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On the nature of the factors that control spring bloom development at the entrance to the Barents Sea and their interannual variability

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Analysis of data obtained by the Institute of Marine Research, Norway, at their regular surveys of the Fugløya-Bjørnøya section, between the northern tip of Norway and Bear Island, has allowed for an identification of the factors that control spring bloom development in the region, and their interannual variability. In the southern part of the section the bloom starts as the waters become stratified due to a northward spreading of low salinity water from the Norwegian Coastal Current. In the middle part of the section the bloom is initiated when vernal stratification develops due to heating of the ocean surface, and the bloom may develop in either of two directions throughout summer, depending on the prevailing atmospheric pressure gradient over the region. A north to south high to low pressure gradient will direct surface winds to the west. Ekman drift will then be to the north and a wedge of low salinity, low nutrient water will spread out over the region, leading to the termination of the bloom. When the pressure gradient is reversed, winds will blow to the east and intrusion of fresh water into the region will be limited. In these years the bloom appears to follow a classical Atlantic pattern, unable to fully utilize available nitrate and probably terminated due to extensive grazing. The central part of the Barents Sea Opening is thus yet another northern high latitude region where the bloom is subject to substantial interannual variations, potentially affecting higher trophic levels.

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INTRODUCTION

The Greenland, Iceland, and Norwegian Seas, collectively known as the Nordic Seas, are, along with adjacent ocean regions such as the Barents Sea, sites of extensive primary production sustaining the large fisheries in parts of the region. Additionally, some of the organic matter produced in the upper layers is exported to the abyssal ocean and sea-bed, resulting in a semi-permanent or permanent removal of carbon dioxide from the atmosphere. The size of this flux, known as export production, may exhibit large temporal and spatial variability, being affected by among other things grazing pressure and the rate of biomass accumulation (Wassmann & al. 1991; Wassmann 1998; Noji & al. 1999).

Primary production in the upper layers is associated with the occurrence of the spring bloom, which is triggered by the rapid increase in ambient light and the formation of a shallow surface mixed layer (SML) during spring (Sverdrup 1953). The vernal stratification of the Nordic and Barents Seas is mainly a consequence of the increase in solar heating of surface waters and, in regions seasonally covered by sea ice, the presence of melt water (Rey & Loeng 1985). Additionally, along the coast of Norway the bloom may start following increased vertical stability caused by the lateral spreading of coastal water (CW) from the Norwegian Coastal Current as shown by Rey (1981). The lateral spreading of CW is a recurrent summer phenomenon along the coast of Norway. It is caused by the monsoon-like seasonal shifts of surface winds in the region. During winter, southerly winds prevail. These are directed by a high pressure system located over Scandinavia and a low pressure system over the Norwegian Sea. During summer the pressure gradient is reversed leading to the prevalence of northerly winds. Therefore, during winter an Ekman drift towards the coast is established, pushing the Norwegian Coastal Current onshore. During summer, however, an offshore Ekman drift is established and low salinity CW is deflected east, ending up as a wedge overlying the high salinity Atlantic waters (AW) of the Norwegian Atlantic Current (Gade 1986; Sætre & al. 1988). As shown by Rey (1981), a wedge of CW or mixed CW and AW may extend over 100–150 km out from the

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Norwegian coast, and may occasionally reach as far out as to Ocean Weather Station M at 66°N 2°E (Halldal 1953; Helland 1963).

The timing and development of the spring bloom may exhibit large interannual variations, particularly in regions subject to interannual variations in sea ice cover. This is, for instance, the case in the Barents Sea south of the polar front. This region is dominated by AW and vernal stratification develops slowly with warming of surface layers. However, the sea ice cover extent in the Barents Sea, which is confined to the north of the polar front, can exhibit large interannual variations, so that when the ice has a large southern extent, sea ice can drift across the polar front and melt in the AW. This causes stratification to develop much more rapidly than due to heating, and a more rapid and intense spring bloom develops (Rey & al. 1987; Olsen & al. 2002a), with consequences for export production (Slagstad & Wassmann 1996). Further south, in the open ocean regions of the Nordic Seas, where stratification develops due to heating of the ocean surface, interannual variations in spring bloom development will probably follow from differential input of heat. This subject has, however, not been extensively treated in the literature. Such a study is likely to be complicated by the varying temperatures of the water feeding the Nordic Seas (Furevik 2001) and varying influence of polar waters (Blindheim & al. 2000). Additionally, the effect of surface wind speed on the mixed layer depth (MLD) must be taken into consideration (Sakshaug & al. 1995), as must also interannual variations in grazing pressure.

The current paper concentrates on the third mode of water column stabilization, namely offshore spreading of CW and how this may vary from one year to another, leading to interannual variations in spring bloom development. The opportunity to study this phenomenon is furnished by the existence of a nearly 10 year long time series of nutrient concentrations in the Barents Sea Opening, running from 1990 to 1999. These data have been acquired by the Institute of Marine Research (IMR) at routine surveys of the Fugløya-Bjørnøya (FB) section, located between Norway and Bear Island (Fig. 1). In this paper we will use these data to study annual and interannual variations in nitrate concentrations and how these relate to the SML properties depth, tempera-

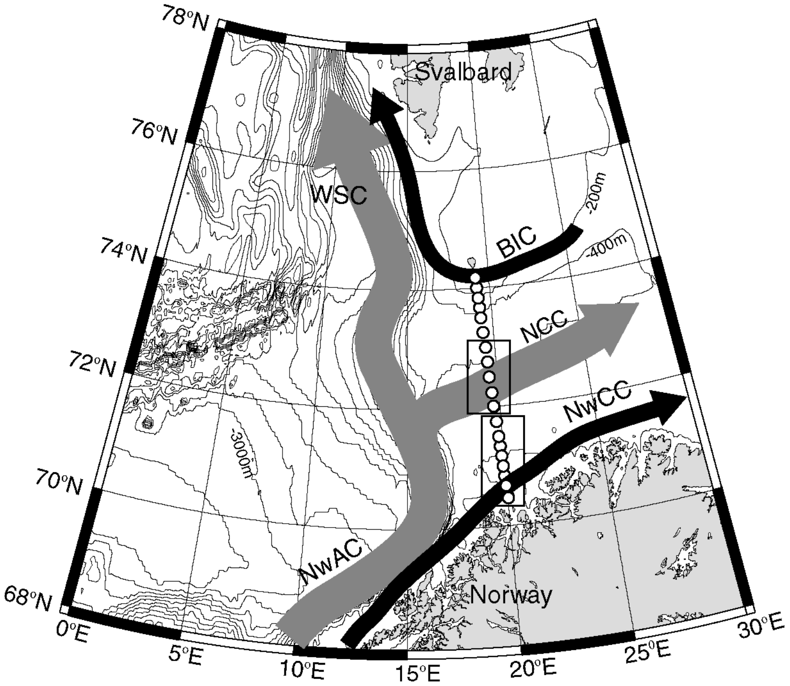


Fig. 1. Map of the Barents Sea Opening. Grey arrows illustrate the flow of relatively salty North Atlantic water, black arrows illustrate the flow of relatively fresh polar or coastal water. Hollow circles indicate the station positions in the Fugløya-Bjørnøya section. The rectangles indicate the middle and southern stations used in this study. BIC – Bear Island Current; NCC – North Cape Current; NwAC – Norwegian Atlantic Current; NwCC – Norwegian Coastal Current; WSC – West Spitsbergen Current.

ture and salinity in the region. Salinity is the chief parameter supplying information on the presence of CW as this water mass is of relatively low salinity (<34.7; Loeng 1991) compared with the AW in this region, which is normally defined by having a salinity above 34.95. Nitrate is used as an indicator of bloom development. The other major nutrients (phosphate and silicate) showed the same pattern of variability.

Furthermore, the nutrient time series is just part of a longer and spatially and temporally more coherent measurement programme of temperature and salinity at the FB section. Therefore, we completed and extended the time series of these two parameters back in time, to 1976, which allowed us to ground truth and expand our findings on the factors that govern the development of the SML during summer in this region.

DATA AND METHODS

This work is based on data obtained by the IMR through repeated visits to the FB section (Fig. 1). The section covers three hydrographic domains, and for the present purpose data selection has been confined to south of 73°N to avoid the influence of polar water. Furthermore, because the presence of CW is expected to vary with latitude, we have split the region in two and analysed data from the middle, Atlantic part (defined here as 72–73°N), and the southern part (70.5–71.75°N) of the FB section separately.

