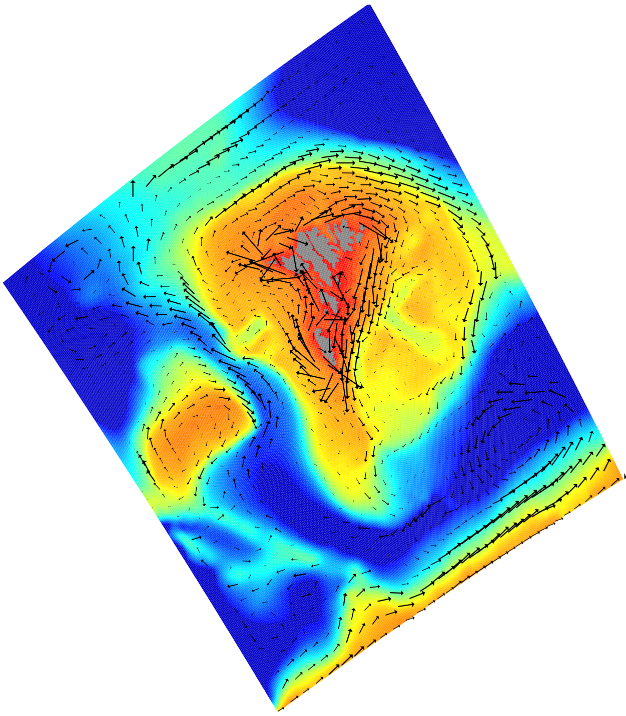
Final report for the research programme on Climate and Ocean Currents around the Faroe Islands 2008 - 2012

Afsluttende rapport for forskningsprogrammet Klima og Havstrømme ved Færøerne 2008 - 2012

Tórshavn · March 2013



Edited by Bogi Hansen

HAVSTOVAN NR.: 13-06
TECHNICAL REPORT

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Dansk sammenfatning

I finansloven for 2008-20011 bevilgede Folketinget, gennem Forsknings- og Innovationsstyrelsen, 9,2 millioner kroner til et 4-årigt forskningsprogram med titlen *"Klima og Havstrømme ved Færøerne"*. Programmet omfattede forskning i klima og havstrømme samt deres betydning for de marine økosystemer på Færøshelfen og i de oceaniske havområder ved Færøerne. Det udførtes i samarbejde mellem Færøernes Havforskningsinstitut, DTU-Aqua, Danmarks Meterologiske Institut og GEUS. Der blev ialt financieret fem projekter inden for programmet:

Phd projekt: Lesser sandeel,* Ammodytes marinus, *as a link between climate and higher trophic levels on the Faroe shelf

[Tobis, som bindeled mellem klima og højere trofiske niveauer på Færøplateauet]

Man har længe haft mistanke om, at tobisen har en nøgleposition i det marine økosystem på Færøplateauet, men uden klare beviser. I dette projekt er det blevet klart påvist, at tobisens rekrutering er højt korreleret med primærproduktionen i forårsopblomstringen, og at dens tilvækst er højt korreleret med zooplankton biomasse. Det er også blevet påvist, at tobisens ernæringstilstand har indvirkning på torskens individvægt, og at mængden af tobis er afgørende for nogle havfugle arters ynglesucces. Derved har Projektet fastslået tobisens rolle som et af de vigtigste mellemled mellem primærproducenterne og højere led i fødekæden, herunder kommercielle fiskebestande og havfugle. Man fandt også, at tobisens fedtreserver reduceres kraftigt ved høje havtemperaturer om vinteren, mens tobisen ligger nedgravet i sandet uden at indtage føde. Med kommende klimaændringer er dette specielt bekymrende i færøsk farvand, som har relativt høj vintertemperatur. En PhD afhandling er indsendt og forventes forsvaret tidligt i 2013. Tre videnskabelige artikler er publiceret eller indsendt.

Phd projekt: Effects of Climate and Ocean Currents on Faroe Saithe.

[Klima og havstrømmes påvirkning på sej ved Færøerne]

Projektets formål har været at beskrive og forklare sejens biologi på Færøplateauet, i forhold til hvad vi ved om klimavariationer i området. To hovedtemaer i forskningen har været at analysere sejens føde og færden. Hvad føde angår, så etablerede projektet en klar forbindelse mellem sej rekrutering som to år gammel og mængde af tobis og spærling larver (0-gruppe) de to foregående år. For 3-6 år gammel sej fandt man også en tæthedsafhængig vækst. Sejens færden er analyseret baseret på mærkningsforsøg og viser, at den færøske sej, over en vis størrelse, kan udvise markante vandringer. Udfra de fundne resultater har vi en langt bedre forståelse af sejens klimaafhængighed og forventer at kunne forbedre rådgivningen om sejbestandens udnyttelse i fremtiden. En PhD afhandling er indsendt og blev vellykket forsvaret tidligt i juni 2012. Seks videnskabelige artikler er publiceret, indsendt eller under udarbejdelse.

Phd projekt: On the forcing maintaining a flow of Atlantic Water to the ventilation areas in the Nordic Seas and their representation in climatic models

[Drivkræfterne for Atlanterhavsvandets indstrømning til de Nordiske Have og deres indkorporering i klimamodeller]

Færøerne ligger på tærsklen mellem det atlantiske ocean og de nordiske have og varmt atlanterhavsvand strømmer forbi Færøerne. Disse havstrømme er er en vigtig årsag til det forholdsvis varme Klime i Nordeuropa og antagelig også for den høje biologiske produktion i havområderne nord for Færøerne. Projektet havde til formål at undersøge størrelsen af kræfterne og de styrende processer bag disse strømme. Denne forståelse er afgørende, bl.a. for at kunne forudsige, hvordan eventuelle klimaændringer vil påvirke havstrømme og biologiske forhold ved Færøerne og i de nordiske have. projektet blev afsluttet uden indsendelse af PhD afhandling eller videnskabelige publikationer.

Post Doc projekt: Ocean model for high resolution modelling of the Faroe shelf circulation and the frontal system
[Havmodeller til højopløselig modellering af Færø-plateauets vandcirkulation og frontsystem]
Havmasserne på Færø-plateauet er delvis adskilt fra de omkring liggende vandmasser af en front, der omkranser plateauet. Denne adskillelse af plateau-vand muliggør et separat marint økosystem på Færø-shelfen, hvilket igen danner grundlag for mange lokale fiskebestande. Den biologiske produktion er dog meget variabel fra år til år, hvilket tilsyneladende har sin årsag i naturlige klima-variationer. Et modelarbejde, der er gennemført i dette projekt, simulerer med stor detalieringsgrad de varierende strømforhold på Færø-plateauet og frontens placering. Modelresultaterne har givet indsigt om mulige årsager til variationerne i den biologiske produktivitet i økosystemet, og en videre analyse planlægges. En videnskabelig artikel er under udarbejdelse.

Post Doc projekt: Paleoceanography around the Faroe Islands
[Palæoceanografiske studier ved Færøerne]
Projektet undersøger variationer i havklima i geologisk tidsskala. Ved at undersøge aflejringer i sedimentet er der påvist perioder med meget varierende klima og dettes indvirkning på marin produktivitet i området ved Færøerne. Projektet har kortlagt væsentlige klimaændringer og deres forbindelse til havstrømme og biologisk produktion i området gennem den holocæne periode. ?? videnskabelige artikler er publiceret, indsendt eller under udarbejdelse.

Alle dele af programmet er ikke gennemført som planlagt; men som helhed har det været vellykket. Vor viden er markant øget, især om det marine økosystem omkring Færøerne og dets afhængighed af klima og havstrømme. En PhD kandidat er afsluttet, og en vil forsvare sin indsendte afhandling i april 2013, 3 videnskabelige artikler er publiceret, 4 er indsendt, og 5 planlægges indsendt i løbet af 2013.

På de følgende sider gives først en engelsk oversigt over programmets formål og gennemførelse efterfulgt af mere detaljerede beskrivelser af de enkelte projekter. Derefter følger en oversigt over de væsentligste videnskabelige resultater fra hvert enkelt projekt. Rapporten afsluttes med et appendix, som viser agenda for to videnskabelige workshops, der er holdt i forbindelse med programmet.

Rapporten afsluttet 20 marts 2013

For styregruppen

Antoon Kuijpers	Bogi Hansen (formand)	Brian McKenzie
Eilif Gaard	Hjálmar Hátún	Steffen M. Olsen

Programme description

In the national budget for 2008-2011, the Danish parliament granted 9.2 million Danish Kroner to a 4-year research programme: *"Climate and Ocean Currents around the Faroe Islands"* (*"Klima og Havstrømme ved Færøerne"*) to be managed by the Danish Agency for Science Technology and Innovation (FI, Forsknings- og Innovationsstyrelsen). The programme was to stimulate research in climate and ocean currents in the region and their influence on the marine ecosystem and fisheries. It was carried out in cooperation between the Faroe Marine Research Institute (FAMRI, "Fiskirannsóknarstovan" later renamed as "Havstovan"), the Technical University of Denmark (DTU-Aqua), the Danish Meteorological Institute (DMI), and the Geological Survey of Denmark and Greenland (GEUS). A steering group was established, consisting of:

Bogi Hansen, PhD, professor, FAMRI, (chairman)
Eilif Gaard, Dr. Philos, FAMRI
Hjálmar Hátún, PhD, FAMRI
Antoon Kuijpers, PhD, GEUS
Steffen Malskær Olsen, PhD, DMI
Brian MacKenzie, PhD, professor, DTU Aqua

In addition, representatives from FI attended steering group meetings and managed financial matters.

At the first steering group meeting, held June 1st to June 2nd 2008 at FAMRI, it was decided to announce four PhD fellowships within the topics:

- *The physical linkage between the global climate and marine currents near the Faroes.*
- *Climate model scenarios for the Faroes.*
- *The influence of climate and marine currents on the oceanic ecosystems and pelagic fish stock in the areas around the Faroes.*
- *The influence of climate and marine currents on the marine ecosystem on the Faroese shelf.*

The fellowships were announced, but when the deadline for the call had expired on September 26th 2008, there were only three qualified applicants. At the next steering group meeting, October 10th 2008 at DTU-Aqua, these three were all accepted and it was decided to announce two additional 2-year postdoc fellowships:

- *High resolution modelling of the Faroe Shelf circulation and frontal system*
- *Reconstruction of Holocene North Atlantic Ocean variability around the Faroe Islands"*

These postdoc fellowships were announced and the two positions filled. The three PhD projects all started in January – February 2009 and the two postdoc projects started later in 2009. All five projects continued through 2010 and part of 2011 and the PhD projects into 2012, as well. Due to maternity and sick leave, the last PhD project was prolonged to January 8th 2013, at which time, the scientific work and the funding within the project ended. During the programme period, there were three additional steering group meetings held at FAMRI, June 2009, September 2010, and April 2011. At these meetings, the PhD supervisors were also invited, the five fellowship holders presented their progress, and the status of each individual project was discussed. In connection with two of these meetings, scientific workshops were held (June 2009 and September 2010), one of which included invited external experts (Appendix).

Details on the five projects are found on the next pages, followed by an overview of the main scientific results for each project individually.

PhD projects

Kirstin Eliasen

Sandeel, *Ammodytes* spp., as a link between climate and higher trophic levels on the Faroe shelf

Starting on February 5th 2009, ending January 6th 2013 with 49 weeks of combined maternity and sick leave. PhD project at Aarhus University with supervisors: Peter Grønkjær, Jens Tang Christensen, Bogi Hansen, Eilif Gaard, Jan Arge Jacobsen. The thesis was submitted on January 6th 2013 and is expected to be defended early in 2013. The project work was mainly carried out at the Faroe Marine Research Institute.

Papers published, submitted or in preparation:

Eliasen K, Reinert J, Gaard E, Hansen B, Jacobsen JA, Grønkjær P, Christensen JT (2011): Early life of sandeel in relation to primary production on the Faroe shelf. Marine Ecology Progress Series, 438:185-194

Eliasen K, Grønkjær P, Christensen JT, Hansen B, Gaard E, Jacobsen JA, Steingrund P, Debes H. (submitted): Biotic and abiotic effects on Faroese sandeel. Under review in Marine Biology.

Paper III: Eliasen K, Olsen B, Reinert J, Steingrund P, Grønkjær P, Christensen JT, Hansen B, Gaard E, Jacobsen JA. (submitted): Sandeel dependent seabird breeding at the Faroes. Under review in Seabirds.

Eydna í Homrum

The effects of climate and ocean currents on Faroe saithe

Starting on January 1st 2009, ending March 31st 2012. PhD project at the University of the Faroe Islands with supervisors: Bogi Hansen, Petur Steingrund, Hjálmar Hátún. The thesis was successfully defended 15th June 2012. The project work was mainly carried out at the Faroe Marine Research Institute.

Papers published, submitted or in preparation:

Homrum, E. í, Hansen, B., Steingrund, P. and Hátún, H. (2012): Growth, maturation, diet and distribution of saithe (Pollachius virens) in Faroese waters (NE Atlantic), Marine Biology Research, 8:3, 246-254.

