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The exchange of water between the Faroe Shelf and the surrounding waters and its effect on the primary production

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ABSTRACT

The interannual variation of the spring bloom and its effect on the marine ecosystem on the Faroe Shelf has been observed for a couple of decades. However, the mechanism controlling the spring bloom has so far not been known and attempts to explain the mechanism have mostly ruled out possibilities. The Faroe Shelf is to a variable degree isolated from the surrounding waters by a tidal front. It has previously been suggested that variations in the density difference across the front and how water masses are transferred across it affect the spring primary production, which is thought to be a driver of the shelf ecosystem. Using air–sea heat flux data and sea temperature observations on the shelf and off the shelf, we estimate the cross-frontal volume exchange in January–April and find that it increases with the tidal current speed and decreases with the cross-frontal temperature difference. Using the observed exchange rates, we show that the phytoplankton growth rate may be reduced by more than 0.05 day^{-1} when the exchange is intense and off-shelf production is still low. Based on frontal dynamics theory, we suggest that the cross-frontal exchange rate in the above mentioned period is determined by the rate of vertical turbulent diffusion through the front. A simple theoretical model is found to support this hypothesis qualitatively as well as quantitatively. This supports that variations in horizontal exchange are an important controlling factor of the initial spring bloom and that the horizontal exchange during the winter can be determined by vertical turbulent diffusion. Our results will be relevant for the primary production in other similar systems of small geographical extent and also for other problems involving cross-shelf exchange, such as oil spill dispersal.

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1. Introduction

An archipelago located between Scotland and Iceland (Fig. 1), the Faroe Shelf is relatively isolated from its oceanic surroundings by the Faroe Shelf Front (FSF) most of the year (Larsen et al., 2009). Inside the FSF, which is typically located close to the 120 m bottom contour, strong tidal currents constantly keep the Faroe Shelf Water (FSW) well mixed throughout the year (Larsen et al., 2008). The shelf marine ecosystem, which is thought to be bottom-up controlled (Hansen et al., 2005), fluctuates interannually on all trophic levels, so understanding the primary production variability is important to the general understanding of the ecosystem. The initiation of the spring bloom varies from early April in some years to the beginning of June in others, and the strength of the spring bloom varies much as well, (Fig. 2). To explore the interannual variability, Gaard et al (2002) calculated an annual primary production index (PP index), which for the updated period 1990–2014 varies by a factor of five interannually. Here we focus on the early spring bloom development, which in this context is defined as April and May.

If we consider the FSW to be an isolated unstratified system of limited depth, the most likely cause of these interannual variations in the initial phase of the spring bloom would seem to be variations in either light or grazing since nutrient limitation is not a constraint inside the tidal front during this phase.

Gaard et al., 1998 argued that interannual variability in photosynthetically active radiation (PAR) is not correlated to variations in primary production and suggested that varying grazing pressure might cause the interannual variability, but Eliasen et al. (2005) and Debes et al. (2008) have argued that grazing alone cannot suppress the spring bloom during its initial phase.

Instead, Eliasen et al. (2005) suggested that much of the variation could be explained by a variable degree of isolation of the FSW inducing a variable loss of phytoplankton biomass. This loss is not through vertical mixing as in the traditional Sverdrup mechanism but through horizontal exchange between FSW and off-shelf waters. Moreover, Hansen et al. (2005) suggested that intensive cooling of the shelf during the winter will strengthen the isolation, thereby reducing the exchange.

The exchange processes are not well investigated on the Faroe Shelf and so far only average estimates of the exchange rate have been made (Larsen et al., 2008; Rasmussen et al., 2014) and no estimates of the temporal variations in the exchange rate have been available. We expect several mechanisms to be active, such as Ekman drain, wind driven

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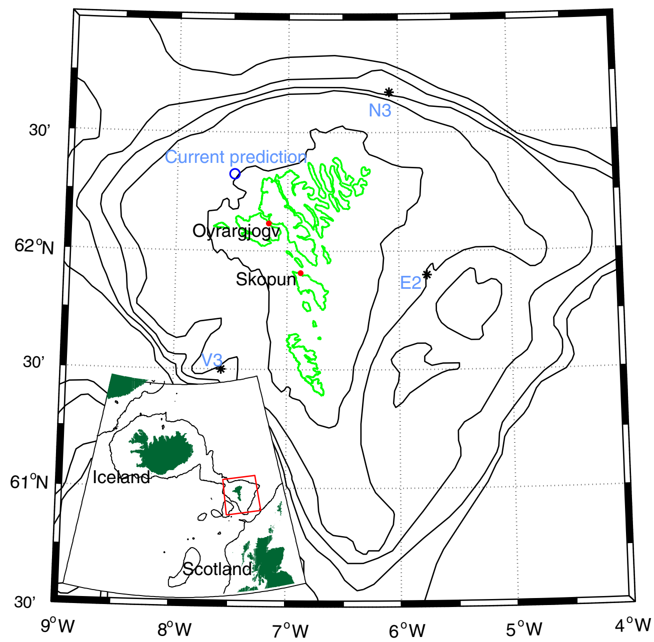

Fig. 1. The Faroe Islands. The positions on the map are mentioned in the text and the bottom contours are 100 m, 200 m, 300 m, 400 m and 500 m. A regional map is inserted in bottom left corner with 500 m bottom contour shown.

mixing and eddies and meanders. However, during the winter (January–April), the FSF separates the vertically well-mixed off-shelf and on-shelf water masses, thereby acting as a barrier, through which exchange happens by vertical diffusion.