We have used data from the 1990s for the analysis of seasonal and interannual variability in nitrate concentrations in relation to physical hydrographical conditions, and only data from stations where a complete set of measurements have been carried out, i.e. of nitrate, temperature and salinity. The spatial and temporal distribution of these stations is depicted in Fig. 2. These data were obtained from the IMR; details of the measurement protocol are given in Olsen & al. (2002b).

The time series shown in Fig. 2 is rather short and also not spatially homogenous, mainly due to a lack of nitrate measurements. Therefore, to substantiate and extend the information provided by these data on the factors that govern SML development in the region, we completed and extended the temperature and salinity time series from the FB section back in time. We used data from all stations visited during the 1990s where

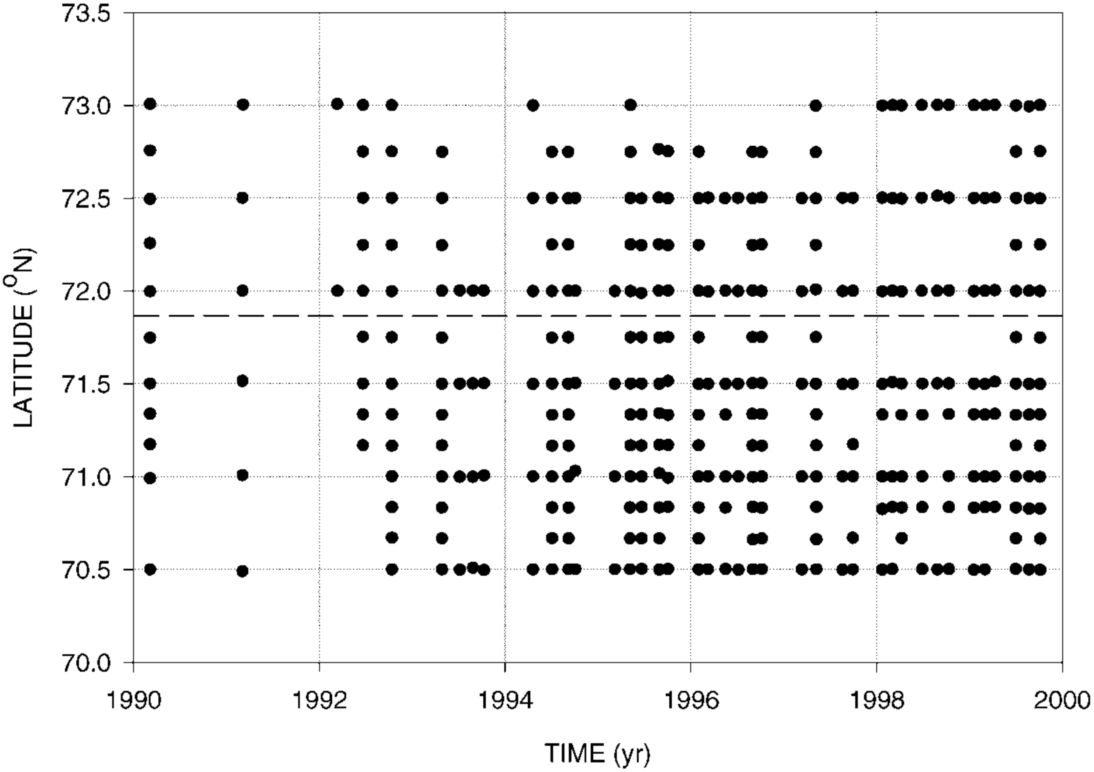


Fig. 2. Time–latitude distribution of the stations included in the nutrient time series.

hydrographic measurements have been carried out. In addition we extended the time series back in time to 1976. The data covering the pre-1990 period were provided by ICES, but originate ultimately from the IMR. The spatial and temporal distribution of the stations included in the completed and extended temperature and salinity time series is shown in Fig. 3. Please note that for this time series we have restricted data selection to summer, which is the season of interest. The FB section has been visited twice each summer since 1976, once in June/July and once in August/September covering the bloom and post-bloom phase of phytoplankton development, respectively.

Data for sea level pressure (SLP) and directional components of wind strength have also been used in this study. These data originate from the NCEP/NCAR project (Kalnay & al. 1996) and were obtained from the NOAA-CIRES Climate Diagnostics Centre (Boulder, Colorado, USA) through their web site (http://www.cdc.noaa.gov). Data for net short wave radiation at the surface (NSWRS), a measure of solar heat input, were obtained from the IRI/LDEO Climate Data Library (http://ingrid.ldeo.columbia.edu/) and also originate from the NCEP/NCAR reanalysis project.

MLD was identified as the depth at which a density difference of 0.125 kg m^{-3} as compared with the surface value was found. For a vertically homogenous water column, the MLD was defined as 250 m.

Throughout this paper we present average values of SML characteristics in either the southern or middle part of the FB section, whose geographical extent has been defined above. This implies that we have first averaged values over the SML at each station. These depth averaged values have then been averaged over either the middle or southern group of stations visited on each cruise. Average values of temperature, salinity and nitrate in the SML (A) at each station were computed according to:

$$A = \frac{1}{\mathrm{MLD}} \sum_{i=1}^{\mathrm{MLD}} a_i$$

where a_i is the value within each cubic metre. Linear interpolation was used between sampling depths.

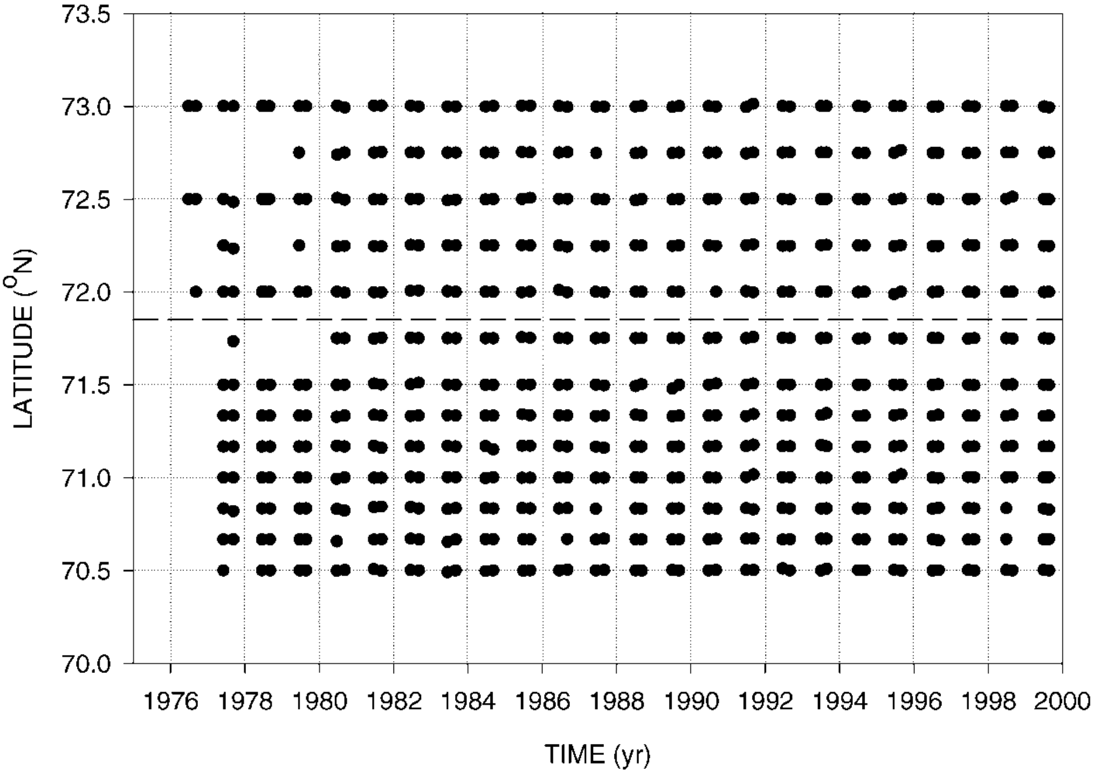


Fig. 3. Time–latitude distribution of the stations included in the completed and extended time series of temperature and salinity.

