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Changes in phytoplankton biomass during a period of significant warming in the south-western Norwegian Sea

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Abstract

Chlorophyll and hydrographic conditions were monitored in the southern Norwegian Sea in spring in the period 1991-2008. The area includes two different water masses: warm and saline Atlantic water in the south, separated from colder and less saline Arctic water in the north by the Iceland-Faroe Front (IFF). Our results show that the inter-annual variations in the chl *a* concentration (F_{av}) were similar in both water masses (regression analysis $p < 0.01$) but with consistently higher concentrations in the Arctic water mass north of the IFF. Furthermore the inter-annual variations in density change through the upper 50 m (D_{dif}) were very similar and highly correlated ($p << 0.01$) in both water masses, and a regression analyses confirmed a statistically significant relationship ($p < 0.01$) between the F_{av} and D_{dif} for the Arctic water mass, but not for the Atlantic. Thus stratification is the main controlling factor for the phytoplankton biomass in May, especially in the Arctic water mass north of the IFF. Our results also indicate that stratification is mainly governed by temperature; this is confirmed by a tight relationship between the temperature gradient in the pycnocline and the chl *a* concentration above the pycnocline (F_{apd}), especially in the Arctic water mass to the north of IFF.

Keywords: Chlorophyll, Hydrography, Stratification, Norwegian Sea

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Introduction

The south-western Norwegian Sea is dominated by warm and saline Atlantic water entering the area from south-west, and cold and less saline Arctic water flowing from the north (Hansen and Østerhus, 2000). These two water masses are separated by the Iceland-Faroe Front (hereafter IFF). The area is highly productive and ecologically very important with large and important pelagic fish stocks (e.g. herring, mackerel and blue-whiting) migrating to and through this area during their annual feeding migration in spring and summer. Despite this importance the area is not well studied, leaving a lack of information on both physical and biological parameters and processes.

Oceanographically the area is highly variable with two very different water masses with their own physical and biological characteristics meeting and forming a front. Regarding biological productivity, the area is also highly variable. Satellite images have revealed that the seasonal progression of the phytoplankton primary production in the area varies considerably between different water masses (Fig. 1). The phytoplankton spring bloom usually starts in April in the cold water north of the IFF, and intensifies in May. Then, it decreases again in June and the rest of the year the production is low in this area. South of the IFF and in the Atlantic waters around the Faroe Islands, the development of the bloom is different. Here, the bloom starts in May and then increases during the following 3 months with still some production in September. In the IFF itself the surface chl. *a* is high throughout the productive season.

Possible causes for this annually reappearing progression of primary production in the area are not well understood. Some studies have been published on the physical variability of the IFF itself (e.g. Hansen and Meincke, 1979; Allen et al., 1994) and some biological studies have been done primarily in the Icelandic part of the area (Stefansson and Olafsson, 1991; Gudmundsson, 1998). Additionally, a model experiment from the area was recently published (Popova and Srokosz, 2009). However, detailed studies of the variability and timing of the phytoplankton spring bloom in the area using *in situ* measurements collected on both sides of the IFF are scarce.

Here, we present results from 18 annually repeated surveys (1991 to 2008) to the southwestern Norwegian Sea in May. The results include profiles of chl *a* concentration, temperature, and salinity. These data are used to investigate the difference in phytoplankton biomass between different water masses in May and to relate phytoplankton biomass to stratification. Since some of the water masses in this region have warmed considerably during the survey period (IROC 2007, 2008), it was also hoped that the study could help understand potential effects of climate change on the production in this region.

