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# Advective loss of overwintering *Calanus finmarchicus* from the Faroe–Shetland Channel

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ABSTRACT

The flow of deep water from the Norwegian Sea to the North Atlantic via the Faroe–Shetland Channel is one of the critical bottlenecks in the meridional overturn circulation. It is also a flow that potentially carries with it a large number of the overwintering copepod, *Calanus finmarchicus*, a regionally important secondary producer. Using a high resolution hydrodynamic model, MIKE 3 FM, we simulate the overflow of deep water and estimate the associated loss rate of *C. finmarchicus* as a function of the water depth strata within which they reside. We estimate a net advective loss from the Norwegian Sea population of $80 \pm 10$ kt carbon bound in lipids of *C. finmarchicus* biomass per year, a number that constitutes about 50% of the total overwintering population. Estimates of water mass characteristics and particle tracking suggest that the fate of individuals transported in the overflowing water is to be entrained into warmer waters of the North Atlantic Basin, a habitat that appears to be unsuitable for successful overwintering.



## 1. Introduction

The copepod *Calanus finmarchicus* is widely distributed over the North Atlantic, and constitutes one of the key ecological species of the region. It is found in high abundance across the North Atlantic from Georges Bank and the Labrador Sea in the west to the North Sea and Barents Sea in the east (Conover, 1988; Heath et al., 2000, 2004; Melle et al., 2014). Its ecological role is that as an intense grazer of primary production, and subsequently an important food source for pelagic fish, seabirds and marine mammals.

The success of *C. finmarchicus* is in part due to its ability to survive the long periods of harsh conditions during the winter by migrating to deep water and entering diapause (a torpid state where activity and metabolism are minimized). *C. finmarchicus* overwinter as pre-adult stage C4 and C5 copepodites, and ascend to surface waters in the spring, maturing to adults and reproduce to take advantage of the spring bloom. In the course of the spring and summer, one or two generations develop from egg to nauplii (6 stages, N1 to N6) to copepodite (5 stages, C1 to C5) then become an adult. During the late autumn and early winter, copepodite *Calanus* stage 4 and 5 start to descend to the deep water. Depending on geographical area, *C. finmarchicus* descends to depths of between 600 and 1000 m (Heath et al., 2004) where it remains in diapause for 4 to 8 months. These overwintering copepods are lipid-rich with typically 50–70% of their dry weight being wax esters (Lee et al., 2006). The stored lipid reserves can be seen to serve 3 main purposes; they fuel overwintering metabolism (albeit at a reduced rate) (Lee et al., 2006), allow the overwintering copepodites to attain neutral buoyancy at overwintering depth (Visser and Jónasdóttir, 1999), and fuel maturation and egg development early the following year (Richardson et al., 1999).

One of the largest populations of *C. finmarchicus* is in the Norwegian Basin where it overwinters in the cold ($-0.5$ °C) Norwegian Deep Water that flows from the Nordic Seas along the continental shelf into the Faroe–Shetland Channel (Heath et al., 2004). The Faroe–Shetland Channel (FSC) is considered as an important overwintering refuge for *C. finmarchicus* where they accumulate in large numbers, and it is a major source from which *C. finmarchicus* populations in the North Sea and Norwegian Sea are re-seeded each year. The distribution of overwintering *Calanus* habitat is associated with the deep water mass with densities greater than $\sigma = 28$ kg/m$^3$ (Heath and Jónasdóttir, 1999). While in its neutrally-buoyant torpid state, overwintering *C. finmarchicus* drift with the deep water currents southwards through the Faroe–Shetland Channel. A proportion of these may eventually flow through the Faroe Bank Channel and so into the Rockall and Iceland Basin, representing an as yet unquantified loss from the overwintering population.

The Faroe Bank Channel (FBC) connects the Nordic Seas and the North Atlantic. At a sill depth of 850 m, it is the deepest passage along the circa 1700 km long Greenland Scotland Ridge (GSR), and

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is only 15 km wide. In this region, cold and saline deep water flows south from the Nordic seas to the North Atlantic, while at the surface, the warm and less saline waters of the North Atlantic current flow northwards. The deep water transport is about 2.1 Sv (1 Sv$=10^6$ $m^3$/s), which is almost a third of the total deep water transport (6.4 Sv) crossing GSR (Hansen and Østerhus, 2000). Due to the size of the channel and the amount of the transport, FBC is considered a bottleneck in the exchange of deep waters from the Nordic Seas to the North Atlantic and beyond.

This work is concerned with estimating the loss rate and the fate of overwintering *C. finmarchicus* transported by the overflow of deep water in this area. We use a high resolution hydrodynamic model to estimate depth (and density) partitioned overflow transport, which together with seasonally resolved abundance measurements provide estimates of the population loss rates. The fate of overflowing individuals is estimated using a particle tracking routine and the characteristics of the water masses into which they are subsequently entrained.

