Variations in the advection of *Calanus finmarchicus* onto the Faroe Shelf

E. Gaard and B. Hansen

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The copepod *Calanus finmarchicus* is a dominant factor in the marine ecosystem on the Faroe Plateau, but its abundance is highly variable. Interannual differences of about one order of magnitude in *Calanus* abundance were observed on the shelf in spring and summer. In winter, *C. finmarchicus* is scarcely found on the Faroe Plateau, but during spring and summer it is imported from offshore by advection. Variations in the numbers of imported overwintered *C. finmarchicus* on the shelf in April are much larger than in the offshore waters feeding the area, and variability in inflow rates is likely the major explanation. Independent estimates of flushing rates for the shelf water exhibit variations of a similar order of magnitude as the interannual variations in the biomass of *C. finmarchicus* on the shelf. Prolonged windstress, especially from the southwest, increases the flushing rate, and there is some observational evidence of a relationship between *C. finmarchicus* abundance on the shelf and water inflow.

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E. Gaard and B. Hansen: Faroese Fisheries Laboratory, Box 3051, FO-110 Tórshavn, Faroe Islands. Correspondence to E. Gaard [tel: +298 31 5092; fax: +298 31 8264; e-mail: eilifg@frs.fo]

Introduction

The Faroe Plateau is situated approximately midway between Iceland and Shetland (Figure 1). Its shallow parts are dominated by a water mass that is well mixed by strong tides. In this shelf water (Hansen *et al.*, 1998), plankton communities are generally quite different from those in the surrounding environment. Phytoplankton (Gaard, 1996; Gaard *et al.*, 1998) and zooplankton species composition and seasonal development are different from the surrounding oceanic environment (Gaard and Reinert, 1996; Gaard, 1999). The shelf community consists to a large extent of neritic species, but it is also very much affected by the surrounding oceanic environment. This oceanic influence is highly variable, and the abundance of *Calanus finmarchicus* varies extensively between years. During the nine years from 1989 to 1997 its abundance on the shelf in spring-summer varied by about an order of magnitude (Gaard, 1999).

The variable abundance of *C. finmarchicus* in late spring and summer may well derive partly from differences in production and predation on the shelf, but changes in the rates of import of overwintered *C. finmarchicus* are also a likely cause. To investigate this mechanism, we compare early spring observations of *C. finmarchicus* with physical evidence of water exchange between the shelf water and offshore. Increased precipitation over and close to the islands reduces the salinity of the shelf water, but import of water from offshore partly compensates for this. Salinity observations, combined with precipitation measurements, may therefore be used to estimate exchange rates between the shelf water and offshore. To explain the import and its variation, we also investigate possible effects of wind-forcing.

Materials and methods

C. finmarchicus was sampled during five cruises in April 1994–1997 (two cruises in April 1997) and seven cruises in June 1991–1997 by vertical hauls from 50 m depth to the surface. In addition, depth-stratified samples were collected at Stn V05 (Figure 1) during the period February–April 1994. A Hensen net was used in 1991 and a WP2 plankton net from 1992 to 1997. Both nets had a mesh size of 200 μm. The samples were collected and treated as described by Gaard (1999). In order to obtain depth-stratified samples, the water column was
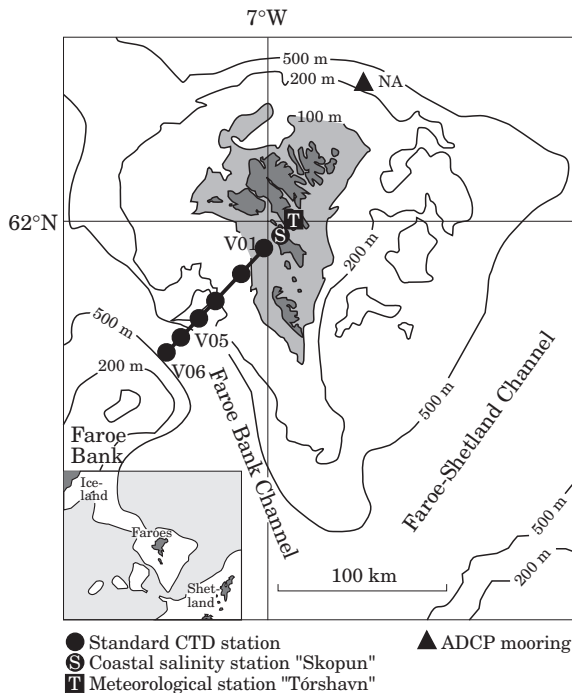
Figure 1. Bottom topography and observational sites. Areas shallower than 100 m are indicated by shading. Inset map in the lower left corner shows the general location of the Faroes.

divided into four depth strata 50, 200, 400, and 600 m to the surface. The vertical distribution was calculated by subtracting the shallower estimates from deeper ones.