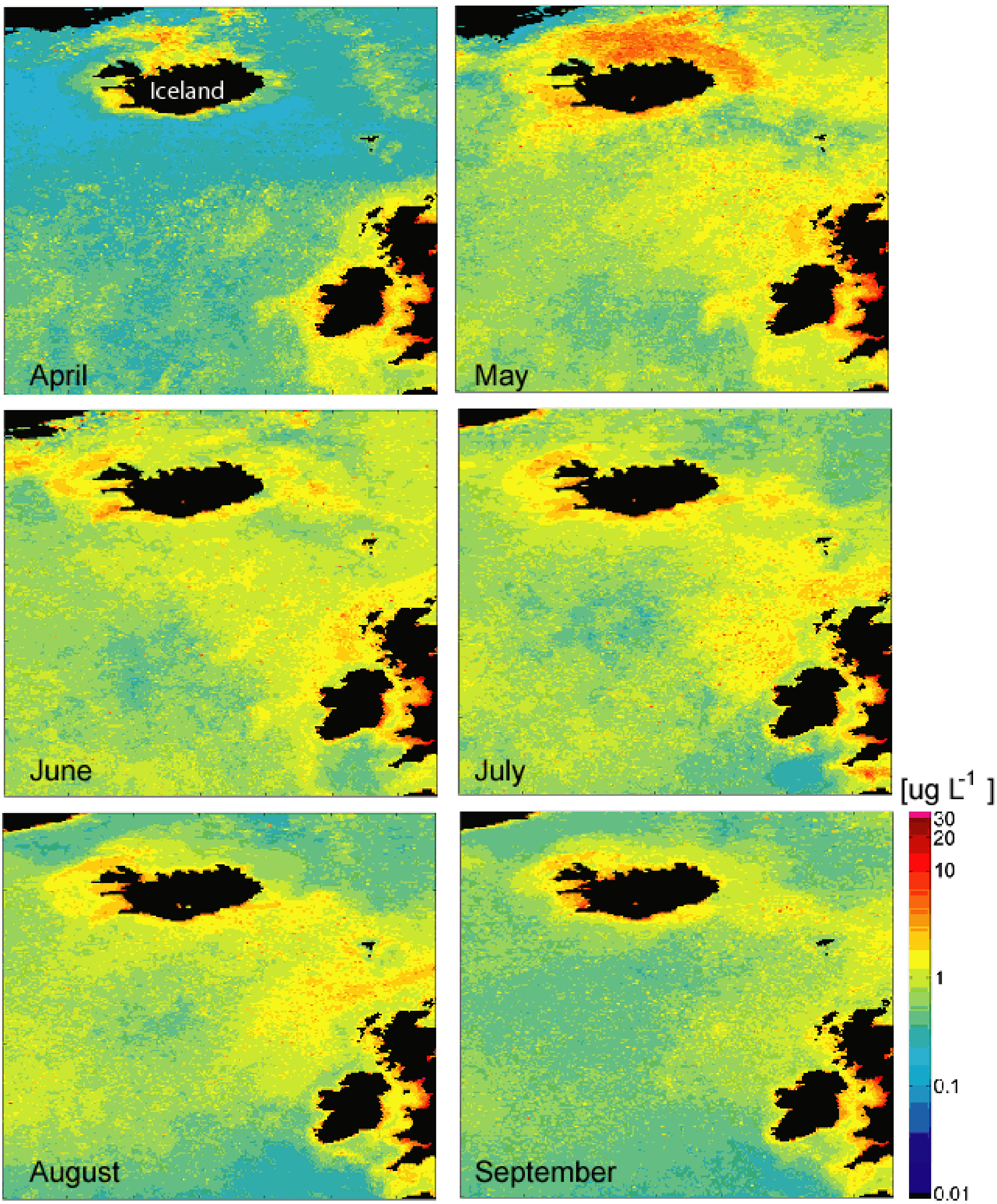

Figure 1. Satellite images of surface chlorophyll from SeaWiFs for the months April through September. Values are averages (μg L^{-1}) for the respective month in the period 1998-2005

Materials and methods

The data were collected in May during the period from 1991 until 2008. The stations occupied have varied slightly from one year to another, but cover approximately the same area with a grid that extends from the northern Faroe shelf into the southern Norwegian Sea. Figure 2 shows the station coverage on a typical year and shows the standard section, which was covered on all the cruises and consists of 14 stations running along 6°05´W, from 62°20´N to 64°30´N.