Homrum, E. í, Hansen, B., Steingrund, P., Ofstad, L. H. and Hátún, H. (2009): Is the growth of Faroese saithe density dependent or climate dependent. ICES CM 2009/E:23.

Homrum, E. í, Hansen, B., Jónsson, S. Þ., Michalsen, K., Righton, D., Steingrund, P., Jakobsen, T., Mouritsen, R., Hátún, H., Armannsson, H. and Joensen, J. S. (submitted): Migration of saithe (Pollachius virens) in the Northeast Atlantic. Under review in ICES Journal of Marine Science.

Homrum, E. í, Eliasen, K., Hansen, B., Hátún, H., Gaard, E., Reinert, J. and Steingrund, P. (manuscript): Recruitment and growth of saithe (Pollachius virens) in Faroese waters. Planned submission in 2013.

Homrum, E. í, Hansen, B., Steingrund, P. and Hátún, H. (manuscript): Seasonal migration of Faroe saithe (Pollachius virens). Planned submission in 2013.

Steingrund, P., Gaard, E., Reinert, J., Olsen, B., Homrum, E. í and Eliasen, K. (manuscript): Trophic relationships on the Faroe Shelf ecosystem and potential ecosystem states. Planned submission in 2013.

Brian Hansen

On the forcing maintaining a flow of Atlantic Water to the ventilation areas in the Nordic Seas and their representation in climate models

Starting on February 1st 2009, ending May 31st 2012, PhD project at Copenhagen University with supervisors: Eigil Kaas and Steffen M. Olsen. All university courses and obligations during the Ph.D. project period have been completed, but no thesis was submitted. The project work was mainly carried out at the Danish Meteorological Institute.

Postdoc projects

Till Andreas Soya Rasmussen

High resolution modeling of the Faroe Shelf

Starting on November 10th 2009, ending May 31st 2011. Postdoc project at the Danish Meteorological Institute.

Papers published, submitted or in preparation:

Rasmussen, T. A. S., S. M. Olsen, B. Hansen, K. M. H. Larsen, H. Hátún (manuscript): Modeling of the Faroe shelf water exchange and variability. Planned submission in early 2013.

Francisca Staines-Urías

Holocene ocean circulation changes around the Faroe Islands

Starting on June 1st 2009, ending May 31st 2011. Postdoctoral project at the Geological Survey of Denmark and Greenland – GEUS.

Papers published, submitted or in preparation:

Staines-Urías, F., Kuijpers, A., Korte, C. (manuscript): Evolution of subpolar North Atlantic surface circulation since the early Holocene inferred from planktonic foraminifera faunal and stable isotope records. Under review in Quaternary Sciences Reviews (submitted May 2012).

Staines-Urías, F., Morigi, C., Sicre, M.-A., Kuijpers A. (manuscript): Recurrence of deep-sea corals around the Faroe Island in association with late Holocene oceanographic changes in the eastern North Atlantic. Planned submission in 2013 (Nature Geosciences).

Sandeel, *Ammodytes* spp., as a link between climate and higher trophic levels on the Faroe shelf

Kirstin Eliasen, PhD project

1. INTRODUCTION

In many of the highly productive ecosystems of the world there tends to be a crucial intermediate trophic level occupied by small planktivorous fish dominated by one, or at most a few, species. These canalise the energy from primary producers to top-predators, such as piscivorous fish, seabirds and marine mammals. Among others, sandeel are often observed to function at this intermediate level (Figure 1). Sandeel are small, elongated, lipid-rich and schooling fish without swimbladder. Sandeel are buried within sandy sediment for up to ten months a year, only emerging to the water column to forage in daylight during the high-productive period in spring/summer and shortly in mid-winter to spawn. This burying behaviour restricts the sandeel distribution to areas of suitable sediment and bottom depths allowing foraging in the upper water masses. Sandeel are throughout their lives zooplanktivorous, with their chief food organisms being copepods (mainly *Calanus finmarchicus* and *Temora longicornis*), crustacean larvae and annelids.

On the Faroe shelf, the annual variations in growth and recruitment of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) have been found to correlate with the annual variation in potential new primary production in the shelf water ecosystem during the high productive period. This implies an almost instantaneous transfer of energy from primary producers to higher trophic levels, and is believed only possible through a fast growing intermediate fish species such as sandeel (Steingrund and Gaard, 2005). Also seabirds have been shown to react rapidly to variations in primary production (Gaard et al., 2002).

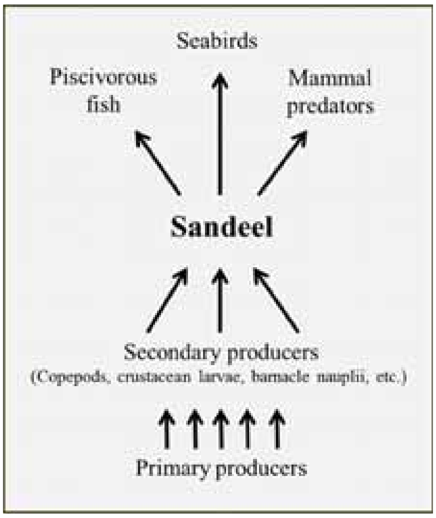


Figure 1. Example of a marine food web with sandeel as an example of an intermediate species channelling energy from primary production via secondary producers to higher trophic levels.

This rapid transfer of energy from primary producers to higher trophic levels observed on the Faroe shelf has left researchers wondering which organism(s) is/are responsible for this. So far, the method of elimination has left us with a fast growing zooplanktivorous fish species, with the best qualified guess being sandeel.

The objectives of the current study are to investigate the ecological role of sandeel in the Faroe shelf ecosystem, and to estimate which influence changes in climate might have on it.

2. MATERIAL

The data used in this study derive from several different sources:

- Water temperature on the Faroe shelf dating back to February 1992.
- Accumulated new primary production (PP-index) in the Faroe shelf ecosystem during spring since 1990.
- Weekly measurements of chlorophyll *a* on the Faroe shelf from April to late June since 1997.
- Juvenile sandeel from 0-group surveys conducted on the Faroe shelf in late June/early July since 1982.
- Age 1+ sandeel from sandeel surveys conducted on the Faroe shelf in mid-April 2007-2011.
- Recruitment (age 2), mean weight-at-age and total biomass of cod on the Faroe plateau since 1982.
- Breeding success of arctic tern, black-legged kittiwake, common guillemot and northern fulmar at Faroes.
- Analysis of sediment samples from 106 locations on the Faroe shelf.
- Zooplankton data from sandeel stomachs and the surrounding environment.
- Cod stomach content data from two annual groundfish surveys on the Faroe Plateau dating back to 1997.

3. RESULTS

3.1 Sandeel habitat on the Faroe shelf

By grouping sediment samples from 106 different sites into the sediment categories of Greenstreet et al. (2010), a preliminary attempt was made at identifying areas suitable for sandeel habitation on the Faroe shelf and 70, 14, 20 and 2 of the sites studied could be defined as unsuitable, suitable, sub-prime and prime for sandeel habitation, respectively.

3.2 Recruitment

Sandeel is not and has never been commercially exploited in Faroese waters, and thus no fisheries data are available. Nevertheless, annual 0-group surveys have been conducted on the Faroe shelf for more than three decades, and although originally designed to obtain information on juvenile cod, the results of the 0-group sandeel sampled on these surveys are of good quality, showing large annual variations in both average length and abundance.

Sandeel are zooplanktivorous throughout their lives, but zooplankton data adequate for estimating food availability in the early life of sandeel are not available for the Faroe shelf area. Nevertheless, continuous recordings of both potential new primary production in the shelf water ecosystem during the high productive period and chlorophyll *a* concentrations have been performed on the Faroe shelf since 1990 and 1997, respectively. Several studies have shown the seasonal development in primary production to be followed by a subsequent and similar development in secondary producers, e.g. zooplankton and this is also the case on the Faroe shelf (Debes and Eliasen, 2006).

Therefore, it was considered reasonable to use the new primary production (defined as an PP-index) and chlorophyll *a* data as proxies for food availability of juvenile sandeel, and 43% and 73% (Figure 2) of the annual variation in the 0-group sandeel biomass index (proportional to the number times length cubed) could be explained by the annual variations in the PP-index and chlorophyll *a* concentration, respectively (Paper I).

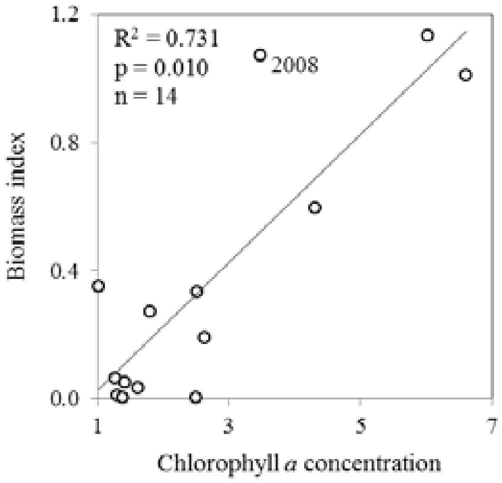


Figure 2. Relationships between the 0-group sandeel biomass index and the chlorophyll a concentration on the Faroe shelf.

The 0-group sandeel data also revealed another interesting relationship, where the abundance (*N*) was significantly correlated ($R^2 = 0.191$, $p = 0.017$, $n = 29$) with the average length (*L*) of juvenile sandeel. This might be explained in terms of food-dependent starvation mortality, but could also be due to length-dependent predation. High availabilities of food do not only reduce starvation mortality, but also lead to an earlier size-related exclusion of predators. Indeed, two models on juvenile sandeel mortality dominated by starvation and length-dependent predation, respectively, came up with exactly the same relationship: $ln(N) = a - b/L$, where a and b are constants. To validate this model, $ln(N)$ was plotted against $1/L$, and it explained 72% of the variance in $ln(N)$ (Paper I).

The year 2008 is seen to be an outlier In Figure 2, which is because the average abundance of 0-group sandeel was observed to be exceptionally high that year. However, year 2008 also appeared to be an outlying year when further data analyses were performed. Thus, there are many indications that the very high 0-group abundance in 2008 was not representative, either due to sampling problems or for other reasons.

3.3 Food of adult sandeel

Sandeel only leave their refuge in the sediment to spawn in mid-winter and to forage in the daylight of spring and summer. Sandeel are visual feeders, and some sort of consistency and selectivity were to be observed in their choice of prey on the Faroe shelf. Their favourite prey seemed to be large copepod species (*C. finmarchicus*, *T.*

longicornis and *Pseudocalanus* sp.), and polychaet, amphipod and decapod larvae. Although large copepods only represented ~50% of the total abundance of prey specimens in the environment, their contribution in the sandeel stomachs ranged from 50 to more than 90% of the total.

3.4 Variation in physical condition

Since the older sandeel sampled were from mid-April, they had most likely recently ended their overwintering phase. It was thus assumed that the results represented the circumstances that influenced the sandeel in their newly ended overwintering phase and/or in their foraging period in the year before, rather than those of the same year.

Large interannual variation has been observed in the zooplankton biomass on the Faroe shelf. Sandeel growth in length was positively correlated with the zooplankton biomass in June of the intervening year (Figure 3), indicating sandeel growth to be food dependent. This is consistent with results from the North Sea and Shetland waters, where the temporally reduced sandeel growth is believed to be due to decreasing trends in *C. finmarchicus* abundances (Bergstad et al. 2002).

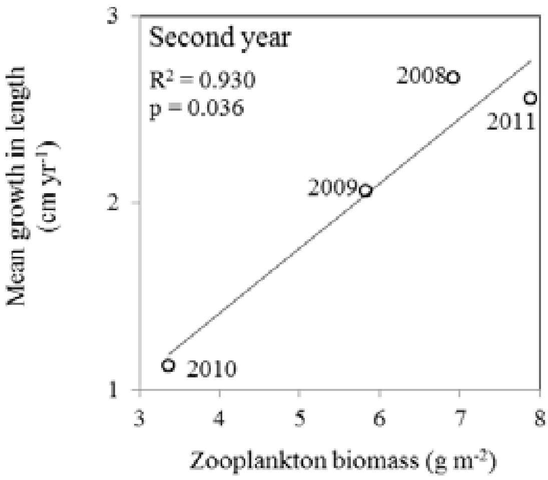


Figure 3. *Growth in length in the second year of life of sandeel sampled in the period 2006-2011 in relation to the zooplankton biomass in June of the intervening year (2006-2010).*

The temperature of the Faroese shelf water varies interannually, and in the years of the present study (2007-2011), the average winter (October-March) temperature varied by 0.5°C. By correlating the condition (Fulton´s *K*) of 1 and 2-yrs-old sandeel with the average winter temperature of the preceding winter, in which they had been buried passively in the sediment, a significant negative relationship was found between the two.

