

Optical properties and optical constituents of the Faroe Islands shelf and off-shelf waters, North East Atlantic

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Abstract The study comprises a data set of CTD, optical properties— $K_0(\text{PAR})$, c_p , $a(\text{PAR})$, $b(\text{PAR})$ —and optical constituents—Chl a , SPM, CDOM—from 72 shelf and off-shelf stations in the Faroe Islands (62°N, 7°W) North East Atlantic, in early spring 2005. Results showed that shelf waters surrounding the islands were cold and low saline, whereas off-shelf waters were warmer ($\sim 1^\circ\text{C}$) and more saline (~ 0.05) PSU. A pronounced oceanographic front separated the two waters, and diffuse light attenuation $K_0(\text{PAR})$, beam attenuation c_p , Chl a , absorption $a(\text{PAR})$, and scattering coefficient $b(\text{PAR})$ were all significantly higher on the shelf. Analyses showed that off-shelf light attenuation $K_0(\text{PAR})$ was governed by Chl a , shown by a high ($r^2 = 0.64$) Chl a – $K_0(\text{PAR})$ correlation, whereas light attenuation on the shelf was governed by both Chl a , SPM, and CDOM in

combination. A Chl a specific diffuse attenuation coefficient $K_0^*(\text{PAR})$ of $0.056 \text{ (m}^2 \text{ mg}^{-1} \text{ Chl } a)$ and a Chl a specific beam attenuation (c_p^*) of $0.27 \text{ (m}^2 \text{ mg}^{-1} \text{ Chl } a)$ coefficients were derived for the off-shelf. It is pointed out that Chl a is the single variable that changes over time as no rivers with high SPM and CDOM enter the shelf area. Data were obtained in early spring, and Chl a concentrations were low $\sim 0.5 \text{ mg Chl } a \text{ m}^{-3}$. Spring bloom Chl a are about $10 \text{ mg Chl } a \text{ m}^{-3}$ and estimations showed that shelf $K_0(\text{PAR})$ will increase about 5 times and beam attenuation about 10 times. The Faroe Islands shelf–off-shelf waters is a clear example where physical conditions maintain some clear differences in optical properties and optical constituents. The complete data set is enclosed.

Keywords Diffuse $K_0(\text{PAR})$ and beam attenuation (c_p) coefficients · Chl a · Faroe Islands · North East Atlantic

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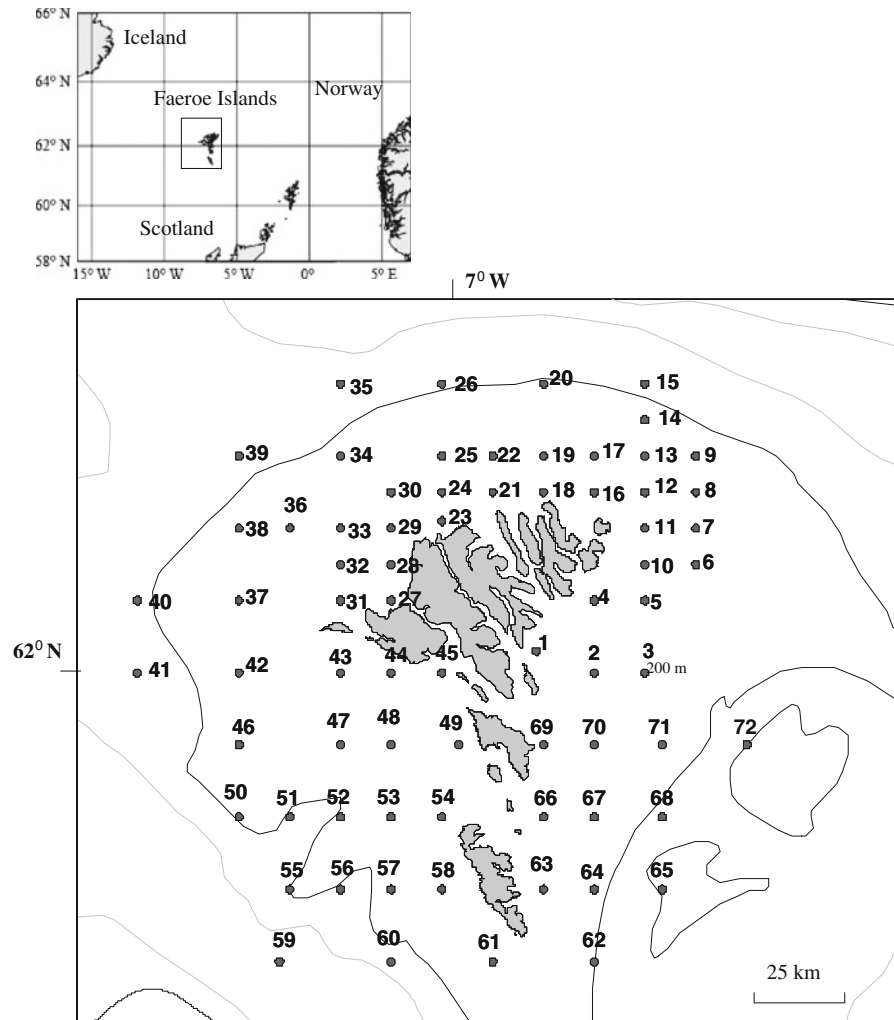
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Introduction

There are only few studies of optical properties from the North East Atlantic (Gardner et al., 1993; Nelson et al., 2007), and part of these are based on satellite imagery (Balch et al., 1996a, b; Hemmings et al., 2003). The Faroe Islands are located in central North East Atlantic (62°N, 7°W) (Fig. 1), and knowledge about the waters is fundamental regarding the Faroe

Fig. 1 Location of Faroe Islands in the North East Atlantic with stations



fisheries and thus local economy (Gaard, 1999; Hansen et al., 2005; Steingrund & Gaard, 2005; Larsen et al., 2008). Virtually, nothing is known regarding the optical properties of these waters in spite of their economic importance. The significance of optical properties in this respect is emphasized as the attenuation of light with depth in the water column, nutrients, and grazing are the governing parameters in relation to the primary production (Kirk, 1994). The Faroese waters comprise the cold shelf and the warmer off-shelf waters separated by the Faroe-Shelf front (Gaard et al., 2002; Eliassen et al., 2005; Hansen et al., 2005). The warm off-shelf water is the North Atlantic Current (NAC), whereas the cold shelf waters are termed the Faroe Shelf Water (FSW) (Larsen et al., 2008).