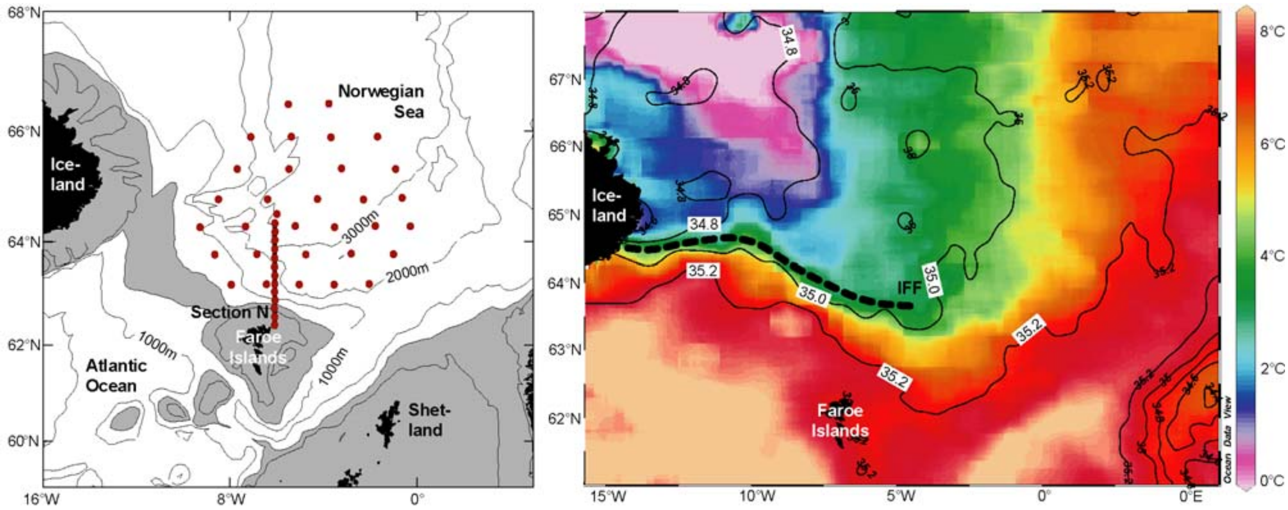

Figure 2. Areal description and observations. Left panel: Bottom topography (gray areas are shallower than 500 m) with red dots showing station coverage in a typical year (2007). Section N is a standard section with 14 CTD stations on a line northwards from the Faroe shelf. Right panel: Typical temperature (background colours with scale shown on the right) and salinity (black lines) distribution at 100 m depth, based on the NISE database (Nilsen et al., 2008). Bold broken line indicates the location of the Iceland-Faroe Front (IFF). Note that the two panels are not in the same geographical projection.

Profiles of temperature and salinity were obtained using a CTD where salinity was calibrated against discrete samples on a salinometer. Fluorescence profiles were obtained from a fluorometer mounted on the CTD and were calibrated against discrete chlorophyll samples measured spectrophotometrically according to Parsons et al. (1984). The fluorescence values are reported as chl *a* concentration in units of μg L^{-1}.

In order to compare results between stations, the following parameters were calculated for each data profile (Table 1).

Table 1. Calculated parameters used for comparing water masses and average values of these for the whole period for the two water masses. In the table, “surface” refers to the shallowest depth measured by the instruments.

Parameter	**Abbreviation**	**Atlantic**	**Arctic**
Average salinity from surface to 50 m	S_{av}	35.20	34.91
Average temperature from surface to 50 m	T_{av}	7.6	4.3
Average fluorescence from surface to 50 m ($\mu g\ L^{-1}$.)	F_{av}	1.6	2.4
Average density from surface to 50 m	D_{av}	27.5	27.7
Difference in salinity between 41-50 and surface-10 m	S_{dif}	-0.008	0.003
Difference in temperature between 41-50 and surface-10 m	T_{dif}	-0.5	-1.3
Difference in density between 41-50 and surface-10 m	D_{dif}	0.07	0.14
Pycnocline depth (m)	P_d	28.4	28.5
Pycnocline thickness (m)	P_t	10.6	9.6
Strength of stratification (°C/m)	Grad	0.036	0.104
Average fluorescence above P_d ($\mu g\ L^{-1}$)	F_{apd}	1.7	3.2

