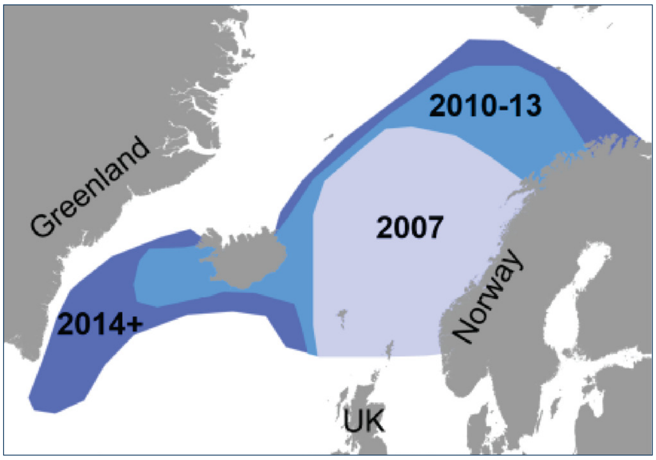
HAVSTOVAN
FAROE MARINE RESEARCH INSTITUTE

Final report for the research programme on Changes in Marine Climatic and Oceanographic Conditions in the Waters between the Faroes and Greenland and their effects on plankton and fish 2013-2017

Afsluttende rapport for forskningsprogammet Klimatiske og oceanografiske ændringer i havområderne mellem Grønland og Færøerne og deres indvirkning på plankton og fisk 2013 - 2017

Tórshavn · December 2017



Edited by Eilif Gaard

Center for climate and ocean currents around the Faroe Islands
Center for Klimaforskning og Havstrømme ved Færøerne

HAVSTOVAN NR.: 17-05
TECHNICAL REPORT

Contents

Dansk sammenfatning

I finansloven for 2013-2015 bevilgede Folketinget, gennem Forsknings- og Innovationsstyrelsen, 10 millioner kroner til "Center for Klimaforskning og Havstrømme ved Færøerne" til udførelse af et 4-årigt forskningsprogram med titlen

"Klimatiske og oceanografiske ændringer i havområderne mellem Grønland og Færøerne og deres indvirkning på plankton og fisk".

Programmet udførtes i samarbejde mellem Færøernes Havforskningsinstitut, Grønlands Natur-institut, DTU-aqua og Aarhus Universitet.

Der blev ialt financieret fem projekter inden for programmet:

PhD projekt:
Primary production on the Faroe shelf – Spatial and temporal variations with links to hydrography
[Primærproduktion på Færøplateauet – variationer i rum og tid, med kobling til hydrografi]

Det er tidligere blevet påvist en klar sammenhæng mellem årlige variationer i primær-produktionen og produktion i højere trofiske niveauer på Færøplateauet. Variationer i primærproduktionen har derved afgørende betydning for variationer i bl.a. fisk og havfugle på Færøplateauet. I dette projekt undersøges mulige årsager til de observerede variationer i primærproduktionen.
En front omkring Færøplateauet adskiller havvandet på Færøplateauet fra det omkring liggende oceaniske vandmasser. Analyser i dette projekt har bl.a. vist, at denne adskillelse har positiv indvirkning på Færøplateauets primærproduktion og at udskiftning af Færøplateauets havvand (og fytoplankton) hæmmer primærproduktionen og forsinker forårsopblomstringen af fytoplankton. Det er også blevet påvist, hydrografisk transition om foråret og frontens placering har betydning. Dette påvirkes positivt av kolde vintre forinden foråropblomstringen.

PhD projekt:
Ecology and production of *Calanus finmarchicus* in relation to environmental conditions in the southwestern Norwegian Sea
[Økologi og production af vandloppen *Calanus finmarchicus* in relation til miljø i det sydvestlige Norskehav]

I Norskehavet findes store mængder af vandloppen *Calanus finmarchicus*. Arten er hovedføde for bl.a. pelagisk fisk, inklusiv de store bestande af makrel, blåhvilling og vårgydende sild, der har sin fødevandring i Norskehavet om sommeren. *C. finmarchicus* har derved enorm økologisk og økonomisk betydning.
Det vestlige Norskehav domineres af varmt atlantisk havvand i den sydlige del, der transporteres fra sydvest og koldt havvand af arktisk oprindelse i den nordlige del, der

transportes fra nordvest med den Østislandske strøm. Dette giver to forskellig oceanografiske regimer i henholdsvis den nordlige og den sydlige del, samt en skarp og produktiv front, der adskiller disse to regimer.
Det er påvist her, at betydelige oceanografiske og biologiske ændringer er sket i området siden 2003. Styrken af den østislandske strøm er reduceret og dette har betydning for advektion af *C. finmarchicus* og den arktiske beslægtede art *Calanus hyperboreus* fra nordvest og ind i det vestlige Norskehav. Den samlede biomasse af dyreplankton i dette havområde er derved reduceret betydelig. På den anden side sker *C. finmarchicus'* reproduktion i området nu tidligere på året, end den var før 2003.
Vandloppernes biologi, relateret til deres miljø studeres og beskrives. Også beskrives pelagisk fisks fødebetingelser, relateret til vandloppernes forekomst og individstørrelser i tid og sted.

PostDoc projekt:
Changes in distribution and migration of mackerel and other pelagic fish in relation to East Greenland waters
[Ændringer i fordeling og migration af makrel og anden pelagisk fisk i relation til Østgrønlandske havområder]

Makrelens opvækstområde i dens første leveår er hovedsagelig vest for de britiske øer, syd for Færøerne og i den nordlige del af Nordsøen. Der er påvist en signifikant sammenhæng mellem overlevelse af larver/yngel og mængder af *Calanus* vandlopper (stadie CI-CIV) i gydeperioden (april-juni).
Samtidig med at makrelens gydebestand er vokset i de seneste år, er dens fødeområde om sommeren også udvidet, både mod nord og mod vest, i islandsk og østgrønlandsk havområde. Selv om føde tydeligvis påvirker makrelens vandringsruter om sommeren, har temperaturen også betydning, idet dens udbredelse begrænses af for lave temperaturer. I de seneste år har sommertemperaturene i Irmingerstrømmen været rekordhøje og ifølge modelprognoser vil dette fortsætte i fremtiden. Under forudsætning af, at makrelbestanden forbliver stor og fortsætter med sin nuværende fødevandring, vil temperaturstigningerne derved muliggøre, at makrelen også i fremtiden kan have sin fødevandring ind i grønlandsk farvand.

PostDoc projekt:
Migration of mackerel and other pelagic fish in relation to oceanography in the Northeast Atlantic
[Migration af makrel og anden pelagisk fisk i relation til oceanografi i det nordøstlige Atlanterhav

Traditionelt har makrelens fødeområde om sommeren hovedsagelig været øst for ca. 6°V. Siden 2007 er fødeområdet udvidet mod nord og vest. Fødeområdet er i denne periode øget betragteligt, samtidig md at gydebestanden også er vokset. Undersøgeler i dette projekt har bl.a. vist, at i perioden 1984-2013 var makrelens kondition og individvækst i det østlige Norskehav negativt korreleret med makrel- og sildebestandens størrelser. Dette indikerer tæthedsafhængig vækst og at planktonproduktionens bærekapacitet for planktonspisende fisk i dette havområdet kan være nået. Det øgede fødebehov for den voksede makrelbestand er derved kompenseret ved øgning af fødeområdet nord- og vestover.

PostDoc projekt:
Climatic changes in the ocean environment of the northern North Atlantic, and their effects on the pelagic fish (mackerel, *Scomber scombrus*)

[Klimatiske ændringer i havmiljøet i det nordlige Atlanterhav og deres ændringer på pelagisk fisk]

Makrelens fødevandring og udvidelsen af fødeområde om sommeren er blevet undersøgt i relation til miljøparametre og bestandens størrelse. Mens fødeområdets udvidelse nordover synes at være begrænset af temperatur, er vandringen vestover stærkere knyttet til mængden af føde (dyreplankton). Vandringen vestover, der har fundet sted i de seneste ca. 10 år, foregår via en smal passage tæt ved den sydislandske sokkelskråning. Her er forholdsvis høje koncentrationer af dyreplankton, mens havområdet længere mod syd er fattigt på dyreplankton. Lave fødekoncentrationer syd for den islandske sokkelskråning er tilsyneladende årsagen til at makrel undgår dette område i sin vandring vestover.

Undersøgelser i dette projekt har endvidere vist, at nærings- og planktonrigt havvand fra den Subpolare Gyre transporteres østover og derefter nordover, hvilket har stor betydning for havområdernes produktivitet i store havområder.

Afsluttende kommentarer

Programmet har i det store og hele været meget vellykket. Alle projekter, på nær et der har været en videreførelse af det forrige program, har omhandlet det samme tema og har derved understøttet hinanden. 24 artikler er publiceret eller er i produktion til publikation i internationale videnskabelige tidsskrift. Derudover er der løbende skrevet populærvidenskabelige artikler samt rapporter og arbejdsdokumenter til bl.a ICES arbejdsgrupper og forelæsninger på pl.a. internationale faglige symposier. Programmet er derved blevet synliggjort internationalt i videnskabelige fagmiljøer og i offentligheden.