A cruise covering both the Faroe shelf and off-shelf waters was conducted in April 2005. One of the main purposes was to study the optical properties of these waters. Following main questions were accordingly raised: (1) What are the general optical properties of these waters? (2) Are there any differences in optical properties and optical constituents between shelf and off-shelf waters? (3) What are the differences and how are the differences maintained? (4) Are the differences constant in time and space?

Methods and data

Data were obtained during a cruise between 15 and 25 April, 2005, onboard R/V “Magnus Heinasson.” A

total number of 72 stations were covered during the cruise with combined optical and CTD casts, and water sampling (Fig. 1). Optical data were obtained with an optical instrument (own design) for measuring temperature, depth (pressure), PAR (Photosynthetically Available Radiation), fluorescence, and light transmission. The different sensors were mounted on a stainless steel frame together with a battery and data logger package. A spherical PAR sensor (Li-193, LICOR) on top of the frame measured scalar irradiance (400–700 nm), and a SEAPOINT fluorometer with excitation wavelength of 470 nm and an emission wavelength of 685 nm measured active fluorescence. A Wetlabs C-Star transmissometer at an operating wavelength of 660 nm (red light) measured light transmission across a path length of 25 cm. The beam attenuation (c) in the red part of the spectrum depends on concentration, optical properties of the particles in suspension, whereas dissolved substances are supposed to be negligible at this wave length (Jerlov, 1976). The transmissometer was calibrated prior to the cruise by the manufacturer. A Seabird (SBE 911Plus) CTD equipped with Niskin bottles (5 l) for water sampling was applied.

The diffuse attenuation coefficient $K_0(\text{PAR})$ was calculated for each station by a linear regression of log-transformed data below about 9 m depth to avoid the influence of surface waves and wave focusing of the light (see later). The linear regression model described data very well ($r^2 \sim 0.97$). Distribution of light with depth followed: $I = I_0 e^{-K_0(\text{PAR})z}$ (Kirk, 1994), which describes the irradiance (I) with depth (z) as a function of surface irradiance (I_0) and attenuation coefficient $K_0(\text{PAR})$. A trail optical cast on the shelf showed a $K_0(\text{PAR})$ of 0.09 m^{-1} , which equals a photic depth (Z_0) of 51 m as $Z_0 = 4.6/K_0(\text{PAR})$, and measurement depths were set to 50 m with a descent velocity of the optical CTD of 0.1 m s^{-1} . The absorption $a(\text{PAR})$ and scattering $b(\text{PAR})$ coefficients (m^{-1}) in the PAR range were estimated according to the Pfannkuche (2002) relations: $a(\text{PAR}) = 0.019 + 0.221(\text{CDOM}_{440}) + 0.037(\text{Chl } a) + 0.018(\text{SPMI})$ and $b(\text{PAR}) = 0.239(\text{Chl } a) + 0.342(\text{SPMI})$. The 0.019 is the PAR attenuation (m^{-1}) of clear water, the 0.221(CDOM_{440}) is the CDOM specific absorption coefficient measured at 440 nm, 0.037($\text{Chl } a$) and 0.018(SPMI) are the $\text{Chl } a$ specific absorption coefficients ($\text{m}^2 \text{ mg}^{-1} \text{ Chl } a$), and the inorganic suspended particulate matter (SPMI) specific absorption

coefficient ($\text{m}^2 \text{ mg}^{-1} \text{ SPMI}$), respectively. The 0.239($\text{Chl } a$) and 0.342(SPMI) are similarly the $\text{Chl } a$ specific scattering coefficient ($\text{m}^2 \text{ mg}^{-1} \text{ Chl } a$), and the inorganic suspended particulate matter specific scattering coefficient ($\text{m}^2 \text{ mg}^{-1} \text{ SPMI}$).

The angle the ray of photons make with the vertical (μ_0) was calculated for each optical cast relative to time and location using nautical handbooks. Multiple correlation analyses were performed but showed no reasonable results and the data set was searched for correlations between $K_0(\text{PAR})$, $a(\text{PAR})$, $b(\text{PAR})$, and beam attenuation coefficient (c_p) on one side and $\text{Chl } a$, SPM, and CDOM on the other side. Weather conditions were mainly calm with cloud cover and a few days of clear sky where optical measurements were carried out on the sunny side of the ship to avoid any interference with the shadow of the ship. Isopleths were produced in SURFER[®] 8.0.

An exact volume (2 l) of water was filtered through GF75 (Advantec) filters with a pore size of 0.7 μm , using a vacuum of maximally 30 kPa (0.3 bar). The filters were packed individually in tin-foil bags and stored in the freezer. In laboratory, filters were stored in 5 ml 96% ethanol at 5°C for a minimum of 6 h and a maximum of 20 h for pigment extraction from the retained phytoplankton. Samples were centrifuged and the absorbance of the supernatant was measured at 665 and 750 nm with a spectrophotometer (Thermo Spectronic HELIOS λ) following Strickland (1972). Samples for $\text{Chl } a$ were collected from 5, 20, and 40 m of depth, and values shown are the average of the three $\text{Chl } a$ samples from each station as stratification and vertical variations in $\text{Chl } a$ are virtually absent (see later). Average values are given for 67 stations as 5 samples were lost in laboratory. The fluorescence signal was converted into $\text{Chl } a$ concentrations by means of a calibration of the fluorometer, which shows a high ($r^2 = 0.70$) and a significant ($P < 0.001$) correlation between fluorescence and $\text{Chl } a$ (Fig. 3A). The line of regression reads: $\text{Chl } a = 0.18 * \text{Fluorescence} + 0.18$ (Fig. 4C).