## 2. Method

In this study, we use the hydrodynamic model MIKE (version MIKE 3 FM) by DHI (http://www.mikebydhi.com). It is based on the solution of the three-dimensional incompressible Reynolds averaged Navier–Stokes equations, subject to the assumptions of Boussinesq approximation and hydrostatic pressure. It is used widely in aquatic and marine systems; from lakes to coastal seas and open ocean circulation, and has been applied in addressing problems ranging from physical and biological oceanography to more engineering perspectives (Elsässer et al., 2013; Passenko et al., 2008; Rasmussen et al., 2009). The model has been extensively tested in terms of its sensitivity to different processes and parameterizations in different scenarios for the Northern Adriatic Sea circulation (Bolaños et al., 2014), and the particle tracking module of this model also has been validated for trace metal dispersion contamination of Beaufort's Dyke, Irish Sea (Callaway et al., 2011). The model has been used for a full hindcast study for the Northern North Sea, including the Faroe–Shetland Channel, and it has been calibrated with current measurements (DHI, 2014).

In our application, the model domain covers all the important areas around Faroe Island, including the Faroe–Shetland Channel, Faroese Shelf, Faroe Bank Channel, and Wyville Thomson Ridge (Fig. 1). Detailed bathymetry of the model is obtained from the Faroe Marine research Institute (Knud Simonsen, University of Faroe Islands, personal communication) and combined with bathymetry data from GEBCO (http://www.gebco.net). The model domain is constructed to be optimal for simulation of the deep water flow through the Faroe Bank Channel.

We use a flexible (finite volume) mesh grid which allows us to refine specific areas as needed. In order to accommodate detailed examination of processes close to the sill area, we define three regional resolutions; the finest horizontal resolution is in the immediate vicinity of the sill and has a maximum element area of 0.0002 $deg^2$, while the second and third domains have maximum element area 0.0006 $deg^2$ and 0.0018 $deg^2$, respectively. In the vertical dimension we used a combination of sigma and $z$ layers. The $z$ layer configuration was used from the bottom to the 50 m below the surface (46 $z$ layers), and was used to accommodate the flow on steep topography of the area. In the upper 50 m, 5 sigma layers were used. The simulation is performed for a one year period from 1 July 2011 to 1 June 2012. Our primary focus is on the overwintering period of *C. finmarchicus*, from October to May.

There are five open boundaries in this model. Each of these boundaries used the data from MyOcean dataset (http://www.myocean.eu), including the temperature, salinity, velocity component and sea surface height. In addition, tidal forcing derived from 2D barotropic tide model, was applied. For atmospheric forcing, wind data from The Climate Forecast System Reanalysis (CFSR) by the National Centers for Environmental Prediction (NCEP) dataset, provided by DHI (http://waterdata.dhigroup.com/mantaray), were applied to the model. Temperature and salinity from MyOcean data were also used as an initial condition. One boundary on the Northern side of Faroe–Shetland Channel is designed to accommodate the deepwater inflow, so that it is perpendicular to the direction main deepwater inflow.

### 2.1. Governing equation

All governing equations are based on the 3D incompressible Reynolds averaged Navier–Stokes equation, and consist of continuity, momentum, temperature, salinity and density (DHI, 2012).

The local continuity equation is written as:

$$\nabla \times \boldsymbol{u} = 0$$

and the horizontal momentum equations:

$$\frac{\partial u}{\partial t}+(\boldsymbol{u}\times\nabla)\boldsymbol{u} = -2\Omega\times\boldsymbol{u}-\nabla\Phi-\frac{\Delta\rho}{\rho_o}g\nabla z+\frac{1}{\rho_o}\nabla\tau$$

where $t$ is the time; $\boldsymbol{u}$ is the velocity vector $(u, v, w)$; $u$, $v$, and $w$ are the velocity components in the $x$, $y$, and $z$ direction; $z$ measured positively up; $\Phi = p/\rho_o + gz$ is the sea surface potential; $p$ is the pressure; $2\Omega\times u$ is the Coriolis force; $g$ is the gravitational acceleration; $\rho$ is the density of the water; $\rho_o$ is the reference density of water; $\tau$ is the turbulence stress tensor.

The fluid is assumed to be incompressible. Hence the density, $\rho$, does not depend on the pressure but only on the temperature, $T$, and the salinity, $s$, via the equation of state:

$$\rho = (T, s)$$

The general transport equation for temperature, $T$, and the salinity, $s$ is written as

$$\frac{\partial T}{\partial t}+(\nabla\times\boldsymbol{u})T = \nabla\times(D_T\nabla T)$$

where $D_T$ is the turbulent diffusion coefficient. The transport for the salinity has the same form with the temperature ($T$ could be replaced by $s$, salinity). For the turbulence model, we applied the $k-\varepsilon$ model.

### 2.2. Transport calculation

We generated depth piecewise estimates of volume transport through the Faroe Bank channel using passive tracers. Specifically, all fluid up-stream of the channel and deeper than a given depth $z_i$ was "marked" by a passive tracer (a Calanus tracer).

$$C(z_i) = \begin{cases} 1 \text{ for } z < z_i \\ 0 \text{ for } z \geq z_i \end{cases}$$

We also apply an up-stream boundary condition that all incoming waters below the same depth are also marked. Thereafter, the tracer is advected, mixed and entrained through the model domain, and the flux through a cross section (Fig. 2) is calculated as the integral:

$$Q(t, z_i) = \int_{\text{section}} C(t, x, y, z)\, \boldsymbol{u}(x, y, z, t) \times d\boldsymbol{a}$$

The same technique was applied for different density layers where all water up steam that is denser than a given density $\boldsymbol{\sigma}_i$ was marked. Boundary conditions for the Calanus tracer were set with inflowing waters along the north east boundary (Fig. 2) below a given depth (or greater than a given density) being