Oceanography and fluorescence at the shelf break off the north Norwegian coast (69°20'N-70°30'N) during the main productive period in 1994

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Data on hydrography, fluorescence, wind and currents from shelf studies on the Norwegian shelf between 69°30'N and 70°30'N are presented. The sampling was performed along five transects, covering a narrow shelf break site, a trench, and a bank. The sampling programme was conducted during cruises of 4-5 days duration each month from March until October 1994. Three distinct water masses were identified: 1) Coastal Water ($S < 35$; $4 < T > 12$ °C) above the shelf and the shelf break (0-300 m depth), 2) Atlantic Water ($S > 35$; $5 < T > 10$ °C) off shelf (0-400 m depth) and below the Coastal Water in the trenches (300-400 m depth), and 3) Norwegian Sea Deep Water ($S < 35$; $T < 0$ °C) off the shelf break, below 700 m depth. Wind direction between southeast and northwest prevailed during all cruises, except in May, when northeasterly wind was most frequent. Typical wind speeds were in the order of 7-12 m s^{-1}, but the wind exceeded 15 m s^{-1} frequently during the whole investigation period. Current regime above the shelf, as obtained by Acoustic Doppler Current Profiler (ADCP) in April, June and September, demonstrated a strong off-shelf flow along the northern side of the trench Malangsdjupet, while a more irregular pattern was found along the southern margin of this trench. Above the bank area Nordvestbanken a clockwise turn in the flow field from east to west was found. This clockwise turn in flow field coincided with modelled flow fields of the major tidal component during most of the cruises. Residual currents were determined subtracting the modelled M2 from the ADCP-measurements. Fluorescence profiles indicated a higher standing crop of phytoplankton above the trench area than above the bank area. No distinct spring bloom was found, but a seasonal maximum in June in surface integrated fluorescence was detected. In June highest values were recorded in shelf waters ($34.2 < S > 34.4$) when the pycnocline was about to be established, while the August and September maxima were found in more saline waters ($34.8 < S > 35.1$) often below the pycnocline in off-shelf waters.

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INTRODUCTION

The coastal shelf of northern Norway is highly productive, with the food chain based in phytoplankton and zooplankton supporting the recruitment of major stocks of fish, such as herring, capelin and cod. Although this region has attracted a lot of scientific research (as for instance the recent Norwegian Research Programme on the ecology of fjords and coastal waters, MARE NOR), multidisciplinary studies covering almost the entire productive period are still lacking from this region of the Norwegian shelf. The project Ocean Margin Exchange Processes (OMEX) recently provided a basis for bridging this gap, and the present paper aims to improve the knowledge on the physical processes which are considered to have major importance in sustaining a high biological production. In this respect our goal is to reveal the vertical and horizontal variation in hydrography and the current pattern during each study period as well the seasonal variation from March to September 1994.

The physical conditions, including the topography in the study area outside Troms, have been described earlier (Sundby 1984). The surface currents of the Norwegian Sea and along the Norwegian coast are strongly influenced by the relatively warm saline water from the Norwegian Atlantic Current (NAC) whose branches cover large areas of the Norwegian Sea. On the Norwegian coastal shelf, water from the Norwegian Coastal