Differences in salinity (S_{dif}), temperature (T_{dif}), and density (D_{dif}) in the top 50 m of the water column are calculated as the average from 41 to 50 m minus the average from the shallowest measurement to 10 m. Pycnocline depth (P_d) is defined as the depth, where density was midway between the average densities at surface to 10 m and 41-50 m, and pycnocline thickness (P_t) is defined as the layer over which density changed by $D_{dif}/2$. The strength of stratification (Grad, in °C/m) is calculated as $(T_{dif})/P_t/2$.

Each station was assigned to a water mass according to its salinity in the top 50 m of the water column. If the salinity was greater than 35.1 the station is assumed to be south of the IFF in the water mass that we term “Atlantic water”. If the salinity was less than 35.0 it is assumed to be north of the front in what is termed “Arctic water”. In the following, we present results for these two water masses by calculating the parameters in Table 1 for each year as averages of all stations within the water masses that year.

Results

The temperature and salinity distributions from the CTD surveys follow the generally accepted pattern in the region (Hansen and Østerhus, 2000), with the warm and saline Atlantic water dominating the southeastern part of the survey area and colder and less saline Arctic water in the northwestern part. This is illustrated in the examples on Figures 2 and 3 and is also reflected in Table 1 and the time series of T_{av} and S_{av} (Fig. 4d, e). In spite of the reported warming in this region since 1995 (IROC 2007, 2008), no consistent trends are seen in the T_{av} time series from the two water masses (Fig. 4d). For salinity, the Atlantic water mass does seem to have had a salinity increase in the upper 50 m, as reported (IROC 2007, 2008), but no consistent trend is seen for the S_{av} of the Arctic water (Fig. 4e).

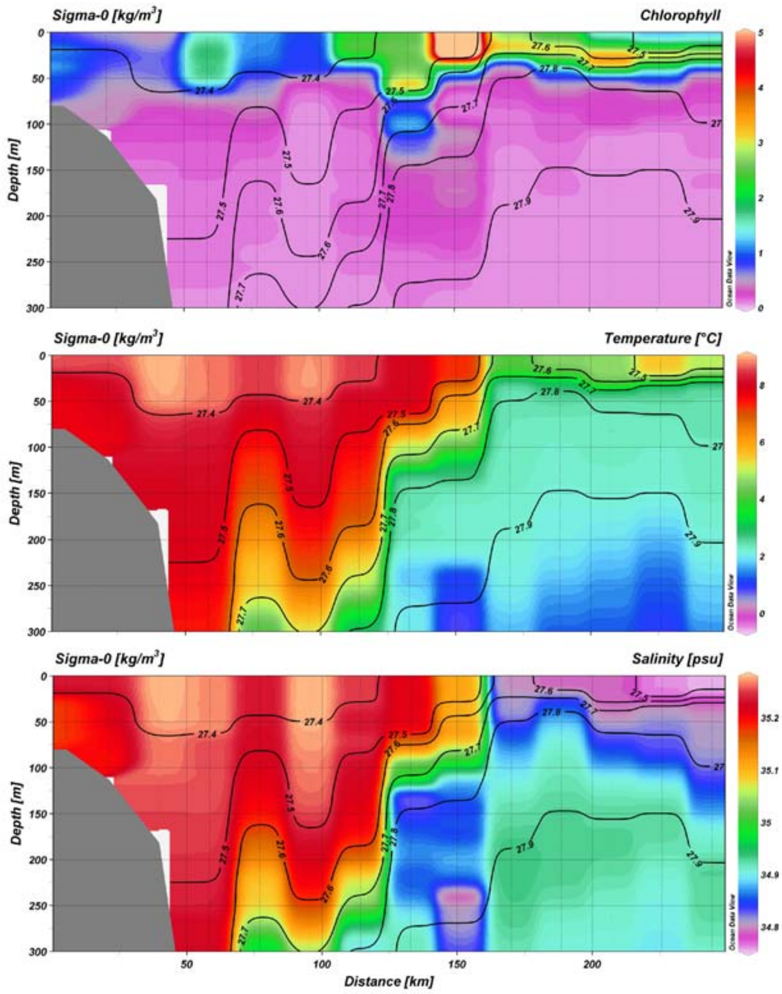

Figure 3. Chlorophyll *a* (top panel), temperature (middle panel), and salinity (bottom panel) with isopycnals shown on all panels in the upper 300 m on transect N (Figure 2) in May 1998.