3.5 Ecological importance

Using the established dependence on the overwintering temperature, sandeel (age 1) condition was simulated back to 1992 (Paper II), and correlated with Faroe shelf cod mean weight-at-age 2. The annual variation in sandeel condition could explain almost one third ($R^2 = 0.285$, $p = 0.007$) of the annual variation observed in the mean weight-at-age of young cod on the Faroe shelf in the period 1992-2010.

Table 3. *Squared correlation coefficients (R^2) of the relationships between 0-group sandeel and the breeding success of four seabird species at the Faroes. The estimated abundance is derived from the established relationship between average length and abundance (section 3.2). * and ** indicate significance of $p < 0.05$ and $p < 0.01$, respectively. ns indicates non-significant relationships.*

		0-group sandeel			
Breeding success	n	Average length	Abundance 2008 incl.	Abundance 2008 excl.	Estimated abundance
Arctic tern	9	0.434 ns	0.194 ns	0.692 *	0.503 *
Black-legged kittiwake	26	0.409 **	0.054 ns	0.334 **	0.534 **
Common guillemot	25	0.251 *	0.193 ns	0.248 *	0.348 *
Northern fulmar	11	0.071 ns	0.019 ns	0.101 ns	0.116 ns

Sandeel are important food for many breeding seabirds and for some species, they are essential for chick survival. The time-series on seabird breeding at the Faroes are of variable lengths. Consistent with findings elsewhere, the annual variance in the breeding of arctic terns and kittiwakes were best explained by variations in the juvenile sandeel stock (Paper III). However, the correlations between seabird breeding and 0-group sandeel abundance were only significant when 2008 had been excluded from the time-series or when an estimated abundance was used (Table 1).

Seabirds have been suggested to make good status indicators of the local marine ecosystem and are used as both bio-monitors of ecosystem state with regard to e.g. pollution, and as quantitative indicators of specific ecosystem components such as the abundance of a prey species, e.g. sandeel.

The results presented in Table 1 indicated that the breeding success of black-legged kittiwake is strongly correlated with 0-group sandeel, and by correlating its breeding success with cod recruitment and biomass in the same and following year, significant correlations were established in all instances (Paper III).

3.6 Climatic effects

Sandeel condition in April was found to decrease with increasing temperature. The same trend was also observed in the absolute fat content of 1-yr-old sandeel, where it decreased by a factor of ~2.5 with an increase in average winter temperature of 0.5°C (Figure 4).

With an extrapolation of the regression between the winter temperature and the absolute fat content of the 1-yr-old sandeel, the absolute fat content hits zero when the mean winter temperature reaches 8.5°C.

The Faroe shelf is characterised by relatively high winter temperatures, which makes Faroese sandeel especially vulnerable to warming. The data material on which this is based is small and further study is needed but, if substantiated, this might indicate that sandeel in the north Atlantic before long will be facing a hard time surviving if climate change in the future leads to further elevations in temperature.

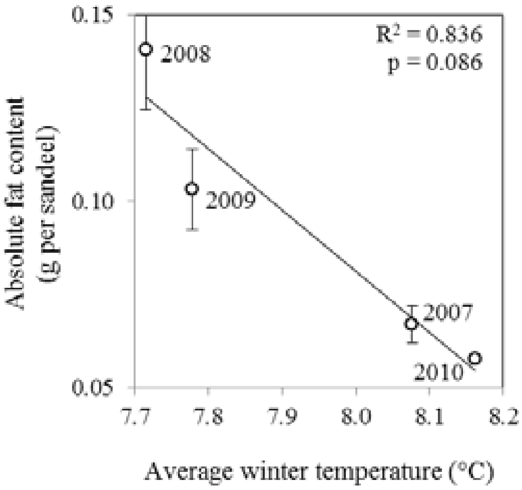


Figure 4. *Absolute fat content of 1-yr-old sandeel in mid-April in relation to the average temperature of the preceding winter (October-March).*

Additionally, the timing and intensity of the spring bloom on the Faroe shelf has been observed to vary considerably from one year to the next and one hypothesis is that these variations are linked to the air temperature during the preceding months (Hansen et al., 2005). Thereby, and through food availability, sandeel might also be indirectly influenced by climate.

4. CONCLUSIONS

By showing the same correlations with primary production as cod, haddock and guillemots, the rapid transfer of energy from primary producers to higher trophic levels observed on the Faroe shelf might well be mainly through sandeel. This was further supported by the sandeel dependent breeding success of four seabird species at the Faroes, in particular that of black-legged kittiwakes. Additionally, when the breeding success of kittiwakes was used as an indicator of sandeel availability, it could explain approximately half of the annual variations observed in cod recruitment and biomass on the Faroe shelf.

Annual variations were observed in some of the physical traits that determine the quality of sandeel as prey for higher trophic species such as seabirds and commercially important fish. The zooplankton biomass in the foraging period had the highest influence on sandeel length and sandeel growth in length, while temperature in the overwintering phase, where sandeel lie buried passive in the seabed, had large influence on their condition (Fulton´s *K*) and absolute fat content (g per sandeel). Although the temperature of the overwintering phase only varied by 0.5°C within the time span of the present study, the results were validated by the work of van Deurs et al. (2011) and conjured one possible and dismal scenario that some of the north Atlantic shelf ecosystems might experience if climate change in the future will lead to further elevations in temperature. Much more research is needed, however, to evaluate this scenario.

5. REFERENCES

Bergstad OA, Høines AS, Jørgensen T (2002) Growth of sandeel, Ammodytes marinus, in the northern North Sea and Norwegian coastal waters. Fish Res 56:9-23Behrens et al. 2009

Debes HH, Eliasen K (2006) Seasonal abundance, reproduction and development of four key copepod species on the Faroe Shelf. Mar Biol Res 2(4):249-259

Gaard E, Hansen B, Olsen B, Reinert J (2002) Ecological features and recent trends in physical environment, plankton, fish stocks and sea birds in the Faroe Plateau ecosystem. In: Sherman K, Skjoldal H-R (eds) Large Marine Ecosystems of the North Atlantic, Elsevier Science BV, Amsterdam, pp 245-265

Greenstreet, S. P. R. Holland, G. J. Guirey, E. J. Armstrong, E. Fraser, H. M. & Gibb, I. M. 2010. Combining hydroacoustic seabed survey and grab sampling techniques to assess "local" sandeel population abundance. ICES Journal of Marine Science 67: 971-984.

Hansen B, Eliasen SK, Gaard E, Larsen KMH (2005) Climatic effects on plankton and productivity on the Faroe Shelf. ICES J Mar Sci 62:1224-1232

Steingrund P, Gaard E (2005) Relationship between phytoplankton production and cod production on the Faroe Shelf. ICES J Mar Sci 62:163-176

van Deurs M, Hartvig M, Steffensen JF (2011) Critical threshold size for overwintering sandeel (Ammodytes marinus). Mar Biol 158:2755-2764

Paper I: Eliasen K, Reinert J, Gaard E, Hansen B, Jacobsen JA, Grønkjær P, Christensen JT (2011) Early life of sandeel in relation to primary production on the Faroe shelf. Marine Ecology Progress Series 438:185-194

Paper II: Eliasen K, Grønkjær P, Christensen JT, Hansen B, Gaard E, Jacobsen JA, Steingrund P, Debes H. Biotic and abiotic effects on Faroese sandeel. Marine Biology (*submitted*)

Paper III: Eliasen K, Olsen B, Reinert J, Steingrund P, Grønkjær P, Christensen JT, Hansen B, Gaard E, Jacobsen JA. Sandeel dependent seabird breeding at the Faroes. Seabirds (*submitted*)

The effects of climate and ocean currents on Faroe saithe

Eydna í Homrum, PhD-project

1. INTRODUCTION

Saithe are distributed widely in the North Atlantic where they are also fished throughout the region. In the Faroe Islands the saithe fishery has become increasingly important in recent years, with an export value as high as for the cod fishery, which has traditionally been the most important demersal fishery in the Faroe Islands. Annual landings have varied between 20 and 60 thousand tonnes in the last fifty years, and the fluctuations in the landings reflect to a large degree that the stock has varied in size. Since 1961, the saithe fishery has been monitored and stock assessments have been conducted. During this period, the saithe stock has increased and decreased cyclically three times – each period lasting approximately 20 years.

In the last decades, much focus has been on scientific research in the interactions between environment and fish stocks. It has been demonstrated, for example, that primary production on the Faroe shelf controls both individual growth and recruitment to the adult stocks of cod and haddock (Gaard et al. 2002; Steingrund and Gaard 2005). Similarly, the biology of blue whiting is affected by oceanographic variability in the North Atlantic, such that the spawning area increases in size and the distribution of blue whiting changes when the subpolar gyre is weak (Hátún et al. 2009a; Hátún et al. 2009b).

The Faroe saithe stock size exhibits a temporal pattern similar to the subpolar gyre index (H. Hátún et al. 2005). This correlation was the background for the present PhD-project. The main objective of the PhD-project was to investigate links between the biology of Faroe saithe and the environment surrounding them.

2. MATERIAL

The project focused on using existing datasets to describe the biology of saithe in Faroese waters. The three most important sources are listed below.

Firstly, material acquired during bottom trawl surveys in February-March and August from 1994 – 2010 was available (Figure 1). The data collected consisted of station data (time, position, depth and catch (weight)) and individual fish data (e.g. length, weight, age, sex, sexual maturation). For a subsample of the aged fish, stomach content data were available. These data allowed for a description of the general biology of Faroe saithe, which was published in Marine Biology Research (Homrum et al. 2012).

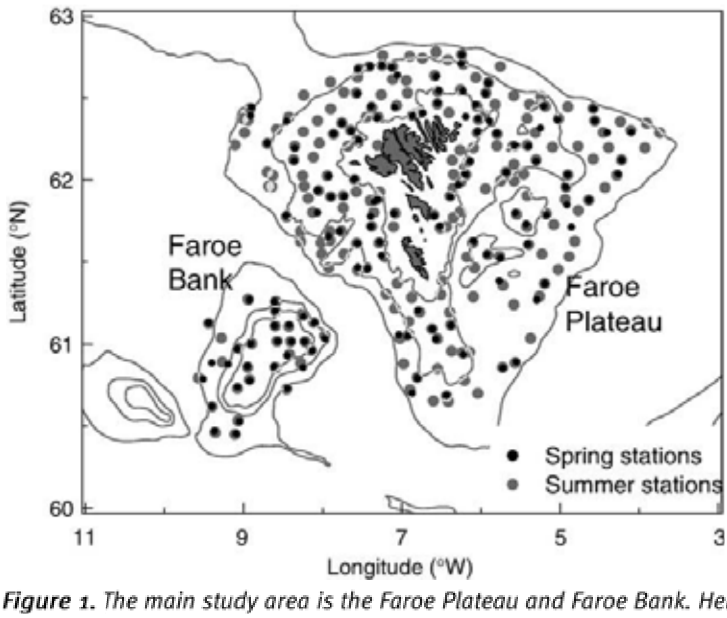


Figure 1. The main study area is the Faroe Plateau and Faroe Bank. Here the trawling stations from the annual spring (black) and summer (grey) groundfish surveys are indicated.

Secondly, we used data from mark-recapture experiments from Faroe Islands, Norway and Iceland, thus covering a large proportion of the distribution area of Northeast Atlantic saithe. The data available in these datasets were generally position, time and length at tagging and recapture. For the Norwegian data, length was unfortunately not available at recapture. Therefore an approximation of age 5 and older was used to describe migration of adult saithe.

Thirdly, samples of landings from the commercial fishery gave information on length, weight and age on a monthly basis.

In addition, several other datasets were used e.g. index on primary production on the Faroe Shelf, the subpolar gyre index, an annual survey on fish larvae (0-group survey), logbook data from commercial vessels targeting saithe in the fishery and finally, stock data from the stock assessments in reports from the ICES working group (NWWG) that quality checks the assessment of Faroe saithe.

3. RESULTS

3.1 General biology

The main spawning of Faroe saithe was found to be in February-March on the eastern side of the Faroe Plateau (Homrum et al. 2012 (Paper I)). The growth of male and female saithe was very similar, but the sexes differed in time of sexual maturity, with half of the female saithe being mature at age 6, which is approximately a year later than the males. At age 6, Faroe saithe were round 60 cm in length. The main diet of Faroe saithe was blue whiting, Norway pout, Euphausiids and sandeel. As saithe grew and moved farther out on the Plateau, blue whiting became a more pronounced part of the diet (Figure 2) (Homrum et al. 2012 (Paper I)).

