Abrupt interruptions in the spring bloom on the Faroe Shelf

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Abstract

Since 1997, phytoplankton abundance (Chlorophyll *a*) has been monitored weekly during spring and summer at a coastal station, „Skopun", in the central parts of the Faroe Shelf. These measurements have demonstrated a large inter-annual variability both in the timing, and the peak magnitude of the spring bloom. In the most productive years, the bloom starts several weeks earlier than in the bad years and may reach high peak values. In some years, however, a rapidly evolving spring bloom may be interrupted by one or more periods of decreasing phytoplankton abundance, until the bloom recovers. This was the case both in 2008 and 2009. Concurrent temperature measurements at various locations indicate that this may have been due to changes in the circulation pattern on the Shelf. Here, we suggest that the shallow parts of the northern shelf area, including Skopun, in some periods may become relatively isolated from the deeper parts of the shelf. Since this region

is shallow, a rapid and intensive spring bloom may develop as long as the isolation is maintained. In some years, such periods of relative isolation seem to alternate with periods of intensive mixing between the shallow and deep parts, in which the phytoplankton in the shallow part is flushed out to the whole shelf. We present a simple box model of the system and show that this can explain the main features of the 2008 and 2009 spring blooms.

Introduction

The shelf area surrounding the Faroe Islands – the Faroe Shelf (Fig. 1) – is influenced by frequent storms and strong tidal currents. In the shallow parts of the shelf, this gives rise to a water mass – Faroe Shelf Water (FSW) – that is very homogeneous vertically and, to some extent, also horizontally (Larsen et al., 2008). FSW is separated from the surrounding water masses by a transition zone, which often can be characterized as a front – the Faroe Shelf Front – usually located outside the 100 m bottom contour (Larsen et al., 2009).

Regular monitoring at the coastal station Skopun (Fig. 1) has demonstrated considerable variation in the seasonal development of the primary production (PP) from one year to
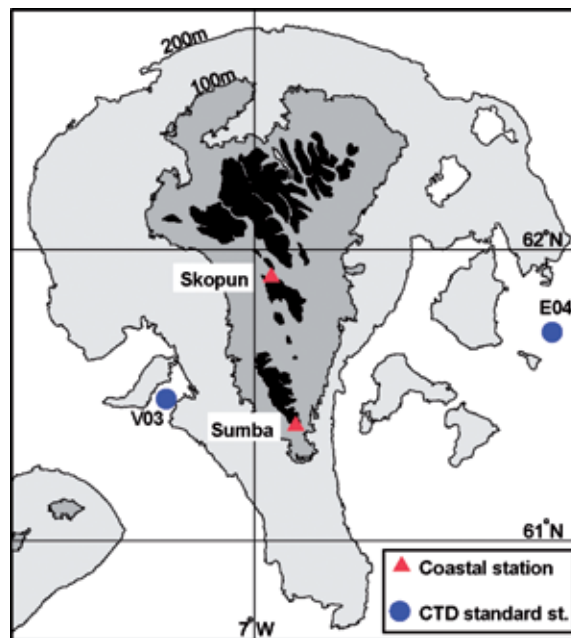

Fig. 1. Bottom topography of the Faroe Shelf with indication of the observational sites.
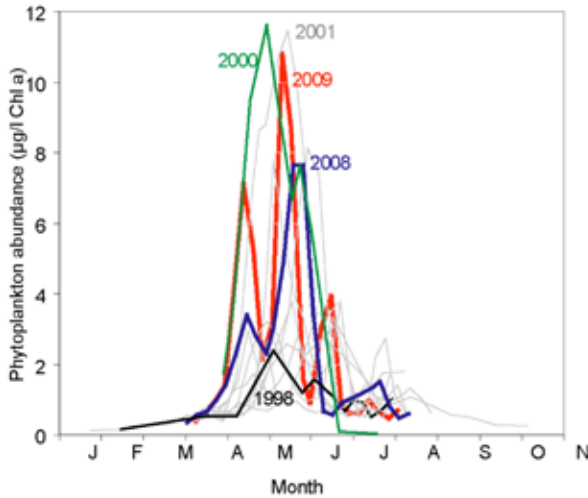
Fig. 2. Seasonal development of phytoplankton abundance at Skopun in different years (thin gray lines). Four years have been enhanced by thicker lines.

