Circulation and exchange of water masses on the Faroe Shelf and the impact on the Shelf ecosystem

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Dissertation for the Degree of Philosophiae Doctor (PhD)

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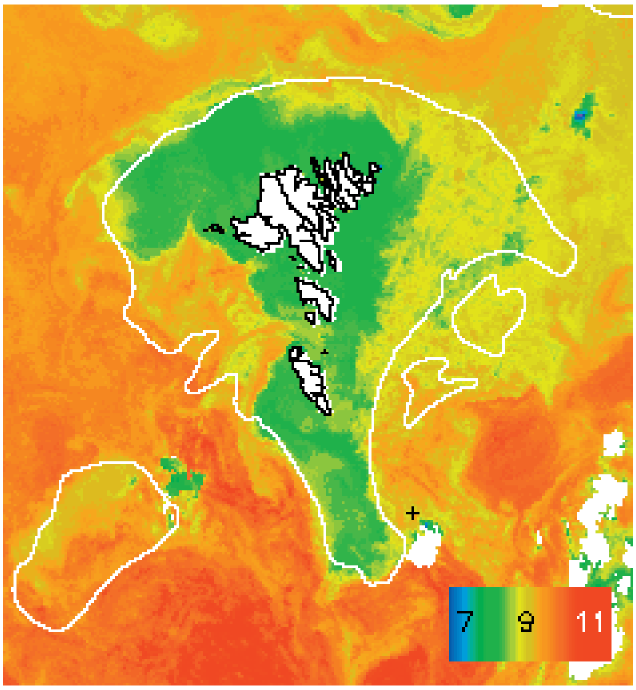

by

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Dissertation for the degree of philosophiae doctor (PhD)
Tórshavn, 2008

University in Bergen   Faroese Fisheries Laboratory

Photo on inside front page: Satellite sea surface temperature on 18. April 2003.
Courtesy of Dr. Peter Miller at Plymouth Marine Laboratory.

Dedicated to the memory of my brother:

J. Hendrik Húsgarð
* 11. September 1965
† 1. December 2007

Preface

This work has been carried out at the Faroese Fisheries Laboratory in Tórshavn, Faroe Islands and constitutes the dissertation for the degree of philosophiae doctor (PhD) in physical oceanography at the Geophysical Institute, University of Bergen, Norway where also a part of the training component was carried out.

In Part I of this synthesis, an introduction is first given in order to present a description of the study area and explain the objectives of the study. This is followed by a description of the material and methods. The results from four papers and discussion thereof are merged in section 3. Finally, the major findings are listed in a summary and some future perspectives are given.

The composition in the synthesis is not in the chronological order of the papers but rather in a more natural way, such that the Faroe Shelf Water is first described, then the Faroe Shelf Front and the exchange through it and, finally, the impact of the physics on the biology is discussed.

Part II constitutes the four papers whereof three are published in peer-reviewed journals and the fourth is resubmitted after review. The papers are as follows:

Paper I
Eliasen, S.K., Gaard, E., Hansen, B., Larsen, K.M.H., 2005. A ‘‘horizontal Sverdrup mechanism’’ may control the spring bloom around small oceanic islands and over banks. Journal of Marine Systems 56 (3–4), 352-362.

Paper II
Hansen, B., Eliasen, S.K., Gaard, E., Larsen, K.M.H., 2005. Climatic effects on plankton and productivity on the Faroe Shelf. ICES Journal of Marine Science 62 (7), 1224-1232.

Paper III
Larsen, K.M.H., Hansen, B., Svendsen, H., 2008. Faroe Shelf Water. Continental Shelf Research 28 (14), 1754-1768.

Paper IV
Larsen, K.M.H., Hansen, B., Svendsen, H., The Faroe Shelf Front: Properties and exchange. Resubmitted to Journal of Marine Systems.

Acknowledgements

First of all, I want to thank Prof. Harald Svendsen for his valuable supervision during this PhD study and the preceding cand. scient. study and for his willingness for coming to the Faroe Islands. It has been a great help and facility in my schedule. Likewise, I want to thank Prof. Bogi Hansen for his great supervision, continuous support and encouragement, and for always having time for discussions and solving all sorts of problems. And thanks to my third supervisor, Dr. Jofrid Skarðhamar, for encouragement and comments on my thesis draft.

A special thank to the Faroese Fisheries Laboratory and its director Hjalti í Jákupsstovu for all kinds of support and encouragement prior to and during this study. Thanks to all my colleagues for support and constructive comments on my work, for always being ready to lend a helping hand, and for creating a pleasant social environment. A special thank to Hjálmar Hátún for constructive comments on my drafts, to Regin Kristiansen and Ebba Mortensen for practical help with instruments, and to Eilif Gaard for new material for some of the figures in this synthesis. Additionally, I want to thank the captain and crew on board R/V Magnus Heinason for all their help with the Towed Temperature Wire and Knud Simonsen for the use of his tidal model.

At GFI/Bjerknessenteret I want to thank Svein Østerhus for so often making practical arrangements for me on my trips to Bergen. And thank you all at the Institute for always being friendly and for your pleasant atmosphere - I certainly will recommend Bergen and GFI to new students.

This work has been funded by Faroes Partnership, which has been greatly acknowledged.

Finally, I want to thank my family and friends for all their help and support during this work, especially for taking care of the children when Aksel and I had distorted working hours (days).

Anna Katrina, Ingi and Elisabet – thanks for your love and patience with me. And Aksel – a special thank to you for all your love and patience and for always having confidence in me.

Tórshavn, November 2008

Karin Margretha Húsgarð Larsen

Contents

1. Introduction

Shelves constitute the shallow water between land and the deep ocean. The seaward border usually is at the shelf break where the bottom slope abruptly increases. At this border, a large number of physical processes are at act, e.g. upwelling, downwelling, and frontal instabilities (Huthnance, 1995), which to a lesser or higher degree influence the exchange between the on-shelf water and the off-shelf water.

In general, shelf waters have a large biological production and especially the shelves at the eastern boundaries of the world's ocean (in which the Faroe Shelf is classified according to Robinson and Brink (1998)) are known to be very productive (Hill et al., 1998). Here, the large upwelling systems are classic examples where physical processes play a major role in controlling the primary production (e.g. Mann and Lazier, 1996).

1.1 The Faroe Shelf

The Faroe Shelf is located on the Greenland-Scotland Ridge between Iceland and Scotland (Fig. 1). It has an approximate form of a triangle with 18 islands in the centre (Fig. 2). The area between the shore and the 100 m bottom contour is 5300 km^2 and has an average depth of 75 m. On the Shelf, strong tidal currents continuously mix the shelf water, which, therefore, is relatively homogeneous and has a different character than the surrounding oceanic water. This is reflected in both temperature and salinity. These properties were discovered already in the beginning of the 20th century and for instance Jacobsen (1915) describes the lower salinities and temperatures in the shallow water of the Faroe Plateau and the Faroe Bank and the intense mixing in these areas, which keeps the water column homogeneous even during summer. But, a detailed analysis of the degree of homogeneity of the on-shelf water and the seasonal variation of its properties has been missing so far.

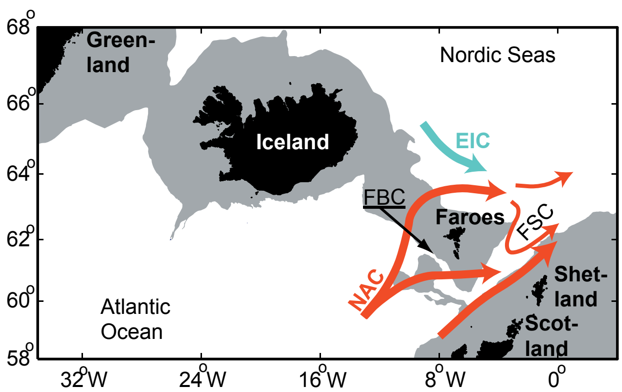

Fig. 1. The Greenland-Scotland Ridge (grey areas are shallower than 750 m) with an illustration of the large-scale circulation in the Faroese area. Red arrows indicate warm and saline North Atlantic Water in the upper layers. The North Atlantic Current (NAC) flows both south and north of the Faroe Shelf where it meets the colder and fresher East Icelandic Current (EIC). Also are indicated the Faroe Shetland Channel (FSC) and the Faroe Bank Channel (FBC).