Suspended matter concentration (SPM) was determined by filtration on board of an exact volume (2 l) of water through pre-combusted (400°C, 6 h) GF/F (Whatman) filters with a pore size of 0.7 μm for SPM. 200 ml of distilled water was used to remove any salt residues from each filter following the filtration. The filters were kept dark and cold until arrival in laboratory where they were dried (60°C,

16 h) and weighed to give SPM. Afterward, filters were burned (500°C, 16 h), cooled, and weighed to derive organic and inorganic content (Bowers et al., 1996). SPM is the total weight of the sample, SPMO the weight of the organic part, and SPMI weight of inorganic part. Previous experiments comprising blank filters and following the described procedure showed no weight changes in blank filters.

Water samples for CDOM absorption coefficients were pre-filtered onboard using GF75 (Advantec) filters with a pore size of 0.7 µm and stored cold and dark in amber colored 250 ml glass containers. Samples were later filtered in laboratory using 0.2 µm membrane filters and analysed spectrophotometrically (Thermo Spectronic HELIOS λ). Samples for CDOM were analysed about 2 weeks after completing the cruise. The absorption coefficient at 440 nm was taken as proportional to CDOM concentrations (Kirk, 1994) by:

$$g_{440} = 2.303(A_{440} - A_{750})/L, \quad (1)$$

where A_{440} and A_{750} are the absorbencies at 440 and 750 nm, L is cuvette path length (0.1 m), and 2.303 converts the base of the logarithm from 10 to e . SPM concentrations and CDOM absorption coefficients were determined for water samples collected at 5 m depth.

Results

Temperature isopleth shows that warm off-shelf waters surround the group of islands with colder shelf waters (Fig. 2A). The average temperature of the off-shelf water is $7.59 \pm 0.47^\circ\text{C}$ as compared to an average shelf temperature of $6.79 \pm 0.16^\circ\text{C}$, and the difference is statistically significant ($P < 0.001$). Spatial distribution of temperature and salinity is comparable with high (35.282 ± 0.023 PSU) saline off-shelf waters and low (35.227 ± 0.016 PSU) saline shelf waters as emphasized by a very high ($r^2 = 0.93$) and significant ($P < 0.001$) correlation between salinity and temperature. The difference in average salinity between the two waters is likewise statistically significant ($P < 0.001$). The 7.0°C isotherm forms roughly the boundary between the warm off-shelf

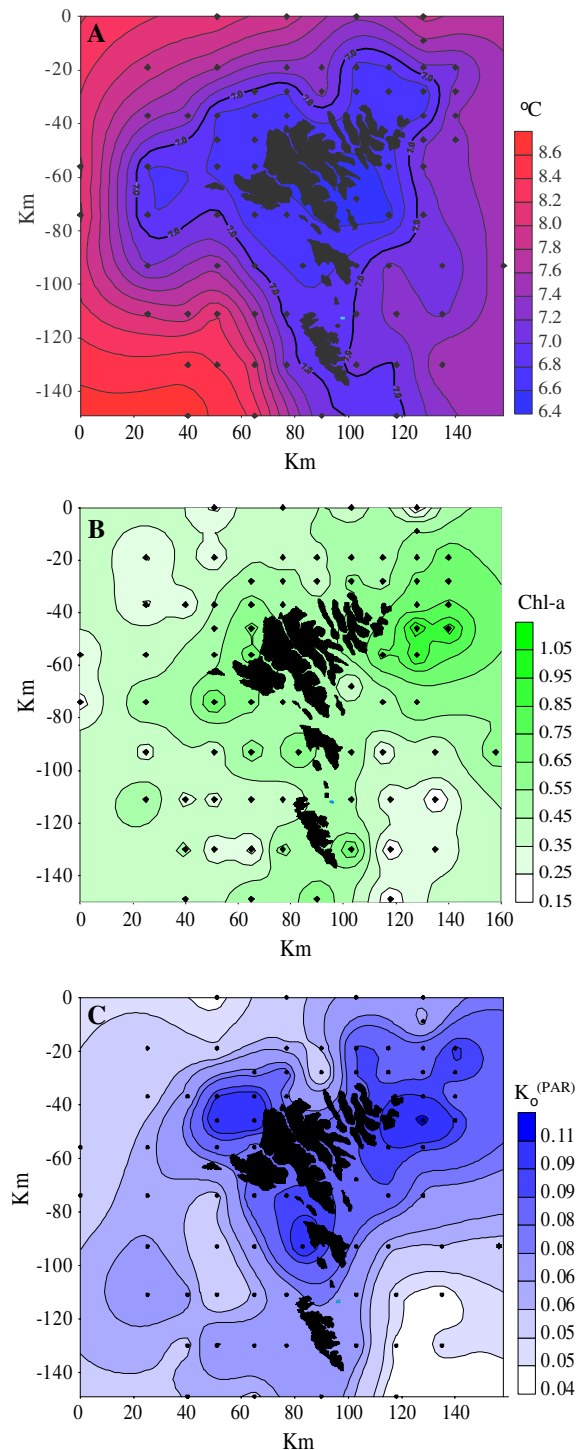


Fig. 2 Isopleths: **A** Temperature ($^\circ\text{C}$), **B** Chl a ($\text{mg Chl } a \text{ m}^{-3}$), and **C** diffuse attenuation coefficient $K_0(\text{PAR})$ (m^{-1})

water and the cold shelf water and establishes the permanent Faroe-Shelf front (Gaard et al., 2002; Eliassen et al., 2005). The waters with an average temperature <7.0°C are accordingly here termed the shelf waters (30 stations) and waters with temperatures >7.0°C off-shelf waters (42 stations). Average temperature at each station comprises the depths between surface and 50 m.