another (Gaard et al., 2006). In some years, e.g. 2000 and 2001, there is a pronounced spring bloom with an early and intensive peak in the phytoplankton abundance (Fig. 2). Other years, e.g. 1998, may have a much later and weaker development in the production. An independent measure of the accumulated new production during the spring bloom has been based on the nutrient depletion on the shelf (Steingrund and Gaard, 2005). This PP-index also was exceptionally high in 2000 and 2001, consistent with Fig. 2, and a high correlation has been found between this index and conditions at higher trophic levels, such as demersal fish and seabirds (Gaard et al., 2006).

Early efforts to explain the primary production variations found little correlation with light intensity or other likely physical parameters (Gaard et al., 1998, Eliasen, 2004 a). They revealed, however, a negative correlation with the biomass of imported zooplankton, which was originally interpreted in terms of grazing (Gaard et al., 1998). Modelling efforts (Eliasen et al., 2005) as well as observations (Debes et al., 2008) conflicted with this and, instead, it has been suggested that variable horizontal exchange between the FSW and off-shelf waters may be the main control of the PP. In a homogeneous system, the abundance of phytoplankton cells, *N(t)*, will develop in time according to the equation:

$$\frac{dN}{dt} = (p - r - m) \cdot N - L \qquad (1)$$

where *p* represents photosynthesis, *r* respiration, and *m* mortality. The loss term, *L*, includes loss (or gain) from (to) the system to (from) the surroundings. In open waters, there is typically a loss by sinking and vertical mixing of cells out of the euphotic layer and the criterion for growth is that *L* is sufficiently small for the right-hand side of (1) to be positive. In the Sverdrup (1953) paradigm, this implies that the critical depth becomes larger than the mixed layer depth.

On the Faroe Shelf, the critical depth exceeds the bottom depth already in early spring (Debes et al., 2008), but the spring bloom is delayed. This cannot be explained by vertical loss, since the bottom stops this. If, however, the surrounding (deeper) waters have been unproductive, there will also be a loss of phytoplankton cells by horizontal exchange between the shelf and the off-shelf regimes, which becomes relatively more important, the smaller the system is (Eliasen et al., 2005). This mechanism – termed „the horizontal Sverdrup mechanism" – has been suggested to control the early stages of the FSW spring bloom (Eliasen et al., 2005) and variable air-sea heat exchange has been hypothesized to cause the inter-annual variations in horizontal exchange rate (Hansen et al., 2005).

Several causal mechanisms have been suggested to have the potential for affecting the horizontal exchange rate (Larsen et al., 2009), but no candidate has been clearly shown to be responsible. It is, therefore, still an open question, to what extent this theory can explain the difference between the „good" years, such as 2000 and the „bad" years, such as 1998 (Fig. 2). But, there are also years when the PP develops in a more irregular manner. This was the case in 2008 that started out with early and rapid increase in the phytoplankton abundance, which was interrupted by two weeks of decrease, after which the increase was re-established.

Such rapid variations seem hard to explain by changes in physical processes that involve the whole FSW. At the same time, sea temperature measurements at two different coastal sites indicated that the PP variations during the spring of 2008

might be linked to changes in the internal circulation or mixing on the Faroe Shelf. This led to a hypothesis for the rapid PP variations that retains the „horizontal Sverdrup mechanism", but on a more local scale. The spring bloom of 2009 was even more irregular than in 2008 with three clearly separated peaks in the phytoplankton abundance and, again, coastal temperature measurements indicated associated circulation changes consistent with the proposed hypothesis.

In this study, we describe the 2008 and 2009 measurements and present a hypothesis to explain them. In order to test the hypothesis quantitatively, we have constructed a simple box model and present the results from it. Finally, we discuss the validity and generality of the hypothesis and model.