På grund af barselsorlov er det ene PhD projekt dog blevet forlænget og vil derfor afsluttes på et senere tidspunkt.

Programmets undersøgelser har påvist den økologiske betydning af den Subpolare Gyre og af dens afgørende betyning for transport af nærings- og planktonrigt havvand rundt i Nordatlanten: fra vest for de britiske øer via Færøerne og ind i Norskehavet og mod mere vestlige områder i Irmingerhavet og Sydøstgrønland.

Den Subpolare Gyre varierer i styrke over år, og disse variationer har tilsyneladende meget stor betydning for produktionen i de ovenfor nævnte marine økosystemer (incl. de store vandrende pelagiske fiskebestande).

Detaljerne i disse betydningsfulde storskala variationer, fortjener nærmere undersøgelser. Disse studier kan med fordel videreføres i nærværende forskningscenter, der både råder over den nødvendige ekspertice og faglige bredde, tidsserier og logistik.

På de følgende sider gives først en engelsk oversigt over programmets formål og gennemførelse, efterfulgt en publikationsliste fra de enkelte projekter. Derefter følger en oversigt over de væsentligste videnskabelige resultater fra hvert enkelt projekt. Rapporten afsluttes med et appendix, som viser agende for de fire årsmøder, der er afholdt i forbindelse med programmet.

December 2017

For styregruppen

Eilif Gaard (formand)

Brian MacKenzie

Helle Siegstad

Jan Arge Jacobsen

Jesper Boje

Søren Rysgaard

Programme description

In the national budget for 2013-2015, the Danish parliament granted 10 million Danish Kroner to "Center for Climate and Ocean Currents around the Faroe Islands" ("Center for Klimaforskning og Havstrømme ved Færøerne") for the research programme
"Changes in marine climatic and oceanographic conditions in the waters between the Faroes and Greenland and their effects on plankton and fish".

The programme is managed by the Faroe Marine Research Institute via the Danish Agency for Science, Technology and Innovation (Forskning- og Innovationsstyrelsen).

The programme was carried out in cooperation between the Faroe Marine Research Institute (FAMRI), The Technical University of Denmark (DTU Aqua), Greenland Institute of National Resources (GINR) and Aarhus University (AU). A steering group was established, consisting of

Eilif Gaard, Director, FAMRI (chairman)
Jan Arge Jacobsen FAMRI
Brian MacKenzie, Professor, DTU Aqua
Søren Rysgaard, Aarhus University
Helle Siegstad, GINR
Jesper Boje, GINR

In addition, representative from FAMRI attending the steering group meetings and managed the financial matters.

Calls and projects

At a steering group meeting, held in Copenhagen on 26 November 2012 it was decided to announce two PhD fellowships and two Post Doc fellowships within the topics

- *Migration of mackerel and other pelagic fish in relation to environmental conditions*
- *Food for mackerel and other pelagic fish: Zooplankton in relation to ocean climate*
- *Marine climate effects on marine primary production around the Faroes*

Fellowships for two PhD projects and two Post Doc projects were announced with deadline on 14. April 2013. There were 11 applications for the four projects. At steering group meeting, 3 May 2013, two applicants for PhD projects and two applicants for PostDoc projects were accepted.

- Sólvá Eliasen for the PhD project *"Marine climate effects on primary production around the Faroe Islands".* Enrolled at the University of the Faroe Island with working place at the Faroe Marine Research Institute.

- Inga Kristiansen for the PhD project "Ecology and production of *Calanus finmarchius* in relation to environmental conditions in the southwestern Norwegian Sea". Enrolled at the University of the Faroe Island with working place at the Faroe Marine Research Institute.

- Teunis Jansen for the PostDoc project *"Changes in distribution and migration of mackerel and other pelagic fish in relation to East Greenland waters"*. Employment at GINR and working place at GINR and DTU aqua.

- Anna Ólafsdóttir for the PostDoc project *"Migration of mackerel and other pelagic fish in relation to oceanographic in the Northeast Atlantic"*. Employment at FAMRI

Fellowship for one additional PostDoc project on Oceanography and climate change/variability in the northern North Atlantic was announced with deadline on 1 November 2013. There was one application from

- Selma Pacariz for the project *"Climatic changes in the ocean environment of the northern North Atlantic, and their effects on the pelagic fish"*.

At steering group meeting on 15 November 2013 the application was accepted.

During the programme period, there were four annual meetings held at FAMRI on

- March 2014 at FAMRI, Tórshavn,
- March 2015 at GINRm Nuuk,
- March 2016 at Hindsgavl, Middelfart
- April 2017 at FAMRI, Tórshavn.

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.
At the last meeting at FAMRI there was held a final symposium which was open for external participants.

The agendas for the annual meetings are shown in Appendix 1.

Publications

Sólvá Eliasen

Primary production on the Faroe shelf – Spatial and temporal variations with links to hydrography
PhD project enrolled at the University of the Faroe Islands with work place at the Faroe Marine Research Institute. Supervisors: Karin Margretha Húsgarð Larsen, Bogi Hansen, Hjálmar Hátún and Till Andreas Soya Rasmussen.
The defense was on 24 August 2017.

Thesis:
Primary production on the Faroe Shelf – Spatial and temporal variations with links to hydrography. NVDrit, 2017:05. 34 pp + 6 papers.

Papers

Eliasen, S.K., Hansen, B., Larsen, K.M.H., Hátún, H., 2016. The exchange of water between the Faroe Shelf and the surrounding waters and its effect on the primary production. J. Mar. Syst. 153, 1–9.

Eliasen, S.K., Hátún, H., Larsen, K.M.H., Hansen, B., Rasmussen, T.A.S., 2017a. Phenologically distinct phytoplankton regions on the Faroe Shelf - identified by satellite data, *in-situ* observations and model*, J. Mar. Syst. 169, pp. 99–110.*

Eliasen, S.K., Hátún, H., Larsen, K.M.H., Jacobsen, S., 2017b. Faroe Shelf bloom phenology - the importance of ocean-to-shelf silicate fluxes. Continental Shelf Research,143: 43-53.

Eliasen, S.K., Hátún, H., Larsen, K.M.H., 2017c. The Faroe Shelf spring bloom linked to change in frontal character. Draft.

Jacobsen, S., Gaard, E., Larsen, K.M.H., Eliasen, S.K., Hátún, H. 2018. Temporal and spatial variability of zooplankton on the Faroe Shelf in spring 1997-2016. J. Mar. Syst., 177: 28-38.

Pacariz, S. V., Hátún, H., Jacobsen, J.A., Johnson, C., Eliasen, S.K., Rey, F., 2016. Nutrient-driven poleward expansion of the Northeast Atlantic mackerel (*Scomber scombrus)* stock: A new hypothesis. Elem. Sci. Anthr., 4: 000105.

Eliasen, S. K. 2016. Fylgisveinamátingar geva nýtt innlit í gróðurin kring Føroyar. Sjóvarmál 2016, 4-7.

Eliasen, S.K. 2017. Gróðurin í sjónum tengdur at hitanum í luftini. Frøði 2: 38-41.

Inga Kristiansen

Ecology and production of *Calanus finmarchius* in relation to environmental conditions in the southwestern Norwegian Sea

PhD project enrolled at the University of the Faroe Islands with work place at the Faroe Marine Research Institute. Supervisors: Eilif Gaard and Sigrun H. Jónasdóttir.
Due to maternity leave the project is prolonged.

Papers published, submitted or in preparation:

Kristiansen, I., Gaard, E., Hátún, H., Jónasdóttir, S.H., and Ferreira, S., 2016. Persistent shift of *Calanus spp.* in the south-western Norwegian Sea since 2003, linked to ocean climate. ICES Journal of Marine Science , 73(5), 1319–1329

Kristiansen I., Gaard, E., Jónasdóttir, S. H. and Hátún, H., 2017a. Seasonal variation in *Calanus finmarchicus* in the southwestern Norwegian Sea. In prep.

Kristiansen I., Hátún, H., Gaard, E., Petursdóttir, H., Gislason, Á., Jacobsen, J.A., Eliasen, S.K., Broms, C and Melle, W., 2017b. Influence of the East Icelandic Current on population dynamics of *Calanus finmarchicus* and *Calanus hyperboreus* in the south-western Norwegian Sea. In prep.

PostDoc projects

Teunis Jansen

Changes in distribution and migration of mackerel and other pelagic fish in relation to East Greenland waters

Andersen, K., Jacobsen, N.S., Jansen, T., Beyer, J.E. 2016. When in life does density dependence occur in fish populations? Fish. Fisheries. DOI: 10.1111/faf.12195

Bachiller, E., Utne, K.R., Jansen,T., Huse, G., 2017. Bioenergetics modeling of the annual consumption of zooplankton by pelagic fish feeding in the Norwegian Sea. PLoS ONE.