Salinity was obtained by CTD on five cruises dedicated to the study of *C. finmarchicus* (Table 1) and along a standard transect (Figure 1) that has been occupied about four times a year since 1988. In addition, salinity

samples were collected from water drawn from 18 m depth at coastal station "Skopun" (Figure 1) twice per week since May 1995 and analysed with a salinometer.

Meteorological observations include monthly precipitation measurements at five different sites in the Faroes between 1988 and 1997 (Cappelen and Laursen, 1998). From these observations, a monthly precipitation index was constructed as an average of the five sites after normalization by the average annual precipitation at each site. In addition, synoptic observations of wind at Tórshavn (Figure 1) were obtained from the Danish Meteorological Institute.

As supporting evidence, we consulted a number of current meter records obtained on the shelf and offshore and documented elsewhere (Hansen and Larsen, 1999; Hansen *et al.*, 1999; Østerhus *et al.*, 1999).

Results

Observations from the Faroe Bank Channel (Stn V05 on Figure 1) in 1994 revealed that, during winter, *C. finmarchicus* were concentrated in deep Norwegian Sea water and ascended towards the surface between late March and late April (Figure 2). Some of the animals are gradually advected into the shelf water, but usually they are in significantly lower concentration on the shelf than farther offshore, as illustrated in the examples in Figure 3. Table 1 summarizes abundances of overwintered *C. finmarchicus* stages CV and adults on the shelf and offshore in April. As the area between the 100 and the 150 m bottom contours largely represents a transitional zone with a mixture of shelf and offshore water, it is not included in the Table.

Salinity observations from the *C. finmarchicus* cruises are shown in Figure 4; salinity was lower on the shelf
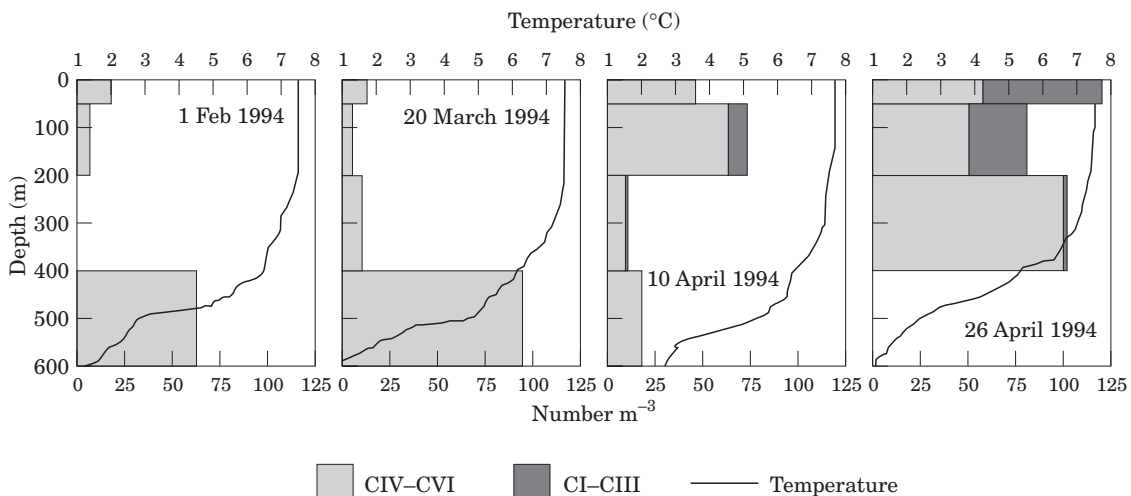