Observational material

The primary dataset on phytoplankton abundance derives from weekly measurements of chlorophyll *a* at a coastal station (Skopun, Fig. 1) established in 1997 (see Debes et al., 2008 for details). At the same station, sea temperature has been measured continuously since 2002. Measurements at other sites have indicated that the sea temperatures measured at Skopun are representative for coastal water throughout the northern part of the Faroe Islands (Larsen et al., 2008) and the phytoplankton abundance values have also been found to be representative for a wider area (Debes et al., 2008).

Sea temperature has also been measured continuously at a site, Sumba, close to the southernmost tip of the islands (Fig. 1) since 2005, although with a gap in 2006-2007 due to instrument failure. For information on the off-shelf temperature, we have used CTD measurements at two standard stations, E04 and V03 (Fig. 1) that are occupied regularly four times a year. Interpolating between the occupation times, a daily time series of off-shelf temperature was constructed by averaging the temperature in the uppermost 100 m at both stations. In addition to our own measurements, we have used the NCEP/NCAR reanalysis data (Kalnay et al., 1996) to construct a time series of daily averaged air-sea heat flux over the Faroe Shelf.

In order to compare these time series, smoothed versions were made of them all. For each day in the period January

to September 2008 and 2009, the temperature changes over a week centred at that day were computed for Skopun and Sumba as well as the average temperatures at those two sites and off-shelf and the accumulated air-sea heat flux during the week. Seven day running means were then computed for all these time series.

Observational results

Time series of phytoplankton abundance at Skopun are shown in Fig. 2, where we have highlighted a „good" year, 2000, a „bad" year, 1998, and the two irregular years, 2008 and 2009. The Jan - Sept period for 2008 and 2009 is shown in more detail in Fig. 3 where the sea temperatures at Skopun and Sumba are also shown as is the air-sea heat flux. On this figure, vertical dashed lines are inserted to denote shifts between periods when the phytoplankton abundance is increasing and decreasing and there seems to be a correspondence between these periods and the difference between sea temperatures at the two sites.

In both years, the beginning of the spring bloom occurs while the difference in sea temperatures at Skopun and Sumba indicates that the two regions are fairly well isolated from one another. After the first peak, the phytoplankton abundance at Skopun starts to decrease in both years in periods when the two temperatures are very similar, consistent with much less isolation between the two regions. This correspondence continues more or less obviously through the spring and summer of both years, which led to the hypothesis that changes in circulation on the shelf could influence the phytoplankton abundance at Skopun.