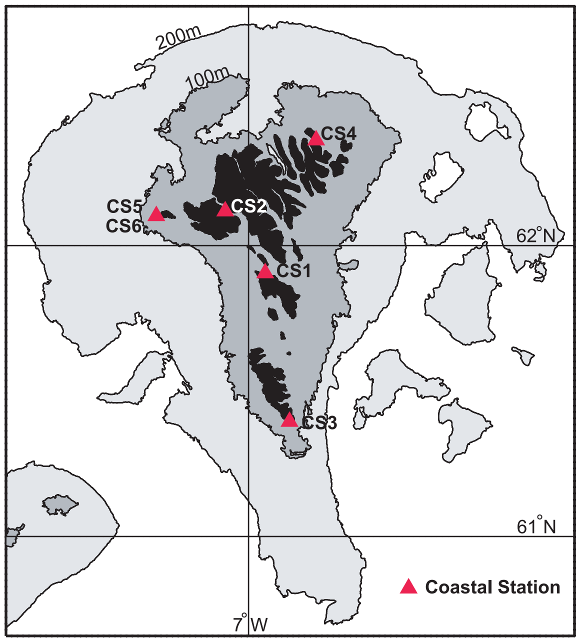

Fig. 2. The Faroe Islands and the Faroe Shelf. Land area is black, dark grey areas are shallower than 100 m and light grey areas are shallower than 200 m. Coastal stations CS1-CS6 are indicated by red triangles. CS5 is located at approximately the same position as CS6, which is a historical time series.

A prerequisite for a front around the Faroe Shelf is the different characteristics of the on-shelf and off-shelf waters and the actual existence of a front, rather than gradual changes in properties, was first reported by Hansen (1979). At other locations, such shelf or bank fronts have been intensively studied since the mid-seventies (e.g. Simpson and Hunter, 1974; Loder and Greenberg, 1986), but a more thorough description of the Faroe Shelf Front and its properties has been missing so far. Throughout this synthesis, the term "Faroe Shelf Water" abbreviated to "FSW" is used for the well-mixed water mass on the Shelf and "Faroe Shelf Front" abbreviated to "FSF" for the front that separates it from the off-shelf water.

The surrounding large-scale circulation determines the properties of the off-shelf water. The large-scale circulation is dominated by the North Atlantic Current, which flows both north and south of the Faroe Shelf (Fig. 1), carrying relatively warm and saline water to the area. North of the Faroes, the Atlantic Water is focused in the Faroe Current, which to some extent mixes with the colder and fresher water in the East Icelandic Current. The East Icelandic Current flows south-eastwards from Iceland and subsides below the Faroe Current in the frontal area (Hansen and Østerhus, 2000). As the Faroe Current reaches the northeastern corner of the Faroe Shelf, one branch of the current with partly diluted North Atlantic water turns southwards to the area east of the

Faroe Shelf (Hátún, 2004). Therefore, the waters to the east of the Faroe Shelf are not as warm and saline as those to the west, but still distinct from the on-shelf water.

1.2 Biological importance

The partly isolated water mass on the Shelf represents a retention system carrying a distinct ecosystem, which is of great biological importance. It has its own cycle of primary production, distinct from off-shelf, which is a prerequisite for the survival of fish larvae from several commercially important fish stocks (Gaard et al., 2002). A large inter-annual variation is observed in the primary production both in magnitude and in timing of the spring bloom. An index, calculated from the observed summer nutrient decrease, is used to estimate the inter-annual variation of primary production and this index varies approximately by a factor of five (Fig. 3). These variations are cascaded up through the food chain to higher trophic levels affecting a broad range of animals ranging from zooplankton, benthos, and various fish larvae to seabirds and the condition of larger fish. For instance, a clear relationship is found between the primary production index and the growth rate of cod and haddock (Fig. 3).

Since cod and haddock are important commercial species, the inter-annual variation in the primary production has great impacts on the Faroese society, and a better understanding of this variation is of great interest. In principle, both top-down and bottom-up mechanisms

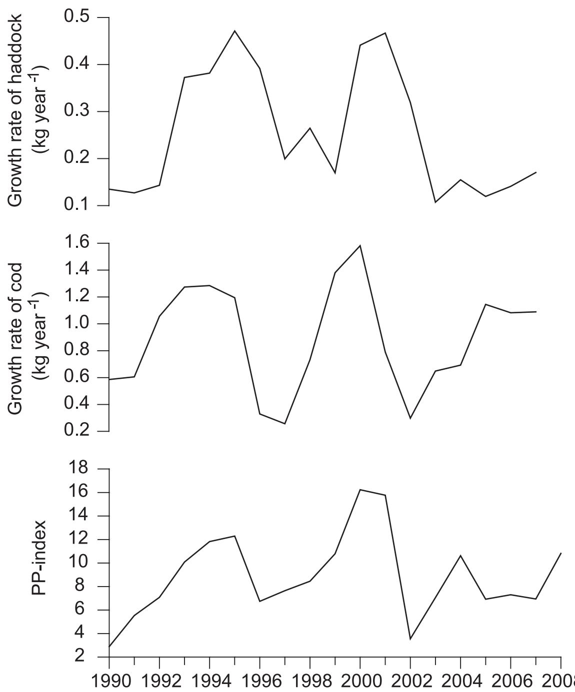

Fig. 3. Relative variability of the primary production estimated as a calculated index and the growth rate of cod and haddock at age 2-8 years for the years 1990-2006. Personal comm., Dr. Eilif Gaard.

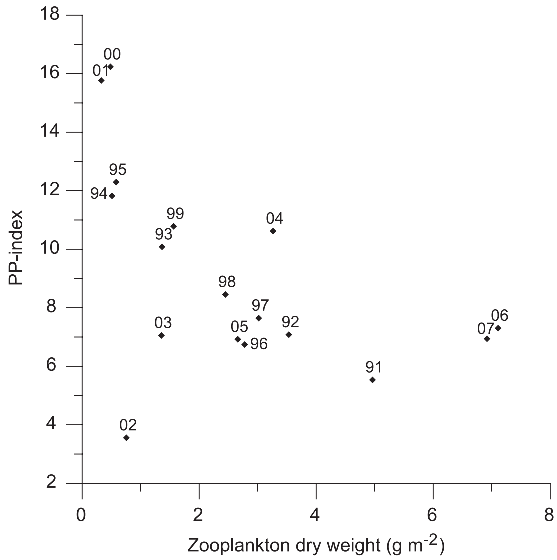

Fig. 4. The relationship between PP-index and on-shelf zooplankton biomass in late June, 1999-2007. Numbers indicate the years. Updated from Fig. 9 in Paper II (Personal comm., Dr. Eilif Gaard).

may be suggested to explain the link between primary production and fish. The abundance of zooplankton (and the related grazing) is a typical top-down control, while in a bottom-up framework, the control of the primary production must be some physical mechanism and, therefore, strongly linked to the properties and processes of the FSW and the FSF.

When it was realized that the primary production on the Faroe Shelf had such a large inter-annual variation (Fig. 3), attempts were made to explain it in terms of physical parameters, such as light, sea temperature, and tidal mixing (Gaard et al., 1998), and initially, they were unsuccessful. These attempts did, however, uncover an empirical relationship between the primary production and the zooplankton biomass on the shelf in late June. Except for one year (2002), this relationship still seems to be valid (Fig. 4).

Originally, this relationship was interpreted in terms of grazing. Large zooplankton abundances in spring would graze the phytoplankton more efficiently and delay and reduce the spring bloom (Gaard et al., 1998). At this season, the zooplankton biomass is dominated by the copepod Calanus finmarchicus, which is absent from the Shelf in winter and imported to the Shelf from off-shelf waters in spring. The large variations in zooplankton biomass in spring could then be explained by variations in the exchange rate between on-shelf and off-shelf water. Since the exchange rate seems to be highly variable (Gaard and Hansen, 2000), this could explain the large variations in zooplankton biomass on the Shelf and, hence, also the variations in primary production.

