced production of deep water should result in a deepening of the upper boundary of the deep water as long as it is above sill level in the channel. Using the velocity profile in Figure 3 and an average temperature profile (Fig. 5), we estimate a flux of about 1 Sv of water colder than -0.5°C through the Faroe Bank Channel. In the extreme case of a total production stop of this water, a continued overflow of this magnitude would be expected to deepen the -0.5°C isotherm by about 5 m per year if the deepening occurred at the same rate all over the Arctic Mediterranean (6 million km^2 at the sill level of the Faroe Bank Channel).

Naturally, the assumption of synchronous deepening throughout the Arctic Mediterranean is not realistic, since the major deep water production sites are far away from the Faroe Bank Channel and a considerable time lag must be expected, especially since the deepest water has to pass through narrow channels to move from one basin to another. Therefore, changes in deep water production rate may be assumed to first affect the height of the deep water boundary only close to the production areas. In the Faroe Bank Channel, a delayed response can be expected, but when it occurs the annual deepen-

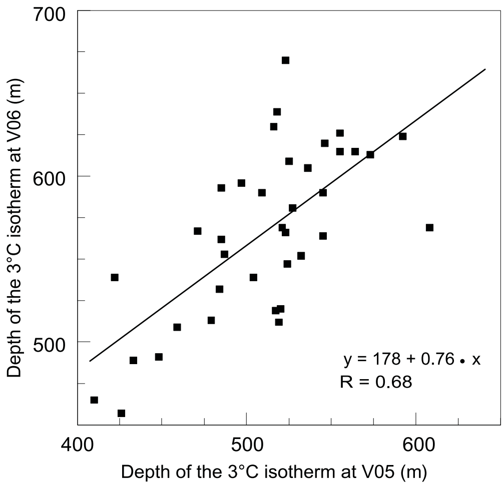

Figure 10. The depth of the 3°C isotherm at standard stations V05 and V06 (Fig. 4) plotted against one another. The line shows a linear regression fit with equation and correlation coefficient indicated.

ing rate may be expected to occur more rapidly than with a homogeneous response of the whole Arctic Mediterranean. This can perhaps explain the fact that our observed deepening of the -0.5°C isotherm is twice as large as could be expected from a total production stop with the assumption of synchronous deepening.

Our observations are thus consistent with a more or less total production stop of the coldest water, but this reduction does not seem to encompass all the overflow water. The interface between the overflow water and the upper water in the Faroe Bank Channel may be defined by the 3°C isotherm which is approximately mid-way in temperature between the coldest bottom water and the Atlantic water above it. Table 3 does not indicate any significant change in the depth of this interface through the 1988-1997 period. This implies that the reduction in the coldest component has to some extent been compensated by increased production of intermediate water.

In addition to long-term variations, Figures 6-8 demonstrate more rapid variations of fairly large amplitudes. The irregular sampling does not allow a detailed analysis, but it seems clear that time-scales down to weeks or even days are important. Although CTD observations do give some insights by themselves, a combination of CTD observations and results from moored equipment (Fig. 3) in a future study will be necessary to more fully understand these variations.

Thus, Figure 10 shows a fairly high and positive correlation between the vertical movements of the 3°C isotherm at the two deep stations V05 and V06 on either side of the channel. This indicates that the variations are not due to waves or other disturbances propagating across the channel. Rather, the whole upper boundary of the overflow water moves up and down in a synchronous manner. The amplitude of these movements seems to be smaller by a factor of 0.76 at V06 as compared to V05. Since the isotherms are closer to one another at V06 than at V05, this is not unexpected.

It is tempting to link these rapid variations to the observations shown in Figure 9. The non-stationary behaviour, implicit in that figure, may be expected to extend some distance into the channel and this may be expected to involve vertical movement of the upper boundary of the overflow water as boluses are formed and released from the overflow tongue. Whether this process is sufficient to explain the rapid isotherm movements in the channel is a question which cannot, however, be resolved by the material presented here and will have to await a more comprehensive study.

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