As expected, the temperature at Skopun as well as Sumba is seen to react to strong air-sea heat exchanges (Fig. 3). This is seen in more detail in Fig. 4, which shows smoothed weekly temperature changes plotted against the heat flux during the week. At Skopun, the relationship is fairly tight with a correlation coefficient of 0.88 for 2008 and 0.82 for 2009. From regression analyses, the temperature change at Skopun associated with a given heat flux is consistent with the heat being distributed over an average depth of 140 m. This implies that
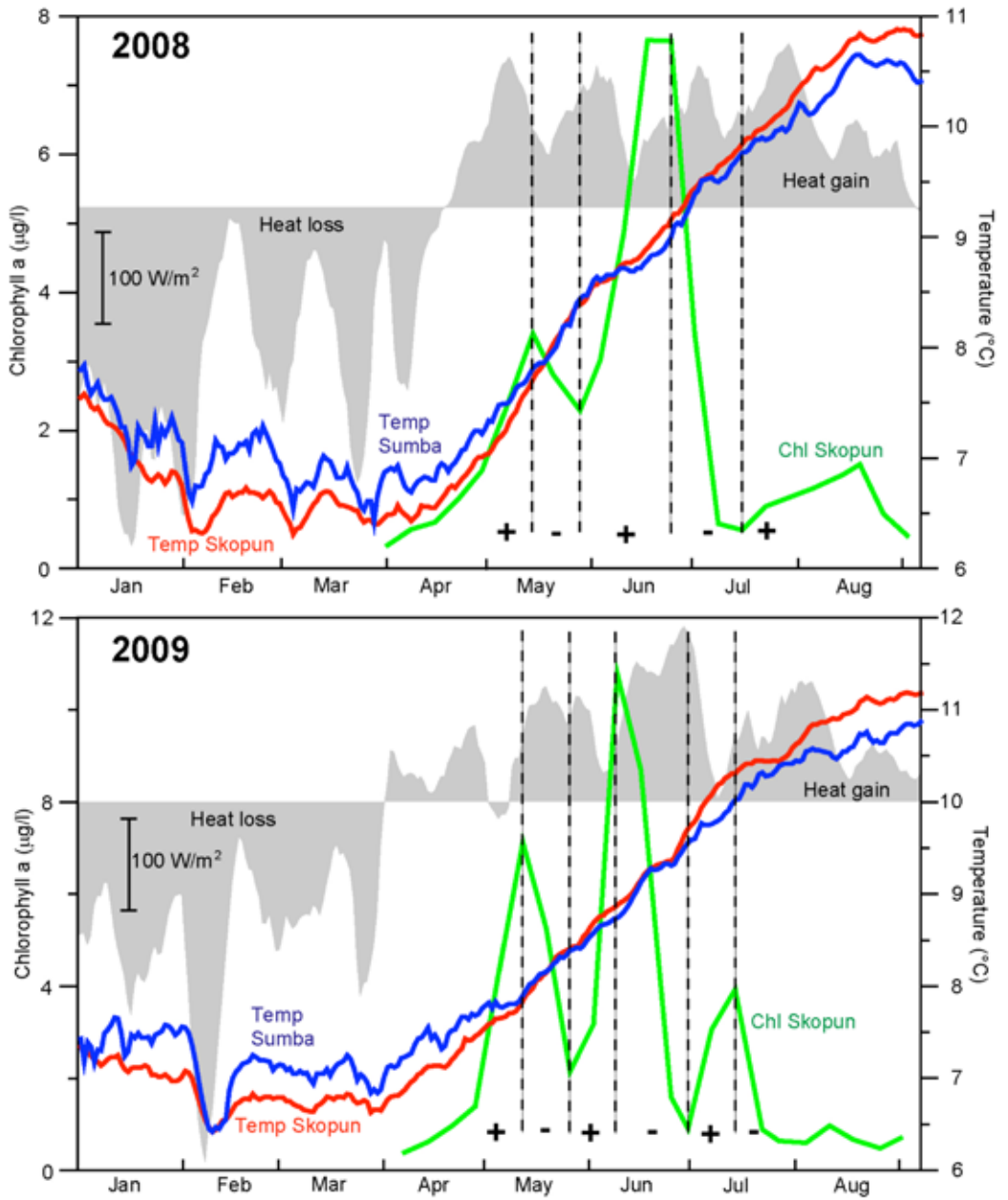
Fig. 3. Time series of phytoplankton abundance (chlorophyll a) at Skopun (green lines), sea temperature at Skopun (red lines) and Sumba (blue lines), and weekly averaged heat flux (shaded areas, positive from air to sea) in January to September 2008 (upper panel) and 2009 (lower panel). Vertical dashed lines indicate shifts between periods with increasing (+) and decreasing (-) phytoplankton abundance.
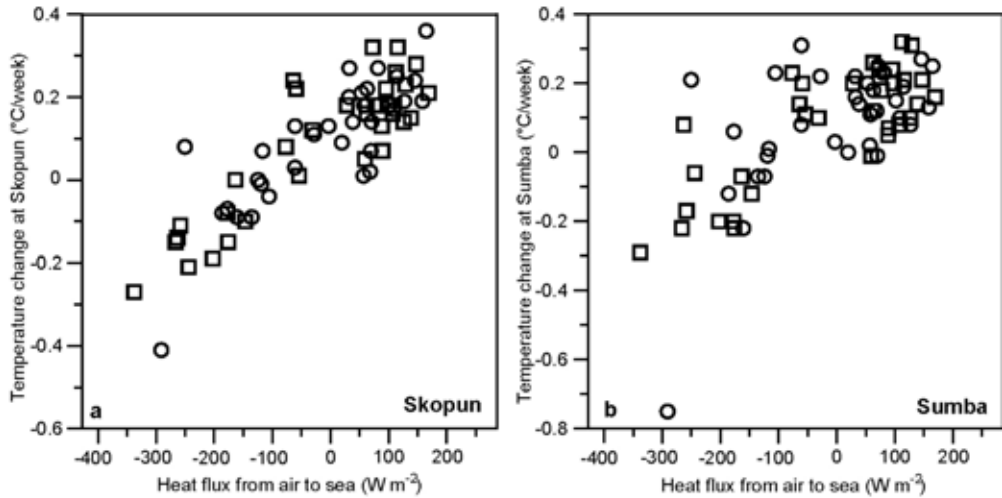
Fig. 4. Temperature change over a week at Skopun (a) and Sumba (b) for the January to early September period 2008 (open squares) and 2009 (open circles), plotted against the average heat flux to the ocean during the week. Each point is an average from seven consecutive days.