The Chl *a* isopleth shows higher (0.59 ± 0.15 mg Chl *a* m⁻³) Chl *a* concentrations on the shelf near the islands and in the northeast corner as compared to the off-shelf (0.40 ± 0.21 mg Chl *a* m⁻³) (Fig. 2B). The difference in average Chl *a* concentration between shelf and off-shelf is statistically significant (*P* < 0.001) (Table 1). Quantitative investigations showed that the diatoms *Chaetoceras* sp., *Thalassiosera*, and *Melosera* dominated both on the shelf and off-shelf. The Chl *a* concentration at each station is the average of Chl *a* measured at 5, 20, and 40 m depth with small variations in Chl *a* concentrations in the vertical direction. This corroborates with temperature and salinity observations that there was no or only a very weak stratification of the water column ($\Delta T < 0.3^\circ\text{C}$) (see later). A comparison of Chl *a* and temperature isopleths (Fig. 2A, B) supports that Chl *a* is higher in the cold shelf waters and lower in the warm off-shelf waters although there is no direct

correlation between temperature and Chl *a* ($r^2 = 0.16$). The spatial distribution of $K_0(\text{PAR})$ shows a higher $K_0(\text{PAR})$ (>0.08 m⁻¹) on the shelf and lower (<0.05 m⁻¹) values in the off-shelf waters and especially in the south east corner (Fig. 2C). The distribution of $K_0(\text{PAR})$ resembles that of Chl *a* with high north east corner and shelf values (Fig. 2B, C) and will be elaborated later. Representative shelf (st. 1) and off-shelf (st. 40) data show accordingly higher average Chl *a* concentrations (0.35 mg Chl *a* m⁻³) in the colder (6.48°C) shelf water (Fig. 3A), as compared to the off-shelf Chl *a* concentrations (0.29 mg Chl *a* m⁻³) and warmer water (8.25°C) (Fig. 3B). Light is shown as ln(PAR) versus depth, and some disturbance of the PAR signal is seen in the surface waters and $K_0(\text{PAR})$ was calculated for the depths >9 m (see “Methods and data” section). Shelf station $K_0(\text{PAR}) = 0.088 \text{ m}^{-1}$ is nearly twice than the off-

Table 1 Average and standard deviation for diffuse attenuation coefficient $K_0(\text{PAR})$ (m⁻¹), beam attenuation coefficient c_p (m⁻¹), absorption coefficient $a(\text{PAR})$ (m⁻¹), scattering coefficient $b(\text{PAR})$, Chl *a* concentration (mg Chl *a* m⁻³), suspended particulate matter SPM (g m⁻³), suspended particulate matter organic SPMO (g m⁻³), suspended particulate matter inorganic SPMI (g m⁻³), and CDOM absorption coefficient (m⁻¹) at the shelf and off-shelf stations with *n* as the actual number of stations

	Avg. ^{shelf}	SD	<i>n</i>	Avg. ^{off-shelf}	SD	<i>n</i>	
$K_0(\text{PAR})$	0.084	0.014	32	0.062	0.014	38	***
c_p	0.181	0.046	33	0.125	0.062	39	***
$a(\text{PAR})$	0.064	0.011	33	0.058	0.011	39	*
$b(\text{PAR})$	0.497	0.122	33	0.414	0.136	39	**
Chl <i>a</i>	0.59	0.15	29	0.40	0.21	39	***
SPM	1.560	0.450	33	1.510	0.400	39	
SPMO	0.460	0.120	33	0.580	0.270	39	*
SPMI	1.100	0.390	33	0.930	0.400	39	
CDOM	0.053	0.038	18	0.059	0.034	22	

The difference in average between shelf and off-shelf is significant: * *P* < 0.02, ** *P* < 0.01, *** *P* < 0.001

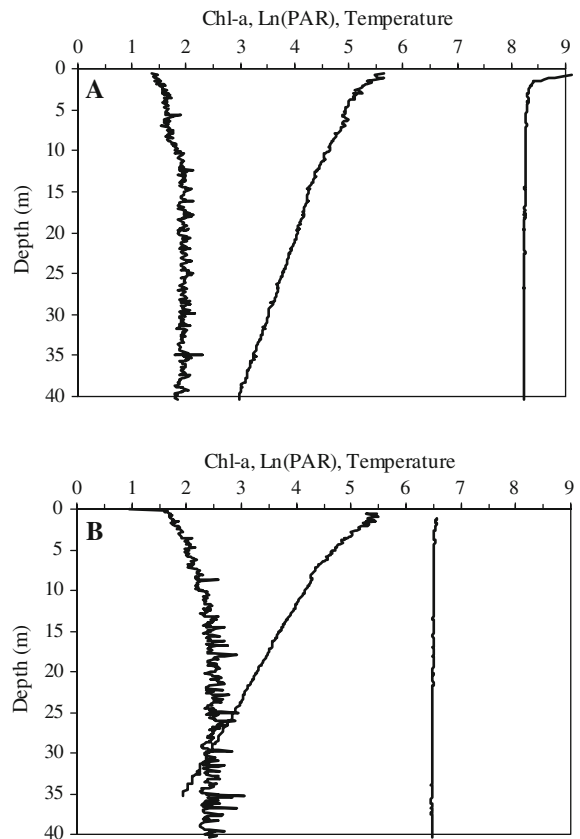


Fig. 3 A *Chl *a* (mg Chl *a* m⁻³), ln (PAR) (μE m⁻² s⁻¹), and temperature (°C) with depth (m) at station 1. B *Chl *a* (mg Chl *a* m⁻³), ln (PAR) (μE m⁻² s⁻¹), and temperature (°C) with depth (m) at station 40

shelf $K_0(\text{PAR}) = 0.052 \text{ m}^{-1}$ and equals photic depths (Z_0) of 52 and 88 m, respectively, as $Z_0 = 4.6/K_0(\text{PAR})$. Photic depth is the depth where 1% of the surface light reaches into the water (Kirk, 1994). All optical data from each station on the shelf and off-shelf are listed in Supplementary Material—Annexes 1 and 2, respectively.