The physical processes that contribute to exchange between on-shelf and off-shelf water, and their impact on the primary production are, therefore, also of great interest.

1.3 Objective of the study

The objectives of this thesis are:

- To quantify the hydrographic properties of the FSW, including seasonal and inter-annual variations in horizontal and vertical homogeneity. Additionally, the tidal and residual currents on the Shelf are to be analysed and an explanation for the circulation system sought.
- To determine the characteristics of the FSF and identify a possible generating mechanism.
- To estimate the typical magnitude of the exchange of water between the on-shelf and off-shelf regions, as well as its variation, and to identify possible physical exchange processes.
- To investigate the effect of water mass exchange on the primary production on the Shelf.

2. Material and Methods

The objectives are reached through observations and a simple numerical model. The physical properties of the FSW and possible exchange mechanisms are investigated using various observations. The observations and related methods are described in section 2.1. The model, described in section 2.2, is used to estimate the average on-shelf/off-shelf exchange and to demonstrate the importance of the exchange on the on-shelf primary production.

2.1 Observations

Vertical homogeneity (or stratification) may be examined using CTD (Conductivity, Temperature and Depth) data. For this purpose, CTD data, collected by the Faroese Fisheries Laboratory in the periods 1976-1984 and 1996-2005, were used (in the intervening period, the data are of reduced quality). The selected data (1911 CTD stations) are scattered around the Shelf at depth intervals between approximately 50 and 300 m (Fig. 5). For these data, a mean density gradient was calculated and analysed for the summer and winter seasons, as well as for the whole year.

To investigate the horizontal homogeneity on the Shelf, temperature data from five coastal stations were used (Fig. 2). Two permanent stations (CS1 and CS2) are located in the central part of the Shelf and three new coastal stations were established and located at more peripheral locations. Daily and monthly averages were calculated for these data and coherency and spectral analyses were performed.

Daily temperature measurements were initiated at the westernmost island, Mykines (CS6, Fig. 2), in 1914 and continued more or less regularly until 1969 (Hansen and Meincke, 1984). Regular temperature monitoring was re-established in 1991 at the more central station, CS2 (Fig. 2). The data from CS2 and CS5 were also used to justify the combination of the historical time series from CS6 with more recent data from CS2 (paper III).

Only one of the coastal stations (CS1) includes salinity. These data range over the decade from 1995 to 2005 and were used to explore the salinity variation on the Shelf. Additionally, they were compared to salinity measurements from standard CTD stations located outside the Shelf (paper III and IV).

In the period 1976-1994, several traditional (Savonius rotor) current meters were deployed on the Faroe Shelf and data from 38 of these deployments are used here to analyse the Shelf circulation (paper III). The current meters were deployed at 10 different sites around the Shelf at bottom depths ranging from 55 to 150 m. Instrument depths are mainly 40 m. Tidal analyses were performed on all the current meter data and the residual current was calculated.

In exploration of the FSF, especially two data sets were used. One of them is underway Sea Surface Temperature (SST) data observed from R/V Magnus Heinason. The ships logging system measures position (DGPS), bottom depth, and temperature at short intervals and these data are averaged over one minute. For the period 1999-2006, a total of 355 quality-controlled tracks where the ship traverses the front, are used in this work. The data were grouped by quality and location on the Shelf in order to analyse differences in the front according to area. When the SST was plotted against bottom depth, the plot typically showed a S-shaped step variation and this property was used to estimate the centre bottom depth

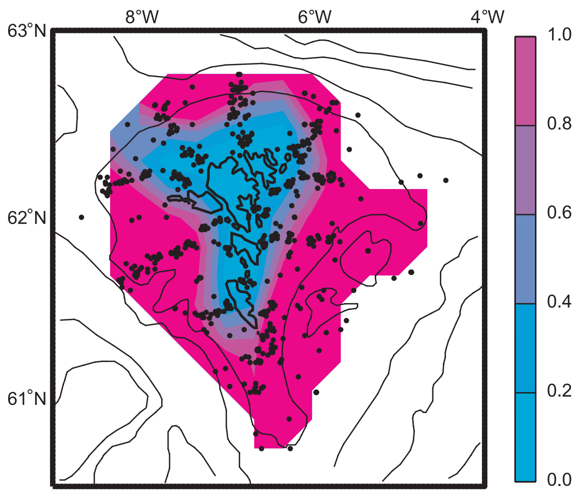

Fig. 5. Contour plot of mean vertical density gradient (10^{-3} kg m^{-3} m^{-1}) (averaged from 10 m depth to the deepest measurement) for 731 CTD stations in June, July, and August. Black dots indicate positions of the CTD stations. Areas with low data representation are omitted. The bottom topography (thin black contours) is based on ETOPO5. Thick black contours represent land area.

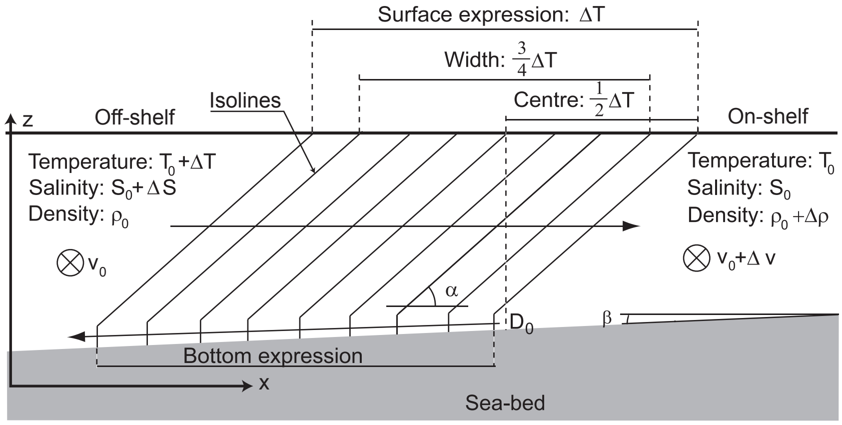

Fig. 6. A schematic illustration of a section perpendicular to the front. Several definitions, related to the front, are indicated on the illustration.

(D_0) and width (in terms of bottom depth) of the front (Fig. 6 and paper IV). The temperature change (ΔT) across the front was also calculated from these data and additionally, time series data from two coastal stations, representing FSW, and two standard CTD stations located off-shelf, thus representing off-shelf water, were used to supplement the results from the SST data.

The other data set used to explore the FSF is data from a Towed Temperature Wire (TTW). This system was designed for this study and consists of a 75 m long wire on which temperature recorders are attached at regular intervals. The deepest recorder also records conductivity and pressure. R/V Magnus Heinason tows the wire across the front, such that a temperature section is achieved from approximately the upper 50 m of the water column and between bottom depths of approximately 75 m (on-shelf) and 200 m (off-shelf). These measurements are done during the ships spare time from other work on the Shelf and are, therefore, randomly occupied, but confined to seven approximate locations around the Shelf. During the years 2005-2008, a total of 65 TTW sections were obtained and 22 of the sections, occupied during spring, could be used to estimate the slope (α) of the front, the density change across it, and the associated geostrophic velocity change (Fig. 6 and paper IV). Refer to paper IV for a more detailed description of the TTW data.

2.2 The model

A simple numerical model was used for three different calculations regarding the Shelf: a temperature budget, a salinity budget, and a primary production model (hereafter termed PP-model), which simulates the spring development of the on-shelf primary production for variable conditions. The temperature and salinity budgets were implemented to get an estimate of the typical exchange between on-shelf and off-shelf water, while the PP-model was implemented to investigate the relative importance of zooplankton grazing and horizontal exchange on the primary production of the Shelf.