The temperature change through the uppermost 50 m (T_{dif}) was consistently higher in the colder water mass (Table 1). On average, T_{dif} was 1.3°C north in the Arctic water and 0.5°C in the Atlantic water. The same pattern but to a much less degree is seen in the salinity difference (S_{dif}). Although the variability was high, the surface layer was generally fresher than at 50m depth in the Arctic water. In the Atlantic water, the general picture was opposite (Table 1).

The average chl *a* concentration in the top 50 m of the water column was consistently higher in the Arctic water mass north of the IFF compared with the Atlantic water to the south (Fig. 4). For the whole period, the average chl *a* concentrations in the two water masses were 2.4 μg L^{-1} and 1.6 μg L^{-1}, respectively. Averaging the chl *a* concentration in the water column above the pycnocline depth only, increases the values slightly to an average of 2.7 μg L^{-1} and 1.7 μg L^{-1}, respectively, but the general pattern is the same with consistently higher values north of the front (Fig. 4). The same pattern is observed in the density change through the upper 50 m (D_{dif}) (Fig. 4), with higher values in the Arctic water mass to the north of the IFF during the period except for 2004.

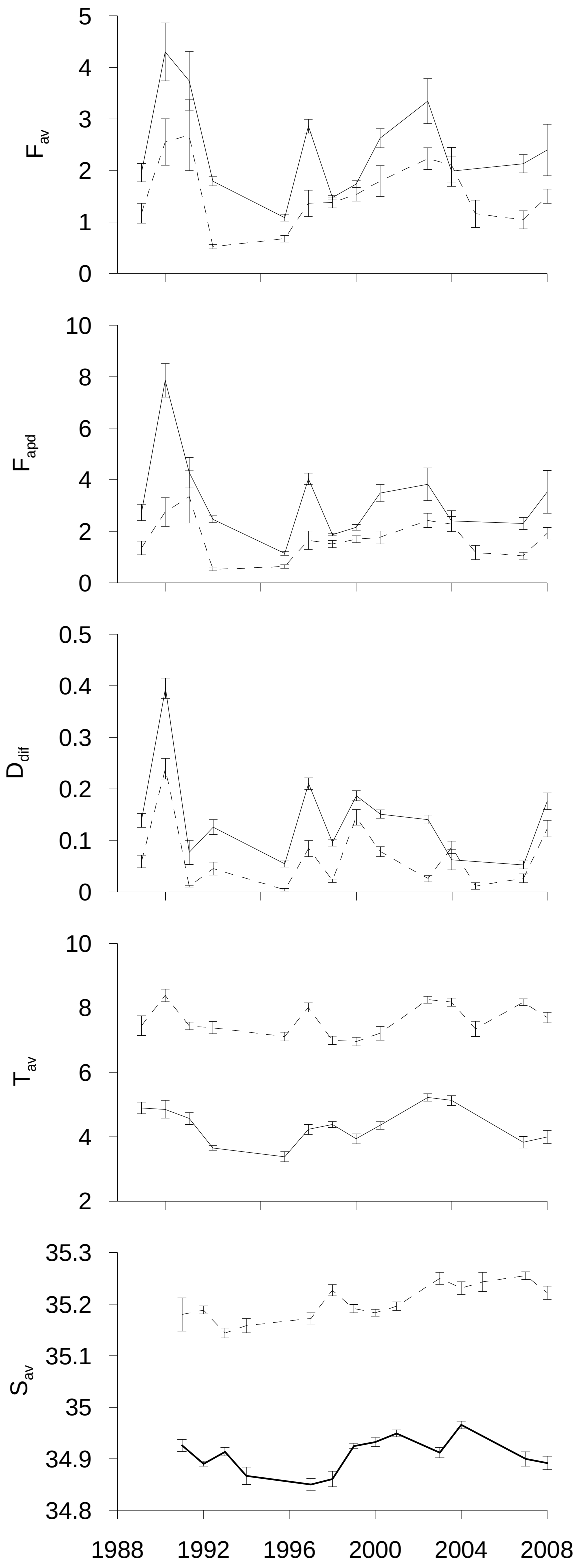