the heat usually is distributed over wide areas of the shelf, but even with zero heat gain, there is an average heating of 0.1 °C per week. This indicates heat gain by horizontal exchange during this period (January to early September) with off-shelf temperatures generally higher than on-shelf. The scatter indicates, however, that the heat gained by horizontal exchange varies considerably. This is even more pronounced at Sumba, where the correlation coefficient was 0.78 for 2008 and 0.60 for 2009.

Hypothesis

In previous studies of the Faroe Shelf, the FSW has generally been treated as one homogeneous water mass, mixed by the strong tidal currents and the clockwise residual circulation around the islands (Larsen et al., 2008). As noted by Larsen et al. (2008), this is, however, not always the case. Coastal temperatures in the northern part of the Faroes do seem to correspond very well and follow the Skopun temperature, but in the southern part, the temperature may in some periods diverge considerably from this, as seen in Fig. 3. At other times,

however, temperatures in the two regions may be very similar and vary synchronously for long periods (Larsen et al., 2008).

There are various ways to interpret these observations but, in any case, they indicate that the oceanic connection between Skopun and Sumba varies in time. A simple interpretation is illustrated in Fig. 5. There, the shelf area is divided into two homogeneous regimes: a shallow-shelf regime, and a deep-shelf regime. The shallow-shelf regime contains all the near-coastal waters in the northern part, which are homogenized by the strong tidal circulation so that their temperature (Larsen et al., 2008) and, presumably, also phytoplankton abundance (Debes et al., 2008) can be described by the values at Skopun.

The deep-shelf regime contains all the rest of the FSW. In Fig. 5, it has been illustrated as the region bounded by the 150 m depth contour. Assuming all of this regime to be horizontally homogeneous and its properties to be equal to the values at Sumba, may be too optimistic, but it can be taken as a first approximation.

In this framework, the observations presented in Fig. 3 can be understood in terms of a variable exchange between the two shelf regimes. In periods with small exchange, the shallow-shelf regime is almost isolated and its small average depth
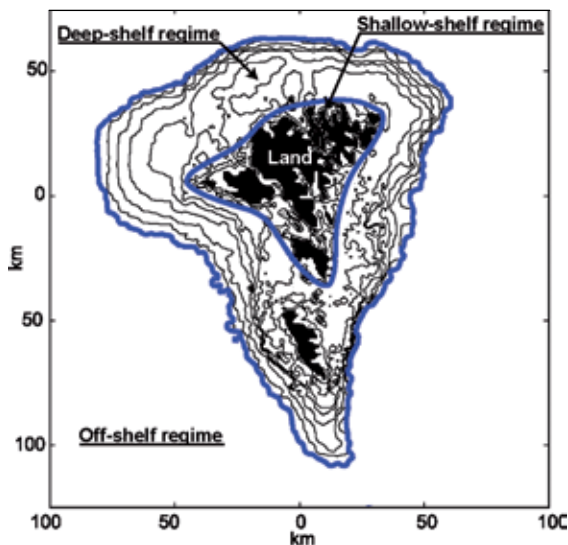