Jansen, T., 2016. First-year survival of North East Atlantic mackerel (Scomber scombrus) from 1998 to 2012 appears to be driven by availability of *Calanus*, a preferred copepod prey. Fish. Oceanogr. 25, 457–469. doi:DOI: 10.1111/fog.12165.

Jansen, T., Burns, F., 2015. Density dependent growth changes through juvenile and early adult life of North East Atlantic mackerel (*Scomber scombrus*). Fish. Res. 169: 37–44. doi:10.1016/j.fishres.2015.04.011

Jansen, T., Kristensen, K., van der Kooij, J., Post, S., Campbell, A., Utne, K.R., Carrera, P., Jacobsen, J.A., Gudmundsdottir, A., Roel, B.A., Hatfield, E.M.C., 2015. Nursery areas and recruitment variation of North East Atlantic mackerel (*Scomber scombrus*). ICES J. Mar. Sci. 72: 1779–1789. doi:10.1093/icesjms/fsu186

Nøttestad, L., Utne, K.R., Óskarsson, G.J., Jonsson, S., Jacobsen, J.A., Tangen, Ø., Anthonypillai, V., Bernasconi, B., Debes, H., Smith, L., Sveinbjörnsson, S., Holst, J.C., Jansen, T., Slotte, A., 2016. Quantifying changes in abundance, biomass and spatial distribution of Northeast Atlantic (NEA) mackerel (*Scomber scombrus*) in the Nordic Seas from 2007 to 2014. ICES J. Mar. Sci. 73: 359–373. doi:10.1093/icesjms/fsv218

Jansen, T., Post, S., Kristiansen, T., Oskarsson, G.J., Boje, J., MacKenzie, B.R., Broberg, M., Siegstad, H., 2016. Ocean warming expands habitat of a rich natural resource and benefits a national economy. Ecol. Appl. 26: 2021–2032. doi:10.1002/eap.1384

Pitois, S.G., Jansen, T., Pinnegar, J., 2015. The impact of environmental variability on Atlantic mackerel *Scomber scombrus* larval abundance to the west of the British Isles. Cont. Shelf Res. 99, 26–34. doi:10.1016/j.csr.2015.03.007

Anna Ólafsdóttir

Migration of mackerel and other pelagic fish in relation to oceanographic in the Northeast Atlantic

Olafsdóttir, A. H., Utne, K., Jacobsen, J. A., Nøttestad, L., and Oskarsson, G. 2014. Westward feeding range expansion of Northeast Atlantic mackerel from 2007 to 2013: effects of temperature, zooplankton abundance and spawning stock size. ICES CM 2014/3599 L:03.

Ólafsdóttir A. H., Slotte, A., Jacobsen, J.A., Oskarsson, G., Utne, K.R., and Nøttestad, L., 2015. Changes in weight-at-length and size at age of mature Northeast Atlantic mackerel (*Scomber scombrus*) from 1984 to 2013: effects of mackerel stock size and herring (*Clupea harengus*) stock size. ICES Journal of Marine Science, 73: 255–1265.

Olafsdottir, A.H., Utne, K.R., Jacobsen, J.A., Jansen, T., Óskarsson, G.J., Nøttestad, L., Elvarsson, B.Þ. Broms, C. and Slotte, A., 2018. Geographical expansion of Northeast Atlantic mackerel (*Scomber scombrus*): driven by stock size and constrained by temperature in the Nordic seas. Deep-Sea Research, accepted.

Selma Pacariz

Climatic changes in the ocean environment of the northern North Atlantic, and their effects on the pelagic fish.

Pacariz, S., Hátún, H., Jacobsen, J. A., Johnson, C., Eliasen, S., and Rey, F., 2016. Nutrient-driven poleward expansion of the Northeast Atlantic mackerel (*Scomber scombrus) stock.* Elementa, Science of Anthropocene; 4: 000105; doi: 10: 12952/journal.elementa.000105.

Hátún, H., Lohmann, K., Matei, D., Jungclaus, J., Pacariz, S., Bersch, M., Gislason, A., Ólafsson, J., Reid, P. C. 2016a. An inflated subpolar gyre blows life towards the northeastern Atlantic.Progress in Oceanography (2016), pp. 49-66.

Hátún, H., Pacariz, S., Jacobsen, J. A., Sentyabov, E., Kalashnikov, Y., Krysov, A. 2016b. Marine climate and mackerel distribution. Havstovan no. 16-01. Technical report.

Hátún, H., Azetsu-Scott, K., Somavilla, R., Rey, R., Johnson, C., Mathis, M., Mikolajewicz, U., Coupel, P., Tremblay, J.-É., Hartman, S., Pacariz, S. V. , Salter, I. and Ólafsson, J.,. 2017a. The subpolar gyre regulates silicate concentrations in the North Atlantic. Scientific Reports, 7: 14576, 1-9. DOI:10.1038/s41598-017-14837-4.

Hátún, H., Olsen, B. and Pacariz S., 2017b. The Dynamics of the North Atlantic Subpolar Gyre introduces predictability to the breeding success of kittiwakes. Frontiers in Marine Science, Vol 4, Article 123, 1-7. https://doi.org/10.3389/fmars.2017.00123.

Project summary

Primary production on the Faroe shelf – Spatial and temporal variations with links to hydrography

PhD project, Sólvá Eliasen

Three distinct regions on the Faroe Shelf have been identified with regard to phytoplankton bloom dynamics (Figure 1):

- The Central Shelf (CS): characterised by a vertically well mixed water column and phytoplankton blooms that on average occur in May.

- The seasonally stratified Outer Shelf (OS): blooms later than the CS, but exhibits persistently high surface chl values from June to August. The strong and persistent growth observed during summer is likely attributed to a shallow upper layer and/or continuous nutrient resupply in the frontal mixing zone. In particular the Western Region (WR) stands out as a highly productive area within the OS.

- The seasonally stratified Eastern Banks (EB): blooms early in the season with moderate chlorophyll values throughout the summer. The extent of biomass accumulation is controlled by a thick upper mixed layer and strong stratification, which limits nutrient renewal.

The average exchange rate between the shallow and the deeper parts of the shelf has been constrained and variations in exchange were found to impact the phytoplankton growth on the Faroe Shelf prior to the onset of spring bloom (Figure 2).

A marked hydrographical transition occurs on the Faroe Shelf every spring (typically in May) when the OS becomes persistently stratified, causing the volume of the well mixed CS water mass to decrease.

The hydrographical transition has been linked to the onset of the CS spring bloom. The reduction in volume of the CS water mass is hypothesized to induce a more favourable light climate for phytoplankton growth. A rapid, and possibly early, transition appears to favour significant biomass development on the CS.

The diatom-dominated phytoplankton bloom on the CS usually becomes silicate limited in late May – early June, following the hydrographical transition, and continued growth depends on nutrient resupply from the OS cold pool.

In the period following the hydrographical transition a link was identified between intermittent short term increases in phytoplankton biomass on the CS and heat loss out of the ocean. It is hypothesized that heat loss causes erosion of the innermost part of the OS stratification, and thereby nutrients from the lower OS layer are admixed to the CS, and bloom development further promoted.

Persistent phytoplankton growth on the OS following stratification is hypothesised to result from favourable diapycnal mixing conditions that delays the onset of nutrient limitation.

Similar large scale patterns in phytoplankton biomass on the OS and European Margin suggest basin-scale forcing is an important factor in explaining the dynamics of adjacent shelf systems in the Subpolar Atlantic.

