



## THOR Deliverable D08

Deliverable description:		Summary data set for historical overflow entrainment studies			
WP No.	3.3	Lead Beneficiary:	FMI		
WP Title	Process studies				
Work duration <sup>1)</sup>	1-12	Delivery deadline <sup>2)</sup> :	2009-11-30	Delivery date:	2009-12-16

<sup>1)</sup> Work duration = project month

<sup>2)</sup> Delivery deadline: as contracted in Description of Work (Annex 1 to Grant Contract)

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## 1. Executive Summary

During the first 12 months of THOR the work in WP 3.3 has been concentrated on exploring different aspects of the entrainment into the overflow plumes.

1) The literature on the Greenland-Scotland overflow has been studied with focus upon the entrainment, the strength as well as the mechanisms of the entrainment and some relevant experiments have been examined in detail. This has been done by partner 22 (FMI).

2) The time series from the current meter array at Angmassalik is being prepared for studying the time variability of the overflow plume and relate it to the entrainment rate. More than 10 years of velocity, temperature and salinity data are available. This is done by partner 15 (CEFAS).

3) The CTD sections taken across the Greenland continental slope during the yearly VEINS and ASOF cruises are re-examined and studied for determining the spatial as well as the temporal variations of the entrainment from downstream changes of the overflow plume throughout the years. This work is done by partner 22 (FMI).

4) A field experiment to study the entrainment by directly observe the turbulence in the overflow plume and at the interface between the overflow plume and the ambient waters in Denmark Strait using measurements from a free falling microstructure sonde as well as ctd and LADCP observations. This experiment was carried out by partners 1 & 22 (UHAM & FMI/SIO). Partner 1 & 22 also participated 2008 in a pre-THOR cruise arranged by the University of Bergen to the Faroe Bank Channel to study the entrainment in the Faroe Bank overflow by direct turbulence measurements.

The main results from the literature study are that much has been done already and that improved future estimates of the entrainment could involve a reduction of 25% of the presently assumed entrainment rate indicating that the present ThermoHaline Overturning Circulation could be overestimated by 10%. To find out whether this is true is the next goal of the work package.

## 2. Main objectives, description of work and role of participants (Annex I: DoW)

### Objectives

- To increase our understanding of the processes that entrain ambient water into the overflows of the Greenland-Scotland Ridge(at the Faroe Bank Channel (FBC) and at Denmark Strait (DS) and to quantify their contribution to the THC
- To provide a better understanding of the shunting of freshwater in the East Icelandic Current (EIC) back into the Nordic Seas and quantify the variations in this process

### Description of work and role of participants

This Work Package involves two different types of processes, which will be studied in two different tasks:

#### Task 3.3.1 Entrainment of ambient waters into the overflows

- In the entrainment area downstream of the FBC, moorings will be deployed for a few months preceding a dedicated cruise to the area, in which CTD and turbulence measurements will be carried out to study the entrainment processes [UiB, FFL, UHAM]
- Instrumentation will be deployed in the entrainment area downstream of the DS and two cruises are planned to study entrainment in this region with CTD and turbulence measurements [FIMR, UHAM, CEFAS]
- The mooring array across the overflow off Angmagssalik will be maintained through the field phase of the project [UHAM, FIMR, CEFAS]

#### Task 3.3.2 Fresh water transport north of Iceland

- A mooring will be deployed in the EIC and CTD sections will be occupied to study freshwater transports in the EIC [MRI]