The principle of the model geometry is to simplify the Faroe Shelf by approximating it as a number of annular rings (Larsen, 2003; paper I and III) where each ring represents a specific depth interval on the Faroe Shelf (Fig. 7). In the temperature and salinity budget calculations, seven annular rings represent the frontal area. In the PP-model, three extra rings are implemented on-shelf, such that 10 annular rings represent the frontal area, while the depth interval of the homogeneous shelf water is reduced. Each of the annular rings is considered homogeneous regarding its properties, whether the properties are temperature, salinity, nutrients or other variables, and any changes in the properties are immediately mixed within the ring. Regarding the temperature and salinity budgets, their property values

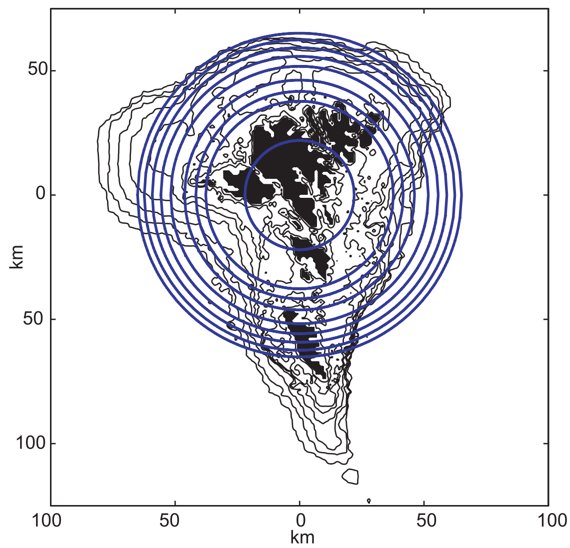

Fig. 7. Annular ring model (blue) superposed on the topography of the Faroe Shelf (black). The surface area and volume of each ring has approximately the same value as their representatives on the Faroe Shelf. The innermost circular domain represents land (or the centre of an off-shelf bank as in paper I) bordering the first annular ring representing the homogeneous shelf water. The first annular ring thus covers a large depth interval, while the next annular rings have a smaller (and constant) depth interval, considered to represent the frontal region. The outermost domain also extends over a large depth interval and represents the off-shelf water.

are changed through exchange with the neighbouring rings and through air-sea interactions (i.e. heat-flux and precipitation). For further details, refer to paper III. In the PP-model, conservative properties are changed in a similar manner as the temperature and salinity, while additional equations calculate the variation of the non-conservative biological parameters. Details are found in paper I.

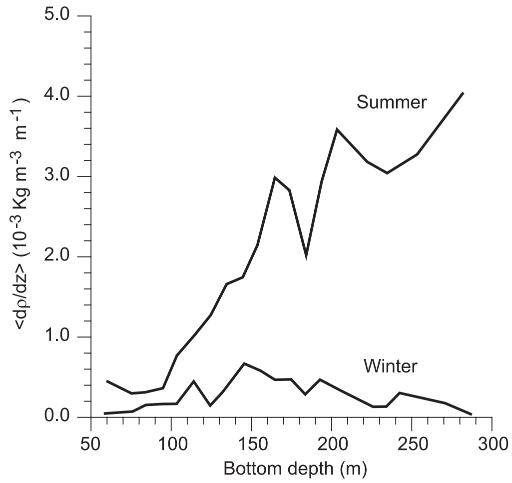

Fig. 8. The 75th percentiles of the mean vertical density gradient plotted against bottom depth. The density gradient is averaged from 10 to 100 m or to the deepest observation if shallower than 100 m. The line marked "Summer" is based on 731 CTD stations from June, July, and August, while the "Winter" line is based on 846 stations from November, February, March, and April (no data are available in December and January).

3. Results and discussion

3.1 Faroe Shelf Water

The strong tidal currents (paper III) and heavy waves that act on the FSW will tend to mix the water efficiently. Qualitatively, it has been known for a long time (Jacobsen, 1915) that the FSW is a fairly homogeneous water mass, but how homogeneous is it vertically and horizontally? What is the extent of this homogeneous water mass? And what is the seasonal variation? These questions were addressed in paper III.

The vertical homogeneity was investigated by using CTD profiles from the Shelf and surrounding waters (Fig. 5) with the stratification (density gradient) as a (inverse) measure of homogeneity. The stratification was examined for bottom depths between 50 and 300 m showing that during winter the typical stratification is weak out to at least 300 m (Fig. 8). In summer, the deeper areas become stratified (Fig. 5 and 8), while the stratification within 100 m bottom depths remains weak.

The horizontal homogeneity was investigated by comparing simultaneous temperature measurements

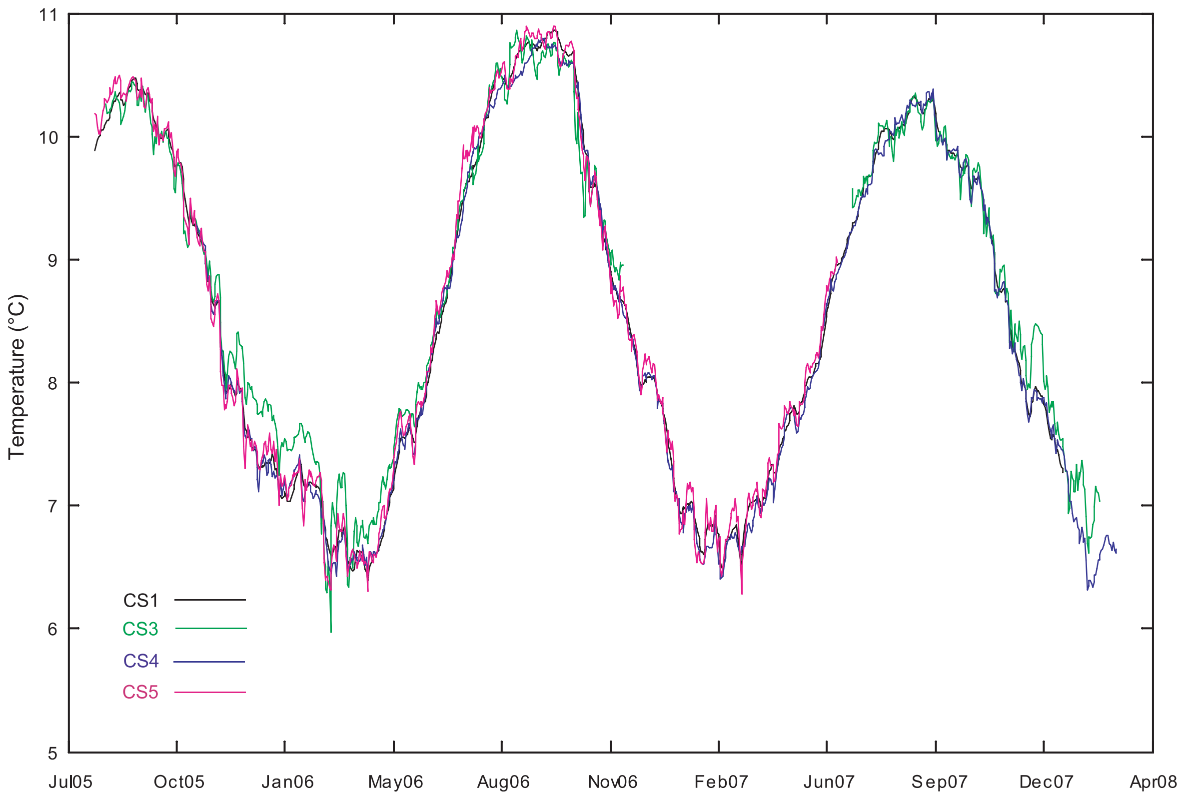

Fig. 9. Daily averaged temperature from four coastal stations in the period June 2005 – February 2008. CS2 is omitted, since it is very similar to CS1. Data are not available from all stations for the whole period, and CS3 has a gap from 1. December 2006 to 30. June 2007 because of an instrument failure.