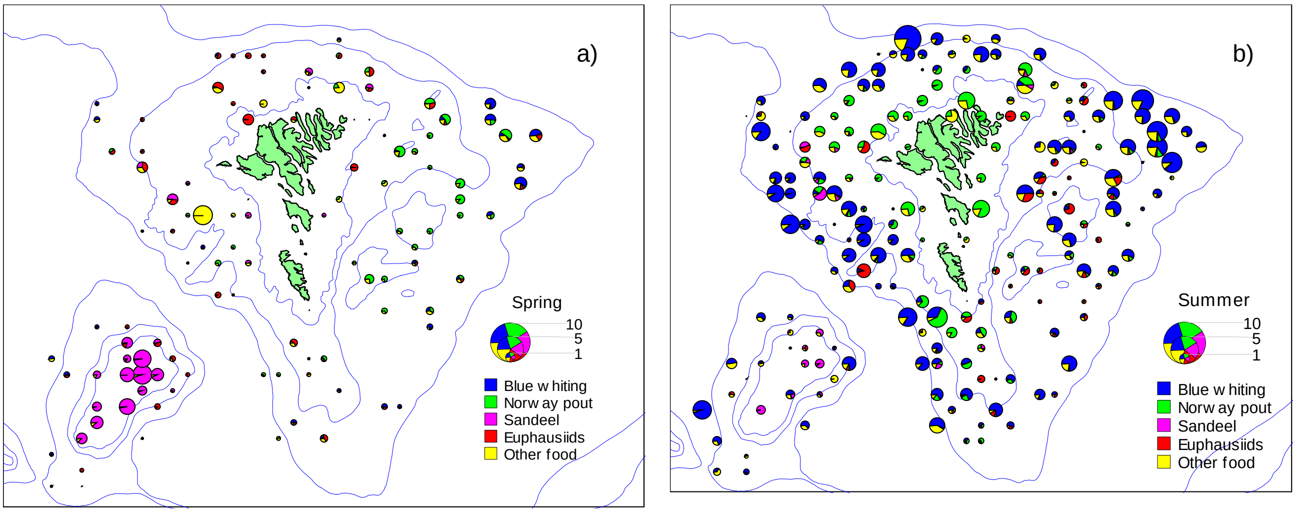


Figure 2. *The diet of saithe on the Faroe Plateau and Faroe Bank in a) spring and b) summer. All age groups pooled. The size of the points corresponds to the weight of preygroups divided by predatorlength cubed.*

3.2 Recruitment

The recruitment of three year old saithe to the adult stock was linked to productivity on the Faroe Shelf (Paper III). This could be seen as a correlation between recruitment of saithe and abundance of sandeel and Norway pout larvae in June in the two years preceding the recruitment, i.e. when saithe were age 1 and 2 (Figure 3). Also the recruitment was positively correlated to primary production, but not as strongly as to the abundance of prey species. The recruitment was also weakly negatively correlated to the subpolar gyre, i.e. increased recruitment when the subpolar gyre was weak.

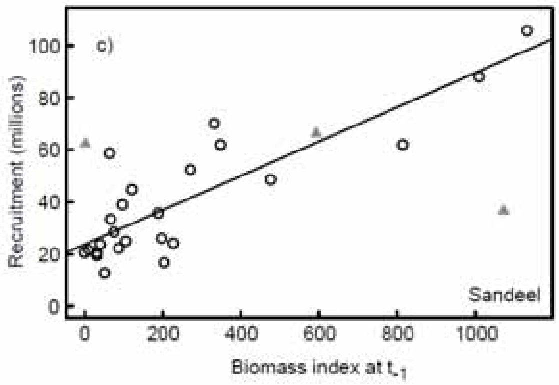


Figure 3. *Recruitment of saithe at age 3 in relation to the biomass index of sandeel fry when saithe were two year old. The grey triangles indicate the three last years in the series, in which the recruitment estimates are generally rather uncertain.*

There are indications that a balance in the ecosystem on the Faroe Plateau has shifted round the mid 20th century (Paper VI). Prior to 1970, the cod and haddock stocks constituted a larger percentage of the combined cod, haddock and saithe stocks than in recent years. In the 1960s, sandeel was in all years a significant part of the cod diet (Rae 1967). In recent years, the saithe stock has increased and sandeel are important diet of cod only few consecutive years. The sum of cod, haddock and saithe production, however, seems to correlate to primary production on the Faroe Shelf. This could indicate that circumstances on the shelf are more crucial for good recruitment to the saithe stock than circumstances in the deeper areas of the Plateau.

3.3 Density dependent growth of Faroe saithe

Individual fish weights have fluctuated in counter phase with the stock size, such that individual fish are smaller when the saithe stock is large. For 3-6 year old saithe, this seems to reflect density dependent growth, where the total number of fish in the saithe stock can explain a great deal of the weight increase from one year to the next. Such density dependent effects were not seen for the oldest saithe (>8 years).

3.4 Migration

Saithe are a migratory species, but the migration rates vary among the regions in the Northeast Atlantic. Emigration rates from Icelandic waters were very limited (less than 1%), whereas approximately 40% of adult Faroese saithe were recaptured outside Faroese waters – the majority in Icelandic waters (Figure 4) (Paper II). Adult saithe, tagged in Norwegian waters exhibited intermediate emigration rates with 7% recaptured outside the European Continental shelf (Paper II). The migrated distances increased with increasing fish length up until 60 cm, after which the migrated distances remained on the same level. Saithe in Norwegian waters migrated the longest differences and young saithe in Faroese waters migrated the shortest distances.

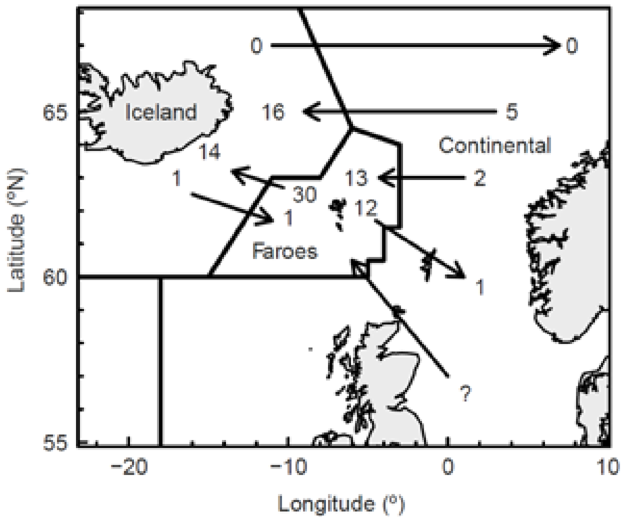


Figure 4. Map showing the estimated migration (in %) among the Faroese, Icelandic and Continental stock areas of saithe, where more than 3 years had elapsed between tagging and recapture. At the start of an arrow, the emigration percentage is listed and at the end of an arrow the immigration percentage is shown.

When saithe were 5-7 years old, the largest saithe in every age-group started a seasonal migration pattern. In the spawning season, all size groups were gathered, but in summer, there were fewer of the largest fish in these age-groups (Paper IV). This was seen as a seasonal pattern in the mean size at age with the smallest mean size in the summer months (Paper V) and most pronounced in years where the mean length was generally higher than 60 cm. The length, at which this emigration started, corresponded to the length, when saithe start to mature sexually, and therefore it is possible that what was observed, was a seasonal migration pattern between spawning areas in winter and feeding areas in summer. These conclusions regarding seasonal migration were based on seasonal changes in length distributions, but the conclusions are supported by tagging data, which show that saithe, tagged on the Faroe Plateau were frequently recaptured in Icelandic waters in summer, but seldom in the spawning season (February – March), when most adult fish were recaptured in Faroese waters (Paper IV).

Virtual population analyses (VPA) do not traditionally incorporate migration. A modified VPA was run, which included migration. This model showed that the stock variations were very similar to VPA without migration (Paper IV). VPA without migration tends to underestimate the abundance of saithe and overestimate the fishing mortality.

4. CONCLUSIONS

The improved living conditions in the deeper regions of the Faroe Plateau, when the subpolar gyre weakens, were originally assumed to cause the concurrent increase in the stock biomass of saithe. As the project has proceeded, not many results have been found that support this hypothesis – although the increased amounts of blue whiting when the subpolar gyre is weak, are valuable to the adult saithe residing in the deeper regions of the Faroe Plateau. Rather, it seems that the primary production on the Faroe shelf has the most profound effect on the Faroe saithe. When productivity increases, the recruitment to the saithe stock improves. As the stock size increases, the growth of individual saithe is impeded and this in turn affects migration, as migration seems to be length dependent (Paper II and IV). Although we do not know the details, there is much that suggests that varying climate has a large impact on Faroe saithe through the effects on productivity.

In addition, substantial emigration of adult Faroe saithe has been found. This migration does, however, not seem to radically change the conclusions from the traditional stock assessments, which do not include migration, although the stock size in absolute numbers may not be accurate.

5. REFERENCES

Gaard, Eilif, Bogi Hansen, Bergur Olsen and Jákup Reinert. 2002. Ecological features and recent trends in the physical environment, plankton, fish stocks and seabirds in the Faroe shelf ecosystem. In: *Changing states of the Large Marine Ecosystems of the North Atlantic*, ed. K Sherman and H.-R. Skjoldal.

Hátún, H., M. R. Payne and J. A. Jacobsen. 2009. The North Atlantic subpolar gyre regulates the spawning distribution of blue whiting (Micromesistius poutassou). *Canadian Journal of Fisheries and Aquatic Sciences* 66: 759–770. doi:10.1139/F09-037, .

Hátún, H., M.R. Payne, G. Beaugrand, P.C. Reid, a.B. Sandø, H. Drange, B. Hansen, J.a. Jacobsen and D. Bloch. 2009. Large bio-geographical shifts in the north-eastern Atlantic Ocean: From the subpolar gyre, via plankton, to blue whiting and pilot whales. *Progress in Oceanography* 80, Nr. 3-4 (March): 149–162. doi:10.1016/j.pocean.2009.03.001, http://linkinghub.elsevier.com/retrieve/pii/S0079661109000135 (Accessed: 31. October 2012).

Hátún, H., A. B. Sandø, H. Drange, B. Hansen and H. Valdimarsson. 2005. Influence of the Atlantic subpolar gyre on the thermohaline circulation. *Science* 309, Nr. 5742: 1841–1844. WOS:000231989500045.

Rae, B. B. 1967. The Food of Cod on Faroese Grounds. *Marine Research* 6: 1–23.

Steingrund, Petur and Eilif Gaard. 2005. Relationship between phytoplankton production and cod production on the Faroe Shelf. *ICES Journal of Marine Science* 62, Nr. 2 (April): 163–176. doi:10.1016/j.icesjms.2004.08.019, http://icesjms.oxfordjournals.org/cgi/doi/10.1016/j.icesjms.2004.08.019 (Accessed: 1. June 2011).

Paper I: Homrum, E. í, Hansen, B., Steingrund, P. and Hátún, H. (2012): Growth, maturation, diet and distribution of saithe (Pollachius virens) in Faroese waters (NE Atlantic), Marine Biology Research, 8:3, 246-254.

Paper II: Homrum, E. í, Hansen, B., Jónsson, S. Þ., Michalsen, K., Righton, D., Steingrund, P., Jakobsen, T., Mouritsen, R., Hátún, H., Armannsson, H. and Joensen, J. S. (resubmitted): Migration of saithe (Pollachius virens) in the Northeast Atlantic: resubmitted for publication in ICES Journal of Marine Science.

Paper III: Homrum, E. í, Eliasen, K., Hansen, B., Hátún, H., Gaard, E., Reinert, J. and Steingrund, P. (manuscript): Recruitment and growth of saithe (Pollachius virens) in Faroese waters.

Paper IV: Homrum, E. í, Hansen, B., Steingrund, P. and Hátún, H. (manuscript): Seasonal migration of Faroe saithe (Pollachius virens).

Paper V: Homrum, E. í, Hansen, B., Steingrund, P., Ofstad, L. H. and Hátún, H. (manuscript): Is the growth of Faroese saithe density dependent or climate dependent.

Paper VI: Steingrund, P., Gaard, E., Reinert, J., Olsen, B., Homrum, E. í and Eliasen, K. (manuscript): Trophic relationships on the Faroe Shelf ecosystem and potential ecosystem states.

On the forcing maintaining a flow of Atlantic Water to the ventilation areas in the Nordic Seas and their representation in climate models

Brian Hansen, PhD-project

1. INTRODUCTION

The proposed work was to use numerical ocean-model experiments to disentangle the driving forces of the Atlantic Inflow, and use the results to form the basis for identifying causes of change in the strength of the inflow in fully coupled climate model scenarios for the 21st century.

2. MODELING

A low resolution and a high resolution model were set up and run during the project:

- Nucleus for European Modeling of the Ocean (NEMO) is a 1x1 degree z-level ocean model run at DMI coupled to an atmospheric circulation model in auspices of the ec-earth project. NEMO was also run as a stand-alone ocean model during the Ph.D. project.
- HYbrid Coordinate Ocean Model (HYCOM) is a 3D ocean circulation model that combines two sets of vertical coordinate, z-layers and isopycnals.

With HYCOM, a hindcast of the latest 10 years was made and analyzed. 2D fields of all ocean parameters have been extracted from the data set. Time series of volume transport were made for the in-, out- and overflow branches across the Greenland Scotland Ridge and compared to available measurements. Statistical analysis has been made, and modes of variability compared to variability of the atmospheric forcing of the model.