Figure 4. Time series May 1991-2008. a) Average chlorophyll *a* concentration in the upper 50 m (F_{av}). b) Average chlorophyll *a* concentration above the pycnocline (F_{apd}). c) Density change through the upper 50 m (D_{dif}). d) Average temperature in the upper 50 m (T_{av}). e) Average salinity in the upper 50 m (S_{av}). Continuous lines: Arctic water, broken lines: Atlantic water.

Discussion

Throughout the survey period 1991-2008, the results clearly show that the chl *a* concentrations were consistently higher in the Arctic water mass north of the Iceland-Faroe Front (IFF) compared to the warmer and more saline Atlantic water mass south of it. From Figure 3a, the inter-annual variations in the chl *a* concentration look very similar in both water masses and a regression analysis confirms that there is a statistically significant ($p < 0.01$) relationship (Fig. 5):

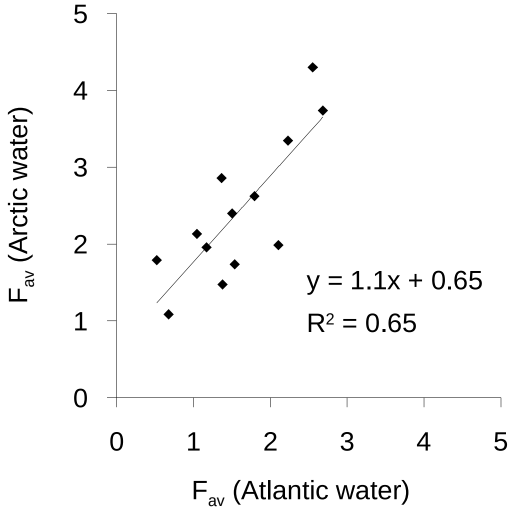

Figure 5. Relationship between mean chlorophyll *a* concentrations in the upper 50 m south and north of the IFF, respectively, in May 1991-2008.

The panels in Figure 4 also show very similar inter-annual variations of chlorophyll *a* concentrations and the density change through the upper 50 m (D_{dif}) and regression analyses confirm a statistically significant relationship ($p < 0.01$) for the Arctic water, but not for the Atlantic. This picture becomes even clearer if the chlorophyll *a* concentration is averaged only for the water above the pycnocline (Fig. 6).