A comparison of shelf and off-shelf optical properties shows that $K_0(\text{PAR})$ is higher ($0.084 \pm 0.014 \text{ m}^{-1}$) on the shelf as compared to off-shelf ($0.062 \pm 0.014 \text{ m}^{-1}$), and the difference is statistically significant ($P < 0.001$) (Table 1). $K_0(\text{PAR})$ shows a considerable range between a maximum (0.115 m^{-1}) at st. 10 and a minimum (0.038 m^{-1}) at the off-shelf st. 62. Note that minimum (0.038 m^{-1}) $K_0(\text{PAR})$ is just slightly higher than in the Sargasso Sea (0.03 m^{-1}), considered to be the ocean with the lowest $K_0(\text{PAR})$ (Tyler, 1975). The beam attenuation coefficient (c_p) is significantly ($P < 0.001$) higher on the shelf ($0.181 \pm 0.046 \text{ m}^{-1}$) as compared to the off-shelf ($0.125 \pm 0.062 \text{ m}^{-1}$) with a big range between a maximum (0.319 m^{-1}) (st. 6) and a minimum (0.047 m^{-1}) (st. 64) (Table 1). The spatial distribution of beam attenuation coefficient on the shelf and off-shelf is similar to the spatial distribution of Chl *a* (Fig. 2B) and $K_0(\text{PAR})$ (Fig. 2C). This is emphasized by a very strong ($r^2 = 0.80$) and significant ($P < 0.001$) correlation between Chl *a* and beam attenuation in the off-shelf waters, although the correlation is low ($r^2 = 0.30$) but still significant ($P < 0.1$) in the shelf waters (Table 1). Absorption and scattering coefficients, $a(\text{PAR})$ and $b(\text{PAR})$, were estimated by applying the Pfannkuche (2002) relations (see “Methods and data” section), and results show that average $a(\text{PAR}) = 0.064 \pm 0.011 \text{ (m}^{-1}\text{)}$ was significantly ($P < 0.02$) higher on the shelf as compared to off-shelf $a(\text{PAR}) = 0.058 \pm 0.011 \text{ (m}^{-1}\text{)}$. The average scattering coefficient $b(\text{PAR})$ was significantly ($P < 0.01$) higher on the shelf $b(\text{PAR}) = 0.497 \pm 0.122 \text{ (m}^{-1}\text{)}$ as compared to the off-shelf average $b(\text{PAR}) = 0.414 \pm 0.136 \text{ (m}^{-1}\text{)}$ (Table 1).

Average shelf and off-shelf Chl *a* concentrations are significantly ($P < 0.001$) different with high shelf concentrations ($0.59 \pm 0.15 \text{ mg Chl } a \text{ m}^{-3}$) as compared to off-shelf ($0.40 \pm 0.21 \text{ mg Chl } a \text{ m}^{-3}$) (Table 1). The SPM concentrations are not significantly different between shelf ($1.56 \pm 0.45 \text{ g m}^{-3}$) and off-shelf ($1.51 \pm 0.40 \text{ g m}^{-3}$) as also for SPMI shelf ($1.10 \pm 0.39 \text{ g m}^{-3}$) and off-shelf ($0.93 \pm$

0.40 g m^{-3}) values. Due to laboratory errors, CDOM absorption coefficients were determined at fewer stations on the shelf ($n = 18$) and off-shelf ($n = 22$) but there was no significant differences between shelf ($0.053 \pm 0.038 \text{ m}^{-1}$) and off-shelf ($0.059 \pm 0.034 \text{ m}^{-1}$) (Table 1). Only SPMO, the organic part of the suspended particulate matter, was significantly ($P < 0.02$) different between shelf ($0.46 \pm 0.12 \text{ m}^{-1}$) and off-shelf ($0.58 \pm 0.27 \text{ m}^{-1}$) (Table 1). It is supposed that the lower organic part of the suspended matter is related to a higher degree of resuspension of sediment particles by currents and waves on the shelf. This is emphasized by the higher inorganic part on the shelf although the difference is not significant (Table 1). The correlation between SPM and SPMI is highly positive ($r^2 = 0.93$) and significant ($P < 0.001$) on the shelf: $\text{SPMI} = 0.85\text{SPM} - 0.23$, which shows that 85% of the SPM is inorganic. The SPM–SPMI correlation is less high ($r^2 = 0.60$) but still very significant ($P < 0.001$) off-shelf: $\text{SPMI} = 0.77\text{SPM} - 0.24$, which shows that 77% of the off-shelf SPM is inorganic.