Two papers were planned to be the outcome of these initial model simulations. Among other findings, the simulations showed two interesting things. 1) A much stronger than expected correlation between local wind stress and volume transport into the Nordic Seas. And 2), A change in the Faroe Branch inflow path, depending on the location of the front between Arctic- and Atlantic water masses. Both of these require more investigation and analysis to validate and publish the results.

High resolution modeling of the Faroe Shelf

Till Andreas Soya Rasmussen, Postdoc project

1. INTRODUCTION

The motivation for this study is to improve the understanding of the variations of the primary production on the Faroe shelf. Observations have given rise to many hypotheses attempting to explain the phenomena but none of these has been proven right. In order to get a better description of the physical properties of the shelf water mass, a 3D ocean model has been set up.

The Faroe shelf water mass is the water mass that is located on the shallow areas near the Faroe Islands between Scotland and Iceland, typically defined to be within the 100 m depth contour that surrounds the islands (Figure 1). The shelf water mass is relatively isolated from the surrounding water masses by a clockwise residual circulation (Larsen et al., 2008). Furthermore, the strong tidal currents mix the shallow parts of the shelf water mass which results in a fully mixed water column.

The isolated character of the water mass influences the ecosystem, thus it differs from the surrounding waters (Debes et al., 2008). The marine ecosystem on the Faroe shelf has been shown to be tightly controlled by the primary production during the spring bloom with sandeel, economically important demersal fish, as well as seabirds clearly linked to the intensity of the spring bloom. The spring bloom has been monitored since the early 1990s (Gaard et al., 1998) and is found to vary greatly from one year to another. A complete explanation for these variations has not been demonstrated but it has been suggested that physical processes on the shelf, including circulation and exchange, are the main controlling mechanism of the spring bloom.

This is based on a large number of in situ measurements obtained by the Faroe Marine Research Institute. A wrap up of these measurements has been described by (Larsen et al., 2008, 2009). The measurements show the shelf circulation and the difference in especially temperature between the on shelf water and the off shelf water. The measurements also show a short term temperature difference to the south of the Faroe Islands, which indicates periods with a different water mass in this area, see white dot on Figure 1. These observations are the key element in the verification of the model. The observations do not give a clear answer to the exact reason for the annual variations of the primary production but they have formed the basis for many hypotheses that try to explain this.

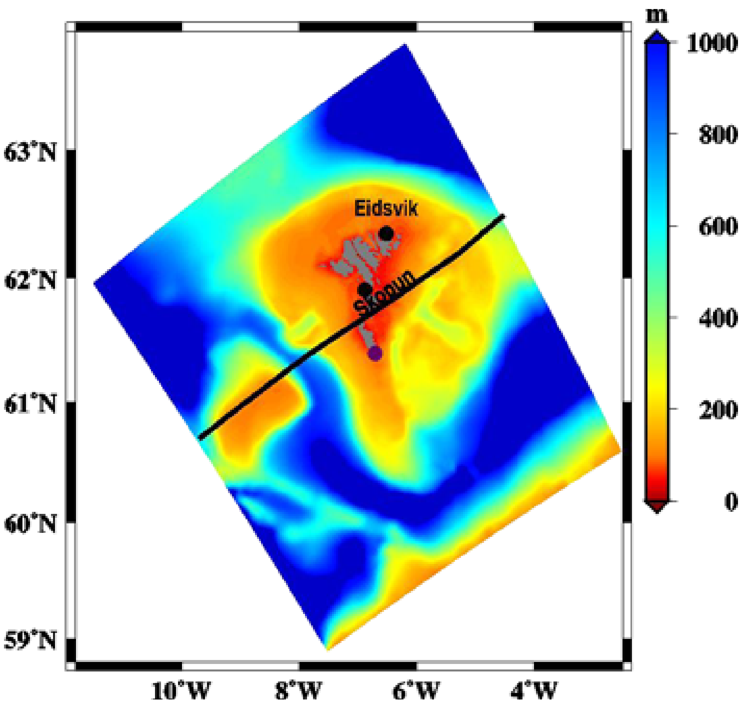


Figure 1. Bathymetry around the Faroe Islands. The black line indicates the cross section where modeled data have been extracted. Black dots are the data points where modeled and measured data are compared. The dot indicates the location of the measured data in the southern part of the Faroe Islands.

2. MODEL DESCRIPTION

The model is a slightly modified version of HYCOM (HYbrid Coordinate Ocean Model) that is isopycnal in the open, stratified ocean, but smoothly reverts to a terrain-following coordinate in shallow coastal regions, and to z-level coordinates in the mixed layer and/or unstratified seas.

This results in a z-level model on the Faroe shelf. The vertical mixing is defined by the KPP scheme. The oceanographic boundary conditions are provided by a hindcast archive from the Danish Meteorological Institute that covers the Arctic and the North Atlantic Ocean with a horizontal resolution approximately 10 km in both directions. The high resolution regional model is based on the same model with horizontal grid size ranging from 750m to 1300m and the resolution is highest near the Faroe Islands. The body tides are described with eight tidal constituents, namely Q1, K2, P1, N2, O1, K1, S2 and M2. The model was run from the beginning of 2000 to the end of 2009 with ERA-Interim atmospheric forcing.

3. RESULTS

3.1 Shelf circulation

The first target of this study was to ensure that the model was able to represent the flow around the Faroe Islands.

Figure 2 shows the clockwise current, which is derived from the average of all velocity vectors extracted on hourly basis in the period from 2000 to 2009. The current has a magnitude which is similar to the observed values. It can also be seen that high velocity vectors with different directions are seen near the southern tip of the Faroe Islands and near the north western part of the islands. Both the Faroe Bank Channel overflow and the boundary current near the Shetland Islands (southern part of the domain) are seen.

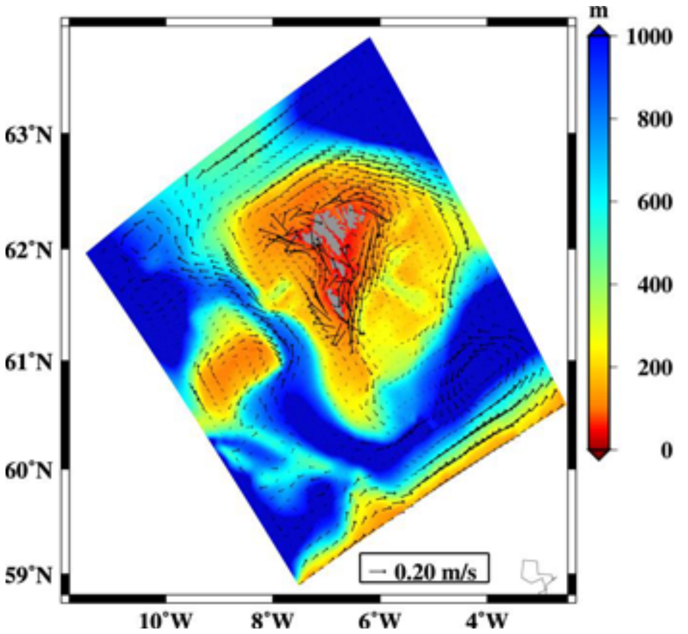


Figure 2. Depth averaged velocity for the period 2000-2009. The colors indicate the depth and the arrows indicate the magnitude and direction of the velocity.

3.2 Shelf water exchange

The shelf water is relatively isolated from its surroundings; but some water is still exchanged. In order to study this, a closed curve has been formed along the 120 meter depth contour that encloses the shelf water. The flux through this contour has been calculated. This shows large variations in the flux with a magnitude close to 25 Sverdrup in both directions (on and off the shelf). By integrations with either depth or location and time averaging, the exchange with respect to either location or depth can be found.

Figure 3 and Figure 4 show that the net in/out flow is much smaller than the magnitude of the total flow. The reason is that most of the water that passes the 120 meter contour returns with the tides; thus much of this is frontal movement without mixing. Most of these fluxes are therefore eliminated in a long time average. Figure 3 shows a depth variation of the flow where the upper part flows towards the Faroe Islands and the lower part flows away from the shelf. The outflow is driven by bottom Ekman forcing

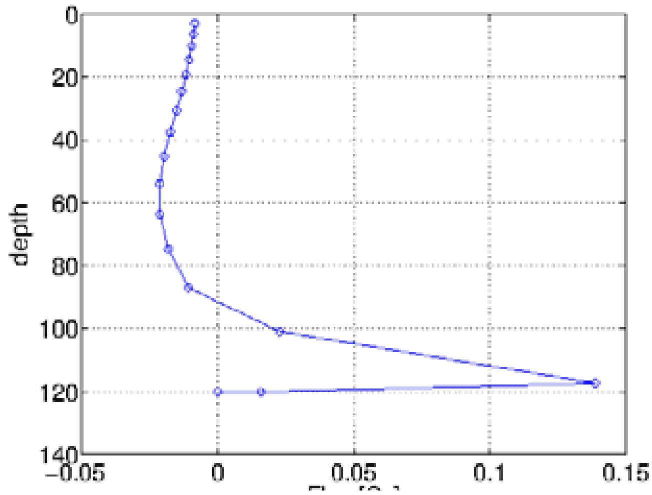


Figure 3. Variation of flux across 120 meter contour. Negative values are toward the shelf and positive are off shelf.

and this generates a compensating inflow in the top. Signs of this are also seen in measurements described by Larsen et al. (2009). Figure 4 shows the time averaged and depth integrated flux.

Intensified outflow is especially seen in two areas. These are located at the southern tip of the Faroe shelf water mass and at the northwestern part of the shelf water. These are both associated with large gradients in the depth contours and they can also be identified as large velocity vectors that change direction as seen on Figure 2.

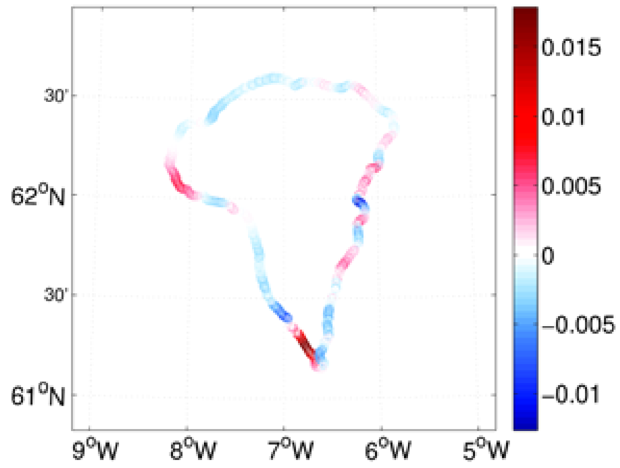


Figure 4. *Time averaged variation of flux at all grid cells on the 120 meter contour. Units on colorbar are in Sverdrup. Negative values are toward the shelf and positive are off shelf.*

3.3 Mixed layer

The mixed layer depth is important for the primary production as a thin mixed layer limits the depth to which algae are mixed and therefore increases the average light intensity that they experience. As long as nutrient concentrations remain sufficiently high, this results in an increased primary production. The mixed layer depth in the frontal region is shown in Figure 5.

The mixed layer depth is in general decreasing during summer and reaches a minimum close to 50 meters. The reason for this reduction is a change of sign of the heat flux at the surface. This means that heat enters the ocean in summer and leaves in winter, which results in a summer stratification of the water column. Even though all years experience the reduction of the mixed layer depth, the timing is different. The years 2000, 2001 and 2008 all have an early onset of stratification. These are all years with a high primary production. Thus it seems as if the timing of the reduction of the mixed layer depth is an indicator of the primary production of the individual year.

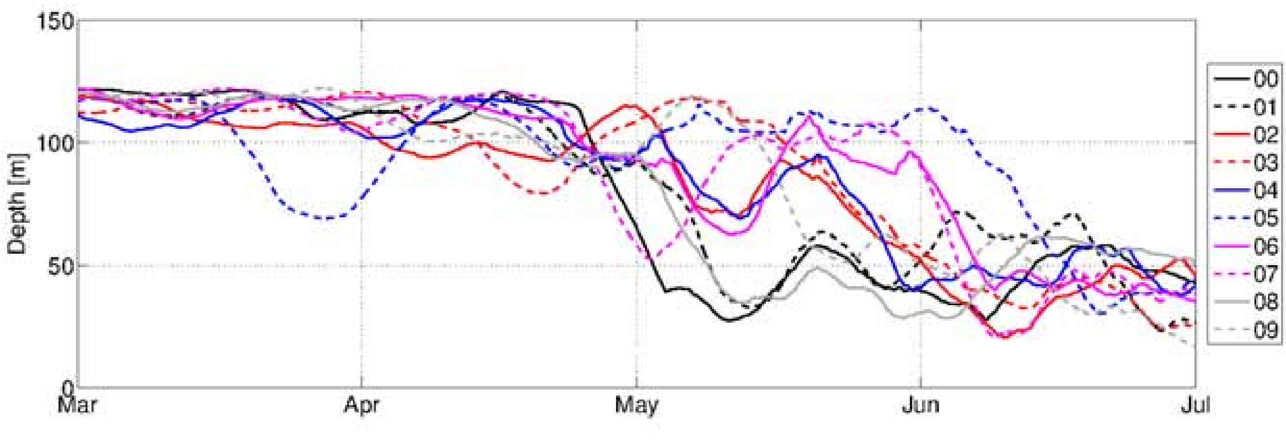
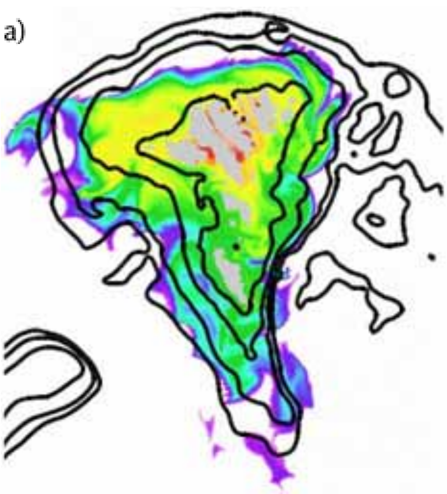


Figure 5. *Mixed layer depth for the area with bottom depths between 100 and 150 m as function of time for each year of the 10 year hindcast.*

3.4 Tracer experiment

A passive tracer has been added to the Faroe shelf water mass in the model within the 80 meter contour on the first of March every year. The tracer's movement has then been tracked until the end of July. The tracer follows the currents, is mixed by model turbulence, but it is indifferent to changes in temperature and salinity. The result is shown in Figure 6. Figure 6a is a snapshot of the surface concentration after 11 days. Figure 6b shows the tracer concentration at the section marked with a black line on Figure 1 at the same time.