RESULTS

The seasonal development of average MLD and the average temperature, salinity and concentration of nitrate in the SML in the southern part of the FB section are shown in Fig. 4, where averaged data from the southern group of stations from all the years of the time series have been combined on a single time axis. The seasonality in the data is obvious and highly recurrent, and the cruises have evidently been carried out at four stages of phytoplankton development. Until day 150 a winter situation prevails, characterized by a fairly homogenous water column and high concentrations of nitrate. In the period between days 150 and 200 we recognize bloom conditions, when a shallow SML has been formed and concentrations of nitrate have started to decrease. The lowest concentration of nitrate is reached during the post-bloom period, between days 200 and 250. After this, moving into fall, the erosion of the SML starts, which will ultimately lead back to winter conditions again. The shoaling of the SML moving from winter into the bloom period is accompanied by both a drop in salinity and a rise in temperatures. This indicates that the change in MLD is caused by a northward spreading of low salinity, relatively warm waters from the Norwegian Coastal Current. There is only a slight drop in salinity on entering the post-bloom period, temperatures, however, peak during this period. These latter features indicate that heating is important for determining the evolution of the SML moving from the bloom to the post-bloom period.

The seasonal development of average MLD and average temperature, salinity and nitrate concentrations in the SML in the middle part of the FB section are depicted in Fig. 5. The data originate from the same cruises as the data shown in Fig. 4, and a similar seasonal pattern is recognized with winter, bloom, post-bloom and fall periods occurring in the same time intervals. The salinity in the SML in this region is generally higher as compared with the southern part, as it is more dominated by AW. We also see that winter-time nitrate concentrations are 1–2 μmol l^{-1} higher. The main difference between the seasonal development in the middle as compared with the southern part is that the shallow SML observed during bloom in the middle part does not appear to be a consequence of the freshening of surface waters as salinities generally drop only slightly. The temperature in the SML has, however, risen, and these features indicate that surface stratification during spring in the middle part of the FB section is not caused by admixture of CW as in the southern part, but rather occurs due to heating. Later,

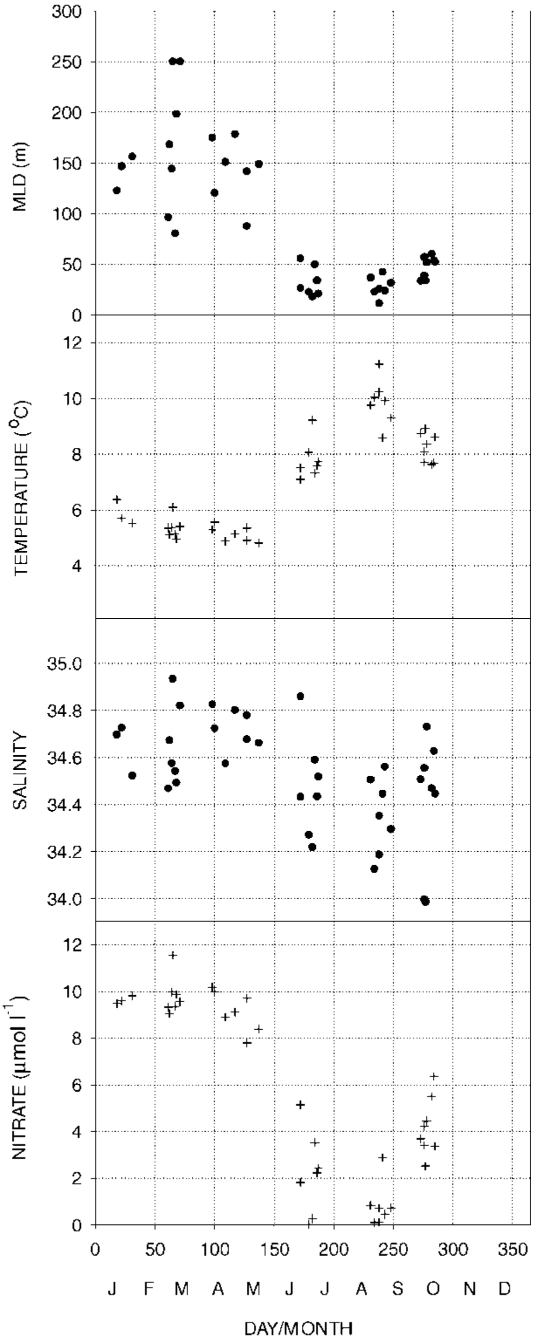


Fig. 4. The average mixed layer depth and the average temperature, salinity and concentration of nitrate in the surface mixed layer in the southern part of the Fugløya-Bjørnøya section plotted as a function of the day of measurement.

however, into the post-bloom period, CW mixes into the SML in the middle part also, as is evident from the drop in salinity that occurs as we enter this period.

Figure 6 shows the time series of average MLD and average temperature, salinity and concentration of nitrate in the SML in the southern part of the FB section, as observed at cruises carried out during the bloom (Fig. 6a) and post-bloom (Fig. 6b) periods, defined above. The MLD correlates well with temperature, salinity and nitrate during both seasons. The SML becomes shallower with increasing temperatures and decreasing salinity. The strong relationship between MLD and salinity during the bloom period indicates that admixture of CW is important for setting the MLD in this period. The development of the SML moving from bloom to post-bloom is apparently more influenced by heat input, as seen with the relaxed correlation with salinity and the strengthened correlation with temperature. These findings confirm those deduced from Fig. 4. Nitrate concentrations depend strongly on MLD, with decreasing concentrations of nitrate in the SML as it shoals. However, because the SML becomes more or less depleted of nitrate each summer, the relationship becomes weaker moving from bloom into post-bloom conditions.

Figure 7(a and b) shows the time series of average MLD and average temperature, salinity and concentration of nitrate in the SML in the middle part of the FB section during the bloom and the post-bloom period, respectively. The pattern of covariance between MLD and temperature, salinity and nitrate is similar to that observed in the southern part of the FB section. There are, however, some differences in the strength of the correlations and their seasonal changes. Temperature is equally important during both the bloom and the post-bloom period. Salinity on the other hand is not related to MLD at all during the bloom season, and the relationship between these two parameters is furthermore quite weak during the post-bloom season. However, the lack of covariation during the post-bloom season is only due to the conditions in 1999 when the SML was relatively shallow despite high salinities; excluding this year from the regression results in a correlation coefficient of 0.95. It appears, therefore, that the vernal stratification in the middle part of the FB section is a result of the heating of surface waters. Throughout summer, however, northward spreading of CW does give rise to a fairly shallow SML, as especially seen in 1993 and 1998. The exceptional 1999 situation is probably due to the extraordinarily nice weather conditions in June of this year, when record high air temperatures were reached at Bear Island, approximately 2.5°C above the 1975–1999 mean (according to station data obtained from the