Figure 2. Temperature profiles and vertical distribution of overwintering (copepodite stages IV–VI) and recruits (stages CI–CIII) on Station V05 in the Faroe Bank Channel (see Figure 1) during winter–spring 1994.
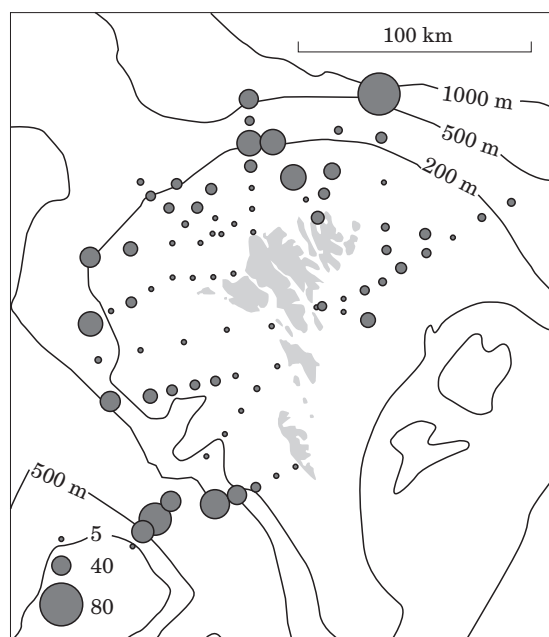
Figure 3. Abundance (number m^{-3}) of overwintered *C. finmarchicus* (copepodite stage V plus adults) in the upper 50 m of the water column, 2–7 April 1997.

than offshore. This is verified in Figure 5 which shows an average salinity difference between offshore and shelf waters exceeding 0.1 along transect V. Temporal salinity variations are shown in Figure 6 for the offshore and shelf water from May 1995 to the beginning of 1998. The close correspondence between the continuous observations at the coastal station and the discrete ones at Stn V01 indicate the reliability of both series. The offshore and shelf water salinities also reveal similar long-term behaviour, but the difference between them is not constant. Part of this variation may derive from variations in precipitation, but the monthly precipitation index, also shown in Figure 6, is not obviously related to the

offshore-shelf salinity difference. This indicates that inflow of offshore water to the shelf may vary.

Discussion

Import of *Calanus finmarchicus* to shelf water

During winter, *C. finmarchicus* is generally not found on the Faroe Shelf (Gaard, 1999, 2000) but rather in deep, cold water where they are in diapause in copepodite stages IV and V (e.g. Hirche, 1983; Heath and Jónasdóttir, 1999; Heath *et al.*, 2000). Owing to sinking of cold water in the Arctic Mediterranean, there is a deep current of cold water that carries overwintering *C. finmarchicus* almost all the way around the Faroe Plateau in a clockwise circulation (Figure 7; Heath and Jónasdóttir, 1999). From this source, *C. finmarchicus* ascends in spring to the upper layers (Figure 2; Heath, 1999). During 1994 the ascent from the overflow water seems to have started in late March and finished in late April or a little later.

The vertical ascent, however, will only bring overwintered *C. finmarchicus* to the upper layers over deep water outside the 500 m depth contour (Figure 7). Import to the shelf water, therefore, requires a considerable horizontal movement as well. As *C. finmarchicus* is a planktonic species, its horizontal movement is through the movement of water.

The general circulation of the upper layers is mostly parallel to the bottom topography, as documented by long-term current measurements (Figure 7). In the upper layers, water movement therefore mostly carries the *C. finmarchicus* around the Faroes in a clockwise direction. The shelf water is roughly delimited by the 100-m depth contour (Hansen *et al.*, 1998) and the distance from this contour to the 500 m contour varies considerably around the islands (Figure 7). Apart from a fairly small area north of the Faroes, the deep water of the Faroe Bank Channel is generally closest to the shelf. The strong deep current carries a large volume of water and

Table 1. Abundance ± standard error s.e. (number m^{-3}) of overwintered *C. finmarchicus* (copepodite stage V plus adults) in the upper 50 m of the water column on the Faroe Shelf (<100 m) and just outside the tidal front (>150 m) during April 1994–1997. N is the number of observations (stations). The ratio between shelf and offshore abundances and windstress expressed as wind velocity squared, vectorially averaged over 60 days prior to observation.