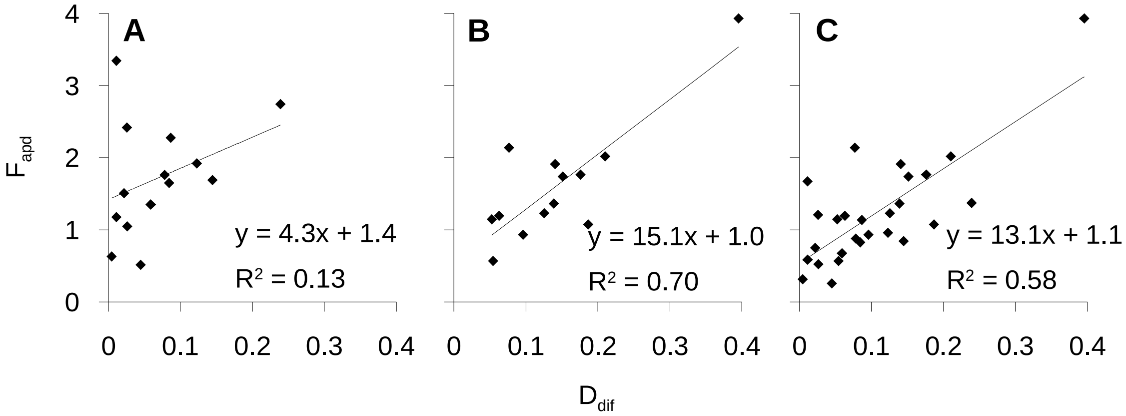

Figure 6. Relationships between mean chlorophyll *a* concentrations above the pycnocline (F_{apd}) and the density change through the upper 50 m (D_{dif}) for the two water masses separately and together. Atlantic water (A), Arctic water (B), both water masses together (C).

This implies that the stratification is one of the main controlling factors for the phytoplankton biomass in May, as might have been expected this early in the production cycle. To a large extent, this can also explain the relationship between chlorophyll *a* concentrations in both water masses (Fig. 5), as can be seen by comparing the stratification (D_{dif}) in both water masses (Fig. 7c).

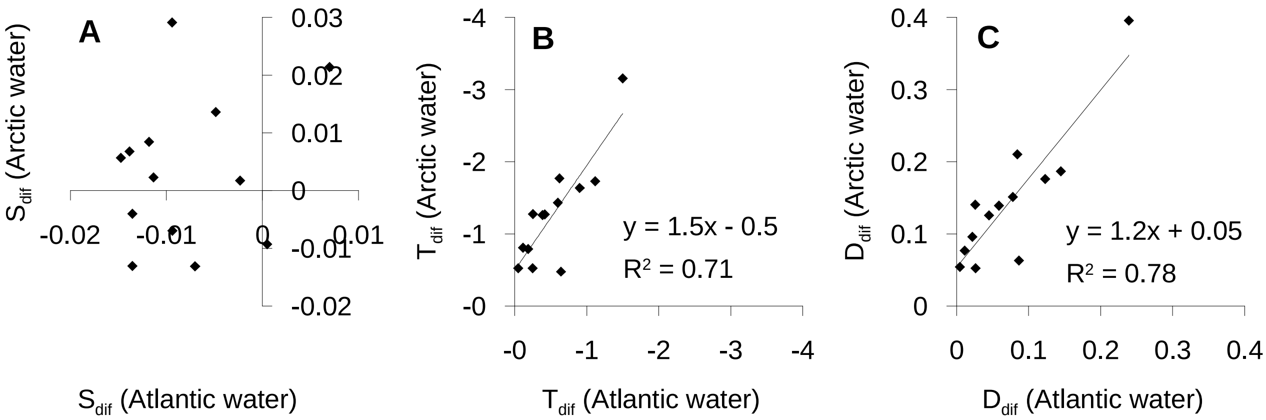

Figure 7. Relationship between differences in surface and 50 m depth in salinity (A), temperature (B), and density (C) north and south of IFF per year in May 1991-2008.

There is a tight and highly significant ($p << 0.01$) relationship between the stratification in both water masses:

$$D_{dif\,(Arctic)} = 1.2\, D_{dif\,(Atlantic)} + 0.05 \; ; \; (R^2 = 0.78)$$

Together with the relationship in Figure 6, this can explain both the higher chlorophyll *a* concentrations in the Arctic water mass and the large similarity between the inter-annual variations of chlorophyll *a* concentrations in both water masses (Fig. 5). Figure 7 also indicates that temperature may be more important for the stratification than salinity and to some extent this is confirmed by considering the distribution of stations (Fig. 8) in each water mass, classed according to the fraction of density change that is due to temperature, which is defined as:

$$\frac{\sigma_t(t_{45}, s_{45}) - \sigma_t(t_5, s_{45})}{\sigma_t(t_{45}, s_{45}) - \sigma_t(t_5, s_5)} \cdot 100$$

where t_5 and s_5 are temperature and salinity averaged between the surface and 10 m, etc.