Fig. 5. The three regimes, into which the area is divided in the box model.

allows rapid phytoplankton growth. When the exchange is high, on the other hand, the two shelf regimes operate more like one regime with a much larger average depth and, hence, lower production. This leads to the hypothesis:

- *The rapid variations in phytoplankton abundance at Skopun are generated by variations in the exchange rate between the shallow-shelf and the deep-shelf regimes with good growth in periods of low exchange rate.*

Model description

In order to test this hypothesis quantitatively, we approximate the system by a model that contains three boxes, each of which represents one of the regimes described above (Fig. 5): the shallow-shelf box, (subscript S), the deep-shelf box (subscript D), and the off-shelf box (subscript O). All the boxes are assumed to be well mixed so that properties are homogeneous within them. The shallow-shelf box has a volume of V_S, a surface area A_S, and an average depth D_S $(=V_S/A_S)$. The phytoplankton abundance N_S in this box will change according to (1) where the loss term represents exchanges with the deep-shelf box and we assume that this can be written:

$$V_S \cdot \frac{dN_S}{dt} = V_S \cdot (p - r - m) \cdot N_S - R_{SD} \cdot V_S \cdot (N_S - N_D) \qquad (2)$$

The first term on the right-hand side represents the total primary production in the shallow-shelf box. To compute this term, we have used the diatom growth model in Eliasen (2004 b) with half-hourly values of surface irradiance based on satellite data averaged for the years 1996-2000 (www.satel-light. com). Additional input is the average depth of the box, D_S, and the nitrate concentration C_S. The second term in (2) represents the exchange with the deep-shelf box and is proportional to the abundance difference $(N_S - N_D)$. The flushing rate, R_{SD}, is the volume of water exchanged between the boxes per time unit divided by the volume of the shallow-shelf box. A similar equation governs the deep-shelf box:

$$V_D \cdot \frac{dN_D}{dt} = V_D \cdot (p - r - m) \cdot N_D - R_{DO} \cdot V_D \cdot (N_D - N_O) + R_{SD} \cdot V_S \cdot (N_S - N_D) \qquad (3)$$

Table 1. Geometrical parameters of the two shelf boxes in the model.

Box	Volume km³	Surface area km²	Average depth m
Shallow-shelf	50	1100	45
Deep-shelf	1100	11000	100

If the computed phytoplankton abundance in the shallow-shelf box is to reach the levels sometimes observed (> 10 µg l⁻¹ Chl *a*), the average depth of the box has to be fairly small and we have chosen the area inside the 60 m bottom contour in the northern part of the Faroe Shelf as the shallow-shelf box. Similarly, the deep-shelf box has been delimited by the 150 m contour. This determines the geometrical parameters of equations (2) and (3) (Table 1), but the two flushing rates are, *a priori*, unknown. Following Larsen et al. (2008), constraints on their values can be determined by considering the heat budget. If T_S is the temperature of the shallow-shelf box, its variation is governed by:

$$V_S \cdot \frac{dT_S}{dt} = \frac{Q \cdot A_S}{c_v \cdot \rho} - R_{SD} \cdot V_S \cdot (T_S - T_D) \qquad (4)$$

where Q is the air-sea heat flux, c_v the specific heat capacity, and ρ the density of sea water, whereas T_D is the temperature of the deep-shelf box, which is governed by a similar equation:

$$V_D \cdot \frac{dT_D}{dt} = \frac{Q \cdot A_D}{c_v \cdot \rho} - R_{DO} \cdot V_D \cdot (T_D - T_O) + R_{SD} \cdot V_S \cdot (T_S - T_D) \qquad (5)$$