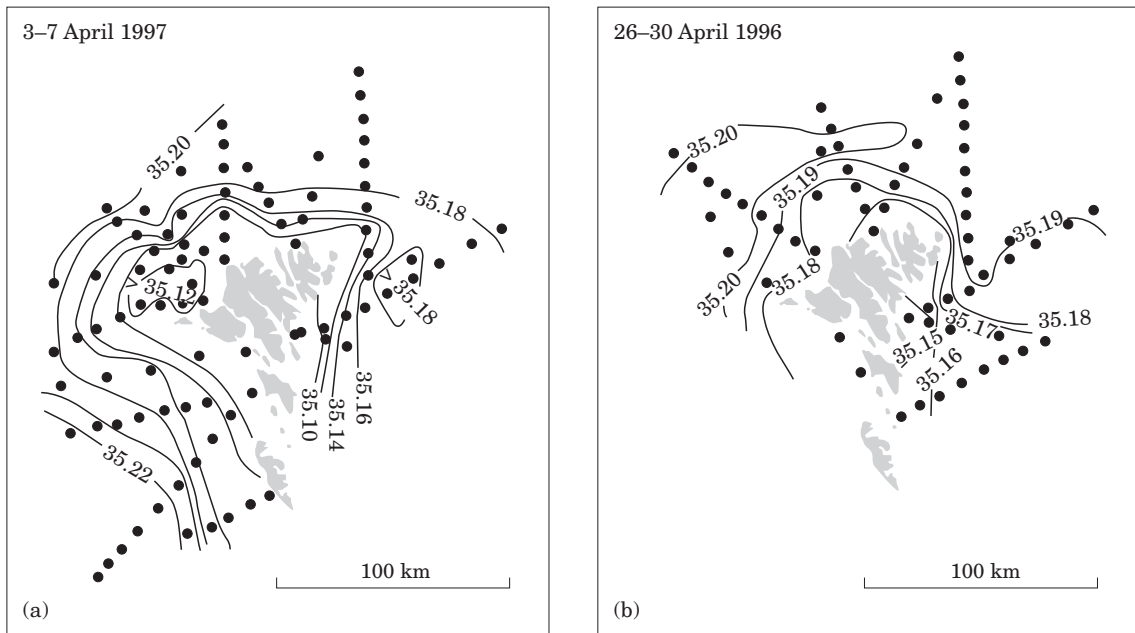| Dates	<100 m bottom depth Mean ± s.e.	N	>150 m bottom depth Mean ± s.e.	N	Shelf/offshore abundance ratio	Windstress vector (m s^{-1})^2
21–26 April 1994	5.3 ± 1.6	12	38.2 ± 7.5	18	0.13	20
10–14 April 1995	32.5 ± 15.0	12	50.9 ± 12.5	20	0.64	36
26–30 April 1996	56.5 ± 10.7	15	56.0 ± 9.9	22	1.01	11
2–4 April 1997	8.7 ± 1.5	18	20.4 ± 4.1	13	0.43	55
25–29 April 1997	24.9 ± 2.4	28	35.4 ± 7.4	12	0.70	45

Figure 4. Salinity 50 m deep around the Faroes exemplified (a) as a typical situation and (b) as a situation with abnormally high inflow (high salinity) in the northeastern part of the shelf (see text).
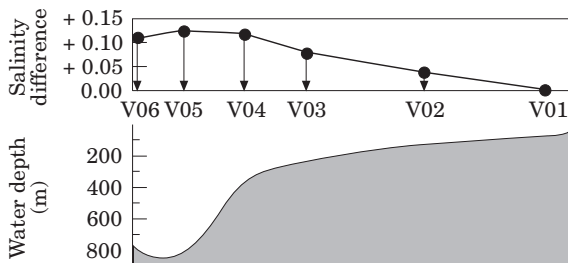

Figure 5. Average salinity (10–50 m depth) increase along transect V (Figure 1) from the shelf southwest of the Faroes (V01) into the Faroe Bank Channel, based on 44 cruises in the period 1988–1998.
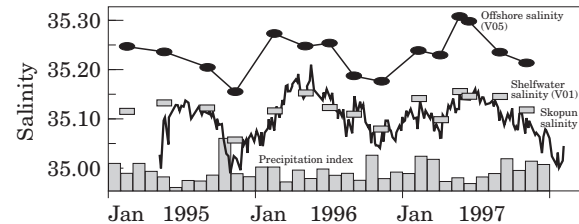

