Journal of Marine Systems 169 (2017) 99–110

Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

Phenologically distinct phytoplankton regions on the Faroe Shelf - identified by satellite data, *in-situ* observations and model

Sólvá Káradóttir Eliasen [a,*], Hjálmar Hátún [a], Karin Margretha H. Larsen [a], Bogi Hansen [a], Till Andreas S. Rasmussen [b]

[a] Faroe Marine Research Institute, P.O. Box 3051, FO-110, Tórshavn, Faroe Islands
[b] Danish Meteorological Institute, Lyngbyvej 100, Copenhagen, Denmark

ARTICLE INFO

Article history:
Received 4 April 2016
Received in revised form 19 January 2017
Accepted 20 January 2017
Available online 23 January 2017

Keywords:
Phytoplankton phenology
Ocean colour
Faroe Shelf
Distinct regions

ABSTRACT

Marked inter-annual fluctuations in the primary production on the Faroe shelf propagate to higher trophic levels and influence commercial fish stocks. This has previously been demonstrated based on weekly chlorophyll samples from a coastal station, dating back to 1997.
However, the spatial extent, for which the coastal samples are representative, has not been well defined, and potential bio-geographical segregations of the shelf have not been considered. By integrating 18 years of chlorophyll satellite data, supplemented by *in-situ*, model, and meteorological reanalysis data, we identify three regions with unique characteristics with regards to surface chlorophyll and vertical structure - the Central Shelf, the Outer Shelf and the Eastern Banks. The observed difference in timing of the spring bloom in these regions helps explain different spawning patterns of important fish stocks, and the spatial division of the Faroe Shelf should be considered when studying biology and hydrography in these waters.
A positive correlation between annual means on the outer Faroe Shelf and parts of the outer northwest Scottish Shelf indicates similarities between these neighbouring regions.
We suggest that this similarity arises from the commonality in nutrient composition of the water masses shared by these neighbouring regions.

1. Introduction

The first level in the marine food chain, phytoplankton, fuels higher trophic levels in the world oceans and is thus a critical regulator of marine ecosystems. The Faroe Shelf (Fig. 1) hosts a large and diverse marine ecosystem, which sustains a large part of the Faroese economy (Homrum et al., 2012; Steingrund and Gaard, 2005). Pronounced inter-annual variability in the conditions of commercial fish stocks and seabird populations on the Faroe shelf has previously been linked to a so-called Primary Production Index, which is based on the nitrate draw-down on the shelf from April to late June (Gaard et al., 2002). Furthermore, a high-resolution chlorophyll (chl) time series from the coastal station Skopun (hereafter station S, Fig. 1) has shown inter-annual fluctuations, which have been linked to several biological indicators (*e.g.*, Eliasen et al., 2011; Gaard et al., 1998).

Many attempts have been made to explain the inter-annual variability in phytoplankton growth on the Faroe Shelf (Hansen et al., 2005; Gaard et al., 1998). Light and grazing are important to primary production, but they are not found to explain the observed, marked inter-annual variability on this shelf (Debes et al., 2008; Eliasen et al., 2016). An *exchange hypothesis* suggests that cross-shelf exchange dilutes the population of phytoplankton inside the tidal front (Hansen et al., 2005; Eliasen et al., 2005; Eliasen et al., 2016). This hypothesis has been found to explain a part of the variability in the early development of the spring bloom, but not later in the season (Eliasen et al., 2016) when nutrient depletion and grazing probably become more important limiting factors (Debes et al., 2008).

Potential off-shelf influence on the Faroe Shelf primary production must be related to the characteristics of the surrounding Atlantic Water. Eastern and western Atlantic water masses with different hydrographical and biogeochemical properties mix in a region west of the British Isles (Holliday, 2003, Hátún et al., 2005), producing Modified North Atlantic Water (MNAW) (Hansen and Østerhus, 2000). The domain covered by the pole-ward flow of this water mass, which flows past the Faroe Shelf and into the eastern part of the Nordic Seas, has in bio-geographical terms been identified as the Boreal zone (Ekman, 1953), hosting rich ecosystems. This faunistic zone is bounded by the Lusitanean zone and the Atlantic drift in the south, and by the Subarctic zone, crossing through Iceland and following the Iceland-Faroe Front north of the Faroe Islands (Ekman, 1953).

* Corresponding author.
E-mail address: solvae@hav.fo (S.K. Eliasen).