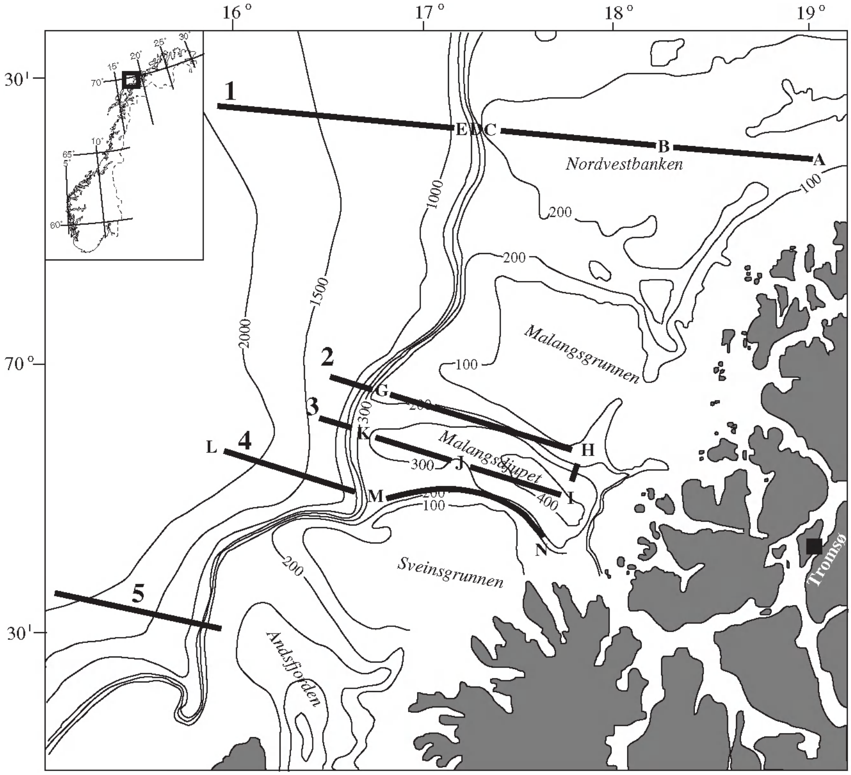

Fig. 1. The coast of northern Norway with bottom topography of the continental shelf in the area of study. The inserted lines denote the transects from where the data were obtained: 1 at Nordvestbanken, 2-4 the northern, central and southern border of Malangsdjupet, and 5 across the steep shelf NW of Andfjorden, respectively.

Current (NCC) contributes to the northward flow (Sætre & Mork 1981). Both the NAC and NCC are narrow, deep and strong in the study area, and follow the bathymetry of the north Norwegian shelf. The continental shelf topography outside Troms is dominated by relatively small banks which are separated by troughs. These troughs are perpendicular to the shelf and create deep connections from the shelf break toward the coastline. The shelf break is in general steep, and the shelf is very narrow (approximately 10 km) outside Andenes in the southern part of our study area. The bottom topography is therefore strongly steering the water masses, where the water flows in and out of the troughs along the southern and northern walls, respectively (Moseidjord & al. 1999). The shallow banks between maintain a clockwise circulation pattern, modified by the tidal cycles (Sundby 1984; Moseidjord & al. 1999).

The main objective of the present paper is to provide a basic understanding of the interaction between topography, hydrography, wind regime and currents during the selected time windows in the study period in 1994, and reveal both short time and seasonal fluctuations in the environmental conditions. A second order objective is to document the environmental data which form the basis for the model concepts designed to scale the along-shelf and across-shelf transport of particulate carbon in the region.

MATERIAL AND METHODS

Topography

The region of study is situated off the coast of Troms County, northern Norway between 69°N and 70°30'N (see Fig. 1). In this region the shelf is narrow (20-60 km), and characterised by quite shallow banks (bottom depth from 50 to 150 m) divided by trenches of 300-400 m depth. From these trenches, which extend almost perpendicular from the shelf break towards the coast, minor and shallow trenches protrude parallel to the coastline and partly separate the banks from the shallow coastal zone. The mean depths of the three banks covered in this study are according to Sundby (1976) 139 m (Nordvestbanken), 91 m (Malangsgrunnen) and 61 m (Sveinsgrunnen). The large trenches between the banks have entrances at the shelf break at depths close to 250 m. From shelf break a steep slope extends seawards to depths between 1500-2000 m.