Results show that Chl *a* is the only optical constituent with positive correlations regarding $K_0(\text{PAR})$ and c_p although with different shelf and off-shelf correlations (Table 2). The correlation between Chl *a* and $K_0(\text{PAR})$ is very low ($r^2 = 0.30$) but significant ($P < 0.1$). This is in opposite to the off-shelf, which shows a quite high ($r^2 = 0.64$) and highly ($P < 0.001$) significant correlation between Chl *a* and $K_0(\text{PAR})$. The equation reads: $K_0(\text{PAR}) = 0.050 \text{ Chl } a + 0.04$, where the coefficient 0.050 is the Chl *a* specific attenuation coefficient $K_0^*(\text{PAR})$ ($\text{m}^2 \text{ mg}^{-1} \text{ Chl } a$) (Fig. 4A). This demonstrates, in combination, that light attenuation is governed by Chl *a* off-shelf, whereas no specific optical constituent

Table 2 The squared correlation coefficient (r^2) for variables as diffuse attenuation coefficient $K_0(\text{PAR})$ (m^{-1}), beam attenuation coefficient c_p (m^{-1}), and Chl *a* concentration ($\text{mg Chl } a \text{ m}^{-3}$)

	Shelf		Off-shelf	
	$K_0(\text{PAR})$	c_p	$K_0(\text{PAR})$	c_p
$K_0(\text{PAR})$	–	–	–	–
c_p	0.46**	–	0.65***	–
Chl <i>a</i>	0.3*	0.3*	0.64***	0.8***

Significance levels: * $P < 0.1$, ** $P < 0.01$, *** $P < 0.001$

was related to the shelf light attenuation. The Chl *a*– $K_0(\text{PAR})$ correlations show that the shelf Chl *a* concentrations are centered between 0.35 and 0.8 mg Chl *a* m^{-3} but covers a larger range off-shelf from 0.17 to 1.05 mg Chl *a* m^{-3} (Fig. 4A, B). Note that one Chl *a* out layer point was removed from the shelf data set.

There is a similar low ($r^2 = 0.30$) but significant ($P < 0.1$) correlation between Chl *a* concentrations and beam attenuation coefficient c_p in the shelf case, whereas the correlation is high ($r^2 = 0.80$) and highly significant ($P < 0.001$) in the off-shelf case (Table 1). The Chl *a* and beam attenuation regression read:

$c_p = 0.27 * \text{Chl } a + 0.017$, where 0.27 is the Chl *a* specific beam attenuation coefficient ($\text{m}^2 \text{mg}^{-1}$ Chl *a*). There is a marked difference in the low correlation between beam attenuation coefficient and $K_0(\text{PAR})$ at the shelf ($r^2 = 0.46$) and that obtained off-shelf ($r^2 = 0.65$) (Table 1).

Discussion

Results showed that warm ($7.59 \pm 0.47^\circ\text{C}$) saline (35.285 ± 0.023 PSU) off-shelf water surrounded the group of islands with more cold ($6.79 \pm 0.16^\circ\text{C}$) and less saline (35.227 ± 0.016 PSU) shelf water. These values are typical for the FSW and the NAC (Larsen et al., 2008). The shelf water is mixed by the strong ($1.0\text{--}1.5 \text{ m s}^{-1}$) shelf tide, and the cooling is maintained by a loss of heat to the atmosphere, and the lower salinity is related to increased rates of precipitation near the islands. The NAC off-shelf waters originate from the warm Gulf Stream. The 7°C isotherm followed approximately the 100-m depth curve that corresponds with the position of the Faroe Shelf front, which separates the shelf and off-shelf waters (Hansen, 1992; Larsen et al., 2002, 2008). As for the optical properties, results showed that average $K_0(\text{PAR})$, beam attenuation coefficient (c_p), $a(\text{PAR})$, and $b(\text{PAR})$ were all significantly higher in the shelf waters although the level of significance varied (Table 1). As for the optical constituents, results showed that only Chl *a* and SPMO, the organic part of the SPM, were significantly different with higher Chl *a* and lower SPMO concentrations on the shelf. There were, on the other hand, no significant differences in SPM, SPMI, and CDOM absorption coefficients between shelf and off-shelf waters.

There were only a few positive and significant correlations between optical properties— $K_0(\text{PAR})$, beam attenuation coefficient (c_p), $a(\text{PAR})$, and $b(\text{PAR})$ —and water constituents as Chl *a*, SPM, and CDOM. In fact, only Chl *a* of the optical constituents, showed positive correlations with $K_0(\text{PAR})$ and (c_p), and only off-shelf correlations were strong (Table 1). The high ($r^2 = 0.64$) off-shelf Chl *a*– $K_0(\text{PAR})$ showed that Chl *a* or in fact phytoplankton governed the light attenuation off-shelf. The low ($r^2 = 0.30$) and just significant shelf Chl *a*– $K_0(\text{PAR})$ correlation strongly indicates that light attenuation on the shelf was also governed by SPM and CDOM. It was