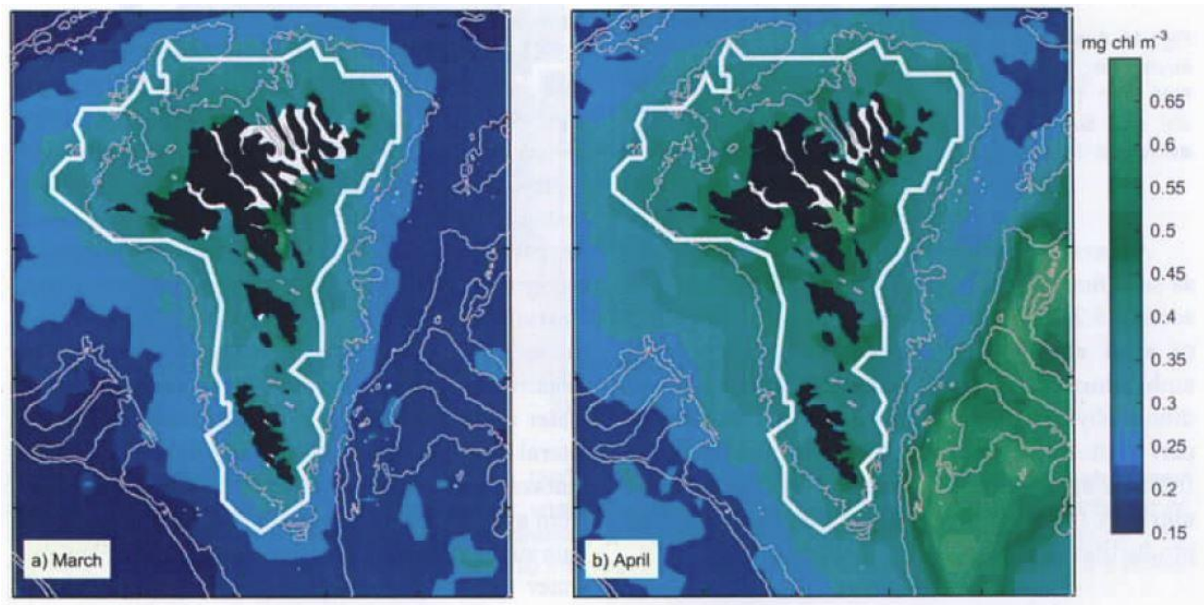


Figure 1. Average surface chl-a concentrations in March and April. The white line indicates the average summer position of the CS region and the gray lines indicate the 100 m, 200 m and 300 m bottom contours.

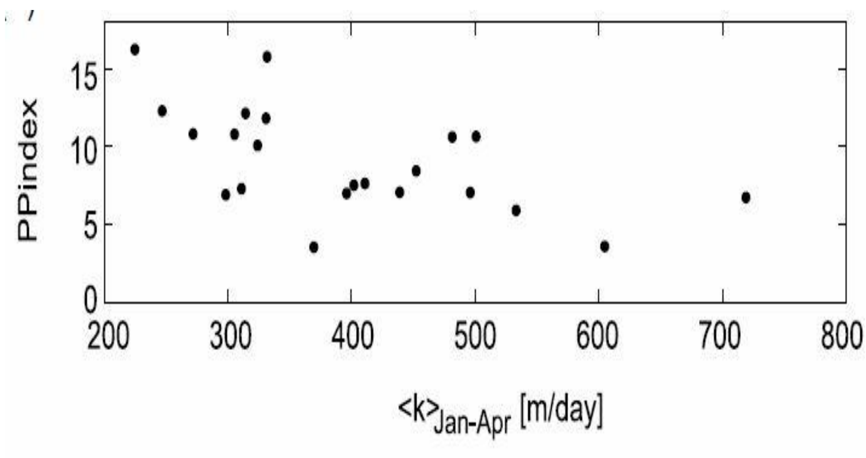


Figure 2. Primary production index (from spring to late June) plotted against average exchange rate (<k>) during the winter.

Outlook

In order to further develop our understanding on the interaction between oceanic waters, the OS and the CS, the following questions should be addressed:

- How significant are short term variations in the exchange rate?
- Are there certain main passages through which water is imported and exported?
- What is the relative importance of the upper and lower OS layer for exchanges between the OS and CS?
- How does frontal mixing supply nutrients to the CS and the upper layer of the OS?
- Why is the Western Region the most productive area on the OS during summer?
- Investigation of the hydrographical transition: Is a rapid and early transition more beneficial for the bloom development than a slow/late transition?

With regards to biology, further knowledge of ecosystems dynamics is required and the following questions should be addressed:

- What is the grazing impact of zooplankton groups other than copepods on the phytoplankton community?
- What is the significance of benthic-pelagic coupling for Faroe Shelf ecosystem dynamics?
- The transfer of photosynthetically-fixed carbon to higher trophic levels and the bathypelagic ocean is crucial for a complete understanding of the climate system and ecosystem dynamics. How important is phytoplankton species composition for regulating nutrient:carbon and carbon:chl ratios?

The present study has identified bio-geographical zones on the Faroe Shelf, detailed the importance of stratification, nutrient limitation and described the interaction of shelf waters with surrounding oceanic waters. This has allowed a more complete understanding of the factors regulating the Faroe Shelf bloom dynamics. However, a complete explanation for the strong interannual variability of the Faroe Shelf primary production and trophic dynamics remains somewhat elusive. Further resources should be allocated to pursue these questions that are of critical importance for the understanding of the Faroe Shelf marine environment.

Ecology of *Calanus finmarchicus* in relation to environmental conditions in the southwestern Norwegian Sea

PhD project, Inga Kristiansen

The southwestern Norwegian Sea is characterized by an inflow of warm and saline Atlantic water from the southwest and cold and less saline East Icelandic Water (EIW), of Arctic origin, from the northwest. These two water masses meet and form the Iceland-Faroe Front (IFF) (Figure 3). The dominating zooplankton in this region is the copepod *Calanus finmarchicus*. In terms of biomass, *Calanus hyperboreus*, a congeneric species of *C. finmarchicus*, is also of importance. Together they play a key role in the pelagic ecosystem. Time-series of *C. finmarchicus* and *Calanus hyperboreus* in May and September, extending back to the early 1990s, were studied in relation to phytoplankton bloom dynamics and hydrography. The main reproductive period of *C. finmarchicus* started consistently earlier south of the IFF, resulting in different life cycles and stage compositions in the two water masses (Figure 4). In 2003, a sudden shift occurred north of the IFF, resulting in a similar phenology pattern to south of the IFF. The numbers of the younger stages of *C. finmarchicus* markedly increased, while the abundance of the overwintering individuals decreased. Simultaneously, *C. hyperboreus*, an expatriate in the Iceland and Greenland Seas, largely disappeared (Figure 5a). Food availability is unlikely the reason for the phenological differences observed across the front, as the typical pattern of the phytoplankton spring bloom showed an earlier onset north of the IFF. Temperature and salinity peaked at record high values in 2003 and 2004, and therefore possible links to oceanography are discussed.

It has previously been assumed that the majority of *C. finmarchicus* is advected to the study area from the Norwegian Basin. However, as the persistent changes of the *Calanus* spp coincide, suggests that the overwintering *C. finmarchicus* population is advected with the EIW, together with *C. hyperboreus*. Therefore these can be considered as indicator species of a biogeographic shift and it was hypothesized that the zooplankton shift was caused by a reduced influence of subarctic waters from the western region.

Further investigations have shown that the abrupt disappearance of *C. hyperboreus* and large stages of *C. finmarchicus* around 2003 coincides with a drastic reduction in the volume of the cold and low-saline EIW tongue (Figure 5), also known as the Modified East Icelandic Water, which subsequently has remained lower compared to previous years. Furthermore, the zooplankton biomass within the EIW east of Iceland was also much reduced around 2003 and has since remained low (Figure 6).

The marked weakening of the North Atlantic subpolar gyre after 1995 (Figure 5b) and the downstream general warming and salinification – 'Atlantification' – of the Nordic Seas might, however have contributed to the declining trend. A marked clockwise wind circulation anomaly over the Nordic Seas, together with a weakening of the Norwegian Sea gyre, during 2003 has likely triggered the rapid westward water mass shift and consequently tipping the zooplankton community into a new state. The reshaping of water mass boundaries might strongly impact the large pelagic fish stock migrating to this region.

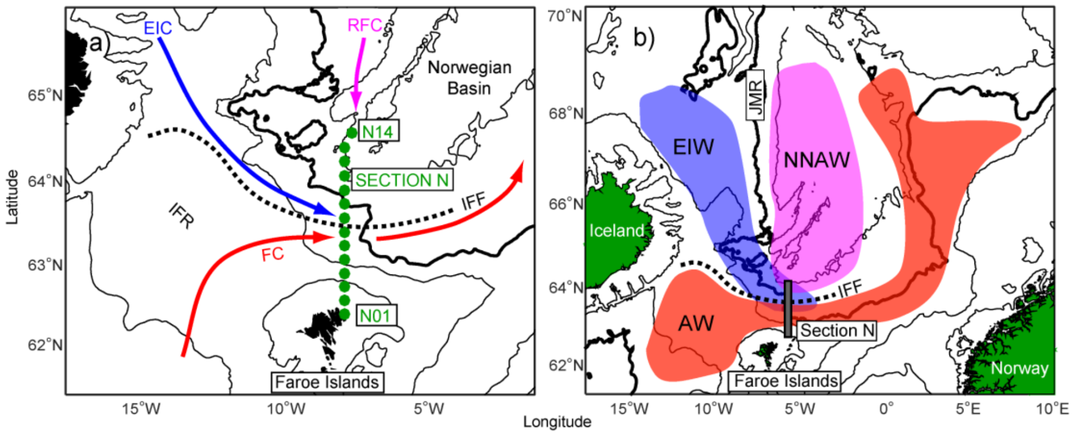


Figure 3. Map of the study area. (a) Main currents and (b) distribution of associated water masses. Abbreviations: Faroe Current (FC), Recirculated Faroe Current (RFC), East Icelandic Current (EIC), Atlantic Water (AW), East Icelandic Water (EIW), Norwegian North Atlantic Water (NNAW), Iceland-Faroe Front (IFF), Iceland-Faroe Ridge (IFR), Jan Mayen Ridge (JMR). The thick grey line north of the Faroe Islands displays the study area (Section N). The 2000 m isobath is shown in bold.