Our field programme was conducted along five transects (1-5) crossing the shelf break at locations having special topographical features (Fig. 1). The northernmost transect (1) crossed Nordvestbanken, the largest bank within the study area. The bottom depth of this bank varied from 170 m close to the coastline (A), 110 m on mid bank (B) to 200 m at shelf break (C). From the shelf break 60 km off the coast, our transect extended further 40 km NW to a position with a bottom depth close to 2000 m. The transects 2-4 covered the trench Malangsdjupet, which is the entrance to the fjord Malangen. One transect was positioned along the axis of this trench covering the deepest areas, while two other transects covered the margins of the banks bordering the trench (Stns G-H, and M-N). Further south, another transect (5) across the shelf at the most narrow site was visited to reveal the strength and variation of the northward geostrophical flow entering our two main study sites (i.e. transects 1 and 2-4, respectively).

Sampling programme

The sampling programme was conducted during cruises of 5-6 days duration each month from March until October 1994. In October the sampling programme was reduced due to rough weather conditions and only data from the three northern transects (1, 2 and 3) were reliably obtained. On the banks and above the trench Malangsdjupet, CTD casts were performed approximately each fifth nautical mile, but close to the shelf break the distance between each cast was reduced to one to two nautical miles.

The hydrography and fluorescence data collected during the cruises from March to July were obtained by a CTD (E.G.&G. Mark IIIB) equipped with a fluorometer. In August, September, and October another CTD (Meerestechnik OTS-1200) with fluorometer was used.

Wind data presented are based on output from the Meteorological Institute's hind-cast database and given as speed and direction of the wind 10 m above sea level at a central position in the study area (Stn G).

Current velocities were measured using a hull mounted Acoustic Doppler Current Profiler (ADCP) (RD Instruments; 150 kHz - narrow band), and by using Aanderaa current meters (RCM-7). The ADCP logged the current regime continuously while steaming at approximately 7 knots along selected transects. Data were collected in 4 m bins, two pings per ensemble using bottom track mode. Current data were recorded on all cruises except in May when the instrument malfunctioned. In April and September additional current measurements were performed using Aanderaa current meters deployed at 50 m and 200 m depth. The use of current meters gave us the opportunity to compare these current recordings with measurements recorded by ADCP at the same time and place. In April this comparative study was performed close to station J in the trench Malangsdjupet, and in September a similar study was carried out at the shelf break of Nordvestbanken (Stn D, transect 1).

Data analysis and calculations

ADCP data were averaged for 15 minutes of continuous recording, which correspond to ca 200 ensembles. This way of averaging gives a fixed number of ensembles and thus a comparable standard deviation in the measurements presented. However the distance presented by each average varied according to small changes in ship speed, but this is considered of little importance for the data acquisition.

Current data from RCM-7 were recorded and logged in five-minute means. For presentation and comparing with ADCP-data 10-minute means were calculated. ADCP measurements were then carried out in close vicinity of the moored rig. The research vessel steamed along short tracks in northward, eastward, southward and westward direction in order to trail any effect of heading direction. The effect of the ship velocity was also tested, by investigating any changes in the current registrations when cruising at different speeds. In September current meters were deployed for a longer time (30 hours) compared to the April study (12 h), and this gave us the possibility to filter off the diurnal tidal component by using hourly means of 25 hours sliding mean.

In this paper we have however focused on presenting currents obtained by ADCP. Net current regime was then calculated by removing the most prominent tidal components (M2, S2) which comprise more than 85 % of the tidal energy in the area of study. Tidal currents varied a lot in time and space due to the rough bottom topography, and by subtracting modelled tidal current from measured currents, a picture of the net flow appeared. In this respect the value of current measurements obtained by ADCP is increased. Tidal currents were modelled by using a baroclinic, 3-dimensional numerical model (level type), which contains fixed but permeable levels (Slagstad 1987; Slagstad & al. 1990). At the open boundaries the Flow Relaxation Scheme (FRS) is applied (Martinsen & al. 1987). In addition to specification of the inflow through the open boundaries, tidal elevation was given according to the data taken from Schwiderski (1980). Amplitude and phase of four