For the 1ˢᵗ April to early September periods in 2008 and 2009, equations (4) and (5) were used to calculate daily estimates of R_{SD} and R_{DO} using the smoothed time series described in the observational materials section. Equations (2) and (3) were then integrated numerically from 1ˢᵗ April assuming start values of 0.1 µg l⁻¹ Chl *a* in all three boxes. This value was maintained in the off-shelf box. No grazing was included in the

model, but nitrate limitation was, and the nitrate concentration, C, in each box was determined from exchange and assimilation loss, assuming 0.44 μmol N kg^{-1} to be used for each μg l^{-1} of Chl a (Eliasen, 2004 b). The equations governing the nitrate concentrations in the two boxes, C_S and C_D, thus, are:

$$V_S \cdot \frac{dC_S}{dt} = -0.44 \cdot V_S \cdot (p - r) \cdot C_S - R_{SD} \cdot V_S \cdot (C_S - C_D) \qquad (6)$$

$$V_D \cdot \frac{dC_D}{dt} = -0.44 \cdot V_D \cdot (p - r) \cdot C_D - R_{DO} \cdot V_D \cdot (C_D - C_O) + R_{SD} \cdot V_S \cdot (C_S - C_D) \qquad (7)$$

where the off-shelf concentration, C_O, is kept constant at the winter value (12 μmol N kg^{-1}).

To determine the flushing rates R_{SD} and R_{DO} from equations (4) and (5), we divide by temperature differences that in some cases become very small. Measurement uncertainties and model approximations also may lead to negative, and hence unphysical, flushing rates. We, therefore, restrict R_{SD} and R_{DO} to be within specified limits. For the shallow-shelf box, we require the flushing rate to be between 1 and 30 days. Similarly, the flushing rate for the deep-shelf box has been restricted to the interval between 1 and 90 days.

Model results

The computed phytoplankton abundance in the shallow-shelf box for 2008 and 2009 is found to compare remarkably well with the observations at Skopun (Fig. 6). The absolute and relative heights of the peaks do not always correspond too well and the first peak in 2009 occurs too early in the computations compared to the observations. Still, the phytoplankton abundance shows two peaks in 2008 and three main peaks in 2009 with relatively good correspondence in timing, especially when noting that the computed values are based on smoothed parameters whereas the observations are obtained at discrete weekly intervals.

The computed flushing rates (Fig. 6) are found to vary considerably and much of the time, they are at either the maximum or minimum specified limit. This makes the computed phytoplankton abundance values dependent on the *ad hoc* specified limits. Varying the limits, shows, however, that the

basic structure of the temporal phytoplankton development is not very sensitive to these limits.