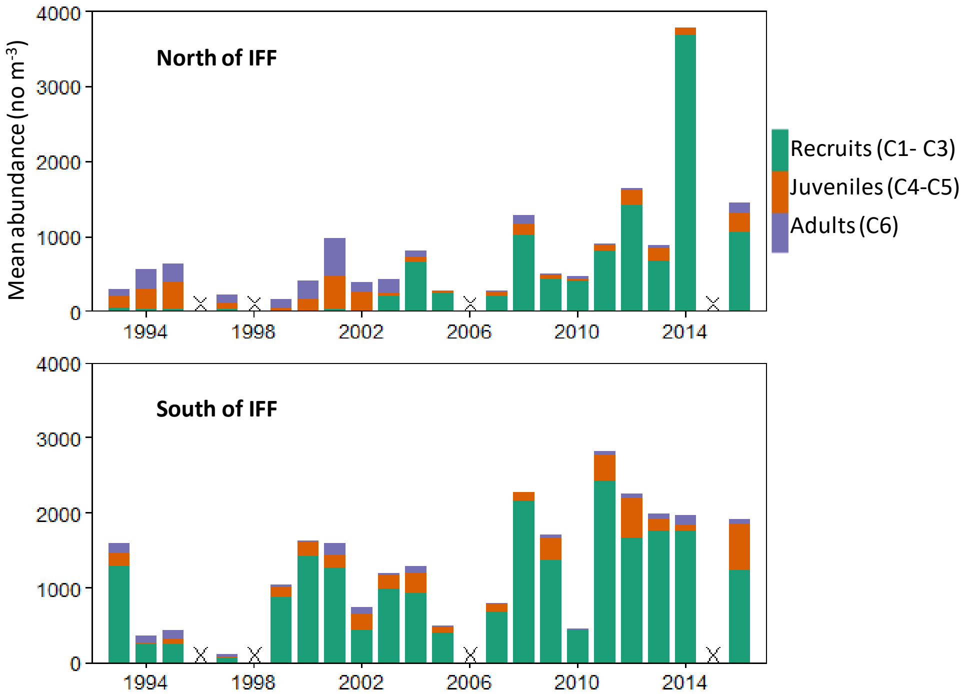


Figure 4. Interannual variations in the mean abundance (numbers m^{-3}) of *Calanus finmarchicus* developmental stages in May, in Atlantic water (south of IFF) and subarctic water (north of IFF) at Section N. Years with missing data are indicated by crosses.

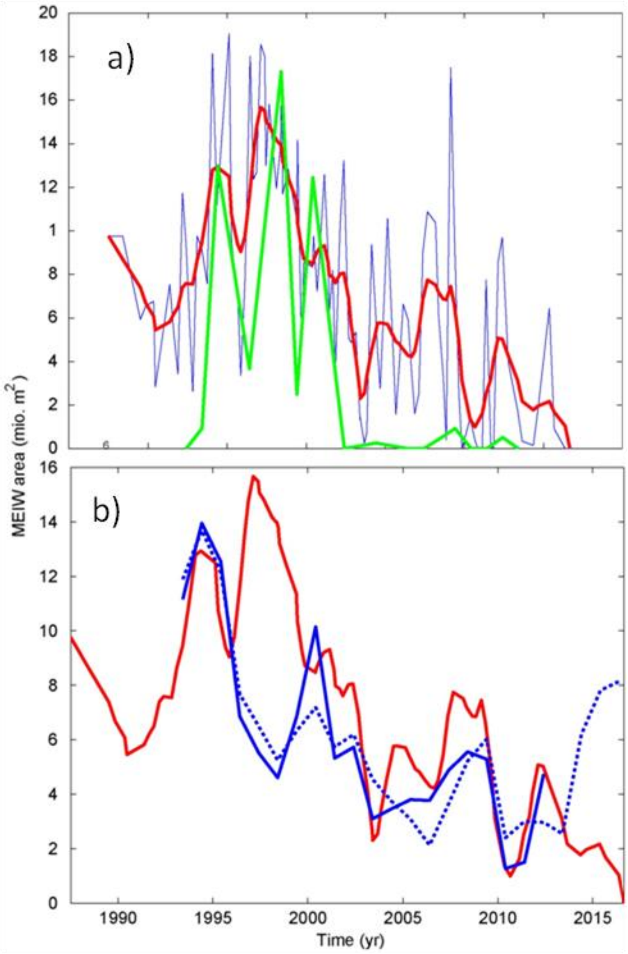


Figure 5. Cross-sectional area of Modified East Icelandic Water (MEIW) at Section N (red) and a) The abundance of *C. hyperboreus* at Section N (green) and b) two versions of the altimetry-based subpolar gyre index (blue). The MEIW area from individual occupations of this section are shown in blue (b), and the red line shows the low-pass filtered (width of four data points) trend (a and b). The old gyre index (Larsen et al., 2012) and the recent most gyre index (Hátún et al., 2017) versions are shown with full and dashed lines, respectively.

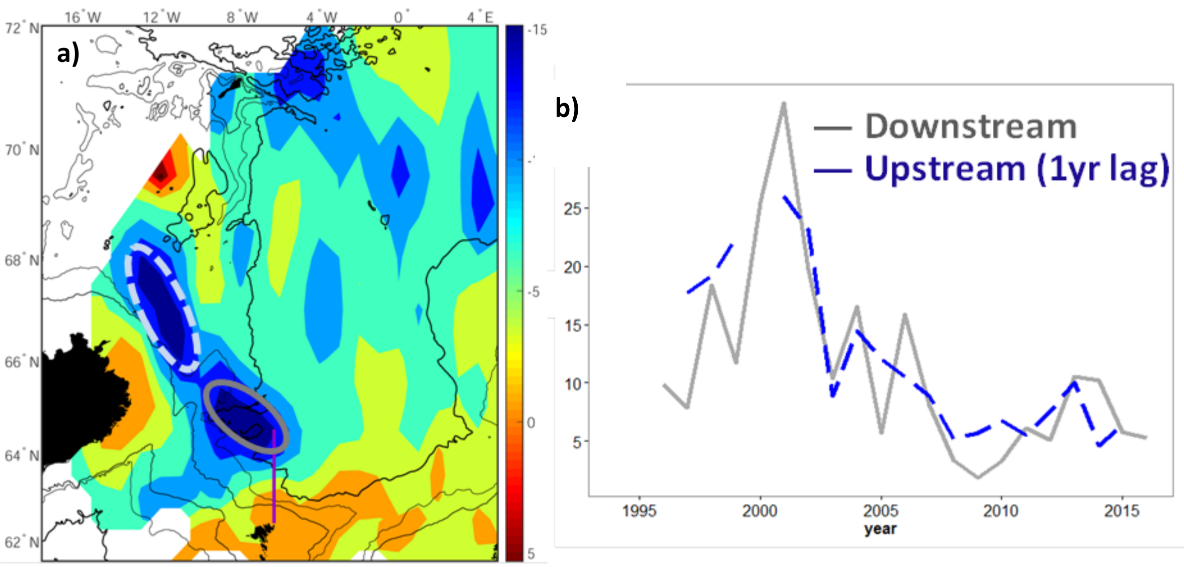


Figure 6. a) Difference in zooplankton biomass (g dw m^2) before (1998-2002) versus after (2004-2016) 2003 in the Norwegian Sea and the eastern part of the Iceland Sea. b) Mean zooplankton biomass (g dw m^{-2}) in May from 1998 to 2016 based on the time series from the selected regions shown in a).

Changes in distribution and migration of mackerel and other pelagic fish in relation to East Greenland waters

PostDoc project, Teunis Jansen

The nursery areas of juvenile mackerel during their first year are mainly west and of the British Islands, south of the Faroe Islands and in the northern part of the North Sea. The majority (75%) of the offspring survivors in the first winter are found north of the oceanographic division at approximately 52°N, despite the fact that mackerel spawns over a wide range of latitudes. Multivariate time series modeling of survivor abundance in the north revealed a significant correlation with the abundance of copepodites (stage I-IV) of *Calanus* sp. in the spawning season (April-June).