## 3. Report on Deliverable D08

### Overflow and entrainment – a literature review

## **Introduction**

The importance of the Arctic Mediterranean Sea for the Atlantic thermohaline overturning circulation was slow in being established. Although it was known early last century (Nansen, 1912) that dense water from the Norwegian Sea was present in the Northeast Atlantic south of the Iceland-Scotland Ridge, it was considered of little importance. In fact, the mass balance for the Arctic Mediterranean presented in the Oceans (Sverdrup et al., 1942) the Arctic Mediterranean is considered to have a fjord like circulation and all Atlantic water that crosses the Greenland-Scotland Ridge northward is assumed to return as less dense upper layer water in the East Greenland Current. The main formation area for the North Atlantic Deep Water (NADW) was assumed located south of Greenland, at the border between the Irminger and the Labrador seas. The importance of the dense overflows from the Arctic Mediterranean became appreciated during the 1950s and 1960s and estimates for the overflows in the Faroe Bank Channel (e.g. Herman, 1967) and the Denmark Strait were given (e.g. Worthington, 1969; Worthington, 1970), and the ICES Overflow 1973 experiment provided a comprehensive overview of the contributions from the Nordic Seas/the Arctic Mediterranean to the Atlantic Thermohaline Overturning Circulation (Doley and Meincke, 1981; Meincke, 1983; Ross, 1984). Three major pathways were identified, the concentrated overflows in the Faroe Bank Channel and in Denmark Strait and a somewhat weaker, more diffuse overflow across the Iceland-Faroe part of the Greenland-Scotland Ridge. In addition a fourth, smaller overflow was known to take place across the Wyville-Thomson Ridge east of the Faroe Bank (Ellett and Roberts, 1973). These studies also revealed that the characteristics of the overflows changed considerably during their descent from the sills in the Greenland-Scotland Ridge. This implies that the overflows do not just provide the dense water from north of Greenland-Scotland Ridge but also, by entrainment, bring warmer, less dense upper waters from south of the ridge into the deep thus further strengthening the production of North Atlantic Deep Water and the lower limb of the Thermohaline Overturning Circulation. In his extensive summary of the North Atlantic Circulation Worthington (1976) estimated an overflow of 1 Sv through the Faroe Bank Channel and 1 Sv between the Faroes and Iceland and 4 Sv in Denmark Strait. In addition he assumed a total entrainment of 3 Sv for the overflows east of Iceland but a weaker entrainment of 1 Sv for the Denmark Strait overflow. These overall estimates have more or less been confirmed by later more detailed observations during the intervening 30 years. The overflows are presently considered more evenly distributed, with 3 Sv occurring east of Iceland, perhaps slightly

more if the Wyville-Thomson overflow is considered, and 3 Sv, perhaps slightly less, in Denmark Strait west of Iceland. The total entrainment is usually given as 6 Sv and assumed evenly distributed east and west of Iceland (e.g. Dickson and Brown, 1994).

The process modelling of the overflow has generally followed two paths. 1) The formulation and use of streamtube models, which concentrate on the descent of the overflow plume and the evolution of the plume characteristics (e.g. Smith, 1975; Price and Baringer, 1994), and 2) the study of the overflow rate, using the assumption of hydraulic or rotational hydraulic flow with a critical control section at or slightly beyond the sill (e.g. Whitehead et al., 1974). An extension of the hydraulic approach from zero to constant, but finite, vorticity was made by Gill (1977). The hydraulic models describe the strength and path of the overflows but normally do not address the question of entrainment and downstream evolution of the plume characteristics. The Denmark Strait overflow differs from the overflows east of Iceland in that not only dense water but also intermediate and less dense water in the East Greenland Current cross the sill and only the denser fractions descend the continental slope into the deep Irminger Basin. It has been proposed that the sinking of the plume involves a stretching of the water column and leads to eddy formation (Spall and Price, 1998), which might be detected at the sea surface (Bruce, 1995).

During the last 10 years more extensive field campaigns to study the nature of the overflows in the Denmark Strait (Girton, 2001; Girton and Sanford, 2003) and in the Faroe-Shetland and in the Faroe Bank Channel (Mauritzen et al., 2005) have been undertaken. In these experiments, in addition to CTD measurements, water sampling and moored current meter observations, XCPs (expendable current profilers) and ship borne and lowered ADCPs have been used. These studies have revealed important details of the overflows, which are summarised below.