Discussion

Although the model (Fig. 5) would appear to be very much simplified, the correspondence between computed and meas-
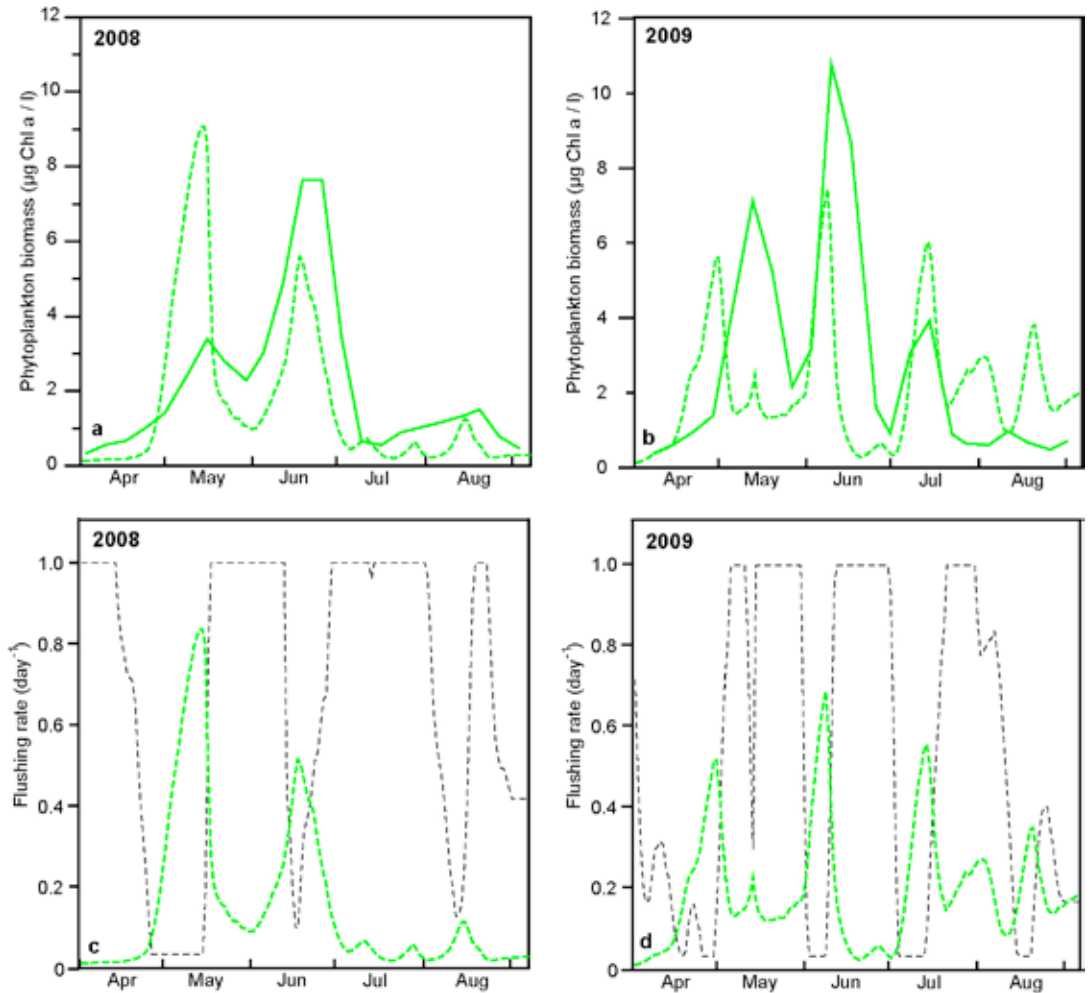

Fig. 6. Upper panels: Comparison of computed (dashed green lines) and measured (continuous green lines) phytoplankton abundance in the shallow-shelf box for 2008 (a) and 2009 (b). Lower panels: The flushing rate (dashed black lines) and computed phytoplankton abundance (dashed green lines in the same scale as in the upper panels) in the shallow-shelf box for 2008 (c) and 2009 (d).

ured phytoplankton abundances (Fig. 6a,b) seems remarkably good. Except for the model geometry and the specified (but not very restrictive) limits on the flushing rates, there are no *ad hoc* assumptions involved. The model results, therefore, support the hypothesis that the shelf can be divided into at least two different regimes and that variations in exchange rate between the regimes dominate the development of the spring bloom in the shallow-shelf regime.

The implied variations in flushing rate (Fig. 6c,d) are quite dramatic and seem most easy to explain by circulation changes on the shelf. What causes these changes is not obvious from this data set. No clear correspondence to the strength of the tidal current or to the wind is seen. Air-sea heat exchange and/or intensive precipitation over land also might induce horizontal density gradients that could affect the circulation and there may be other mechanisms. Perhaps future observational campaigns or high-resolution numerical modelling of the Faroe Shelf may shed some light on this. A numerical model might also give a more realistic interpretation than the simplified box model used here (Fig. 5).

In the model results, we have focused on the production in the shallow-shelf regime, but the results indicate that this may not be representative for the deep-shelf regime, which represents an area that is an order of magnitude larger. This might indicate that the phytoplankton abundance at Skopun may not be a good proxy for the total shelf production in spite of the correspondence of „good" years (2000 and 2001). Further studies are needed to clarify this.

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