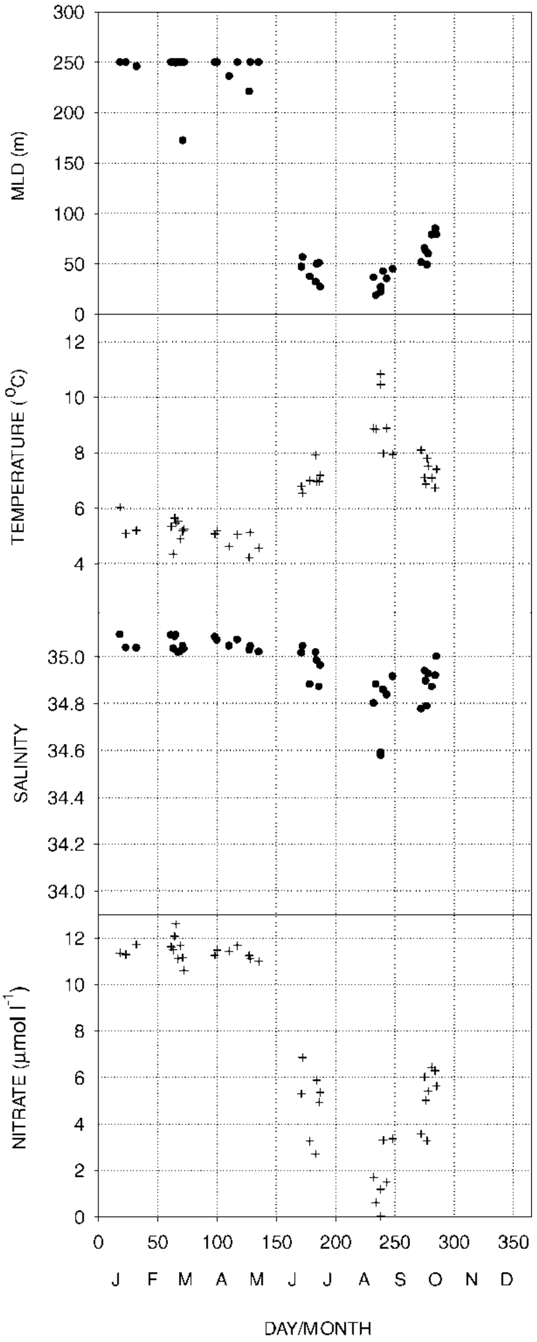
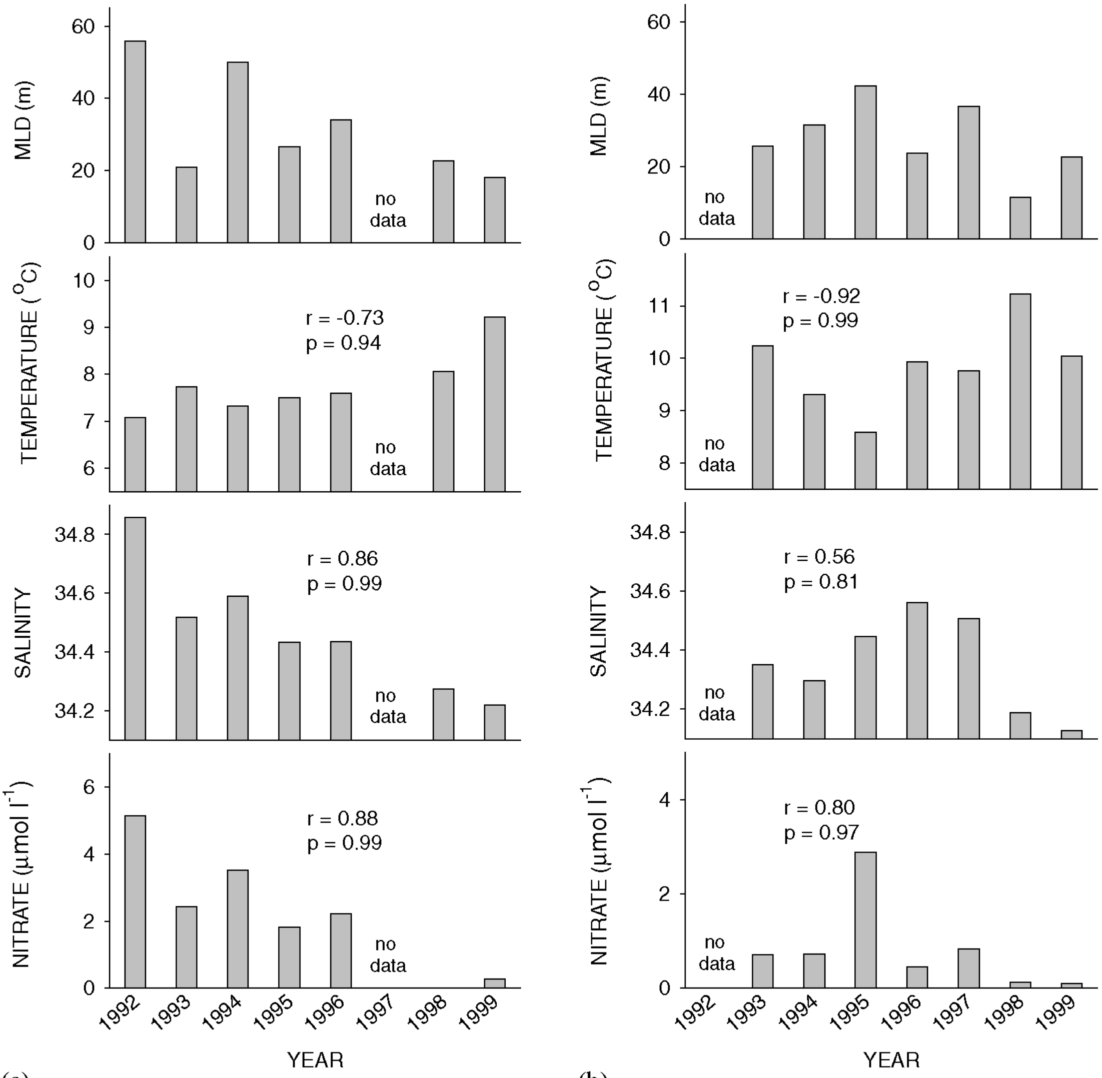


Fig. 5. The average mixed layer depth and the average temperature, salinity and concentration of nitrate in the surface mixed layer in the middle part of the Fugløya-Bjørnøya section plotted as a function of the day of measurement.

Norwegian Meteorological Institute). We believe that these favourable weather conditions gave rise to the very warm, salty and shallow SML observed at the bloom cruise (Fig. 7a) and that this SML remained more or less unchanged over summer and into the post-bloom period. As for nitrate, the seasonal evolution of the correlation with MLD is opposite to that observed in the southern part of the FB section; strengthening over summer. It appears, therefore, that the MLD is not the sole factor controlling the rate of nitrate consumption early in summer. It is furthermore evident, from the post-bloom data, that the bloom does not always deplete the SML of nitrate, that occurs only in years when the SML is relatively shallow. We do not, therefore, see a weakening of the relationship between MLD and nitrate concentration over summer as in the southern part, but rather a strengthening as full utilization of nitrate is dependent on a shallow SML.



(a) (b)

Fig. 6. Time series of the average mixed layer depth and the average temperature, salinity and nitrate in the mixed layer as observed in the southern part of the Fugløya-Bjørnøya section, at cruises carried out during the bloom (a) and post-bloom (b) periods. The regression diagnostics (r and p values) given in each panel are for the linear regression between the respective parameter and mixed layer depth.