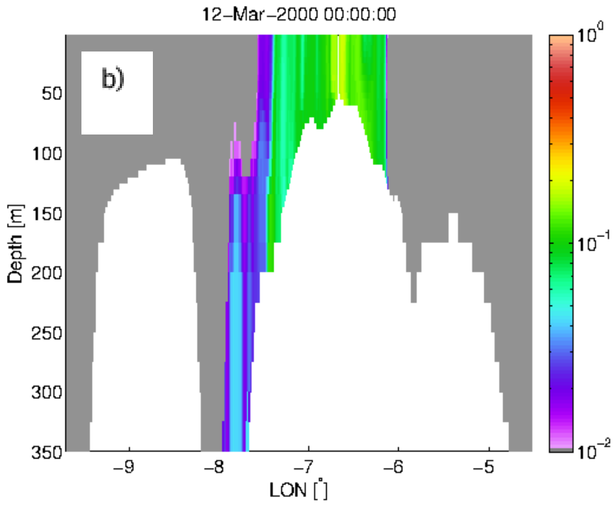


Figure 6. Snapshot of tracer concentrations 11 days after release. a) Surface concentrations. b) Concentrations along the section marked with a black line in Figure 1.

The tracer experiment shows that the tracers are mixed within the entire Faroe Shelf water mass within days, whereby their concentration forms a strong gradient towards the off shelf. The shelf water mass is not stationary as it moves back and forth with the tides and from time to time, the southern islands are isolated. Indications of a similar behaviour are also seen in the observations. The tracer experiment also indicates that the tracers escape the shelf water mass near the bottom as seen on Figure 6b. Based on the reduction of the tracers on shelf, a half life period has been found to be between 30 and 40 days.

4. CONCLUSIONS

The 3D model of the Faroe shelf water represents the measurements reasonably well and confirms some of the hypotheses that previous studies have pointed towards. First of all, the clockwise circulation around the Faroe Islands, that isolates the shelf water from the off shelf water, is formed.

A closed circle has been formed around the Faroe Islands at the 120 meter depth contour. This shows two hotspots where water exits the Faroe shelf water. The first one is located at the north western part of the shelf the second is located at the southern tip of the shelf water. Both locations are associated with large gradients of the depth contours. The depth variation of the cross-shelf exchange at the 120 meter contour shows an inflow towards the shelf in the upper part of the ocean and outflow near the bottom. The outflow is driven by bottom Ekman forcing and this generates a compensating inflow in the top.

The tracer experiment confirms this and it clearly shows high concentrations of tracer remaining on the shelf. The tracer experiment also shows that the tracer spreads within the shelf water quickly and that the half life for the tracers within the shelf is between 30-40 days.

The mixed layer depth correlates well with the variation of the primary production, thus an early reduction of the mixe layer depth results in a high primary production; however this is not seen to be the only mechanism that controls the spring bloom.

The current setup forms a basis for further studies of the Faroe shelf. If the model setup is to be improved, the tracer experiments should be exploited further and more advanced tracers should be implemented. HYCOM (3D ocean model) already includes NPZ models, which can be used along with more complex models coupled online to HYCOM.

5. REFERENCES

Debes, H., Gaard, E., Hansen, B., 2008. Primary production on the Faroe shelf: Temporal variability and environmental influences. Journal of Marine Systems 74, 686 – 697.

Gaard, E., Hansen, B., Heinesen, S. P., 1998. Phytoplankton variability on the Faroe Shelf. ICES Journal of Marine Science 55, 688 – 696.

Larsen, K. M. H., Hansen, B., Svendsen, H., 2008. Faroe Shelf Water. Continental Shelf Research 28, 1754 – 1768.

Larsen, K. M. H., Hansen, B., Svendsen, H., 2009. Faroe Shelf Front: Properties and exhange. Journal of Marine Systems 78, 9 – 17.

Holocene ocean circulation changes around the Faroe Islands

Francisca Staines-Urías, Postdoc project

1. INTRODUCTION

The Faroe Islands continental margin—located beneath the northward surficial Inflow of warm Atlantic water from the Gulf Stream System and the southward cold Overflow from the Norwegian Sea—has proven to be an important area in the research of North Atlantic oceanic circulation and regional climate change (e.g. Kuijpers et al., 1998; Hansen et al., 2001). Due to the sensitivity of this region to climate variability, expressed as changes in surface water temperature, water column structure, and bottom current strength; the sedimentary deposits from around the Islands constitute an important record of past oceanographic and climatic conditions. Accordingly, the analysis of sedimentary cores recovered from this area constitutes an essential step to reconstruct the oceanographic history of the region and, consequently, to predict the possible consequences of a future climate change.

Throughout this project, we investigated the oceanographic variability (i.e. sea surface temperature, primary productivity and bottom current variability) occurred during the Holocene around the Faroe Islands. The oceanographic records generated within this investigation were reconstructed by analyzing sedimentary material from two gravity cores, and based on granulometric estimations, foraminiferal faunal analyses and the evaluation of the isotopic composition of foraminiferal carbonate.

2. METHODOLOGY: CORE RECOVERY, DATING, SAMPLING AND PROCESSING

Each of the recovered cores corresponds to a distinctive oceanographic and geological setting. Core ENAM 33, was recovered west of the Islands near the Faroe Banks and Faroe Bank Channel, an area with moderate to high primary productivity rates associated with the warm and more eutrophic waters carried by the Gulf Stream System (North Atlantic Drift). In this area, changes in bottom current strength are associated with changes in the overflow of dense water from the Nordic seas into the North Atlantic. On average bottom currents are strong and sedimentation rate is low.

In contrast, core LINK 14 was retrieved from the eastern Faroese shelf near the Faroe-Shetland Channel, a region characterized by lower surface primary productivity, higher sedimentation rates and weaker bottom currents. Here, phytoplankton density variability is clearly seasonal with maxima observed during spring and summer (fig. 1).

A third core was recovered in this area, HOLOVAR 03. This core was recovered from within a deep-water coral mound. Due to the influence of the corals, results from this core were not considered in this paleoreconstruction.

Age models for the sedimentary cores were constructed based on AMS radiocarbon dates. For ENAM 33, AMS were obtained from monospecific samples of the planktic foram *Globigerina bulloides*. Radiocarbon analyses were performed at the AMS ^{14}C Dating Center in Aarhus University. The AMS dates were calibrated using the CALIB 6.0 software and a 400-year reservoir.

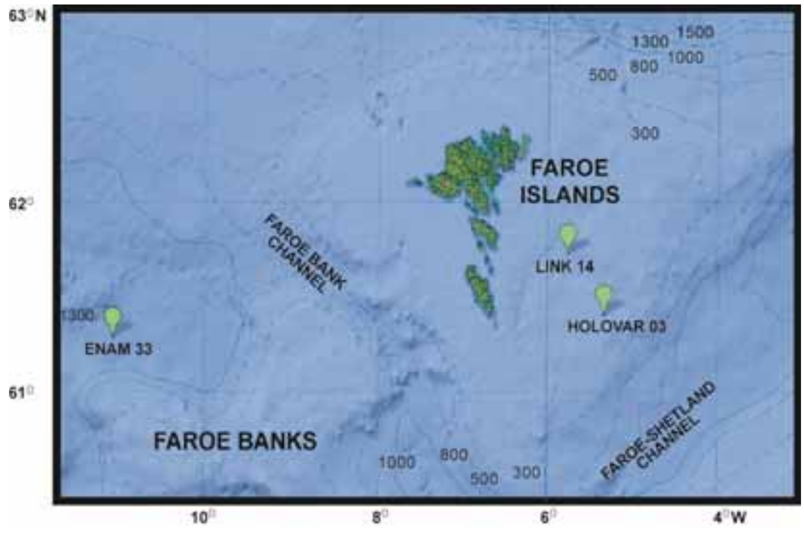


Figure 1. *Bathymetric map of the region surrounding the Faroe Islands showing the location of the recovered cores and main features of the sea floor.*

For LINK 14, radiocarbon dates were obtained from Rasmussen and Thomsen (2010). For all the other analyses, the cores were sampled longwise every 5 mm. In ENAM 33, the time resolution of each sample varied between 110 and 156 years. For LINK 14, given the higher sedimentation rates of the area, time resolution fluctuated between 11 and 72 years per sample.

The sediment samples were dried and weighed and then washed over a 63 µm sieve. Once the remaining sediment dried out, it was also weighed. The percentage of the sand fraction (grain diameter › 63 µm), a proxy for bottom current strength, was calculated from these sediment residuals.

Faunal analyses were performed on core ENAM 33. Changes in the foraminiferal assemblage were evaluated by determining the number of benthic and planktic foraminifera ›125 µm contained in an aliquot that ranged from $^1/_{32}$ to $^1/_{128}$ of the total sample. The number of splits to produce each aliquot was selected to secure a minimum of 400 benthic and 300 planktic specimens per aliquot. Results are expressed in specimens per gram. Relative abundance (%) was used for data interpretation.

For both cores, samples for isotopic analysis (oxygen and carbon) were obtained from the sediment fraction ›250 µm where 300 to 500 µm of *G. bulloides* shells (~50-70 specimens) were picked. To improve analytic accuracy, the samples were sonicated in deionized water and an alkaline solution, to remove any carbonate aggregates and to clean sand and other remains from within the chambers.

3. RESULTS

3.1 Grain size analysis

In both locations, granulometric analyses show increasing grain size from the beginning to near the end of Holocene Climate Optimum (HCO), roughly from 8000 to 4500 BP. However, in LINK 14 changes are more gradual than in ENAM 33 (fig. 2).

During the mid-Holocene and up to modern times, changes in the sedimentary record are noticeably different among locations. While in ENAM 33 grain size shows a steady decrease, except for a secondary maximum at 750 BP, in LINK 14 sand content decreases progressively up to a minimum *ca.* 3200 BP to gradually increase once more, until reaching the series maximum at 1000 BP.

The observed changes suggest weaker but steadily increasing bottom currents during the early HCO, followed by a shift in the conditions near the end of this period (5000 to 4000 BP), with the mid-Holocene characterized by a further differentiation in the sedimentary record between locations indicating contrasting changes in the bottom conditions at each site (Mørk et al., 2010).