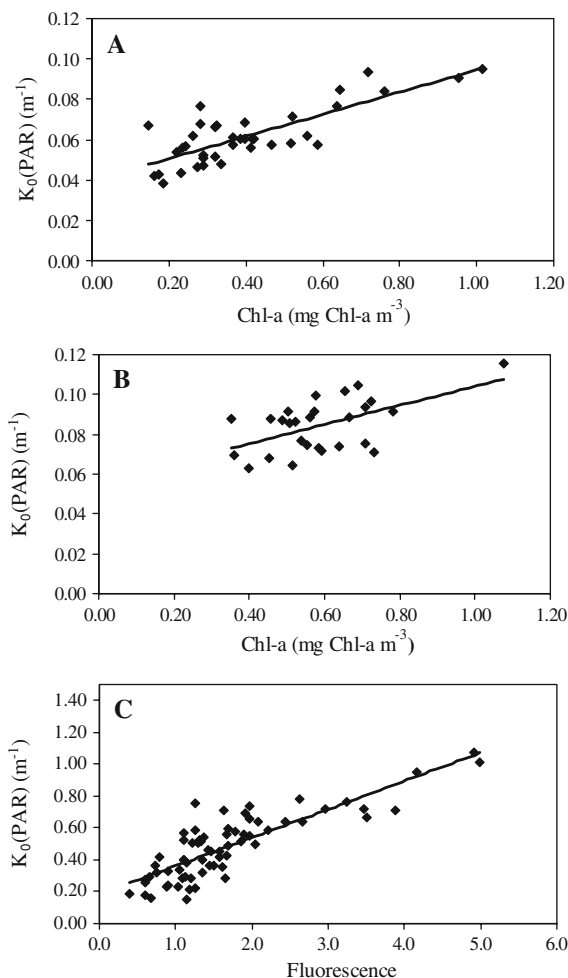


Fig. 4 **A** Correlation between Chl *a* (mg Chl *a* m^{-3}) and diffuse attenuation coefficient $K_0(\text{PAR})$ (m^{-1}) for the off-shelf, **B** correlation between Chl *a* (mg Chl *a* m^{-3}) and diffuse attenuation coefficient $K_0(\text{PAR})$ (m^{-1}) for the shelf, **C** correlation between fluorescence and Chl *a* (mg Chl *a* m^{-3})

supposed that the slightly higher shelf SPMI concentration was related to stronger wave and current-related resuspension of the shelf sediment with a lower organic matter content. The estimated absorption, $a(\text{PAR})$, and scattering, $b(\text{PAR})$, were both significantly higher on the shelf, which is in support of the higher light attenuation on the shelf. The Pfannkuche (2002) relations were applied for estimating $a(\text{PAR})$ and $b(\text{PAR})$ in spite that the relations were derived from a New Zealand shelf environment. It was supposed, however, that the relations could be applied here as both optical properties and New Zealand open shelf conditions are comparable to those obtained on the Faroe shelf. The $a(\text{PAR})/b(\text{PAR})$ ratio was 0.13 on shelf and 0.14 off-shelf, which is similar to the average ($n = 31$) $a(\text{PAR})/b(\text{PAR}) = 0.15$ obtained at the New Zealand shelf.

Chl a concentrations were measured at 5, 20, and 40 m depth, and the average was the Chl a concentration at that station with small Chl a variations with depth in the unstratified water column (Fig. 3A, B). The average of the three measurements was applied in the correlations (Table 1), whereas Chl a concentrations (Fig. 3A, B) were obtained by the calibration of the fluorometer, which showed a very high ($r^2 = 0.70$) and significant correlation. There were no significant differences in the fluorescence–Chl a relations between shelf and off-shelf and the calibration comprised all stations.

The quantitative phytoplankton analyses showed that the same species of diatoms *Chaetoceras* sp., *Thalassiosera*, and *Melosera* dominated both on the shelf and off-shelf. This is supposedly the reason that there were no separate fluorometer calibrations for shelf and off-shelf (Fig. 4C), as fluorescence signal depends on algae species and their physiological and nutritional conditions, etc. (Falkowski & Raven, 1997). The present range of Chl a concentrations (1.07–0.15 mg Chl a m $^{-3}$) equalled previous early spring shelf Chl a concentrations (Gaard, 1999). However, during spring (May–June) shelf Chl a concentrations rise to 10–12 (mg Chl a m $^{-3}$), whereas off-shelf concentrations remain low (0.5–1.0 mg Chl a m $^{-3}$; Gaard, 1999). The rise in shelf Chl a concentrations will amplify differences in optical properties between shelf and off-shelf waters. $K_0(\text{PAR})$ on the shelf will increase more than five times from present 0.084 to 0.46 m $^{-1}$ at a Chl a concentration of

10 mg Chl a m $^{-3}$ on the shelf, as derived from the shelf Chl a – $K_0(\text{PAR})$ correlation. The shelf beam attenuation will increase about 10 times from 0.181 to 0.480 m $^{-1}$ by a 10 times higher Chl a concentration. There are no big fresh water rivers entering the Faroe shelf and it is accordingly assumed that there are no major annual variations in SPM or CDOM. It is interesting to note the very small difference between maximum (0.115 m $^{-1}$) and minimum (0.058 m $^{-1}$) $K_0(\text{PAR})$ range of the shelf (Table 1) that establish a shelf-ecosystem (Hansen et al., 2005).

The derived Chl a specific diffuse $K_0^*(\text{PAR})$ attenuation coefficients for the shelf and off-shelf was 0.055 (m 2 mg $^{-1}$ Chl a) is similar to coefficients in other North Atlantic studies (Gardner et al., 1993) but higher compared to New Zealand estuarine environments (0.016–0.03 m 2 mg $^{-1}$ Chl a ; Vant, 1990) and the Kattegat (0.029 m 2 mg $^{-1}$ Chl a ; Lund-Hansen, 2004). A high $K_0^*(\text{PAR})$ coefficient implies a higher diffuse attenuation $K_0(\text{PAR})$ per Chl a concentration. The explanation for the high specific attenuation coefficient might be different optical properties of phytoplankton species and size of the algae as more small algae will attenuate more effectively for the same Chl a concentration (Fujiku & Taguchi, 2002).

Present beam attenuation coefficients (c_p) were similar to those measured in the Faroe-Shetland Channel of 0.5–1.1 m $^{-1}$ (Raaphorst et al., 2001) at low Chl a (~ 0.1 mg Chl a m $^{-3}$) and SPM (~ 0.57 g m $^{-3}$) concentrations. The (c_p) figures were also comparable to other North Atlantic studies, where c_p varied between 0.17 and 0.46 (m $^{-1}$) at low (0.55–1.72 mg Chl a m $^{-3}$) Chl a concentrations at NABE (48°N, 20°W; Gardner et al., 1993). The high ($r^2 = 0.80$) correlation between Chl a and beam attenuation as for the off-shelf is typical for Case I waters where $r^2 > 0.7$ –0.8 between Chl a and beam attenuation coefficient (Mitchell et al., 1991). The off-shelf and shelf Chl a specific beam attenuation coefficients (c_p^*) of 0.27 and 0.17 (m 2 mg $^{-1}$ Chl a) were very similar to those obtained during the NABE cruises in the North Atlantic (Gardner et al., 1993) at comparable Chl a concentrations. Absorption and scattering coefficients— $a(\text{PAR})$ and $b(\text{PAR})$ —were significantly higher on the shelf, while absolute values were low but similar to coefficients obtained on a clear water New Zealand shelf (Pfannkuche, 2002).