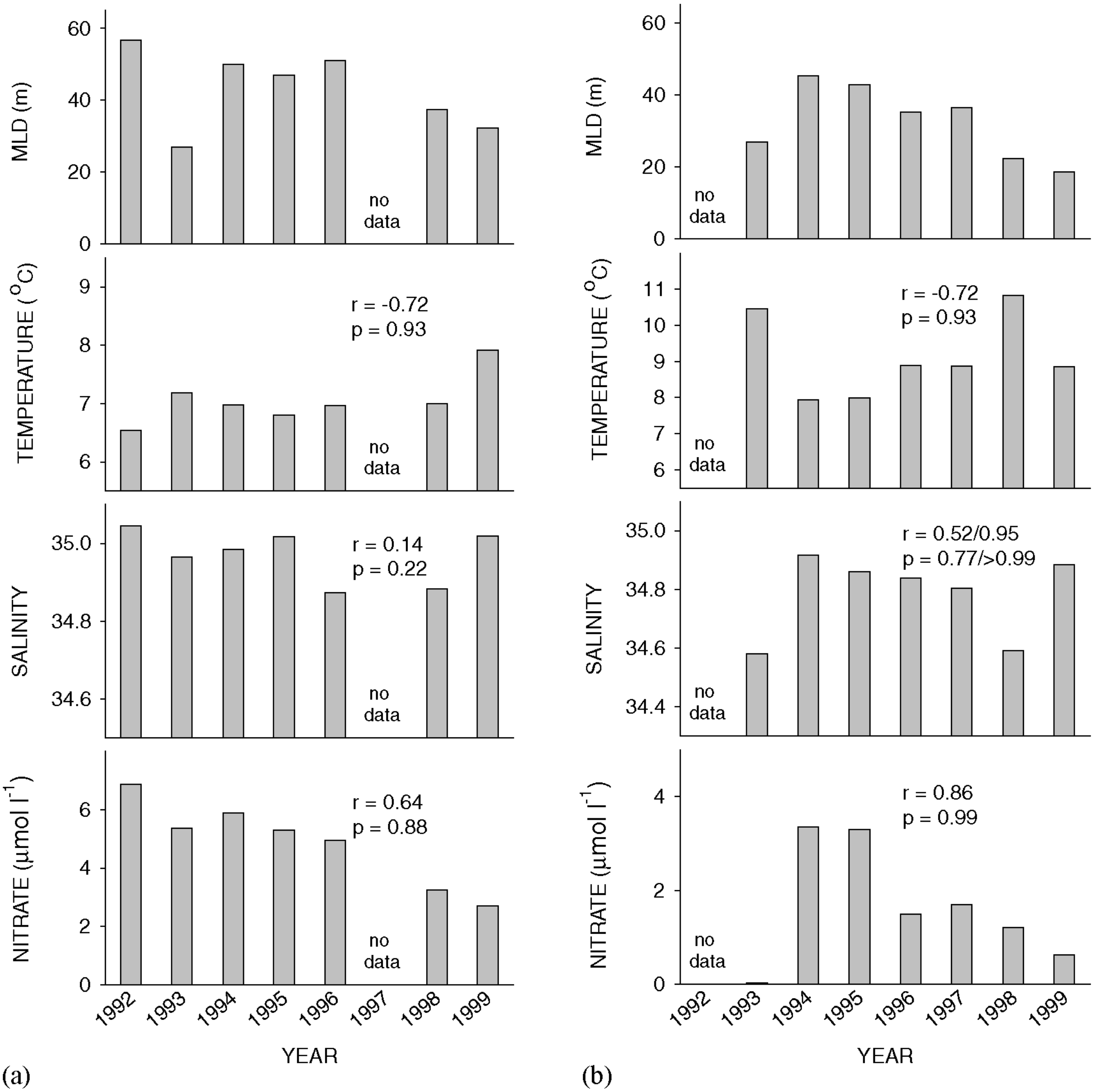
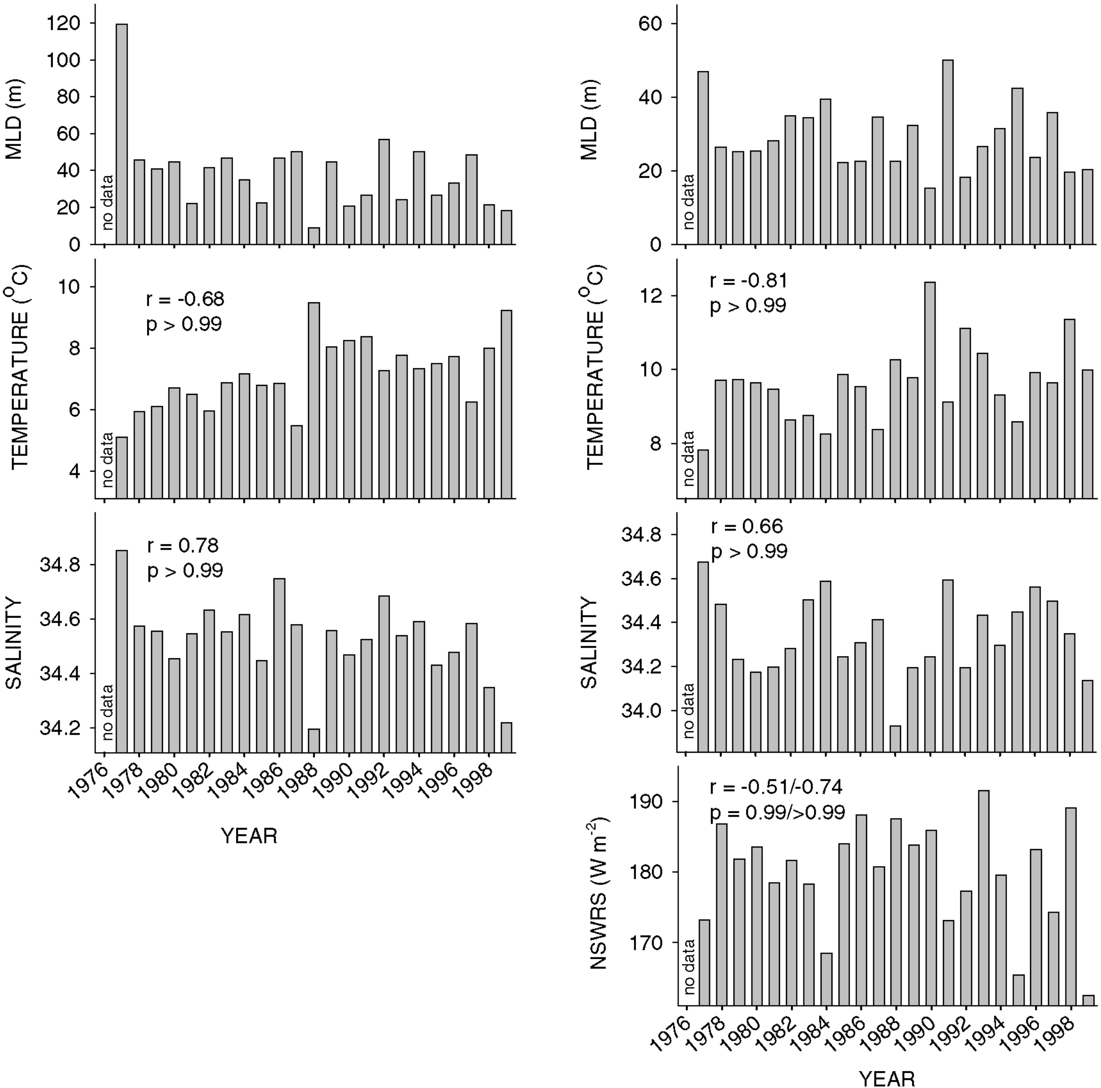


Fig. 7. Time series of the average mixed layer depth and the average temperature, salinity and nitrate in the mixed layer as observed in the middle part of the Fugløya-Bjørnøya section, at cruises carried out during the bloom (a) and post-bloom (b) periods. The regression diagnostics (r and p values) given in each panel are for the linear regression between the respective parameter and mixed layer depth.

To substantiate and extend the findings on the factors that determine the MLD in summer we now move over to the data from the completed and extended time series shown in Fig. 3. Figure 8(a and b) shows the extended time series of the average MLD and the average temperature and salinity in the SML in the southern part of the FB section during the bloom and post-bloom seasons, respectively. In Fig. 8b we have also plotted the average July–August NSWRS in the grid point 71.4°N 20.6°E. This is a measure of the solar heat input to the region, positive numbers reflect a heat flux into the ocean.