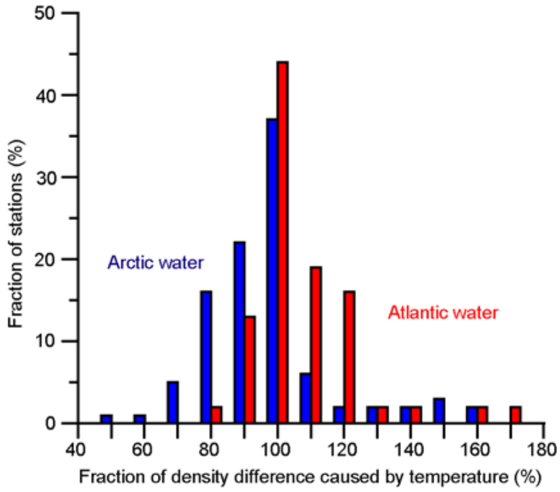

Figure 8. The frequency distribution of stations within each water mass classed according to the fraction of density difference through the upper 50 m (D_{dif}) that was caused by temperature. Fractions larger than 100% along the abscissa occur when salinity decreases with depth.

The importance of temperature stratification for the primary production may be further studied by relating the chlorophyll *a* concentration to the temperature gradient in the pycnocline (Grad, see materials and methods). The result (Fig. 9) confirms that temperature stratification is especially important north of the front.

This might appear somewhat in conflict with the statement by Popova and Srokosz (2009) that low-saline Arctic surface water reduces mixed layer depth considerably to the north of the IFF, indicating that this may be the mechanism for the earlier initiation of the phytoplankton bloom in the water mass. The process of stratification is, however, highly nonlinear and pre-stratification by salinity may well be important in the initial formation of the pycnocline although temperature dominates during the survey time in May. With the present data set, alone, we can not resolve this question, but the similarity between the temperature stratification in both water masses (Fig. 7) may indicate that the air-sea heat flux before and during each survey may be of large importance for the development of the stratification and the primary production.

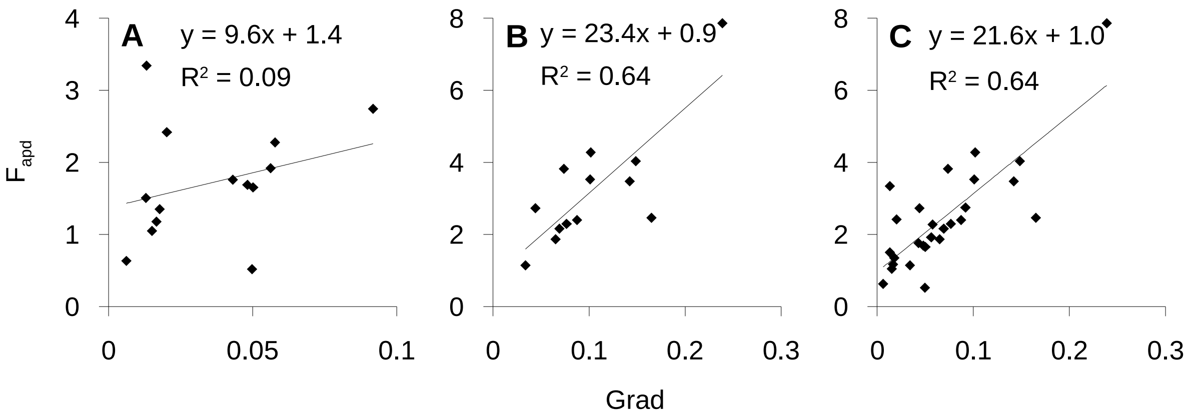

Figure 9. Relationship between stratification strength and mean chlorophyll *a* concentration above the pycnocline depth (F_{apd}) in the Atlantic (A), Arctic (B), and both water masses (C).

One of the original aims of this study was to see the response of the primary production to warming and, hence, to climate change. As shown in the results (Fig. 3d), the surface-near waters do not, however, indicate any systematic warming. It seems likely that the future development of the air-sea heat flux will be important for the primary production, perhaps especially in the Arctic water mass, but more detailed studies will be required to clarify this.

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