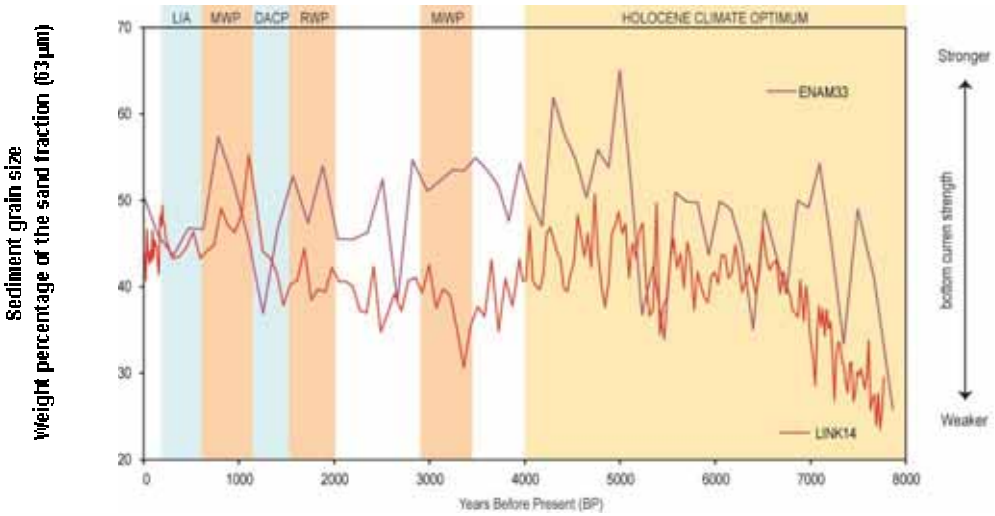


Figure 2. *Sediment grain size changes. Increments in the sand fraction weight % were used to indicate changes in the strength of the bottom current. Results show that sand content is comparable between locations, despite the distinctive oceanographic settings and differences in water depth between them. However, slightly lower values occurred east of the Faroe Islands indicating persistently weaker bottom currents. The colored bars denote periods of significantly warmer (orange) and colder (blue) climate: Little Ice Age (LIA), Medieval Warm Period (MWP), Dark Ages Cold Period (DACP), Roman Warm Period (RWP) and Minoan Warm Period (MiWP). The Holocene Climate Optimum, an interval of slightly warmer and very stable climate, is also indicated.*

3.2 ENAM 33 Faunal analysis

3.2.1 Planktic foraminifera

Six species dominate the planktic assemblage representing nearly 98% of the total planktic foraminifera: *Neogloboquadrina incompta* (previously *Neogloboquadrina pachyderma dextralis*), *Globigerinita uvula, Globigerina bulloides, Turborotalita quinqueloba, Neogloboquadrina pachyderma* (previously *N. pachyderma sinistralis*) *and Globorotalia inflata.* Along the core, two of these species consistently display the lowest relative abundance: the polar *N. pachyderma* and subpolar *G. inflata* (fig. 3A). The reduced numbers and lower variability in the percentages of these cold water species indicate that for most of the Holocene, summer sea surface temperatures (SST) west of the Faroe Islands, particularly in the area above the Faroe Banks, were persistently higher than 9°C. Nonetheless, *G. Inflata* appears more abundant during the early Holocene indicating that lower temperatures may have occurred.

The downcore variability of the planktic assemblage further indicates significant changes in the water column conditions through the Holocene. Except for few samples, *N. incompta* is the most abundant species in the top core section. However, prior to 4000 BP its relative abundance was considerably lower. The same behavior is observed in *G. uvula* (fig. 3B). These two species have broad depth habitat preferences, moving up and down the water column (0-400 m water depth) in response to changes in water stratification and temperature. When conditions in the surface change (e.g. water stratification decreases, surface waters get colder, higher interspecific competition), these species migrate to deeper horizons near or below the thermocline but because food availability declines with depth, their numbers are reduced, and their relative abundance is compromised. Hence, their abundance is commonly used to establish changes in water temperature. Accordingly, the change in *N. incompta* and *G. uvula* abundance suggests that during the HCO, particularly prior to 5000 BP, summer temperatures were lower than those occurring from 1000 to 5000 BP.

Globigerina bulloides and *Turborotalita quinqueloba* also display a mid-Holocene abundance shift. Their behavior, however, is opposite to that of *G. incompta* and *G. uvula*, by displaying higher relative abundance from 8000 to 4500 BP and a significant reduction from 4500 to 1500 BP (fig. 3C).

World wide, large numbers of *G. bulloides* and *T. quinqueloba* live specimens are associated with upwelling conditions, a homogenized water column, and high nutrient concentrations. As a result, these species are considered excellent proxies for changes in surface primary productivity. Accordingly, the downcore variability observed in ENAM 33 suggests that surface waters above the Faroe Banks were more productive during the HCO and near present times than during the mid-Holocene, including the Minoan and Roman warm periods. Furthermore, the reduction in the relative abundance of both species appears associated with warmer SSTs, indicating a higher stratification of the water column and a consequent reduction in nutrient concentrations. In this respect, the changes in *G. bulloides* abundance are particularly significant, as this species (a non-symbiont bearing) is extremely sensitive to changes in the abundance and quality of the microalgae that constitute its prey, thus variations in phytoplankton biomass related with nutrient concentrations variability of surface waters, are clearly and promptly reflected in *G. bulloides* populations.

3.2.2 Benthic foraminifera

The benthic assemblage was divided in three groups representing 89% of the total assemblage. Rare species (corresponding to less than 0.5% of the total population) and those with undefined ecological preferences were not considered. The faunal associations represented by each of the groups are of ecological significance. Thus, downcore variability in the relative abundance (%) of each group has been used to interpret changes in the benthic environment (Staines et al., 2010).

Group A: *Globocassidulina subglobosa, Trifarina angulosa, Cibicides* spp, *Cassidulina laevigata, Cassidulina obtusa and Astrononion gallowayi.* These species are common in the area today. Together they indicate strong bottom currents. This group dominates the benthic assemblage in the top part of the core (0 - 4500 BP) representing up to 57% of the total. During the HCO the relative abundance of Group A shows remarkable

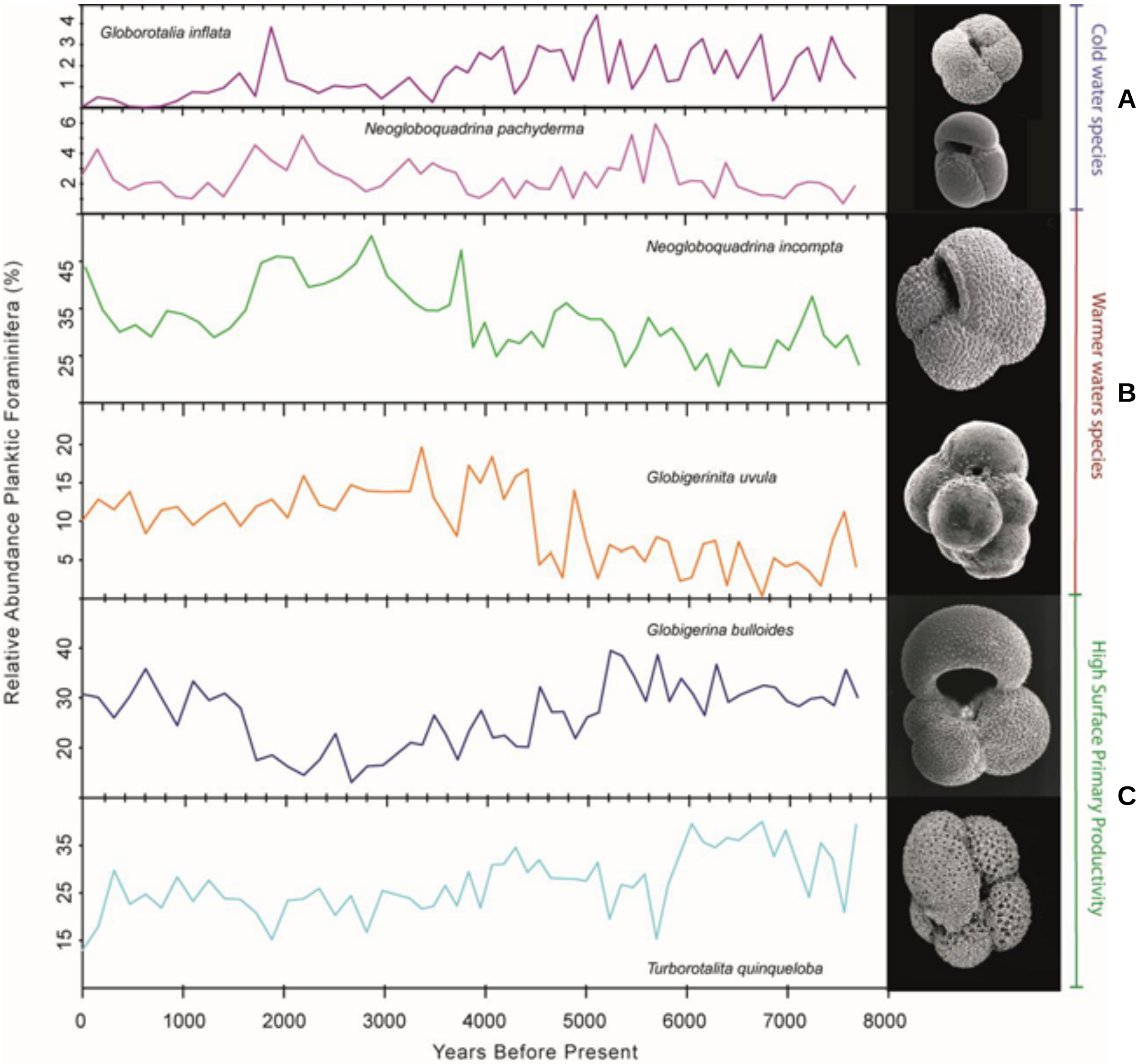


Figure 3. Planktic foraminifera relative abundance (%). Species have been grouped according to their ecological preferences. Species with similar preferences exhibit comparable behavior.

variability, indicating abrupt and recurring changes in the strength and persistence of the bottom current. By the end of the HCO, variability decreases significantly and the series exhibits a positive trend, suggesting a progressive and steady increase in bottom current strength for the past 4000 years (fig. 4A)

Group B: *Epistominella vitrea, Epistominella exigua, Gavelinopsis praegeri, Bolivina pygmaea* and *Nonionella spp.* Species in this group are commonly referred as "phytodetritus opportunistic species". Individuals are adapted to high but irregular inputs of labile organic matter to the sea floor and can tolerate suboxic conditions. They exist in small numbers for long periods when conditions are far from optimal but when conditions change in their favor, typically when pulses of phytodetritus from the surface reach the sea floor, they rapidly increase their numbers. Both, the relative abundance and abundance variability of this group, appear higher in the lower part of the core (fig. 4B). This elevated abundance suggests that for most of the HCO organic matter rain to the bottom was enhanced. However, the simultaneous increase in variability implies that fluxes of phytodetritus from surface to the bottom were not steady. Furthermore, Group B abundance appears to vary inversely to that of Group C (species adapted to oligotrophic conditions), most conspicuously prior to 5000 BP. Together, the increased variability and the intensification of the inverse relation suggests that during the HCO the organic rain was high but variable, alternating between periods characterized by large amounts of fresh organic material reaching the sea floor and periods of low and scarce organic carbon input.

Group C: *Eggerella bradyi, Bolivina costata, Gyrodina spp, Sigmoilopsis schlumbergeri, Sphaerodina bulloides, Sigmoilina tenuis* and *Pyrgoella sphaera*. These are epifaunal or shallow infaunal species, adapted to survive in infertile areas where organic carbon content in the sediments is low (mostly humic matter) and food supply is sporadic. They have no tolerance to suboxic or anoxic conditions or to high interspecific pressure. As with Group A and B, species of Group C also display higher variability during the HCO (fig. 4C).

The increase in benthic variability as well as the inverse relation observed between Group C and B more than substantiated the proposed interpretation of the foraminiferal records as to indicate that late in the Holocene and until de end of the HCO benthic conditions around the Faroe Bank, oscillated between intervals of low organic carbon input and episodes of large fluxes of organic matter from the surface as a consequence of increased rates of primary productivity. A conspicuous change is observed at the end of the HCO, when conditions became more stable, shifting towards higher SST, reduced surface productivity, and a more oligotrophic and energetic benthic environment.

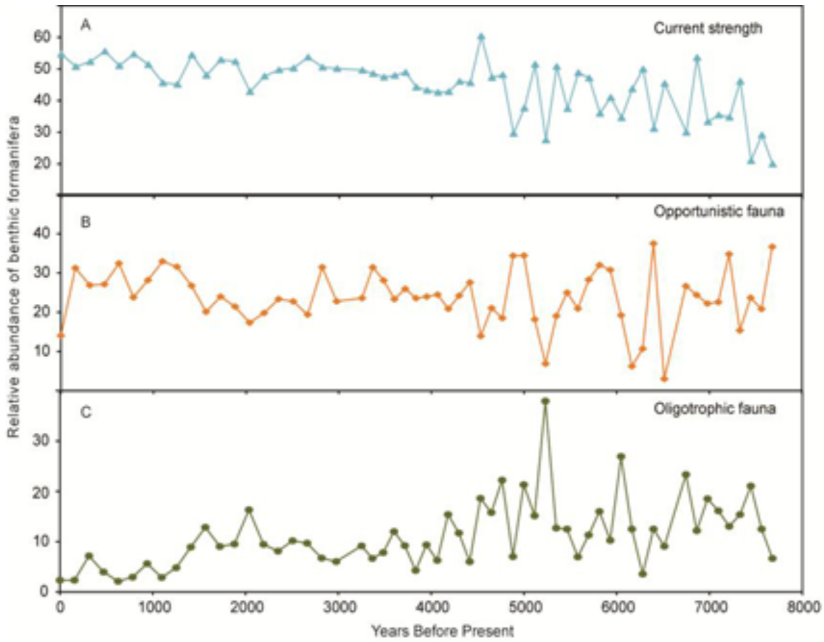


Figure 4. Benthic foraminifera relative abundance (%). A total of 18 species were separated in three groups each according with their environmental preferences and ecological behavior.