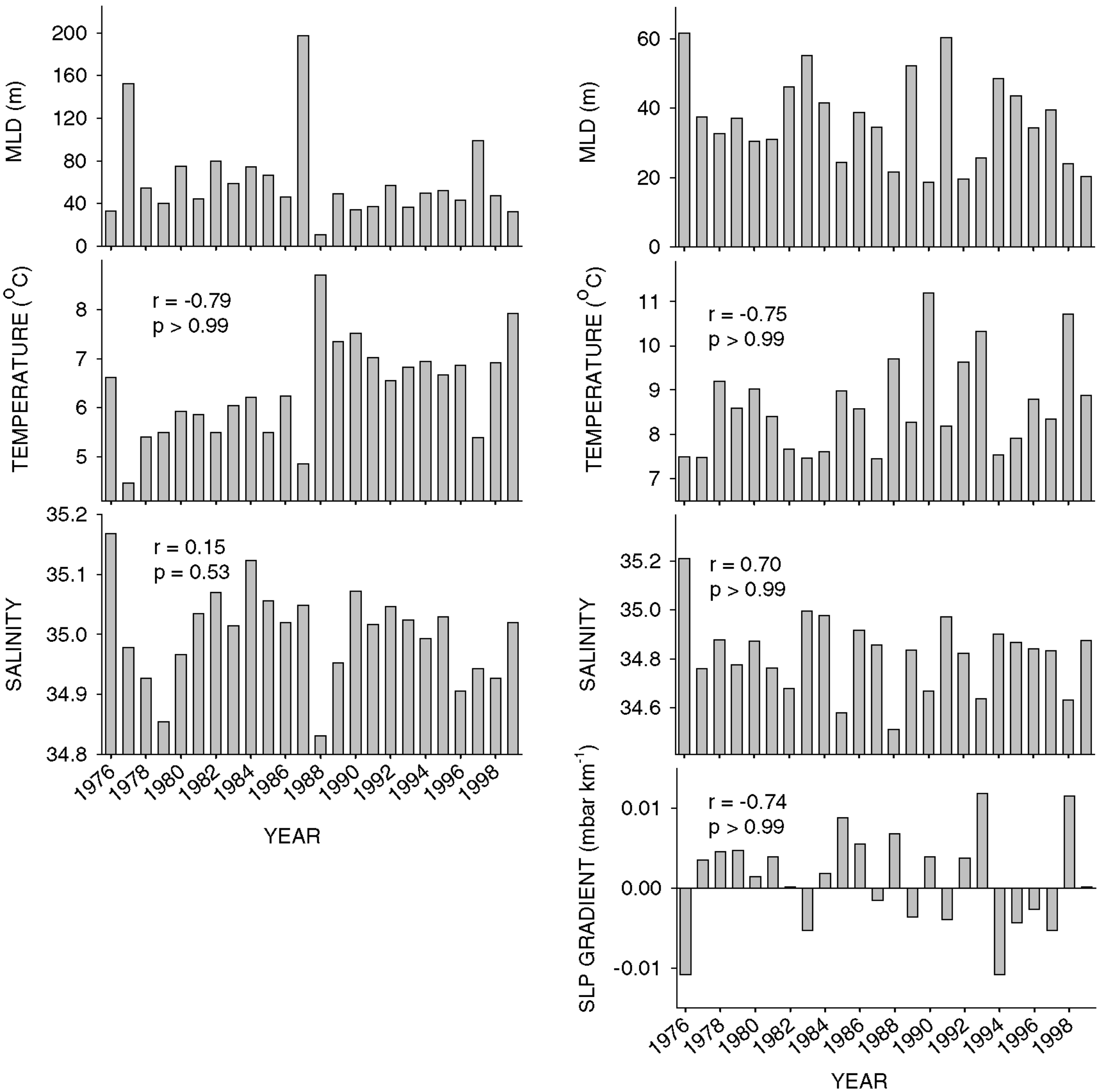
Figure 8(a and b) confirms the picture that materialized with the first analysis. In the southern part, the MLD relates strongly with salinity in the bloom period and the relationship is relaxed in the post-bloom period. Temperature is less related with the MLD in the bloom period, but the relationship strengthens moving into the post-bloom period. These features confirm that the spreading of low salinity CW is important in setting the MLD during bloom, and that heating takes over as the most important mechanism in setting the MLD as we move into the post-bloom period. This latter deduction is substantiated with the covariance between post-bloom MLD and average July–August NSWRS, the larger the heat input, the shallower the SML. The only exception is the situation in 1999 when the SML was quite shallow despite low heat input, probably also related to the exceptional weather in June of this year; excluding these data from the regression analysis gave a correlation coefficient of −0.74.

The extended time series from the middle part of the FB section is shown in Fig. 9a (bloom) and Fig. 9b (post-bloom). Here we have also plotted the average



(a) (b)

Fig. 8. Extended and completed time series of the average mixed layer depth and the average temperature and salinity in the mixed layer as observed at the southern stations of the Fugløya-Bjørnøya section during bloom (a) and post-bloom (b). Additionally, the average July–August net short wave radiative energy input to the surface in the region has been plotted in (b). The regression diagnostics (r and p values) given in each panel are for the linear regression between the respective parameter and mixed layer depth.



(a) (b)

Fig. 9. Extended and completed time series of the average mixed layer depth and the average temperature and salinity in the mixed layer as observed at the middle stations of the Fugløya-Bjørnøya section during bloom (a) and post-bloom (b). Additionally, the average July–August atmospheric pressure gradient over the region has been plotted in (b). The regression diagnostics (r and p values) given in each panel are for the linear regression between the respective parameter and mixed layer depth.

July–August mean SLP gradient over the region, in the figure covering the post-bloom period. The pressure gradient has been computed as the difference in SLP between 75°N 20°E and 70°N 20°E divided by the distance between these two positions, and is closely related to wind speed and direction over the FB section. With a high pressure in the north, winds will blow from the east, whereas a negative pressure gradient will direct winds to blow from the west. This can be appreciated from Fig. 10, which shows the direction and speed of daily averaged surface winds from May throughout summer to September in 1993 (Fig. 10a) and in 1994 (Fig. 10b). The pressure gradient averaged over July and August was positive in 1993 and negative in 1994, this difference is clearly recognized in the prevailing wind direction each year. In 1993, winds

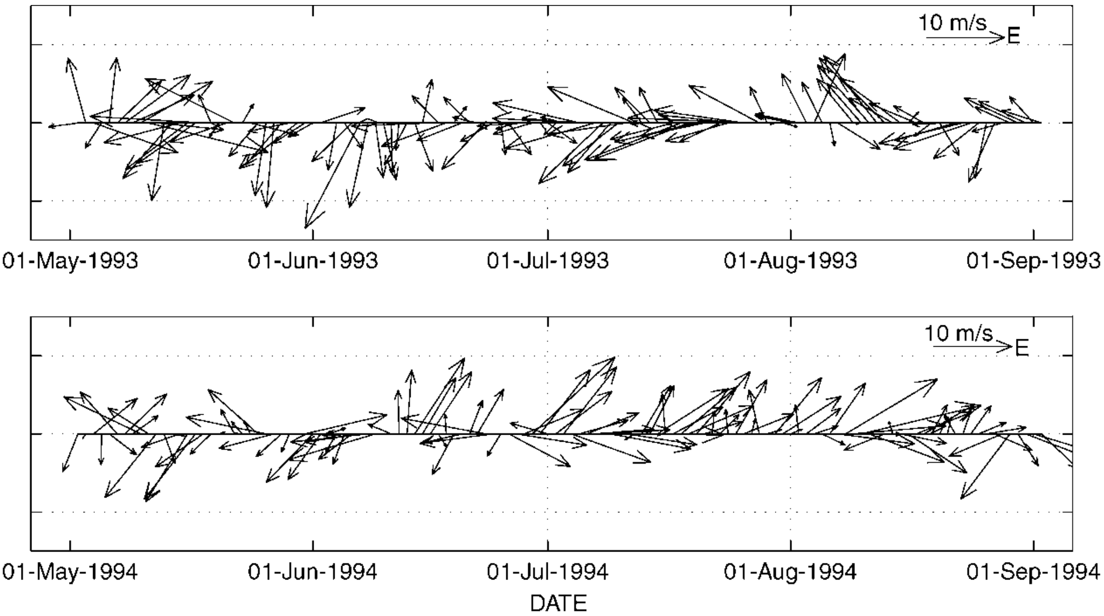


Fig. 10. Daily wind speed and direction at 72.5°N 20°E in the time interval 1 May to 1 September 1993 and 1994.

were almost steadily blowing from the east over the 2 months, whereas in 1994 westerly surface winds prevailed.

In the middle part of the FB section (Fig. 9a and b) the relationship with surface temperature is of essentially equal strength during both the bloom and the post-bloom period, and salinity is only significant during the post-bloom period, as also observed in the analysis of the nutrient time series data. Moreover, we see that the impact of the 1999 data on this relationship is weakened; excluding these data from the analysis gives a correlation coefficient of 0.78. There is, furthermore, a clear relationship between post-bloom MLD and the average July–August SLP gradient over the FB section, the MLD being shallower when the gradient is positive (Fig. 9b). The easterly winds that are associated with a positive SLP gradient will drive a northward Ekman drift, which will cause low salinity CW to spread out over this part of the FB section throughout summer.

DISCUSSION

The above breakdown of the factors controlling the development of the SML and spring bloom at the entrance to the Barents Sea represents, of course, a simplification of a system that is controlled through a set of complex and interrelated mechanisms. A more thorough analysis should, for instance, consider the effect of short-term and small-scale variations. Given also that there are interannual variations in the temperature and salinity of the source water masses AW and CW, stronger correlations than the ones identified here are not to be expected. Notwithstanding this, the coherent variations observed in the MLD, temperature, salinity, concentrations of nitrate and atmospheric forcing conditions provide explicit information on the mechanisms of the major processes that occur throughout the year and their interannual variability.