### *The Faroe-Shetland overflow*

In the Faroe Shetland Channel Mauritzen et al. (2005) found during a five weeks cruise in 2000 with RV Discovery that a considerable mixing and homogenisation of the overflow water occurred already in the Wyville-Thomson Basin upstream of the sill in the Faroe Bank Channel. This mixing removed the water from the densest water class and was attributed to turbulence generated by strong bottom stress. The mixing at the sill had similar strength but the most enhanced mixing occurred downstream of the sill, where the overflow plume

accelerated due to an increase in bottom slope and descended from 800m to 1200m (average depth) and became spread over a larger depth range. The temperature increased from below 0°C to above 3°C, indicating substantial entrainment of ambient water. As the plume reached beyond 1200m depth the changes in the overflow characteristics became smaller due to smaller difference in properties between the overflow water and the ambient water column. The overflow plume had already here almost the characteristics of the Iceland-Scotland Overflow Water (ISOW) that is carried to the southern Northeast Atlantic and through Gibbs Fracture Zone into the Irminger Sea and the Northwest Atlantic.

### *The Denmark Strait*

A similar study was carried out in the Denmark Strait in 1997 and 1998 from RV Aranda and RV Poseidon using CTD observations, ship borne and bottom mounted ADCPs and XCP (Girton, 2001; Girton and Sanford, 2003). The observations showed, as did the Faroe Bank Channel experiment, that the short period measurements of the overflow agreed well with the estimates obtained from the bottom mounted moorings (ADCPs) at the sill and the conventional current observations at the Angmassalik array. The path of the overflow shifted south of the sill from being strongest on the Iceland side to following the Greenland continental slope, in agreement with the theory for channel flows crossing a ridge (Gill, 1977). Also here an acceleration of the overflow took place about 150km downstream due to the increasing slope of the passage. This was also the region, where changes in the plume characteristics became noticeable.

The Denmark Strait overflow is initially stratified, more strongly than the Faroe Bank overflow, where only a thin intermediate layer of higher temperatures is found in the upper part of the overflow waters. The upper part in the Denmark Strait overflow plume comprises a less saline and (initially) colder lid of Polar Water, which lies above a warmer layer of Recirculating and/or Arctic Atlantic Water (Rudels et al., 1999). The deepest and densest part of the plume is colder and occasionally less saline than the Atlantic contribution. The front between the southward flowing water and the warmer water of the Irminger Current, moving northward in the strait, is vertical, not horizontal as in the Faroe-Shetland Channel, and lateral mixing and interaction between the two water columns take place. The presence and persistence of the low salinity lid during the upper part of the descent indicate that little ambient water is being entrained through the interface. As the plume sinks the temperature minimum disappears rapidly but the salinity minimum remains, suggesting the possibility of

internal mixing within the plume and a gradual merging of the two upper layers of the plume (Rudels et al., 1999). When the plume has descended deeper than 1000m an increase in temperature and a decrease in density take place and at the Angmassalik the minimum temperature has increased from below 0°C to about or above 1°C and the highest density has been reduced to less than 28. However, these changes and this mixing occur so deep that the ambient waters, which become entrained into the plume, are no longer water of the warm water sphere being transferred to the lower limb of the ThermoHaline Overturning Circulation (THC). These waters are already part of the lower return limb and therefore do not add to the strength of the overturning circulation and to the production of North Atlantic Deep Water (NADW).

This then implies that the contribution of the Denmark Strait Overflow plus entrainment to the MOC might only be between 3 and 4 Sv rather than the 3+3 Sv, which is commonly suggested and accepted (e.g. Dickson and Brown, 1994). This means a reduction of the entrainment of 25% and a total reduction of the MOC by 10%. Water, which, if the current estimate of the strength of the MOC is valid, must be supplied from other sources.

This interpretation is primarily based on studies of the TS properties of the Denmark Strait overflow plume and not on direct studies of the entrainment and mixing into the plume. What are the processes dominating the entrainment and volume increase of the Denmark Strait Overflow Water? Are they created by bottom stress, by interfacial instabilities or are they dominated by lateral exchanges with eddies bringing water into and out of the plume? The presence of eddies has been noticed in the numerical modelling of the overflow plume (Käse et al., 2003), and in a study of the temperature changes observed in the overflow plume based on data from the moored current meter array Voet (2007), Voet and Quadfasel (2010), has shown that the lateral eddy exchanges of heat between the plume and its surrounding are into the plume and occur both from shallower and deeper part of the continental slope. The plume gains in heat while the ambient waters deeper in the basin but also higher up on the slope lose heat.