3.3 Stable isotopic composition of planctic foraminifera

Globigerina bulloides is considered a surface dweller with maximum abundances occurring between 0 and 50 m depth. On a global scale, this species thrives in the surface mixed layer above the thermocline in environments where phytoplankton density and prey abundance are high. Around the Faroe Islands, this species is most abundant from late spring to the end of summer, when surface temperatures are within its preferred range and phytoplankton density is the highest.

By considering its preferred habitat—and if the oxygen isotopic composition of the sea water is regard as constant or it is independently calculated— *G. bulloides* $\delta^{8}O$ signal constitutes a proxy for SST changes with higher (heavier, more positive) $\delta^{8}O$ values indicating cooler waters and lower (lighter, more negative) values as indication of warmer temperatures. Furthermore, as forams use the dissolved inorganic carbon of the water to precipitate their shells, the $\delta^{3}C$ signal of foraminiferal carbonate also constitutes a record of past changes in the carbon isotopic composition of the water. Accordingly, the $\delta^{3}C$ of *G. bulloides* also constitutes a good proxy for surface primary productivity, with heavier $\delta^{3}C$ values indicating more productive waters and lighter values revealing lower productivity rates.

3.3.1 Oxygen isotopic composition ($\delta^{8}O_{GB}$)

The comparison of LINK 14 and ENAM 33 $\delta^{8}O_{GB}$ series, shows that for the entire record (past 5500 years) $\delta^{8}O_{GB}$ values from the eastern Faroese shelf (LINK 14) have been considerably heavier (~0.5‰) than those from the Faroe Banks (ENAM 33), evidencing that SST east of the Faroe Islands has been significantly lower (~2 to 3°C) than off the western Faroese margin (fig 5A). The calculated SST difference appears in good agreement with modern oceanographic data.

Some comparable features were observed on both $\delta^{8}O_{GB}$ records, near 4500 BP a drop towards lighter values $\delta^{8}O$ (warmer SST) can be detected in both series. This drop is follow by a trend towards heavier values, more noticeable in ENAM 33 but also apparent in LINK 14 especially after 2500 BP, that indicates a small but steady decrease in SST until recent times when values drop rapidly indicating a sudden warming.

3.3.2 Carbon isotopic composition ($\delta^{3}C_{GB}$)

Prior to 4000 BP, comparable $\delta^{3}C_{GB}$ values are observed in both records. However, following this period, the carbon signature on the eastern shelf displays a well defined trend towards lighter values whereas in the Faroe Banks area the $\delta^{3}C_{GB}$ progress towards slightly heavier values (fig. 5B). This progressive differentiation suggests a divergent transition: as surface waters around the eastern shelf are becoming gradually less productive it appears that near the Faroe Banks primary productivity is intensifying.

As changes in the nutrient content of surface waters and, consequently, in primary productivity are closely related with changes in water column structure, it appears that since the end of the HCO the water column east of the Faroe Islands has become more stratified. Such process is perhaps the result of changes in water depth, due to ice melting and/or in the volume of the water mass filling up this area resulting from the reorganization of the surface circulation.

On the other hand, the changes observed around the Faroe Bank are better explained by changes in the nutrient content of the water bathing the area, possibly due to changes in the speed and/or source of the water transported by the North Atlantic Drift.

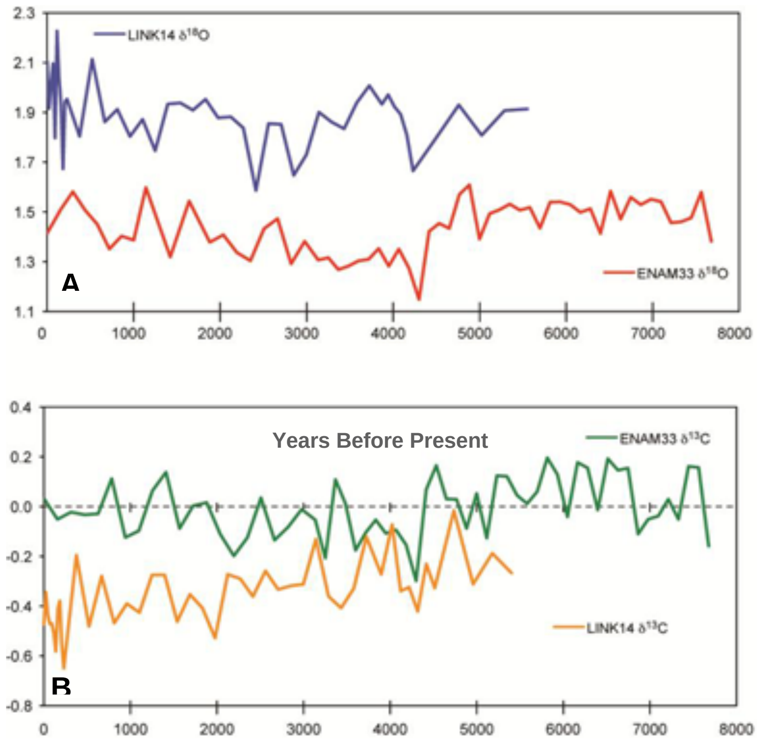


Figure 5. Isotopic composition of Globigerina bulloides shells. Results are reported in parts per thousand with respect to the international standard PDB. The analytical reproducibility of the method, based on repeated standards, proved better than ±0.1‰ for $\delta^{8}O$ and ±0.2‰ for $\delta^{3}C$.

4. CONCLUSIONS

During the Holocene Climate Optimum (4000 to 8000 BP) comparable oceanographic conditions prevailed in surface waters east and west of the Faroe Islands. At the end of this period, a pronounced environmental shift clearly denoted in the sedimentary record of both sites, indicates a transitional period after which the oceanographic conditions in each location gradually differed.

Between 4000 and 4800 BP, changes in the *G. bulloides* isotopic signal and the composition of the planktic assemblage indicate that conditions around the Faroe Islands changed from an unsteady environment with marked variability, cooler SSTs and high primary productivity, to a more stable, warmer and oligotrophic surface setting. In the benthos, where this transition appears to occur earlier, the composition of the benthic assemblage indicates that prior to 5000 BP organic carbon input to the sea floor was higher and more irregular. During the transitional interval, organic carbon fluxes became increasingly stable as the bottom currents became stronger.

In the following period, from 4000 BP to present, conditions at each location appear to diverge. Among locations, the isotopic composition of the inorganic carbon in surface waters becomes gradually and significantly different. The waters on the western side of the Faroe became slightly more eutrophic, whereas on the eastern Faroese shelf a negative trend in $\delta^{13}C$ values indicates a considerable reduction in surface primary productivity.

A significant reorganization of the surface circulation, related with changes in regional current patterns, probably due to changes in the strength and position of the Subpolar Gyre, as proposed by other authors based on instrumental and paleoceanographic data (e.g. Hatun et al., 2009; Thornalley et al., 2009), represents the most likely mechanism explaining the local differences within the current oceanographic context.

Further evidence of this recent reorganization can be established from the relation between SST and primary productivity. It appears that during the late and mid Holocene higher SSTs were associated with lower productivity rates, most probably due to increased stratification of the water column and the consequent nutrient depletion of the surface waters. However, such pattern, more noticeable around the Faroe Banks area, appears to inverse during the past 200 years, with warmer surface waters now associated with increased productivity. This reversal is also an indication that a new mode of oceanographic variability is operating in this region and further indicates a recent-Holocene reorganization of the regional circulation processes, increasing the uncertainty of the possible consequences of a future rise in regional and global temperatures.

5. REFERENCES

Hansen B., Turrell, W. R., Østerhus S. 2001. Decreasing overflow from the Nordic seas into the Atlantic Ocean through the Faroe Bank channel since 1950, Nature doi:10.1038/35082034

Hatun, H., Payne, M.R., Beaugrand, G., Reid, P.C, Sandø, A.B., Drange, H., Hansen, B., Jacobsen, J.A., Bloch, D. 2009. Large bio-geographical shifts in the north-eastern Atlantic Ocean: From the subpolar gyre, via plankton, to blue whiting and pilot whales, Progress In Oceanography doi:10.1016/j.pocean.2009.03.001

Kuijpers A., Andersen, M. S., Kenyon, N. H., Kunzendorf H., van Weering, T. C. E. 1998.Quaternary sedimentation and Norwegian Sea overflow pathways around Bill Bailey Bank, northeastern Atlantic, Marine Geology doi:10.1016/S0025-3227(98)00066-8

Mørk, F., Nielsen, T., Staines-Urías, F., Kuijpers, A. 2010. Geological evidence of Norwegian Sea Overflow pathways into the Iceland Basin, Deep-water Circulation: Processes & Products International Congress, Baiona, Spain

Rasmussen, T., Thomsen, E. 2010. Holocene temperature and salinity variability of the Atlantic Water inflow to the Nordic seas, The Holocene doi:10.1177/0959683610371996

Staines-Urias, F.; Kuijpers, A.; Hansen, B. 2010. Mid-Holocene Rapid Oceanographic Change Around The Faroe Islands, American Geophysical Union, Fall Meeting, San Francisco, USA #P21B-1684

Thornalley, D.J. R., Elderfield, H., McCave, I. N. 2009. Holocene oscillations in temperature and salinity of the surface subpolar North Atlantic, Nature doi:10.1038/nature07717

Appendix

Workshop on climate and ocean currents and their impact on the biology of Faroese waters
23 – 24 June 2009, Faroe Marine Research Institute, Tórshavn

<u>Tuesday 23 June 09:00</u>
Welcome

Session 1 (chair: H. Hátún): Paleoceanography in Faroese waters/NE Atlantic

09:05 Tine L. Rasmussen:	Changes in Atlantic Water inflow to the Nordic seas during the Holocene
09:25 Antoon Kuijpers:	North Atlantic ocean and atmospheric circulation changes in the late Holocene
09:45 Jesper Olsen:	Holocene climate variability - Evidence from three Faroese lakes
10:05 Francisca Staines:	Reconstruction of North Atlantic oceanographic variability from foraminiferal records

10:35-10:50 Coffee

Session 2 (chair: A. Kuijpers): Biological production in open waters of the NE Atlantic and saithe

10:50 Hjálmar Hátún:	Physical control of the primary production in the NE Atlantic
11:10 Brian MacKenzie:	Ecological and Fishing Influences on Presence of Bluefin Tuna, Thynnus Thunnus, in Northern European Waters.
11:30 Hlynur Ármannsson:	Tagging of saithe around Iceland
11:50 Tore Jakobsen:	Saithe in Norway - Biology and Migrations
12:10 Eydna í Homrum:	Faroe Saithe

12:40-13:40 Lunch (Steering Group meets during lunch)

Session 3 (chair: B. McKenzie): Biological production in Shelf seas and sandeel

13:40 Eilif Gaard:	Primary production on the Faroe Shelf
14:00 Karin M. H. Larsen:	Physical control of the primary production on the Faroe Shelf
14:20 Bogi Hansen:	Changing shelf circulation as a driver of primary production

14:40-15:00 Coffee

Session 3 continued (chair: E. Gaard)

15:00 Jens T. Christensen:	Trophic relationships by proxy: food chains and stable isotopes
15:20 Peter Grønkjær:	Otolith-based time series of cod growth and trophic level
15:40 Kirstin Eliasen:	Sandeel on the Faroe Shelf

19:30 Dinner at Havstovan

<u>Wednesday 24 June 2009</u>
Session 2 (chair: B. Hansen): Climate and ocean modelling

09:00 Knud Simonsen:	Barotropic modeling of the Faroe Shelf
09:20 Brian Hansen:	On the forcing of the Atlantic inflow to the Nordic Seas
09:50 Till A. Rasmussen:	Initial thoughts on High resolution modelling of the Faroe shelf.

10:10 Separate meetings in advisory groups for PhDs and postdocs

Workshop on climate and ocean currents and their impact on the biology of Faroese waters
9 – 10 September 2010, Faroe Marine Research Institute, Tórshavn

Thursday 09:00

Francisca Staines Urias: Oceanographic variability during the holocene in Faroese waters

Antoon Kuijpers: Climate of the coming decades in a marine geological perspective - back to colder European winters ?

Eigil Kaas: On the atmospheric role during abrupt climate shifts

Hjálmar Hátún: Forecasting climate and ecosystems along the North European ocean-shelf margin

Bogi Hansen: Abrupt interruptions in the spring bloom on the Faroe Shelf

Steffen M. Olsen: Exchanges across the GSR in global ocean models

Brian Hansen: Currents and hydrography in the Nordic Seas in the control run of a coupled model

Till Soya Rasmussen: High resolution modelling of the Faroe Shelf

Peter Grønkjær & Jens Tang Christensen: The role of food-web changes in the boom and bust of North Atlantic cod stocks: Tracking cod growth and trophic position during the last century using otoliths, 20 min

Kirstin Eliasen: Recruitment and condition of juvenile sandeel on the Faroe Shelf in relation to primary production

Eydna í Homrum: Growth and diet of Faroe saithe

Friday 10 Sept

Separate meetings in advisory groups for PhDs and postdocs

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