Figure 6. Salinity at the coastal station "Skopun" (see Figure 1), shown as a continuous curve, salinity of the 10–50 m layer at Stn V01 in the shelf water, shown as shaded rectangles, salinity of the 10–50 m layer at Stn V05 in the offshore waters of the Faroe Bank Channel, shown as black ellipses connected by straight lines, and variation in the monthly precipitation index based on five meteorological stations (in a relative scale), shown as a histogram.

hence *C. finmarchicus* through this narrow channel. In the upper layers of the Faroe Bank Channel, current measurements furthermore indicate horizontal recirculation (Figure 7), and Johnson and Sanford (1992) found evidence for a secondary circulation which involves both vertical and cross-channel horizontal flow. Both types of circulation might facilitate flow from deeper regions towards the shelf.

Together with the prevailing southwesterly wind direction, these processes indicate the Faroe Bank Channel as a major site of transfer of offshore water and *C. finmarchicus* onto the shelf. The details of the offshore to shelf water exchange mechanisms (localized on-slope advection, tidal mixing, diffusion) are, however, largely unknown.

Import variation

Observations of overwintered *C. finmarchicus* in April (Table 1) reveal variations in abundance within the shelf water of about an order of magnitude. Abundance offshore varies much less, especially if we disregard the observations from early April 1997, a cruise made earlier than the others and that apparently only caught the early phases of ascent and import. This indicates interannual variations in the horizontal water movements bringing *C. finmarchicus* into the shelf water. Salinity observations may be used to study these variations.

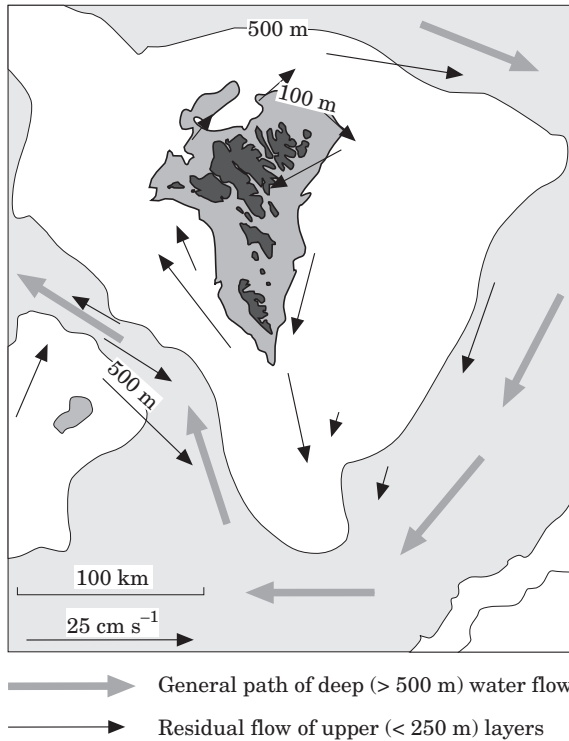Salinity observations (Figures 4–6) clearly show that the shelf water is consistently fresher than the offshore

Figure 7. Main features of the flow field around the Faroes. Thick arrows indicate the general path of the deep cold water passing southwestwards through the Faroe–Shetland Channel and from there northwestwards through the Faroe Bank Channel out into the Atlantic. Thin arrows show residual currents from long-term moorings on the shelf and in the upper layers offshore (Hansen and Larsen, 1999; Hansen *et al.*, 1999; Østerhus *et al.*, 1999).

water. This may be explained by the supply of fresh water as a result of increased precipitation over and close to the islands. If A is the surface area of the shelf water and D is its average depth (74 m for the area within the 100 m depth contour, K. Simonsen, pers. comm.), then the volume $(D \times A)$ of the shelf water is supplied by precipitation and inflow of offshore water:

$$D A = \sum_j (A P_j + Q_j) \qquad (1)$$

where P_j is the average precipitation (minus evaporation) to the shelf water during day j (in m) and Q_j is the net inflow of offshore water during the same day (in $m^3 \, d^{-1}$). The sum is over the period required to renew all the volume of the shelf water. The total salt content of the shelf water may similarly be expressed as

$$S_s D A = \sum_j S_o Q_j \qquad (2)$$

where S_o and S_s are the salinities of the offshore and shelf water, respectively. These two equations lead to the relationship

$$\sum_j P_j = \frac{S_o - S_s}{S_o} D \qquad (3)$$

The sum, again, is over the period required to renew the shelf water; this period may be considered a flushing time for this water. If we have a time series of P_j, the flushing time may therefore be determined as the period prior to the salinity observations necessary to sum P_j in order to fulfil Equation (3).