### **Field studies of turbulence and entrainment**

#### *Experiments in the eastern overflow area*

To further study the importance of entrainment of warmer, less dense water from the upper to the lower limb of the THOC a twofold approach has been planned. 1) A detailed study of the turbulence and entrainment processes in the overflow plume by direct observations of the microstructure and the turbulent dissipation rates using a freefalling microstructure sonde combined with CTD and LADCP observations. 2) Observing the upstream conditions of the overflow waters to determine the characteristics of the water masses contributing to the overflow and assessing their origin and their variability. Without this information entrainment estimates based on downstream water mass characteristics will amount to little more than guesswork.

A field experiment similar to that planned for the Denmark Strait overflow has recently been performed in the Faroe Bank Channel by Ilker Fer from Geophysical Institute in Bergen (Fer et al., 2010). In May-June 2008 RV Håkon Mosby conducted a two weeks survey in and beyond the Faroe Bank Channel. In addition to CTD and LADCP observations also microstructure and turbulence measurements were made using a freefalling (loosely tethered) microstructure sonde. More than 60CTD/LADCP stations and 90 microstructure casts were taken in and beyond the Faroe Bank Channel. The station positions were chosen so that the station pattern of the Discovery cruise in 2000 (Mauritzen et al., 2005) was largely repeated. The major finding agreed with those reported by Mauritzen et al. (2005). The strongest mixing and entrainment took place about 80 km downstream of the sill. There were also indications that the flow was critical at this position downstream of the sill. This agrees with suggestion made by Girton et al. (2006) that a control section was located 20-90 km beyond the sill in the Faroe Bank Channel.

Two parts of the overflow plume showed high turbulent activity. One was located close to the bottom, where the turbulence generated by the bottom stress in the logarithmic constant stress layer was maintained at a high level. The second region was at the interface between the overflow plume and the ambient water, where the shear was strong enough to keep the Richardson number low, occasionally below  $\frac{1}{4}$  suggesting instability and the formation of Kelvin-Helmholtz billows. By contrast the high velocity core in the central part of the plume was characterised by low turbulence levels. This distribution of the turbulence also suggested strong transverse circulation in the plume with a flow to the right, looking downstream, at the interface and an Ekman driven flow to the left in the bottom layer. A similar secondary flow was also noted by Johnson and Sanford (1992) and Mauritzen et al.

(2005) The flow to the right at the interface is most likely in geostrophic balance and caused by the downward downstream slope of the plume. This transverse circulation may be instrumental in the lateral spreading of the plume and also in the exchange of buoyancy from the ambient water and the interface to the well-mixed bottom layer (Fer et al., submitted).

Earlier, in June 2007, another experiment was conducted in the Wyville-Thomson Basin with a similar approach (Venerable & Sherwin, pers. comm., 2009). This experiment concentrated on the upstream mixing of the overflow water and how it becomes transformed before it passes through the Faroe Bank Channel or crosses the Wyville-Thomson Ridge. Such mixing of the overflow water, mostly internal but perhaps also involving some entrainment, was discussed by Mauritzen et al. (2005). This time XCP observations were replaced by LADCP and microstructure measurements. From the observed high turbulent dissipation rates strong mixing was inferred. The high dissipation rates were located at the interface between the overflow water and the overlying, warmer Atlantic water. Observations from moored instruments showed semi-diurnal variation in depth of the interface of 100m suggesting that resonant tidal motions could, by interaction with the topography, generate internal tides that subsequently break and release energy to maintain the observed high turbulence level.