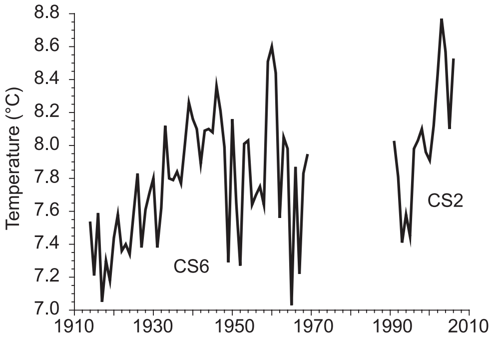

Fig. 10. Annual mean temperature observed at CS6 and CS2.

from five coastal stations located around the islands (Fig. 2). The temperature is found to be horizontally homogeneous, as is demonstrated with the coherent temperature variability between the individual stations, especially between the two central stations (paper III). Typical differences between monthly mean temperatures from different stations were below 0.1ºC, except for one station, which, during a period, had a significantly higher temperature than the others. It appears that the northern part of the FSW is very horizontally homogeneous throughout the year. The southern part seems to have the same temperature as the rest of the FSW most of the time, but may become isolated during periods of a few weeks or months. More recent measurements (Fig. 9) indicate that this may occur regularly during winter.

Time series from CS6 and CS2 (section 2.1 and Fig. 2) represent the temperature observations of longest duration from the Faroe Shelf. Comparison of temporally overlapping measurements at the two sites demonstrates that they are almost identical, and thus represent the same water mass (paper III). A joint time series (Fig. 10) is, therefore, expected to represent the long-term changes in the northern FSW to the extent that the old measurements are reliable. The typical seasonal variation of this water mass has a temperature range on the order of 4 ºC (Fig. 9).

A similar analysis of the horizontal homogeneity of salinity is more difficult, since only one coastal station records this parameter regularly. However, a comparison of this station to a standard CTD station on the Shelf indicates a fair degree of homogeneity in salinity (Fig. 11). Compared to measurements at a standard CTD-station located off-shelf, the on-shelf salinity is always lower than off-shelf (paper III). The typical salinity difference between off-shelf and on-shelf waters is on the order of 0.1 and their long-term trends are similar (Fig. 11).

The homogeneous character of the FSW indicates strong mixing, and tidal mixing is an obvious candidate. The observations also verify that the tidal currents on the Shelf are strong. A tidal analysis showed that they are predominantly semi-diurnal, but vary somewhat in relation to location and bottom depth (Fig. 12). A quantitative estimate of the tidal mixing potential was made using the Simpson and Hunter (1974) theory (paper III). This verified that most of the current measurement sites should be unstratified during most of the year, but the theory predicted summer stratification at some sites within the 100 m depth contour. A more realistic estimate was found by the Soulsby (1983) theory, as discussed in section 3.2.

The residual currents follow the topography with a clockwise circulation around the Shelf (Fig. 12). This indicates the possibility of "tidal rectification" as a generating mechanism for the residual flow. A correlation and regression analysis was performed between the

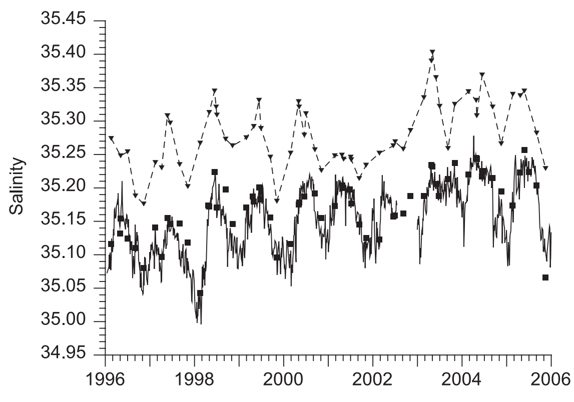

Fig. 11. Salinity measurements in the period 1996-2005 at CS1 (continuous line) and at two standard CTD stations: one located on-shelf (black squares) and the other off-shelf (broken line with black triangles at data points).

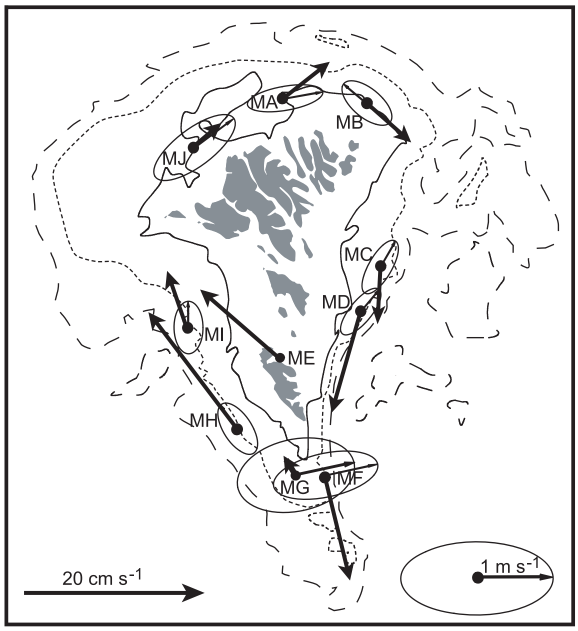

Fig. 12. Residual currents (indicated by thick arrows) at each site based on vectorial averages of the different deployments, weighted by their duration. M_2 tidal ellipses are plotted at all sites, except at ME where the current is rectilinear. The scale of the residual currents is shown in the lower left corner and the scale of the ellipses in the lower right corner (note that the two scales are different). Instrument depth is typically 40 m. Depth contours are 100 m (full line), 150 m (dotted line) and 200 m (dashed line), and are courtesy of Knud Simonsen.

cross-shelf tidal velocity and the along-shelf residual, which showed that 9 out of 10 sites had a significant maximum correlation at lags between 0 and 2 days where the residual lagged behind the tidal amplitude (paper III). Other mechanisms may also contribute to the residual circulation, but the analysis verifies that tidal rectification can explain a large fraction of the average residual circulation and its variation (paper III).

At five of the sites, the deployment duration (from one or consecutive deployments) was long enough to allow a regression analysis on a possible seasonal variation of the residual current (paper III). Only two of these sites turned out to have a considerable seasonal variation with maximum currents in August.

3.2 The Faroe Shelf Front

The FSF is defined as the transition zone between the well-mixed FSW and the off-shelf water. At times, it may be a wide region with slowly varying characteristics, but often, it is a narrow zone with sharp horizontal gradients, as illustrated by the satellite image on the inside front cover. Usually, temperature and salinity, as well as density, change across the front (Fig. 13).

The density change across the front, and hence its dynamics, are mainly dominated by temperature with lower temperatures on-shelf, except for a short period in autumn with small temperature differences and occasional higher temperatures on-shelf (Fig. 13a). The largest temperature differences are observed in spring and together with the seasonal salinity variation, which is less pronounced, the density difference across the front experiences a reversal in summer or autumn (Fig. 13c) (paper IV).

The origin of temperature and salinity changes across the front are clearly linked to air-sea interactions. Increased precipitation over the land and central shelf, as well as a shallow water column to mix the freshwater into, explain the low salinities inside the front. The temperature change across the front may likewise be explained by the air-sea heat exchange. Due to the relatively (to latitude) warm off-shelf water, the air is colder than the sea during most of the year (Fig. 14). On the shallow shelf, the atmospheric cooling is sufficient to induce a maximal temperature change across the front of 2 ºC in March (Fig. 13a).

The location of the front in terms of bottom depth has been determined mainly from the SST data, logged continuously by R/V Magnus Heinason (section 2.1). From these data, estimates of the bottom depth (D_0; Fig. 6) at the centre of the front were calculated for the different areas. These calculations reveal a change in D_0 with values increasing from the east through the north and to the west and south (Fig. 15). Attempts were made to relate variations in D_0 in each area to the neap-spring tidal cycle and to season. No consistent relationships were found, but the variations are not much larger than the tidal excursion on/off the Shelf and comparable to the typical radius of deformation. It will, therefore, be difficult to extract consistent relationships from the noise.

When searching for a theoretical explanation of the FSF and its location, it would be tempting to compare it to the much discussed fronts in the European shelf seas (e.g. Simpson and Hunter, 1974; Fearnhead, 1975), but the FSF is clearly not the result of a balance between stratifying and mixing processes. As mentioned, the atmosphere cools the water during most of the year (Fig. 14) and the off-shelf water is usually almost homogeneous down to below 200 m (paper III and IV) during the most pronounced period (early spring) of the FSF. It is also difficult to see any link between the location of the front (Fig. 15) and the shelf break (Huthnance, 1995, Larsen, 2003).