The hypothesis that enhanced winter cooling could stimulate an early spring bloom by reducing horizontal exchange has had some observational support (Hansen et al., 2005) but has suffered from two fundamental weaknesses: (1) No theoretically based mechanism has been suggested that could be evaluated quantitatively and (2) Lack of detailed measurements of horizontal exchange rate has made evaluation difficult. In this study, we seek to address both these shortcomings.

Here we present a method to estimate the rate of exchange through the front. It is based on a simple model (Fig. 3) and has limitations, but it may to some extent be tested by observations. For the January–April

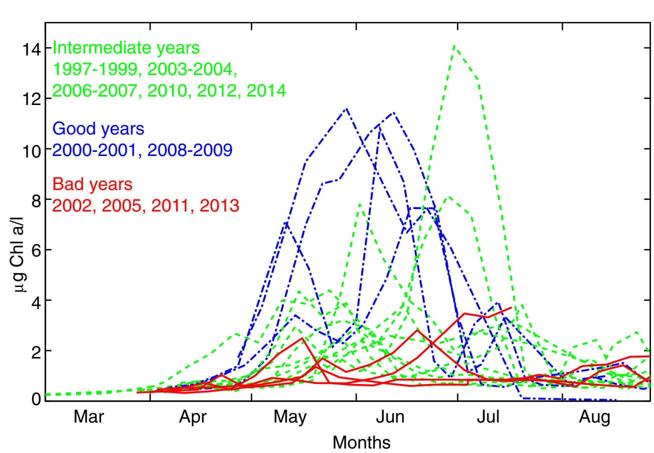

Fig. 2. Chlorophyll *a* concentrations at coastal station Skopun, (Gaard *et al.*, 1998) updated figure. The variations observed at Skopun are similar to variations in phytoplankton concentrations in the FSW (Debes et al., 2008; Rasmussen et al., 2014). The 4 years with highest primary production are drawn in blue (dash-dot), the 4 years with lowest primary production in red (full lines) and the intermediate years in green (dashed). Based on data from 1997 to 2014.

period, we assume no off-shelf stratification, that the FSF is strong (i.e., has a high density gradient) and that vertical exchange through the almost horizontal front (Larsen et al., 2009) is an important process regulating the exchange and the associated loss of phytoplankton biomass. We use temperature observations and air–sea heat flux to derive a time series of the exchange in January–April for the period 1992–2013. Based on these results and theoretical considerations on how the mixing between the FSW and off-shelf waters must occur, we can draw conclusions about the exchange beyond the analysed period and how it might affect the primary production in May. Later in the bloom period, when nutrients have decreased, this mechanism will enhance the bloom by supplying new nutrients to the shelf water.

Our hypothesis is that the strength of the front influences the spring bloom. The front inhibits mixing between the FSW and the off-shelf water, and the temporal variability in it might be important to the bloom. If the front is strong when the bloom starts and nutrients are still abundant, the exchange of water masses is reduced and circumstances for a spring bloom favourable, whereas if the front weakens before the bloom, mixing will be stronger and primary production lower.

The results presented here will also apply to other areas with a relatively small shelf surrounded by a large oceanic body and more generally to any area characterised by a limited shelf water volume, which is in contact with a much larger oceanic body.

In the following, the main emphasis is on the observations that may help evaluate the effect of variable exchange, but we also consider new data on the effect of variable solar radiation, which is one of the main competing explanations for the variable spring bloom.

2. Materials and methods

2.1. Solar radiation

Data on irradiance on the Faroe Shelf are limited. Earlier analysis of these data showed no correlation between irradiance and primary production (Gaard et al., 1998). We have compared the sparse local data from various periods and various sources with the comprehensive reanalysis meteorological short-wave radiation data set from the National Centers for Environmental Prediction (NCEP), given in daily values, provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, and downloaded from ftp://ftp.cdc.noaa.gov/Datasets/ncep.reanalysis.dailyavgs/, (Kalnay et al., 1996). We found that there is a good correspondence between these data sets which allows us to use the short-wave radiation time series as a proxy for irradiance and compare it to the primary production, which we have done for the period 1990–2013.

2.2. Temperature

On-shelf sea temperature (T_i) has been observed at coastal station Oyrargjogv (Fig. 1) since June 1991 (with a month gap in 1997), and average daily values have been used when computing the energy used to heat the FSW. To generate a time series (To) for the off-shelf temperature, we used CTD observations from three standard stations shown on Fig. 1 (N3, V3 and E2) at depths 200–280 m. Temperature has mainly been observed four times a year and averaged over the uppermost 120 m (Larsen et al., 2012). From these observations, we produced a time series with a low-passed variation plus a seasonal signal. Individual observations may deviate considerably from this series. To a large extent, we assume this to be due to meso-scale variations that ought to be cancelled out when averaging over the off-shelf area. In the supplementary material, we discuss the uncertainties induced by this. We use data from this time series only for the period January–April, when the FSF is dividing two homogeneous well-mixed water masses and the temperature difference across the front is generally high (Larsen et al., 2009).

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