#### *The THOR experiment in Denmark Strait*

In May-June 2009 a similar turbulence study was carried out within the THOR project in the south of Denmark Strait with RV Maria S. Merian. Because of the deeper path of the plume and the larger distance between the sea surface and the plume a different approach was followed. Using a design developed by the Shirshov Institute of Oceanology for the THOR project the microstructure measurements were concentrated to the lower, overflow dominated, part of the water column. The microstructure sonde was initially attached to the CTD/Rosette and when the deepest observation had been made the rosette was raised to 300m above the bottom and the microstructure sonde was released and sank towards the bottom, while the Rosette was hanging still. When the time estimated for microstructure profile had passed the whole package was brought back onboard. Apart from reducing the observation time and the lateral drift of the microstructure profiler during its descent, this also allowed for small differences in time and space between the CTD/LADCP observations and the microstructure measurements.

The Denmark Strait overflow is less confined than the Faroe Bank overflow and the obtained sections did not show a transverse circulation pattern similar to that found at the Faroe Bank Channel. It rather indicated the absence and presence of the overflow plume. This could be due to the variability of the overflow at the sill (Girton and Sanford, 2003), but also could be caused by meandering of the overflow plume. The preliminary results from the measurements, however, show similar structure of the distribution of the turbulence as for the Faroe Bank overflow with two regions with strong turbulence, close to the bottom and at the interface, with a more quiet layer in between. The Richardson number at the interface was low and at times even below  $\frac{1}{4}$  suggesting that instabilities were possible. The analyses of the observations have barely begun and will be continued.

### **Preparatory work on existing data**

In addition to the review of earlier studies of entrainments and overflows a preparation of the existing data in the Denmark Strait overflow area will be undertaken. Two major data sources will be examined.

- 1) The time series from the mooring array at Angmassalik, which give more than 10 years of velocity, temperature and salinity data from the array. The preparation of the data for this has started but has not yet been finalised. CEFAS (partner 15) is responsible for this work.
- 2) The CTD section available from the VEINS and ASOF programme as well as later sections and the WOCE section going across the Irminger Sea from Greenland to Ireland will be examined and the water mass transformations will be studied. The work has already started at FMI (partner 22).

Furthermore, large efforts will be put into obtaining CTD observations north of the sill to determine the characteristics of the water masses contributing to the overflow, their sources and variability. This work should be done by partner 13 (MRI) and partner 22 (FMI).

### **Future work**

The continued study of the entrainment processes will be concentrated on the Denmark Strait overflow and it will, in addition to direct microstructure and turbulence observations that are to be repeated in 2010, also involve a thorough analysis of the upstream water

masses contributing to the overflow and their variability. The downstream development of the overflow plume along the Greenland continental slope will be estimate from the different CTD sections and from the temporal and spatial variability observed at the Angmassalik array. The possibility of detrainment of overflow water from the plume will be examined and the effects of cold, dense water, initially separated from the main overflow at the sill but later descending down the Greenland slope south of Denmark Strait, on the characteristics of the warm southward flowing Irminger Current will be investigated.

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## 4. List of Publications

### Peer reviewed articles:

- Paka, V.T., Rudels, B, Quadfasel, D and Zhurbas, V. (2009) Measuring of turbulence in a strong near bottom current of the Denmark Strait. Doklady RAS, Earth Science (in Russian)
- Voet, G. & Quadfasel, D., (2010), Entrainment in the Denmark Strait overflow plume by meso-scale eddies (submitted to Ocean Science)

Fer, I., Voet, G., Seim, K.M. Rudels, B. and Latarius, K. (2010) Intense mixing of the Faroe Bank Channel Overflow (submitted to Geophys. Res. Lett.)

**Plan for future publication:**

No plan yet.

**5. The project / deliverable is delayed:  Yes  No**

Late start in working up the data from the Angmassalik array and from the ctd sections at the Greenland continental slope.

**6. Changes made and difficulties encountered, if any**

No.

**7. Efforts for the deliverable D08**

Approximate values

Institute	Person-Months	Period
UHAM	1	12.2008-11.2009
FMI	4	12.2008-11.2009
SIO	8	12.2008-11.2009
CEFAS	1	12.2008-11.2009

**8. Sustainability**

No input yet