After spawning, there is a feeding migration of the adult stock northwards and westwards during spring and summer. During the last ten years, the feeding area has expanded significantly, northwards and also westwards into Icelandic and Greenlandic areas. At the same time as the geographic range of the mackerel fishery has expanded and the spatial distribution of the stock been defectively determined, the stock assessment has been considered to be highly uncertain by ICES. Limited tuning data, with only a triennial egg survey, have created challenges for the assessment and management of NEA mackerel, and ICES has repeatedly stated the need for an annual age-disaggregated abundance index of this stock. These were the motivations for establishment of an international pelagic trawl survey in 2007, the International Ecosystem Summer Surveys in the Nordic Seas (IESSNS). The estimated total biomass indices for NEA mackerel based on coordinated and standardized swept-area surface trawling in July–August from IESSNS increased from 1.96 million tonnes in 2007 to 8.77 million tonnes (RSE = 7.95%) in 2014 (Figure 7). Simultaneously, the mackerel stock expanded its geographic range during the feeding season from 1.3 million km^2 in 2007 to at least 2.9 million km^2 in 2014, mainly towards western and northern regions (Figure 7). Estimates of abundance indices by age group were fairly precise (RSE ~20%) for ages 3–12, while the precision was poorer for ages 1 and 2 and for age groups 13 and older (RSE > 50%). Furthermore, evaluation of the performance of the estimated abundance indices by age for this time-series, based on internal consistency and catch curves, suggest that the abundance indices of ages 3–12 track the temporal variation in abundance reasonably, and thus is applicable for stock assessments.

Geographic redistribution of living natural resources changes access and thereby harvesting opportunities between countries. Internationally shared fish resources can be sensitive to shifts in the marine environment and this may have great impact on the economies of countries and regions that rely most heavily on fisheries to provide employment and food supply. In this project, there is presented climate change-related biotic expansion of a rich natural resource with substantial economic consequences, namely the appearance of northeast Atlantic mackerel in Greenlandic waters.

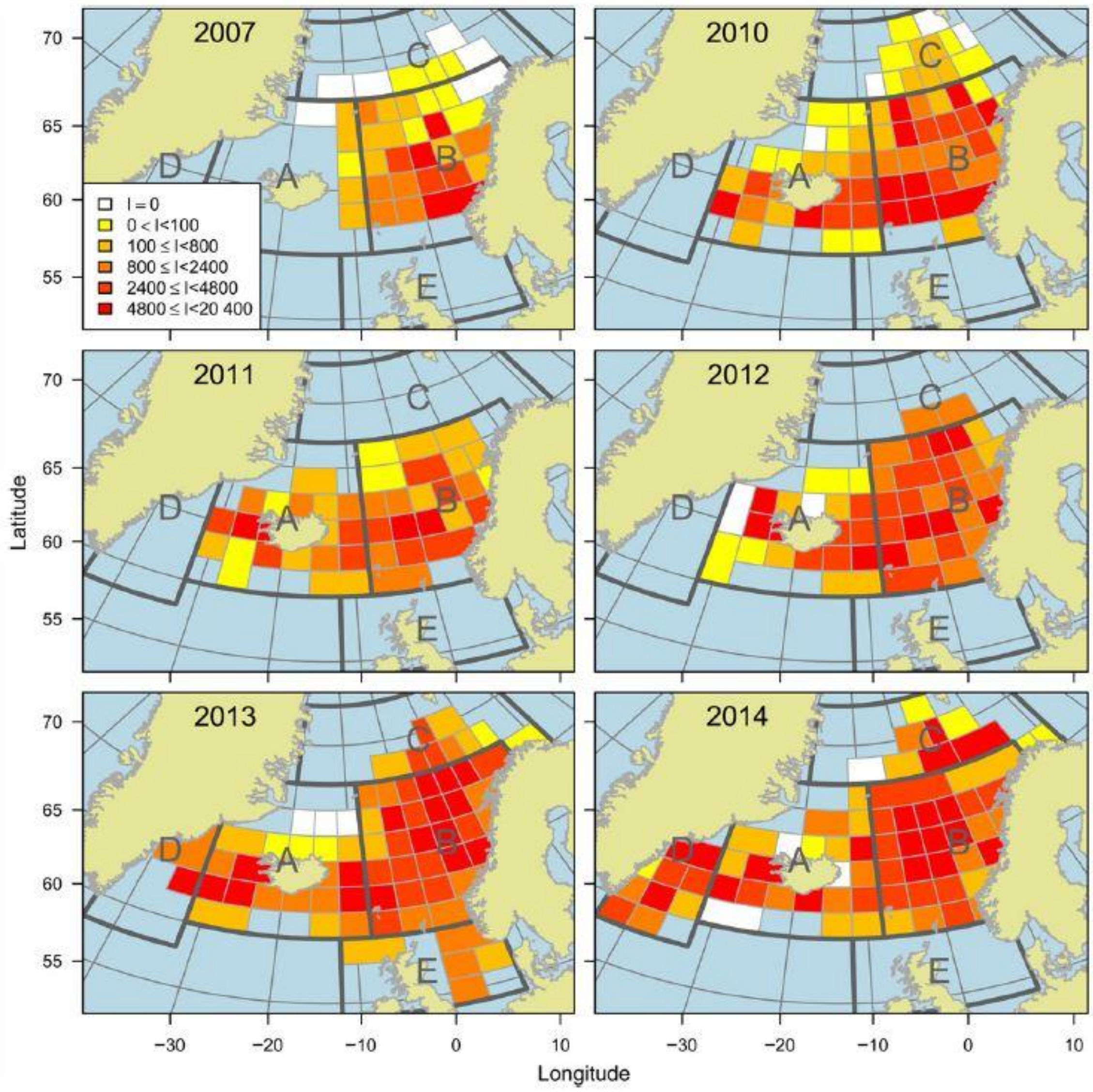


Figure 7. Average catch index (kg km^{-2}) by pseudostrata (see text) for NEA mackerel in July–August 2007 and 2010–2014 with spatial coverages of 1.66, 2.48, 1.92, 2.19, 2.65, and 3.11 million km^2, respectively. The interval widths for the colours are scaled based on the 0, 20, 40, 60, 80, and 100% quantiles of estimated densities in each pseudostratum across years.

In recent years, the summer temperature has reached record highs in the Irminger Current, and this development has expanded the available and realized mackerel habitat in time and space. Observations in the Irminger Current in east Greenland in 2011 of this temperature- sensitive epipelagic fish were the first records so far northwest in the Atlantic. This change in migration pattern was followed by a rapid develop-ment of a large-scale fishery of substantial importance for the national economy of Greenland (23% of Greenland's export value of all goods in 2014). The pelagic trawl survey, conducted in mid-summer 2014 (Figure 7), showed that the bulk of ~1 million t of mackerel in the Irminger Current in southeast Greenland were located in the relatively warm (>8.5°C) surface layer. Mackerel was also observed in southwest Greenland.

Finally, 15 CMIP5 Earth System Model projections of future marine climate were used to evaluate the epipelagic environment in Greenland. These projections for moderate and high CO_2 emission scenarios (representative concentration pathways [RCP] 4.5 and 8.5) suggest how the available mackerel habitat may expand further in space and time. Overall, our results indicate that, if the stock remains large, productive, and continues its current migration pattern, then climate change has provided Greenland with a new unique opportunity for commercial exploitation. However, positive cases like this should not be cherry-picked and misused as arguments against timely and effective mitigation of climate change.

Migration of mackerel and other pelagic fish in relation to oceanography in the Northeast Atlantic

PostDoc project, Anna Ólafsdóttir

Traditionally, majority of the mackerel stock feed in surface layer of the Norwegian Sea and in the North Sea (55-75°N and <6°W) during summer. An annual coordinated ecosystem survey in the Norwegian Sea and surrounding waters conducts swept area trawling in the surface layer, zooplankton samples and collects CTD profiles. Analysis of the surface trawling indicates mackerel feeding range expanded westward by approximately 1200 km from 2007 to 2013 (Figure 7 and 8). In 2013, western boundary of the mackerel feeding migration had entered Greenland waters (longitude 38°W). Range expansion coincided with 75% increase in spawning stock biomass. Preliminary results suggest that the northern edge of the mackerel westward expansion, into the East Iceland Current, was limited by colder temperatures, whereas the southern edge, into the North Atlantic Current, was defined by higher temperatures and lower zooplankton abundance.

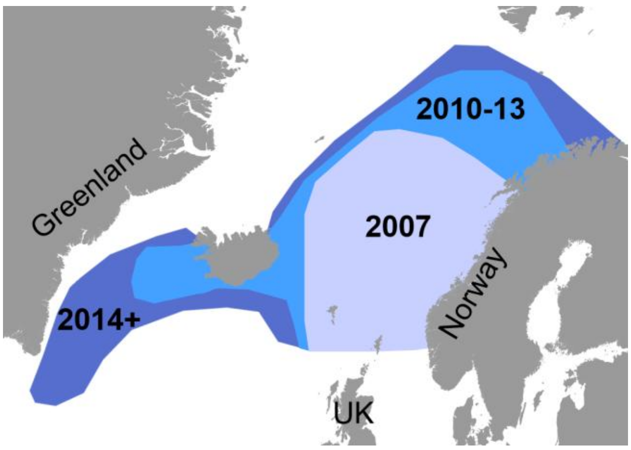


Figure 8. Expansion of the mackrel feeding area in summer.