Equation (3) is based on a very crude model in which all the inflow from offshore has salinity S_o and all the outflow has salinity S_s. More refined models are difficult to construct as long as we do not know which physical exchange processes are most important; but, also, the crude model of Equation (3) has the benefit that it does not require a steady state. As long as offshore salinity S_o does not vary too rapidly compared to the flushing time, the flushing time calculated from Equation (3) should be representative for the period before the salinity observations. Although the exact numbers for the flushing time may be debatable, we thus may have some faith in the relative variations in flushing time assuming representative observations of salinity and precipitation minus evaporation.

Unfortunately, we do not have any good time series of P_j. Precipitation measurements at different sites on the islands range from about 800 mm to more than 3000 mm annually (Cappelen and Laursen, 1998). There is also little information about evaporation, while the net freshwater input to the ocean surface away from land is considerably below this range (Schmitt *et al.*, 1989). We have tried to circumvent this problem by using the normalized monthly precipitation index p_j multiplied by a scaling factor R. Determination of this scaling factor is beyond the scope of this paper, but it is restricted by the total annual precipitation minus evaporation to the land and shelf water area, which we assume to be between 500 and 1500 mm. Equation (3) then becomes:

$$R \sum_j p_j = \frac{S_o - S_s}{S_o} D \qquad (4)$$

To utilize this equation, we have used observations of offshore and shelf water salinity from 38 cruises during the period 1988–1997 in which transect V was occupied. For each set of observations, we calculated the flushing time with three different choices of the precipitation scaling factor R. Salinity observations from Stns V01 and V05 have been used for shelf water and offshore salinity, respectively. Figure 8 shows the results of these calculations. The flushing time naturally increases if a low precipitation (small R) is used. It is clear from Figure 6 that the shelf water salinity generally follows the offshore salinity variations. This implies that the renewal of shelf water from offshore must occur on time scales not more than a few months, which argues that
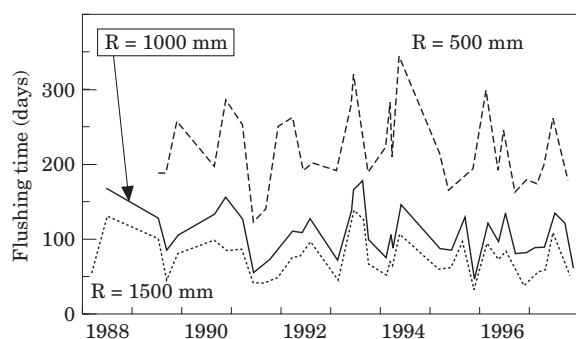
Figure 8. Flushing time of the shelf water calculated from salinity observations during 38 standard cruises with three different assumptions for the total annual precipitation (R) to the shelf water.

Figure 9. Mesozooplankton biomass ratio between the shelf water and offshore in June, plotted against flushing rate in May, 1991–1997.

the uppermost curve in Figure 8 (with total annual precipitation of 500 mm) gives flushing times that are too high.

The other two curves in Figure 8 (R = 1000 mm and R = 1500 mm) give flushing times ranging from about one month to six months. These values seem more realistic. We may define also a flushing rate as the inverse of the flushing time. In the unit year^{-1}, it should represent how often the shelf water is flushed per year. To the extent that these simple calculations bear any resemblance to nature, the flushing rate varies by a factor of about 5. Although the absolute values for the flushing rate depend on the assumed value for R, the relative variations do not appear to change significantly with this assumption. This may indicate that the changes in flushing rate reflect a variable inflow of offshore waters to the shelf, and indeed a factor of 5 variation in inflow rate could explain much of the variation in the abundance ratio of *C. finmarchicus* between the shelf water and offshore (Table 1).

To test this hypothesis more decisively, flushing rates should be calculated for periods with known *C. finmarchicus* abundance. Unfortunately, there are few salinity observations from the transect stations in April. However, comparison between water inflow in May and mesozooplankton biomass (largely dominated by *C. finmarchicus*) in June indicates a relationship (Figure 9). Processes other than import may influence the *Calanus* abundance on the shelf in June, and the significance of the relationship in Figure 9 depends critically upon one year (1991). We therefore do not have a statistically sound basis for drawing strong conclusions, but the available evidence does support a relationship between *Calanus* biomass on the shelf and inflow.