The time series data reveal that annual and interannual variations in the middle and southern parts of the FB section are influenced by offshore spreading of low salinity CW as well as by solar heating of surface waters. As regards the seasonal development, our findings confirm and extend those of Rey (1981). In southern, near-shore areas, northward spreading of CW gives rise to the haline stratification of the water column which triggers the spring bloom. The further development of the SML throughout summer is dependent on heat input. Further north, in the middle part of the FB section dominated by AW, heating is important for the vernal stabilization of the water column. However, over summer and depending on the atmospheric pressure gradient, a layer of low salinity water originating from the Norwegian Coastal Current will spread out over this region. It is this phenomenon that we would like to emphasize here, as the degree of transport of CW into this region appears to be subject to great interannual variations with clear implications for the development of the bloom. The CW is being deflected offshore through Ekman drift, as can be appreciated from Fig. 9b. Through this mechanism a large amount of CW reaches the middle part of the FB section when there is a positive north–south pressure gradient, as compared with the situation when the pressure gradient is reversed. The amount of nutrients supplied with the CW is probably not large. On the contrary, we expect nutrient levels in this water to be quite low, as primary production has probably been going on here for quite some time. Moreover, as low salinity water spreads out over the AW in the region, vertical mixing will become limited, efficiently cutting off nutrient supply from below. The northward spreading of CW will therefore probably lead to the termination of the spring bloom through nutrient depletion, and we see from Fig. 7b that in the post-bloom period, shallow low salinity SMLs are also, for all practical purposes, depleted of nitrate. From the same figure we see that ample amounts of nitrate are left in the SML when it is still quite deep and of high salinity in the post-bloom period, as was especially the case in 1994 and 1995. This situation occurs when the SLP gradient is negative over the FB section (Fig. 9b) which will limit the Ekman drift of CW out over the Atlantic part of the FB section. The total amount of nutrients available to primary producers in the region will be greater these years for three reasons: (1) low nutrient CW does not enter the region; (2) less vertical stability means larger upward transfer of nutrients from below; (3) the deeper mixed layer enables nutrients to be drawn from a greater volume. In light of this, we expect the bloom to continue until terminated by excessive grazing, and greater primary production is to be expected in these years compared with the years when the low salinity CW spreads out over the region.

The middle part of the FB section is thus another northern high latitude Atlantic region subject to large interannual variations in spring bloom development. The situation can be compared with the situation in the Barents Sea that has received great attention over the years. In the Barents Sea, total production over a year depends greatly on the distribution of sea ice. In cold years, when the ice field has a large southward extension, melt water will spread out over the AW in the region in spring. In these years, vertical stabilization of the water column takes place earlier and is stronger than in warm years, when vertical stabilization follows from the warming of the ocean surface. This phenomenon gives rise to interannual variations in spring bloom development (Rey & al. 1987; Olsen & al. 2002a), export production (Slagstad & Wassmann 1996), air–sea gas exchange (Olsen & al. 2002a), and probably also secondary production (Rey & al. 1987). In the present case, low salinity water from the south can spread out over the AW over summer, not directly affecting the spring bloom as such, but rather the later phases of the bloom and production over summer. Surely this will have implications for total annual production, air–sea gas exchange, and possibly also for higher trophic level organisms. The latter issue is made especially relevant by the apparently inverse relationship between zooplankton biomass in the region as observed in August/September and the SLP gradient, illustrated in Fig. 11. It is generally accepted that zooplankton biomass in the Barents Sea is regulated mainly through advection from the Norwegian Sea and by grazing pressure exerted by the planktivorous fish capelin (Skjoldal & Rey 1989), although the former theory has been questioned (Tande & al. 2000). However, the relationship observed merely begs for further inquiries into the factors that determine the size of the zooplankton stock in the region. For instance, has extensive offshore spreading of CW had adverse effects on the feeding possibilities for *Calanus finmarchicus*, the main zooplankton species in the region, due to early termination of the spring bloom? This is merely a hypothesis and the covariance observed may equally possibly come about due to different contents of zooplankton in the interacting water masses AW and CW. As regards air–sea gas exchange, lateral spreading of CW will efficiently cut off communication between AW and the atmosphere. AW in the region is undersaturated with carbon dioxide (Takahashi & al. 1997), and carbon dioxide is transferred from the atmosphere to the ocean. The flow of AW through the region represents, therefore, an important pathway of carbon dioxide from the atmosphere to the abyssal ocean, as AW becomes enriched with carbon dioxide as it travels through the Barents Sea before it is transported to great depth in the Arctic Ocean (Fransson & al. 2001), where it enters the great conveyor belt (Broecker 1991). Reduced contact between the atmosphere and the AW following lateral spreading of CW will probably act to reduce the size of this pathway of carbon dioxide to the deep ocean, depending, of course, on the mixing processes that take place during fall and the carbon dioxide chemistry of the CW.

The interannual variability in bloom development caused by wind-driven differences in CW spreading is probably not confined to the middle part of the FB section. For instance, a similar mechanism was observed by Helland (1963) who identified great interannual variations in summertime surface salinity

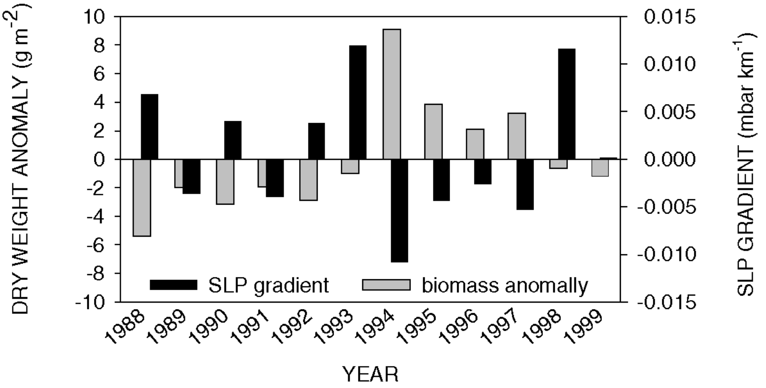


Fig. 11. Time series of anomaly of mean zooplankton biomass (size fraction 180–2000 µm, ash-free dry weight 1988–1989, dry weight 1990–1999, vertical hauls from bottom to surface) in the Barents Sea Opening and the average July–August sea level pressure gradient over the area. The biomass data stem from cruises carried out in August and September in a region covering the central parts of the Fugløya-Bjørnøya section and westwards to the Greenwich meridian. See Fosså (2001: fig. 1.7a) for a map (region 4). Only data from shelf stations are included in the presented average values. The biomass data were kindly provided by Arne Hassel at the Institute of Marine Research, Norway.

at Ocean Weather Station M which were linked to interannual variations in the direction and strength of surface winds in that region. The Norwegian Coastal Current follows the whole Norwegian coast from the Skagerak region all the way to the Nordkapp region, which has been studied in the present paper. It extends further into the Barents Sea as the Murman Coastal Current and is traceable far into the Barents Sea (Loeng 1991). Interannual variations in CW spreading coupled with the prevailing winds, similar to that observed, may, therefore, affect an extensive region and deserves further attention given: (1) the effects on bloom development, potentially propagating through the marine ecosystem, hence, possibly constituting one of the factors regulating the size of the fish stocks in the region and (2) the potential effects on air–sea carbon dioxide exchange.

Can similar inferences on interannual variation be drawn from the post-bloom data covering the southern part of the FB section? And what about the data measured during the bloom period, do they also reflect interannual variation? As regards the former issue, the answer is yes. This can be appreciated from the close link observed between average July–August NSWRS and MLD (Fig. 8b), with an r value of −0.74, excluding the 1999 data. The NSWRS is in essence a measure of the cloudiness over the region. Therefore, the more sunny days over summer, the shallower the SML, reflecting that heat input controls the summertime development of the SML in near-shore CW-dominated areas, as concluded earlier. This also has consequences for the degree of nitrate utilization in the region, as can be appreciated from Fig. 6b, although the relationship is not as strong as that observed in the middle part of the section (Fig. 7b), as the bloom goes more or less to completion each year. Bloom development in the southern part of the FB section thus also appears to be sensitive to the weather conditions in the region. However, to make safe conclusions on this issue requires more data, as up to present there has only been one observation of a SML that has not been essentially depleted of nitrate (i.e. in 1995).

As regards the data measured during the bloom phase, these have been obtained in a period of rapid change and capture the properties of a SML en route to more stable conditions. We do not, therefore, see the ultimate response to some external forcing factors, but rather a transient state. This is also illustrated by the fact that the data from the bloom cruises, both from the middle and the southern part, were, contrary to the data measured in the post-bloom phase, dependent on the day of measurement (not shown). Therefore, no direct inferences on interannual variability can be drawn from these data.