Weight-at-length and length-/weight-at-age were analysed for mature 3- to 8-year-old Northeast Atlantic mackerel, collected annually in autumn (September and October) at the end of the annual feeding season during 1984–2013 in the northern North Sea. The age range represented 92% of the mackerel stock size (age 3+). During the most recent decade, mackerel length- and weight-at-age continually declined. In 2013, the average mackerel was 3.7 cm shorter and weighed 175 g less than the average individual in 2002. Individual weight-at-length, demonstrating annual summer feeding success, continually declined during the most recent 5 years, whereas somatic growth of cohorts aged 3–8 continually declined for the last 11 of 25 cohorts investigated. Growth of the latest cohort was 34% of the maximum cohort growth recorded. Both weight-at-length and cohort growth were negatively affected by mackerel stock size and Norwegian spring-spawning herring stock size (weight-at-length: $r^2 = 0.89$; growth (length): $r^2 = 0.68$; growth (weight): $r^2 = 0.78$), while temperature was not significant.

Conspecific density-dependence was most likely mediated via intensified competition associated with greater mackerel density. Negative effects of herring were likely mediated by exploitative competition for shared food resources rather than direct competition due to limited spatio-temporal overlap between mackerel and herring during the feeding season. Herring begin their seasonal feeding migration at least a month before mackerel; therefore, herring consumption influences prey availability for the later-arriving mackerel. Record low mackerel growth and negative effects of mackerel and herring stock size suggest that the carrying capacity of the Norwegian Sea and adjacent areas for plankton-feeding fish stocks have been reached. However, compounding effects of a less productive Norwegian Sea during the 30-year period cannot be excluded.

In the last decade, mackerel geographical distribution, during the summer feeding season, expanded extensively into areas where mackerel presence has never been documented in large quantities before. Catch-per-unit-effort data from 2540 scientific trawl stations, collected in Nordic seas during summer (July and August) from 1997 to 2016, revealed a sixfold increase in geographical distribution. The expansion began in 2007 and was in two major directions. Northward in the Norwegian Sea by approximately ~500 km, and westward along the south coast of Iceland towards Greenland by approximately ~1200 km. Mackerel preferred temperatures ranging from 9°C to 13°C (high occurrence and high density), tolerated temperature >7°C (high occurrence but low density) and avoided waters <5°C (absence). During the expansion period, the mackerel stock almost doubled in size. As stock size increased, distribution expanded, mackerel density in the traditional feeding area increased, adjacent areas became occupied by mackerel, and mackerel weight-at-length were similar between the traditional area and adjacent areas. It appears density dependence was the operational mechanism of expansion as predicted by MacCall´s basin model, and direction of expansion was delineated by temperatures of the surface currents as mackerel prefer warm Atlantic waters and avoid cold Polar waters.

Climatic changes in the ocean environment of the northern North Atlantic, and their effects on the pelagic fish (mackerel, *Scomber scombrus*)

Selma Pacariz, PostDoc project

Expansion of North Atlantic mackerel stock during summer feeding migration has been attributed to the changes in the water temperature, increase in size of the stock, and decrease in food availability in the Norwegian Sea (ICES CM 2014, WKPELA). In the first part of the project, possible key parameter in the ocean environment were identified, such as a temperature or salinity threshold, presence/absence of stratification, which could be limiting the poleward distribution of the mackerel stock. For this purpose, data from international mackerel surveys (2009-2014), were analysed. These included mackerel catches (kg mackerel per km^2), zooplankton dry weight (g in the upper 200 m), temperature, salinity, density, and at some stations fluorescence. The results showed that there is no clear connection between the mackerel distribution and the marine climate, and probably no single parameter that can describe the post-2006 expansion in all regions. The reason why mackerel is expanding in the way it does, might be different in north compared to west and there was therefore looked for another explanation instead of the frequently assumed direct connection to ocean temperatures. The northward expansion is though most likely to be limited by low temperatures in the surface layer, and this was further investigated by other researchers in this research programme. However, from the mackerel catch data, it was clear that mackerel avoids the central Iceland Basin (zero mackerel catches), and this species migrates westwards through a narrow passage close to the south Iceland slope where the catches of mackerel can be high. Zooplankton data showed the same pattern, high levels of zooplankton were found close to the south slope of Iceland and low levels further south in the Iceland Basin (Figure 9). Lack of food might be the reason why mackerel avoids this area, as zooplankton is main prey source for mackerel.

Our first hypothesis is: *mackerel is avoiding waters that are poor in nutrients (nitrates and silicates)*. Analysis of all available nutrient data from World Ocean Databases (1970-2014) show that concentrations of nutrients in the surface layer in the central Iceland Basin decline fast and reach minimum during the summer. Phytoplankton utilise nitrates and phosphates, but the fast growing diatoms also need silicates for building cell membranes. Thus, low levels of nutrients are likely to limit growth of phytoplankton, which might then influence the zooplankton community. In the passage, along the south Iceland slope, the levels of nutrients are higher, implying higher productivity in this narrow area.

Second hypothesis is: *nutrient limitation might be driving mackerel from nutrient poor regions in the east towards nutrient rich regions in the west*. Rey, 2012 has shown that silicates have been decreasing (and salinity increasing) in the Norwegian Sea since around 1990 (Hátún et al. 2017). Long-term averaged nutrient data from WOA showed higher concentrations of nutrients in the west (Labrador Sea) than in the eastern northern North Atlantic. The potential nutrient limitation is therefore most severe in the east, and we suggest that this could be explain the post-2006 westward expansion of mackerel (Figure 9).

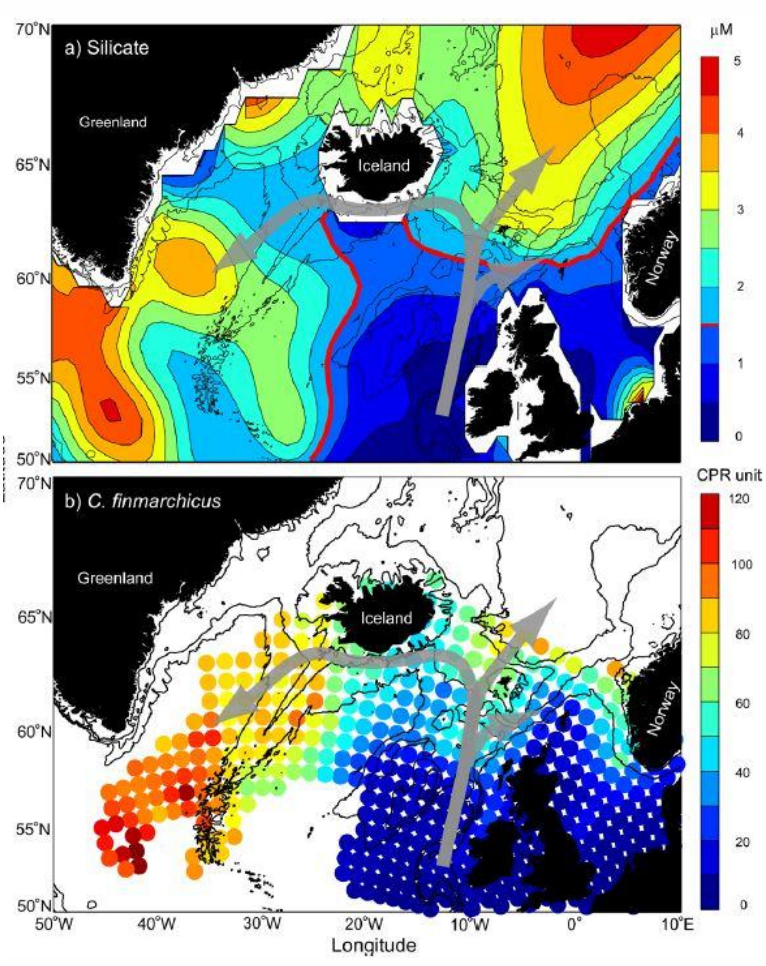


Figure 9. a) Near-surface (50 m) silicate concentrations averaged over the period 1960-2013. The tick red contour line enphasizes the diatom-limiting level of 1.5 µM. b) *Calanus finmarchicus* abundance (stages CV and CVI) from the near-surface continuous plankton recorder (CPR) survey are shown for the period 1958-2005. The general mackerel feeding migration is illustrated with grey arrows.

In another study, led by Hjálmar Hátún, Havstovan, we examined how the Labrador Sea convection is influencing productivity in the Irminger Sea and on the southern Iceland shelf. Particle tracking experiment showed possibility and timing of the transport of Labrador waters northwards into the Irminger Sea and onto the Iceland shelf. We showed that influence of Labrador waters could strongly influence the zooplankton abundance on the Icelandic shelf.