An alternative explanation was given by Soulsby (1983), in which the front is located where the height of the bottom mixed layer becomes smaller than the bottom depth. Soulsby (1983) emphasized the importance of rotating tidal currents and recently, Simpson and Tinker

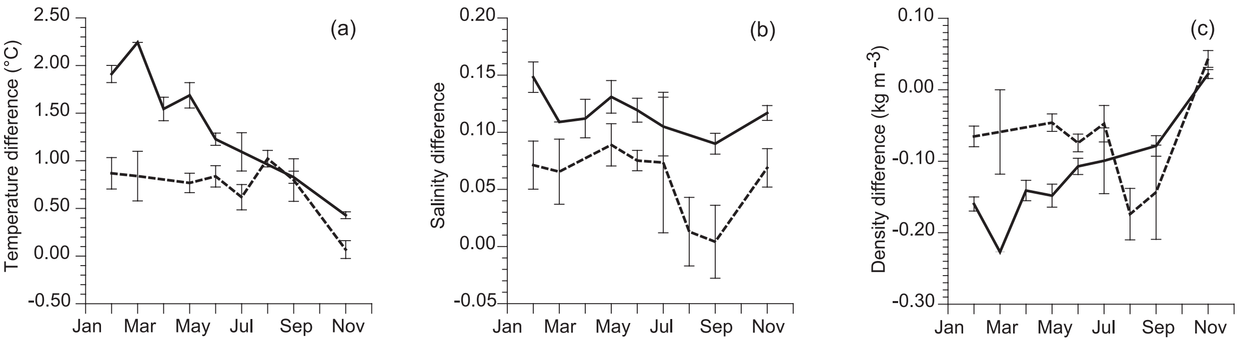

Fig. 13. Average cross-frontal differences to the west (continuous lines) and east (dashed lines) of temperature (a), salinity (b), and density (c). The differences represent off-shelf minus on-shelf and are based on observations at two coastal stations (on-shelf) and two standard CTD stations located to the west and east, respectively (off-shelf). The CTD observations are calculated as the 10 – 50 m average, while the observations at coastal stations are daily averages (temperature) or temporally closest observations (salinity/density) at CS2 and CS1, respectively (Fig. 2). Vertical bars indicate standard errors.

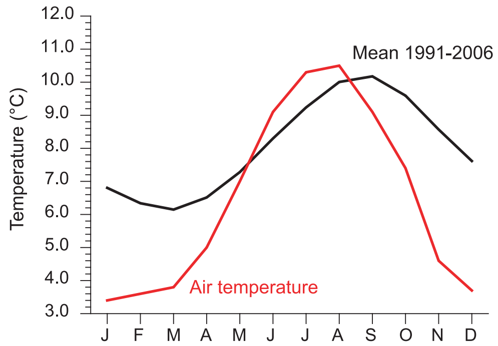

Fig. 14. The monthly mean sea temperature (black curve) from coastal station CS2 (1991-2006) and the monthly mean air temperature (red curve) in Tórshavn according to the Climatological Standard Normals, 1961-1990 (Cappelen and Laursen, 1998).

(2009) have provided observational evidence to support this. Simonsen (1999) has implemented a high-resolution barotropic tidal model of the Faroe Shelf, which allows calculation of the parameters in Soulsby's theory on the different areas of the Shelf. The resulting frontal location (Fig. 15) is found to fit the observed location remarkably well in most areas.

Like other fronts with a density change, the FSF usually slopes with the denser water lying below the lighter. During most of the year, the FSF, therefore, hits the bottom farther off-shelf than it hits the surface. The tilting angle (α; Fig. 6) of the slope may be calculated from TTW data for cases when the front is sharp and not too deformed by mesoscale activity. Combining the observed angle with the density difference across the front and the available information on current speed, it was concluded (paper IV) that the data were consistent

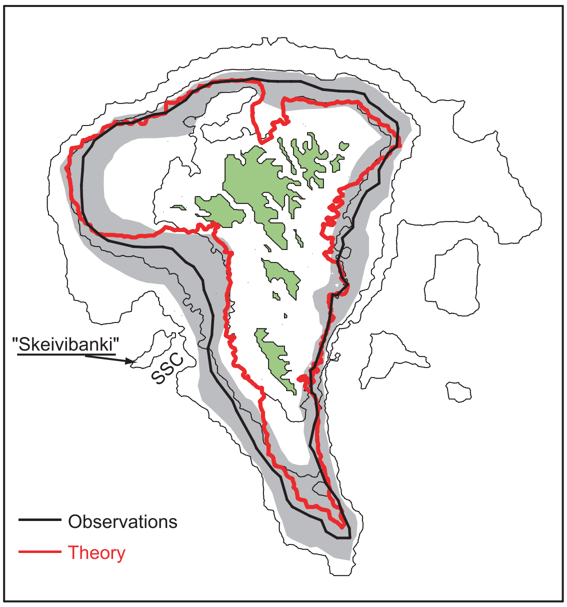

Fig. 15. The frontal position based on the mean centre depths from SST data (thick black line) (paper IV). The grey area covers a depth interval equal to one standard deviation on either side of the centre depth. The red line indicates the frontal position predicted by the Soulsby theory (Soulsby, 1983). SSC indicates the »Southern Skeivibanki Canyon«.

with geostrophic control of the frontal slope.

In early spring when the front is most pronounced, the tilting angle of the front is typically on the order of 0.02 (paper IV) so that it hits the bottom some 5 km farther off-shelf than the surface expression. This is about half the typical width of the frontal zone, defined as the distance giving 75% of the total temperature change (Fig. 6 and paper IV).

3.3 Exchanges between on-shelf and off-shelf waters

On the Faroe Shelf, there is an annually averaged net loss of heat from the water to the air (section 3.2, Fig. 14). To maintain the balance, there must be a net heat-flux from the surrounding off-shelf waters. The requirement of a balance allows an estimate of the exchange rate of water across the FSF. In paper III, a typical (on annual timescales) exchange rate was determined by implementing the seasonal temperature variation of the FSW (Fig. 14) in a version of the model described in section 2.2.

The FSW also receives a net input of freshwater from the air and from land, which in the long term must be balanced by export of freshwater through the FSF. A model of the seasonal salinity variation of the FSW (paper III) was found to fit the observations fairly well, by using the same exchange rate as for temperature.

Together with the given seasonal variations in the atmosphere and the off-shelf water, this typical exchange rate, which is equivalent to a turbulent diffusivity of 67 $m^2 s^{-1}$, thus, explains the seasonal variation of temperature and salinity on the Faroe Shelf. But, on shorter timescales, the exchange rate must vary considerably around this value. This is implied by the short-term temperature variations that are seen at the coastal stations, especially those at the periphery (Fig. 9). Even on timescales of a few months, Gaard and Hansen (2000) concluded from CTD salinity and precipitation data that the exchange rate varies by a factor of about 5.

A large number of processes may contribute to the exchange of FSW and these may be continuous or episodic. Continuous, although varying, exchange may be achieved through horizontal and vertical diffusion through the front. From autumn to early spring, the density change across the front increases and the front probably gets flatter, which should increase the relative importance of vertical versus horizontal diffusion (paper IV). Horizontal advection on or off the Shelf can also result in continuous exchange. Associated with the clockwise circulation (Fig. 12), there must be an off-shelf transport in the bottom Ekman layer, which must be compensated by inflow in the upper layers. Estimates indicate that the associated heat import is large enough to supply the heat needed to maintain a quasi-stationary balance of the front in early spring (paper IV).

The large exchange rates indicated by some observations are, however, likely to be confined to extreme episodic events, and in the available data, there are indications of two different processes. One of them is the intrusion of off-shelf water onto the southern part of the Shelf (paper III) and the other is cascading (paper IV) of FSW through a canyon on the western part of the Shelf, the “Southern Skeivibanki Canyon” (Fig. 15). Hydrographic (CTD) data show the occurrence of FSW at large depths in the chanel, thus indicating cascading, but the observations do not allow determination of the detailed characteristics or importance of these processes as exchange mechanisms.