SUMMARY AND CONCLUSION

The Norwegian Coastal Current and the Norwegian Atlantic Current flow parallel along the Norwegian coast, with the former situated at the continental shelf and the latter adhering to the slope. The two currents enter the Barents Sea through the Barents Sea Opening which is the area studied in the present paper. Each summer, water from the Norwegian Coastal Current is deflected offshore, and a wedge of low salinity water spreads out over the saltier and heavier AW. The large density gradient between these two water masses is the main factor determining the MLD in near-shore areas during early summer, as observed through the close correlation between the MLD and salinity in the SML in the southern part of the FB section (Figs 6a, 8a). The further seasonal development of the SML in this region depends on the heating of the ocean surface, with large heat input promoting a further shoaling of the SML (Figs 6b, 8b). The springtime spreading of CW is, of course, limited and further out from the coast, in Atlantic areas that are not under the influence of CW, vernal stratification appears primarily to be caused by the increased temperature of the surface waters. This was reflected in the close correspondence between bloom period MLD and temperature in the SML in the middle part of the FB section (Figs 7a, 9a). Later in the year, however, the wedge of low salinity water also reaches this part of the FB section, but to various degrees depending on wind speed and direction. Offshore Ekman drift is large in years dominated by easterly winds (Fig. 9b), and in these years large amounts of fresh water flush out over the middle part of the FB section as compared with the situation in years when the prevalence of easterly winds is less or westerly winds predominate – as expressed by the atmospheric pressure gradient over the region. To summarize, in the middle part of the FB section, the spring bloom is initiated with the vernal stratification following the heating of surface waters. Throughout summer the bloom may evolve in either of two directions. If there is a negative north–south pressure gradient then winds will blow from the west, and spreading of CW into the region will be limited. The SML will remain quite deep throughout summer and the bloom will follow a typical Atlantic pattern, unable to fully utilize available nitrate and probably terminated by extensive grazing. With a high pressure situated in the north, however, winds will blow from the east, and the Ekman drift will be directed to the north. Large amounts of CW will flush out over the region. This is low nutrient water as production has been taking place here for quite some time. Additionally, the strong vertical density gradients efficiently cut off communication between the SML and the deeper nutrient-rich waters. We expect the bloom to be terminated due to nutrient limitation in these years, and annual primary production will probably be reduced. These effects may potentially propagate further up into the marine food chain. Air–sea exchange of carbon dioxide is also likely to be affected, with lessened transfer of carbon dioxide from the atmosphere into the AW en route to the deep Polar Ocean. Looking deeper into these effects and mapping the spatial extent, both how coherent the spreading of CW is along the Norwegian coast and how far off it spreads, seem to be worthwhile.

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REFERENCES

Blindheim J, Borokov V, Hansen B, Malmberg S-Aa, Turrell WR, Østerhus S. 2000. Upper layer cooling and freshening in the Norwegian Sea in relation to atmospheric forcing. *Deep-Sea Research I* 47:655–680.

Broecker W. 1991. The great ocean conveyor. *Oceanography* 4:79–89.

Fosså JH. 2001. Havets miljø 2001. *Fisken og havet* særnr. 2–2001 [in Norwegian].

Fransson A, Chierici M, Anderson LG, Bussmann I, Kattner G, Jones EP, Swift J. 2001. The importance of shelf processes for the modification of chemical constituents in the waters of the Eurasian Arctic Ocean: implication for carbon fluxes. *Continental Shelf Research* 21:225–242.

Furevik T. 2001. Annual and interannual variability of Atlantic water temperatures in the Norwegian and Barents Seas: 1980–1996. *Deep-Sea Research I* 48:383–404.

Gade HG. 1986. Features of fjord and ocean circulation. In: Hurdle BG, editor. *The Nordic Seas*. New York: Springer. 183–189.

Halldal P. 1953. Phytoplankton investigations from Weather Ship M in the Norwegian Sea, 1948–1949. *Det Norske Videnskaps Akademi. Hvalrådets Skrifter* 38:1–91.

Helland P. 1963. Temperature and salinity variations in the upper layers at Ocean Weather Ship M (66°N 2°E). *Årbok for Universitetet i Bergen 1963. Matematisk-Naturvitenskaplig Serie* 16:1–26.

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woolen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D. 1996. The NCEP/NCAR 40. Year Reanalysis Project. *Bulletin of the American Meteorological Society* 77:437–471.

Loeng H. 1991. Features of the physical oceanographic conditions of the Barents Sea. *Polar Research* 10:5–18.

Noji TT, Rey F, Miller LA, Børsheim KY, Urban-Rich J. 1999. Fate of biogenic carbon in the upper 200 m of the central Greenland Sea. *Deep-Sea Research II* 46:1497–1509.

Olsen A, Anderson L, Johannessen T. 2002a. The impact of climate variations on fluxes of oxygen in the Barents Sea. *Continental Shelf Research* 22:1119–1128.

Olsen A, Johannessen T, Rey F. 2002b. Interannual variability in the factors controlling phytoplankton seasonal development at the entrance to the Barents Sea. In: Olsen A, editor. Three studies of interannual variations in ocean biogeochemistry at northern high latitudes. Doctoral thesis, Geophysical Institute, University of Bergen. 100 p.

Rey F. 1981. The development of the spring phytoplankton outburst at selected sites off the Norwegian coast. In: Sætre R, Mork M, editors. *The Norwegian Coastal Current*. Bergen: University of Bergen. 649–680.

Rey F, Loeng H. 1985. The influence of ice and hydrographic conditions on the development of phytoplankton in the Barents Sea. In: Gray JS, Christiansen ME, editors. *Marine biology of polar regions and the effects of stress on marine organisms*. Chichester: John Wiley. 49–63.

Rey F, Skjoldal HR, Slagstad D. 1987. Primary production in relation to climatic changes in the Barents Sea. In: Loeng H, editor. *The effect of oceanographic conditions on distribution and population dynamics of commercial fish stocks in the Barents Sea*. Bergen: Institute of Marine Research. 29–46.

Sakshaug E, Rey F, Slagstad D. 1995. Wind forcing of marine primary production in the northern atmospheric low pressure belt. In: Skjoldal HR, Hopkins C, Erikstad KE, Leinaas HP, editors. *Ecology of fjords and coastal waters*. Amsterdam: Elsevier. 5–25.

Skjoldal HR, Rey F. 1989. Pelagic production and variability of the Barents Sea ecosystem. In: Sherman K, Alexander LM, editors. *Biomass yields and geography of large marine ecosystems*. Washington D.C.: AAAS Selected Symposium 111. 241–285.

Slagstad D, Wassmann P. 1996. Climate change and carbon flux in the Barents Sea: 3-D simulations of ice distribution, primary production and vertical export of particulate organic carbon. *Memoirs of the National Institute of Polar Research* 51:119–141.

Sverdrup HU. 1953. On conditions for the vernal blooming of phytoplankton. *Journal de Conceil Permanent International pour l'Exploration de la Mer* 18:287–295.

Sætre R, Aure J, Ljøen R. 1988. Wind effects on the lateral extension of the Norwegian Coastal Current. *Continental Shelf Research* 8:239–253.

Takahashi T, Feely RA, Weiss R, Wanninkhof R, Chipman DW, Sutherland SC, Takahashi TT. 1997. Global air–sea flux of CO_2: an estimate based on measurements of sea–air pCO_2 difference. *Proceedings of the National Academy of Sciences USA* 94:8292–8299.

Tande KS, Drobysheva S, Nesterova V, Nilssen EM, Edvardsen A, Tereschenko V. 2000. Patterns in the variations of copepod spring and summer abundance in the northeastern Norwegian Sea and the Barents Sea in cold and warm years during the 1980s and 1990s. *ICES Journal of Marine Science* 57:1581–1591.

Wassmann P. 1998. Retention and export food chains: processes controlling sinking loss from marine pelagic systems. *Hydrobiologia* 363:29–57.

Wassmann P, Peinert R, Smetacek V. 1991. Patterns of production and sedimentation in the boreal and polar Northeast Atlantic. *Polar Research* 10:209–228.

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