http://dx.doi.org/10.1016/j.jmarsys.2017.01.015
0924-7963/

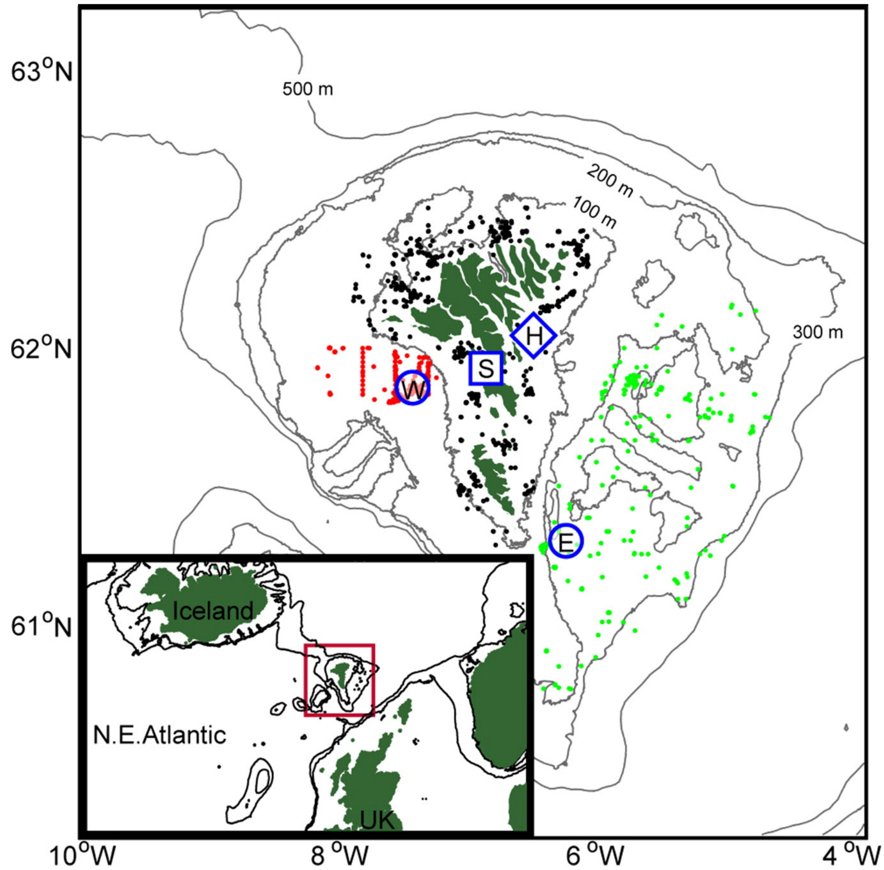

Fig. 1. Map of the Faroe Shelf with regional map inserted. The blue square is coastal station S, the blue circles show wave buoy moorings E and W, respectively, and the blue diamond indicates standard station H, which previously has been sampled (Debes et al., 2008). Red, black, and green dots are positions of CTD profiles, used in the data analysis. The 200 m and 500 m isobaths are shown on the inserted map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The Faroe Shelf is characterized by strong tidal currents with a clockwise residual circulation around the islands (Larsen et al., 2008) where the Faroe Shelf Front (FSF) separates the Faroe Shelf Water (FSW) on the inner shelf from the surrounding water masses (Larsen et al., 2009). During winter, both shelf and off-shelf waters are vertically well mixed (Fig. 2a) and replenished with nutrients.

At the start of spring, several mechanisms can lead to increased primary production. On a well mixed shallow shelf (Fig. 2a), increased light will increase the critical depth and the total production in the water column may become positive. Growth will depend on the amount of nutrients and light in the whole water column with grazing, vira, and other biotic factors affecting the phytoplankton community. During the progression of spring on the deeper parts of the shelf, a shoaling upper mixed layer, due to a weakening in wind mixing, cessation of winter convection, stratification due to air-sea heat input (Chiswell et al., 2015), and/or eddy slumping (Mahadevan et al., 2012), will gradually cause the system to change to the situation illustrated in Fig. 2b, with sufficient light in the stratified environment, as well as in the shallower well mixed region. This leads to favourable circumstances for phytoplankton growth outside the tidal front, but nutrients can quickly become depleted and continuous growth hindered. Thus, growth will mostly depend on the resupply of nutrients from the lower layer and across the front to the well mixed area. The frontal zone is expected to be especially favourable for growth during this phase due to intermittent stability and nutrient injections (*e.g.* Chiswell et al., 2015; Simpson and Sharples, 2012).

Seasonally stratified temperate shelf seas ('Outer Shelf' in Fig. 2b) generally support high phytoplankton growth and rich ecosystems (Simpson and Sharples, 2012). These regions might, furthermore, be an important sink of atmospheric CO_2 on a global scale (Holt et al., 2009). Studies from the northwest European shelf have highlighted the importance of ocean-to-shelf nutrient fluxes to the phytoplankton production (Holt et al., 2012). This nutrient flux is mainly driven by a net down-welling circulation, with onto-shelf transports in the upper stratified layer and off-shelf transport in a thin near-bed Ekman layer (Huthnance et al., 2009). A previous model study, employing the same model as presented in the present paper (Rasmussen et al., 2014), shows similar net down-welling transports between the well mixed inner part of the Faroe Shelf and the surrounding, seasonally stratified waters.

The nutrient fluxes onto these two neighbouring shelf ecosystems, the Faroe Shelf and the northwest European shelf, might therefore be sensitive to the mixed layer dynamics in the open ocean shared between them, and one could speculate that similar physical and biological processes in the broad Boreal zone (Ekman, 1953) might collectively impact the Faroe shelf and the European margin.

As far as we are aware of, phytoplankton studies from the northwest Scottish Shelf are mostly based on satellite data (*e.g.* Miller et al., 2015), models (*e.g.* Holt et al., 2012), Continuous Plankton Recorder (CPR) counts (*e.g.* Barton et al., 2003), and cruises (*e.g.* Fehling et al., 2012). We have not found any scientific publication on time series from monitoring stations on the northwest Scottish Shelf with emphasis on the open shelf water. According to Holt et al. (2012), the average net primary production is lower on the Northwest Scottish Shelf than on the Faroe Shelf.

On the Faroe Shelf, a study in 2004–2005 at the standard station H (eastern side of the shelf, 5 km offshore, bottom depth 55 m, see Fig. 1) showed a similar pattern as observed at station S (Debes et al., 2008), indicating spatial coherency. The same study estimated the annual primary production on the shelf to be 201 g C m^{-2} y^{-1}. However, with regard to phytoplankton and primary production farther off-shore, only scattered fluorescence observations from research cruises, mostly