3.4 Biological impact of the Faroe Shelf physics

In section 1.2, an inverse relationship between zooplankton abundance and the magnitude of primary production was presented (Fig. 4). As mentioned, this relationship was first interpreted in terms of grazing and based on this hypothesis, a production model was developed for the phytoplankton on the Faroe Shelf (Eliasen, 2004a). But it could not be brought to agree with the observations with any reasonable parameter values. For the grazing to control the early phase of the spring bloom, the model indicated that the zooplankton biomass would need to be much larger than observed. Later, direct observations have also verified that the grazing pressure on the phytoplankton is not sufficient to control the spring bloom initiation (Debes et al., 2008).

It was, however, realized that the relationship between primary production and zooplankton (Fig. 4) could be interpreted differently. A large exchange rate will import much zooplankton to the shelf, but it will also export phytoplankton, which acts as a loss term for phytoplankton production, since the off-shelf phytoplankton abundance in spring is usually smaller than on the Shelf (Gaard, 2000).

The work reported in paper I was initiated to test whether phytoplankton loss by on-shelf/off-shelf exchange could be sufficiently important to control the spring bloom. The physical exchange model (Larsen, 2003) was combined with the phytoplankton model (Eliasen, 2004b; paper I) to generate a model (the PP-model) in which the equations governing the biology were modified to include loss of phytoplankton, input of nutrients, input of zooplankton, etc., by exchange (Fig. 16).

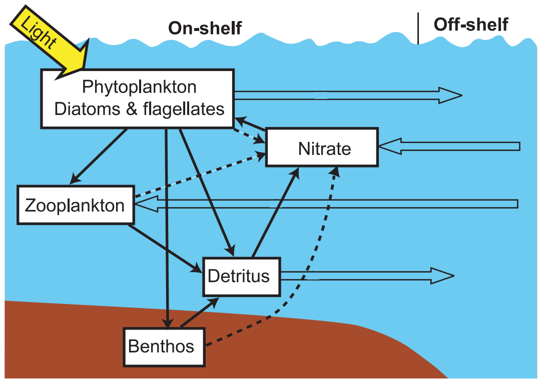

Fig. 16. Schematic diagram of the PP-model (paper I).

The PP-model was run for various prescribed conditions, which are similar to observed conditions for the Faroe Shelf. The main results are plotted in Fig. 17, which shows the effect of a varying exchange rate with or without grazing by zooplankton. The model runs are seen to span a range of a factor 5.4 in exchange rate (from ½ to 2.7), which is reasonable for the Faroe Shelf (section 3.3). The curves in Fig. 17 demonstrate that a high exchange rate is able to delay the spring bloom

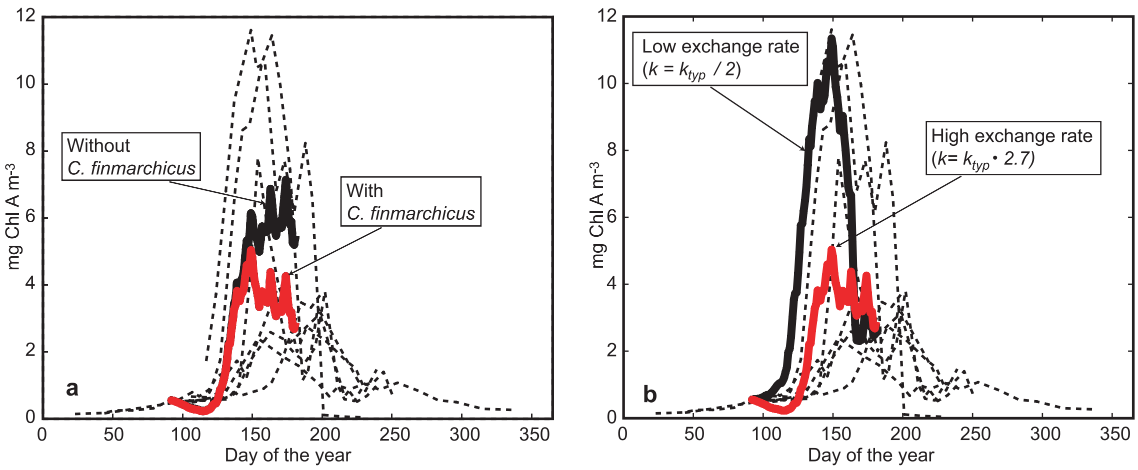

Fig. 17. Modelled chlorophyll *a* concentrations (thick lines) in the on-shelf water based on the PP-model compared to observations (thin dashed lines) at CS1 (Fig. 2). In (a) the difference between extreme abundance (red) and no abundance (black) of *Calanus finmarchicus* is shown in both cases with a high exchange rate. In (b) is shown the difference between a high (red) and a low (black) exchange rate and both with an extreme abundance of *C. finmarchicus*. (The red curves in (a) and (b) are identical).

by up to three weeks compared to low exchange and to reduce the peak value considerably. Including a typical abundance of zooplankton off-shelf has almost no effect on the spring bloom delay and only a small effect on the spring bloom peak value (paper I).

Although not much cited in the literature, the effect of horizontal exchange loss on the primary production must be a general mechanism, not restricted to the Faroe Shelf. Paper I, therefore, also included model runs with different geometries, e.g. a shallow oceanic bank, and these runs showed, as expected, that the effect of the varying exchange rate is dependent on the model geometry and its horizontal scale in relation to the exchange rate. The overall results in paper I clearly indicate that the horizontal exchange rate may have a considerable effect on the timing (and magnitude) of the spring bloom in some island or bank systems.

For the Faroe Shelf, there are thus two independent lines of evidence (Fig. 4 and 17) that indicate on-shelf/off-shelf exchange to be the dominant control of the spring bloom. The question then arises, why there is such a large inter-annual variation in the exchange rate during early spring and what physical processes generate it. For water to be exchanged between the shelf and off-shelf regions it has to pass the FSF and the characteristics of the front might well affect the exchange rate.

The main dynamical characteristic of the front is the density difference across it and it appears (paper II) that in May (around the time of the spring bloom), the density difference across the front experiences large inter-annual variations followed by a reversal of the density difference during summer. The index of primary production for each year was, therefore, plotted against the density difference in May of that year, determined from standard CTD cruises. The result indicated a clear relationship, which still seems to be valid (Fig. 18). The correlation coefficient between the two data series is 0.78 (statistically significant at $p < 0.01$).

This led to the working hypothesis that a strong front (large density difference) would reduce the exchange across it. Strong density gradients reduce vertical diffusion. If vertical diffusion in the frontal zone is important during this season (section 3.3), then that might perhaps explain Fig. 18. But, as discussed in section 3.3, a large density difference should also make the front flatter, which would increase its width and hence the area through which vertical diffusion acts. There are, however, also other possible exchange processes than vertical diffusion and at present, it is not clear what the dominant processes are and how they are affected by the density difference across the front. The relationship in Fig. 18 must, therefore, still be considered a working hypothesis.

If future work supports this hypothesis, the primary production, as well as the production at higher trophic levels, must be tightly linked to the air-sea heat exchange

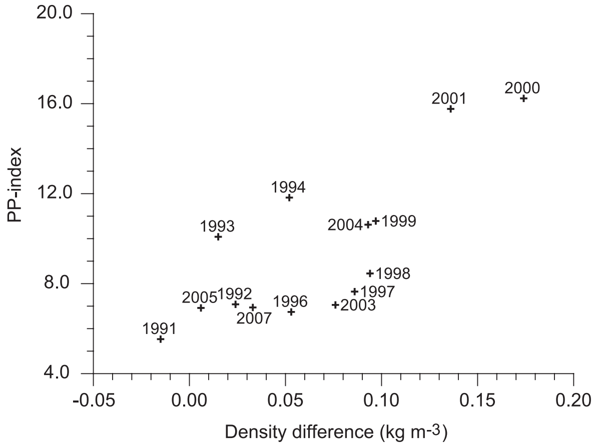

Fig. 18. The relation between the PP-index and the density difference between two standard CTD stations in May. This is an extended version of Fig. 11 in paper II, adding both older and recent years were data are available. Additionally, the density at each station now is calculated over the 10 – 50 m depth layer instead of the 10 – 100 m depth layer. Generally, the differences between the to calculations are only minor and do not influence the interpretation of the overall result.

in late winter and early spring. Large density differences are observed from February through May and are a result of intense and effective atmospheric cooling over the shallow shelf during winter. Strong winter cooling induces a large density difference across the front in May and by the hypothesis, this should give a small exchange rate and an early and intensive spring bloom. Weak cooling, on the other hand, should result in a small density difference, a large exchange rate, and a weaker spring bloom.