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References

- Balch, W. M., K. A. Kilpatrick & C. C. Trees, 1996a. The 1991 coccolithophore bloom in the central North Atlantic. 1. Optical properties and factors affecting their distribution. *Limnology and Oceanography* 41: 1669–1683.
- Balch, W. M., K. A. Kilpatrick, P. Holligan, D. Harbour & E. Fernandez, 1996b. The 1991 coccolithophore bloom in the Central North Atlantic. 2. Relating optics to coccolith concentration. *Limnology and Oceanography* 41: 1684–1698.
- Bowers, D. G., G. E. L. Harker & B. Stephan, 1996. Absorption spectra of inorganic particles in the Irish Sea and their relevance to remote sensing of chlorophyll. *International Journal of Remote Sensing* 17: 2449–2460.
- Eliassen, S. K., E. Gaard, B. Hansen & K. M. H. Larsen, 2005. A “horizontal Sverdrup mechanism” may control the spring bloom around small oceanic islands and over banks. *Journal of Marine Systems* 56: 352–362.
- Falkowski, P. G. & J. A. Raven, 1997. *Aquatic Photosynthesis*. Blackwell Science, London: 484 pp.
- Fujiku, T. & S. Taguchi, 2002. Variability in chlorophyll a specific absorption coefficient in marine phytoplankton as a function of cell size and irradiance. *Journal of Plankton Research* 24: 859–874.
- Gaard, E., 1999. Zooplankton community structure in relation to its biological and physical environment on the Faroe Shelf, 1989–1997. *Journal of Plankton Research* 21: 1133–1152.
- Gaard, E., B. Hansen, B. Olsen & J. Reinert, 2002. Ecological features and recent trends in the physical environment, plankton, fish stocks, and seabirds in the Faroe shelf ecosystem. In Skjoldal, H. R. & K. Sherman (eds), *Large Marine Ecosystems of the North Atlantic*. Elsevier, Amsterdam: 356 pp.
- Gardner, W. D., I. D. Walsh & M. J. Richardson, 1993. Bio-physical forcing on particle production and distribution during a spring bloom in the North Atlantic. *Deep Sea Research II* 40: 171–195.
- Hansen, B., 1992. Residual and tidal currents on the Faroe Plateau. *ICES CM*, 1992/C:12.
- Hansen, B., S. K. Eliassen, E. Gaard & K. M. H. Larsen, 2005. Climatic effects on plankton and productivity on the Faroe shelf. *ICES Journal of Marine Science* 62: 1224–1232.
- Hemmings, J. C. P., M. A. Srokosz, P. Challenor & M. J. R. Fasham, 2003. Assimilating satellite ocean colour observations into oceanic ecosystem models. *Philosophical Transactions of Royal Society of London: Mathematical, Physical and Engineering Science* 362: 33–39.
- Jerlov, N. G., 1976. *Marine Optics*. Elsevier, Amsterdam: 231 pp.
- Kirk, J. T. O., 1994. *Light and Photosynthesis in the Aquatic Ecosystems*. Cambridge University Press, Cambridge: 401 pp.
- Larsen, K. M. H., B. Hansen, H. Svendsen & K. Simonsen, 2002. The front on the Faroe Shelf. *ICES CM* 2002/P:10, 15 pp.
- Larsen, K. M. H., B. Hansen & H. Svendsen, 2008. Faroe shelf water. *Continental Shelf Water* 28: 1754–1768.
- Lund-Hansen, L. C., 2004. Diffuse attenuation coefficients $K_d(\text{PAR})$ at the estuarine North Sea–Baltic Sea transition: time-series, partitioning, absorption, and scattering. *Estuarine, Coastal and Shelf Science* 62: 251–259.
- Mitchell, B. G., E. A. Brody & O. Holm-Hansen, 1991. Light limitation of phytoplankton biomass and macronutrient utilization in the southern Ocean. *Limnology and Oceanography* 36: 1662–1677.
- Nelson, N. B., D. A. Siegel, C. A. Carlson, C. Swan, W. M. Smethie & S. Khatiwala, 2007. Hydrography of chromophoric dissolved organic matter in the North Atlantic. *Deep Sea Research I* 54: 710–731.
- Pfannkuche, J., 2002. Optical properties of Otago shelf waters: South Island New Zealand. *Estuaries, Coastal and Shelf Science* 55: 613–627.
- Raaphorst, W. V., H. Malschaert, H. V. Haren, W. Boer & G.-J. Brummer, 2001. Cross-slope zonation of erosion and deposition in the Faroe-Shetland channel, North Atlantic Ocean. *Deep-Sea Research I* 48: 567–591.
- Steingrund, P. & E. Gaard, 2005. Relationship between phytoplankton production and cod production on the Faroe Shelf. *ICES Journal of Marine Science* 62: 163–176.
- Strickland, J. D. H. & T. R. Parson, 1972. *A Practical Handbook of Seawater Analyses*, 2nd ed. Bulletin of the Fisheries Research-Board of Canada: Vol. 167, 310 pp.
- Tyler, J. E., 1975. The in situ quantum efficiency of natural phytoplankton populations. *Limnology and Oceanography* 20: 976–980.
- Vant, W. N., 1990. Causes of light attenuation in nine New Zealand. *Estuarine, Coastal and Shelf Science* 31: 125–137.