Final remarks

The ecological importance of the Subpolar Gyre (located in the Laborador Sea-Irminger Sea has been studied. This gyre is rich in nutrients and plankton and its variable size and circulation strength (Figure 10) can therefore regulate the advection of nutrients and zooplankton to its peripheral regions from west of the British isles to the Labrador Sea, as well as to the Atlantic inflows into the Nordic Seas. Thus, the dynamics of this gyre has a potential to affect marine ecosystems over a large geographical scale, including feeding conditions for the large straddling pelagic fish stocks as well as the production of adjacent shelf ecosystems (Hátún et al. 2017a). This important topic thus merits further studies.

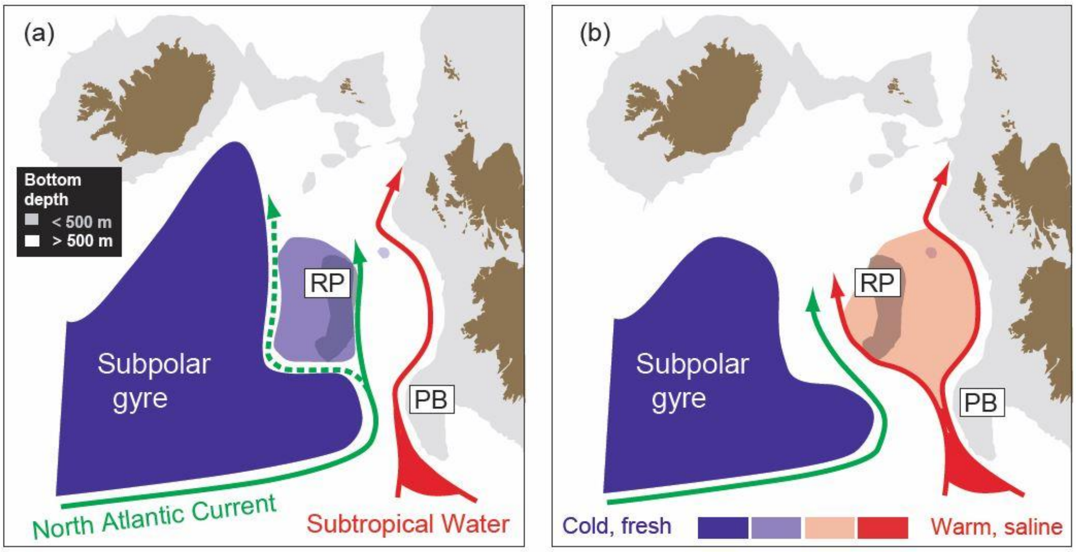


Figure 10. Schematic illustration of variable strength of the eastern part of the Subpolar gyre. Abbreviations: Rockall Plateau (RP) and Porcupine Bank PB).

Appendix

Annual meetings

Kick-off meeting:

Changes in Marine Climate and Ocenographic Conditions in the Waters between the Faroes and Greenland and their effects on plankton and fish

Torshavn, 10 March 2014

9.00	Introduction	*Eilif Gaard*
Faroe shelf		
9.15	Hydrography	*Margretha H. Larsen*
9.30	Modelling primary production	*Sólvá Eliasen*
NE Atlantic Oceanography		
9.45	Oceanography	*Hjálmar Hátún*
10.00	Large Scale Oceanography	Selma Pacariz
10.15	Coffe break	
10.30	Zooplankton	*Høgni Debes*
10.45	Calanus finmarchicus	*Inga Kristiansen*
11.00	Mackerel and herring	*Jan Arge Jacobsen*
11.15	Mackerel East	*Anna Ólafsdóttir*
11.30	Mackerel West	*Teunis Jansen*
11.45	Discussion	
13.00	Lunch	

2nd annual meeting:

Changes in Marine Climate and Ocenographic Conditions in the Waters between the Faroes and Greenland and their effects on planton and fish

Nuuk, 10-11 march 2015

Tuesday 10 March

9.00 – 9.10 *Eilif Gaard & Helle Siegstad:* Velkommen + praktiske informationer.

Faroe Shelf

9.10 – 9.40 *Sólvá Eliasen:* How does horizontal mixing affect the primary production on the Faroe Shelf?

Oceanography – biological influences

9.40 – 10.10 *Selma Pacariz:* Nutrient limitation in the subpolar North Atlantic drives mackerel westwards.

10.10 – 10.30 Coffe break

10.30 - 11.00 *Eilif Gaard (Hjálmar Hátúns presentation):* Labrador Sea convection blows life to the northeastern Atlantic

11.00 - 11.30 *Till Soya Rasmussen:* Ocean and sea ice modelling at DMI.

Plankton

11.30 – 12.00 *Inga Kristiansen:* Diversity and phenology changes of *Calanus* in the south-western Norwegian Sea, 1990-2014, linked to ocean climate

12.00 – 12.30 *Sigrun Jónasdóttir: Calanus finmarchicus* and the biological carbon pump

12-30 – 13.30 Lunch

Fish

13.30 – 14.00 *Teunis Jansen:* Mackerel research status and plans

14.30 – 15.00 *Anna Ólafsdóttir:* Changes in mackerel biology and ecology during the last decade

Diskussion

15.00 – 16.00	Discussion: - How are the projects going? - How can the projects support each other? - Publications?
16.00 – 19.30	We will have opportunity to have a look at Nuuk
19.30	Dinner at restaurant in Nuuk

Wednesday 11 March

9.00 - 10.00	Steering Group meeting: - Budgets - Decisions - Continuation of the Center after the end of this program? - AOB
9.00 – 11.00	PhD student-Supervisor discussion (Steering Group members who are supervisor will join when the steering group meeting has ended.
11.00 – 12.00	Summary Next meeting

3th annual meeting:

Changes in Marine Climate and Ocenographic Conditions in the Waters between the Faroes and Greenland and their effects on plankton and fish

Huset, Hindsgavl Allé 2, DK-5500 Middelfart.
30-31 March 2016

Wednesday 30 March

12.00 –13.00 Lunch

13.00 –14.00 Steering Group meeting

Plenary presentations and discussion
14.00-14.15 Welcome & information

Faroe Shelf
14.15 – 14.45 *Sólvá Eliasen:* Phenologically distinct phytoplankton regions on the Faroe Shelf, identified by satellite data, *in-situ* and model data.

Plankton
14.45 – 15.15 *Eilif Gaard (Inga Kristiansens presentation. Maternity leave):*
Seasonal variation in population dynamics of *Calanus finmaricus* in the south-western Norwegian Sea from 2013-2014.

15.15 – 15.45 Coffee break

Oceanography – biological influences

15.45 – 16.15 *Selma Pacariz:* Nutrient-driven poleward expansion of the Northeast Atlantic mackerel (*Scomber scombrus*) stock – a new hypothesis

16.15 – 16.45 *Hjálmar Hátún:* Declining silicate concentrations in the North Atlantic

16.45 – 17:15 Discussion of the days presentations

Thursday 31 March

9.00 – 9.30 *Anna Ólafsdóttir:* Biology and ecology of the NE Atlantic mackerel stock

9.30 -10.30 Teunis Jansen

i. Recruitment of North East Atlantic Mackerel (*Scomber scombrus*) from 1998 to 2012 appears to be driven by availability of *Calanus* - a preferred copepod prey.

ii. Diel vertical feeding behaviour of Atlantic mackerel (*Scomber scombrus*).

iii. Changes in overwintering habitat of North East Atlantic mackerel (*Scomber scombrus*) from 1993 to 2014 (by Jansen and Pacariz)

10.30 – 11.00 Break

11.00 – 12.00 Discussion & Summary
End of meeting

Final symposium:

Changes in marine climatic and oceanographic conditions in the waters between the Faroes and Greenland, and their effects on plankton and fish

Tórshavn, 19 April 2017

9.00 – 9.20 *Eilif Gaard*: Welcome and introduction

Faroe Shelf

9.20 – 9.50 *Sólvá Eliasen:* Phytoplankton on the Faroe Shelf - an overview

9.50 – 10.20 *Sólvá Jacobsen:* Temporal and spatial variability of zooplankton on the Faroe shelf in spring 1997-2016

10.20 - 10.50 *Anna Ólafsdóttir:* Density dependent range expansion of mackerel in the NA-Atlantic during the last decade

*10.*50 – 11.10 Coffee break

Oceanography, Plankton, biological influences

11.10 – 11.40 *Inga Kristiansen:* Seasonal variation in *Calanus finmarchicus* in the southwestern Norwegian Sea

11.40 – 12.10 *Hjálmar Hátún:* Winter convection blows life - A Bird's-eye view

12.10 – 13.15 Lunch

Pelagic fish

13.15 – 13.45 *Selma Pachariz:* Effect of the marine climate on mackerel distribution in the Norwegian Sea and Iceland Basin

13.45 – 14.15 *Teunis Jansen:* The everyday life of mackerel in Greenland

14.15 – 14.30 Coffee break

14.30 – 15.00 T*eunis Jansen:* Drift simulations of capelin larvae around Iceland and East Greenland

15.00 – 15.45 Discussion, Summary and future focus

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