Since the sea temperature varies relatively little from one year to another, the air temperature should be a fairly good proxy for the air-sea heat exchange. A comparison was, therefore, made (paper II) between the late winter-early spring air temperature and the PP-index and a fairly good relationship was found with a correlation coefficient of –0.66 (statistically significant at $p < 0.01$). An updated version is shown in Fig. 19. The correlation coefficient is now –0.59 and still significant at $p < 0.01$. This is consistent with the working hypothesis and

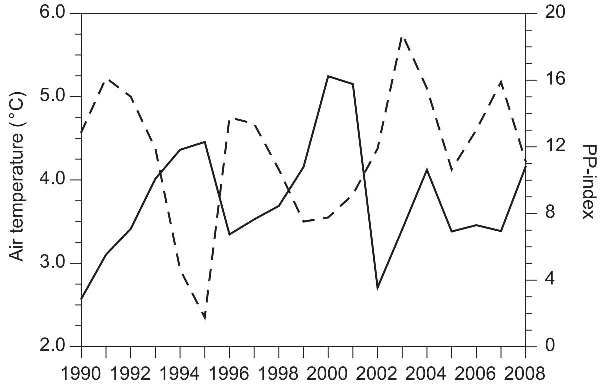

Fig. 19. The relation between PP-index (continuous line) and average air temperature January-April (dashed line) for the years 1990-2008. Updated from Fig. 12 in Paper II.

suggests that the air-sea heat exchange in late winter and early spring may be the main control of the spring bloom on the Faroe Shelf. Further work is, however, necessary to explain in more detail the mechanisms behind this link and to ensure that it is not the result of a statistical fluke.

4. Summary

The findings in this work can be listed as follows:

FSW: Based on CTD data, the FSW is found to be relatively vertically homogeneous through-out the year inside the 100 m depth contour. Temperature measurements at coastal stations reveal that the FSW is also horizontally homogeneous especially in the central and northern part of the Shelf. The southern part can become isolated from the rest of the Shelf during winter. Temperature disturbances originate mainly at the off-shelf boundaries and are transmitted to the inner shelf. The seasonal range in temperature is approximately 4 °C.

From a coastal station and a standard CTD station on the Shelf, the FSW is found to be fairly homogeneous in salinity too, with a seasonal range on the order of 0.1.

Tidal currents are strong and predominantly semi-diurnal. The residual currents follow the topography in a clockwise manner and are on the order of 10 cm s^{-1}. A correlation and regression analysis verifies that the residual circulation can be generated by tidal rectification. A seasonal variation in the residual current is found in two out of five sites.

FSF: The FSF experiences a seasonal variation such that it has the largest cross-frontal temperature difference (~2 °C) in spring induced by effective atmospheric cooling over the shallow shelf during winter. The temperature difference is maintained, although diminished, during summer, and the lowest temperature differences are observed in autumn. During a short period in autumn, the cross-frontal temperature difference is close to zero and may occasionally be reversed, so that the on-shelf water becomes slightly lighter than the off-shelf water. Salinity differences experience a small seasonal variation on the order of 0.1. Density differences are, therefore, mainly determined by temperature variations.

The bottom depth where the centre of the FSF is observed, varies around the Shelf, and increases from east through north to the west and south. Tidal currents determine the location of the FSF and the theoretically predicted location of the front (Soulsby, 1983) fits fairly well with the observed location.

The tilting angle of the front during spring is found to be on the order of 0.02 and in near geostrophic balance. The tilt induces a bottom contact some 5 km farther off-shelf compared to the surface expression.

Exchange: The typical exchange rate of FSW is found to be equivalent to a turbulent diffusivity of 67 $m^2 s^{-1}$, estimated using a temperature and a salinity budget. Indications in temperature and salinity observations reveal that the exchange rate is highly variable and typically varies by a factor of five.

Continuous exchange through the front can be achieved through advection and turbulent diffusion. The associated on-shelf advection of an off-shelf transport in the bottom Ekman layer is found to be large enough to supply the heat needed to maintain the front in a quasi-stationary balance during spring.

Extreme exchange is likely to be induced by episodic exchange events. Two extreme exchange processes are indicated: cascading through a canyon and an extreme intrusion of off-shelf water into coastal waters. The importance of these processes is uncertain.

Biological impact: The relationship between the primary production on the Shelf and the magnitude of the exchange rate was investigated using a PP-model. When the exchange rate is small, the plankton is mainly confined to the FSW, and a strong spring bloom develops. If the exchange rate is high, the plankton is exported off the Shelf, delaying the spring bloom by up to three weeks. This is a general relationship and may be important for other island or bank systems, as well. With updated observational material, the hypothesised relationship between the primary production and the physical parameters is still found to be statistically significant. Years with an intensive spring blooms, thus, seem to occur when there is a large density difference across the front due to strong winter cooling.

5. Future perspectives

In this study, the importance of the exchange between FSW and off-shelf water has been revealed leading to the hypothesis that a strong front reduces the exchange across it, resulting in a large primary production. Thus, the main future goal is to proceed with the investigations of the exchange mechanisms to find their relative importance and variation. When we understand these processes, we might, for instance, become better at predicting the magnitude of the primary production and thus get a more reliable forecast of the fishing potential ahead.

The exchange mechanisms in the frontal area at the »Southern Skeivibanki Canyon« are already planned to be investigated further. The main aim will be the transport in the bottom Ekman layer, but also cascading (or upwelling) through the canyon is of large interest. This will be done by deployment of a current profiler (ADCP) on the bottom at the canyon mouth, with an additional temperature and salinity recorder, to identify water masses.

A subject not considered in this thesis is the effect of wind. This is a vital issue, since obviously the wind contributes to exchange across the front through enhanced mixing in the frontal area and advection across the front as already found by Gaard and Hansen (2000). This subject, therefore, deserves higher priority in future studies.

Another way to investigate the exchange is the use of satellite data (phytoplankton abundance, sea surface temperature, sea surface height). Some of these data sets now cover almost three decades, and although a drawback with the satellite data is the frequent cloud cover in the area, some information is obtainable from the data.

Finally, an improvement of the numerical modelling is also desirable, especially the implementation of a high-resolution three-dimensional model.

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Errata for
Circulation and exchange of water masses on the Faroe Shelf and the impact on the Shelf ecosystem

Karin Margretha Húsgarð Larsen

Thesis for the degree philosophiae doctor (PhD)

at the University of Bergen

(signature of candidate)

(signature of faculty)

30. January 2009

Errata

Page V: New page inserted with the text: “*Dedicated to the memory of my brother:* J. Hendrik Húsgarð * 11. September 1965 † 1. December 2007“

Page VI: New blank page inserted.

Page V – IX in original thesis are now corrected to page VII – XI, according to the two new inserted pages.

Original page IX: Page numbers regarding the above corrections are updated.

Original page V: ”The Faroe Shelf Front and its disturbance by canyon cascading” corrected to ”The Faroe Shelf Front: Properties and exchange”. In review from the Journal of Marine Systems 14. January 2009 the only comment was to consider a new title. The paper was resubmitted 22. January 2009 with the title ”The Faroe Shelf Front: Properties and exchange”.

Page 7-8: “Simpson and Tinker (in press)” corrected to “Simpson and Tinker (2009)”

Page 13: ”Simpson, J. H., Tinker, J. P., in press. A test of the influence of tidal stream polarity on the structure of turbulent dissipation. Continental Shelf Research (2007)” corrected to “Simpson, J. H., Tinker, J. P., 2009. A test of the influence of tidal stream polarity on the structure of turbulent dissipation. Continental Shelf Research 29, 320-332”

Paper IV, page 1: ”The Faroe Shelf Front and its disturbance by canyon cascading” corrected to ”The Faroe Shelf Front: Properties and exchange”.