The origin of inflow variations

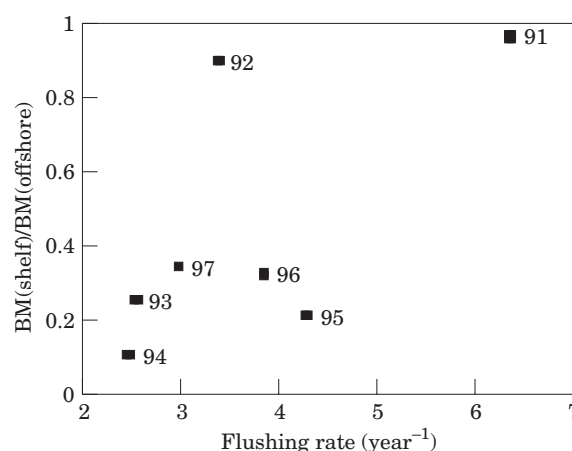*A priori*, wind-forcing would seem the most likely cause of the inflow variations. We have correlated the computed flushing rates to wind observations using the magnitude of the windstress vector as the relevant wind parameter. Using the synoptic wind observations from Tórshavn, we computed daily averaged east and north components of the windstress vector (assumed proportional to windspeed squared). These were averaged over a longer period, and then the magnitude of that vector was correlated to the flushing rates determined from the values in Figure 8.

The result was similar for annual precipitation of 1000 and 1500 mm, and the correlation coefficient was positive for averaging periods extending from one to more than three months. The best correlation was when the wind was averaged over 60 d prior to the salinity observations. As this appears to be a typical flushing time that is a reasonable period over which to average windstress, and the resulting correlation coefficient (+0.42) is statistically significant at a 1% level. It should be noted that 71% of the averaged windstress vectors originated in the 180–270° quadrant, underlining the importance of southwesterly winds.

A significant correlation indicates that wind can explain inflow of *C. finmarchicus* to the shelf, at least to some extent. To test that hypothesis, we calculated the magnitude of the windstress vector for a 60-d period before the *C. finmarchicus* observations in Table 1. The result is included in the table, and there is some consistency between the ratio of shelf to offshore abundance and wind, but the observations from 1996 are completely the opposite, with the highest *C. finmarchicus* abundance in the shelf water and the lowest windstress.

There is, however, independent evidence to indicate that the 1996 *Calanus* cruise was carried out during abnormal conditions. This is partly seen in the salinity distribution in Figure 4(b), which reveals high salinity (and hence inflow) in the northeastern part of the shelf,
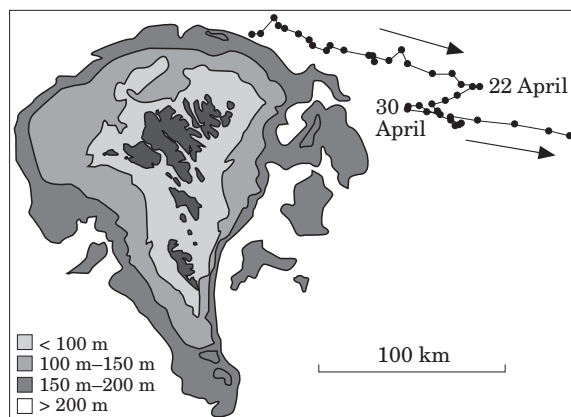
Figure 10. Progressive vector diagram from ADCP current measurements 147 m depth for the period 1 April 1996 to 11 May 1996 at a long-term current monitoring site (300 m bottom depth) shown by the triangle in Figure 1 (Hansen *et al.*, 1999).

but it can also be seen in Figure 10. A few days before the cruise, the normal eastward flow along the bottom topography turned onto the shelf. In the 3.5-year time-series, only 21 d were found with daily averaged current direction towards the shelf (between 180 and 270°) and this was the only occurrence with several days of such flow. Therefore, Table 1 cannot be used to support the hypothesis of a general wind influence on *C. finmarchicus* import to the shelf water, but neither does it disprove the validity of the hypothesis under normal conditions.

Acknowledgements

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