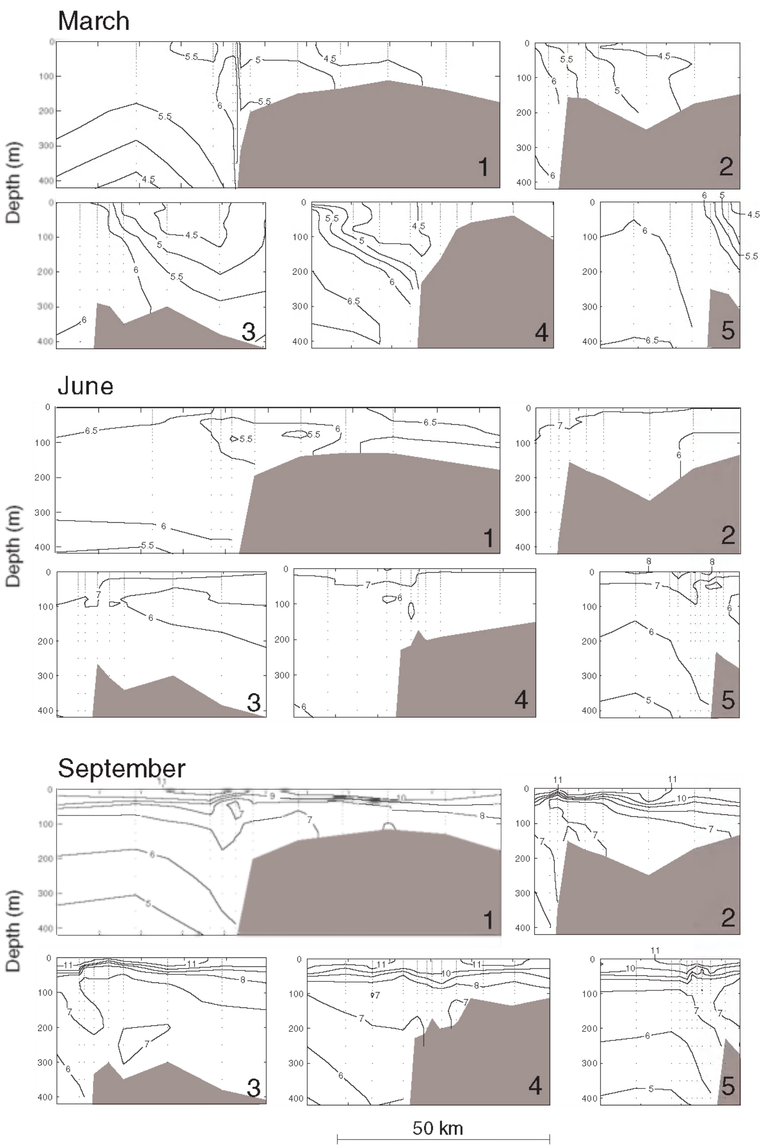

Fig. 2. Temperature isolines from the five transects grouped according to the three sampling periods in March, June and September, respectively. Numbers at lower right identify the transects (see Fig. 1).

tidal components (M2, S2, O2, and K1) has been implemented and compared the data found in Gjevik & Straume (1989) and Flather (1981). A detailed description of the hydrodynamic model can be found in Slagstad (1987) and Slagstad & al. (1990) and Støle-Hansen & Slagstad (1991). This hydrodynamic model has also been used in a model study on topographical steering of the main flow in the area studied (Moseidjord & al. 1999).

RESULTS

Temperature

Isolines along all transects, illustrating the temperature in spring, early summer, and early autumn are displayed in order to present seasonal changes in temperature regime in the study area (Fig. 2). The seasonal amplitude in temperature were close to 7 °C in upper 50 m. This amplitude was slightly greater above banks than in off-shelf waters, due to the lower temperature above banks

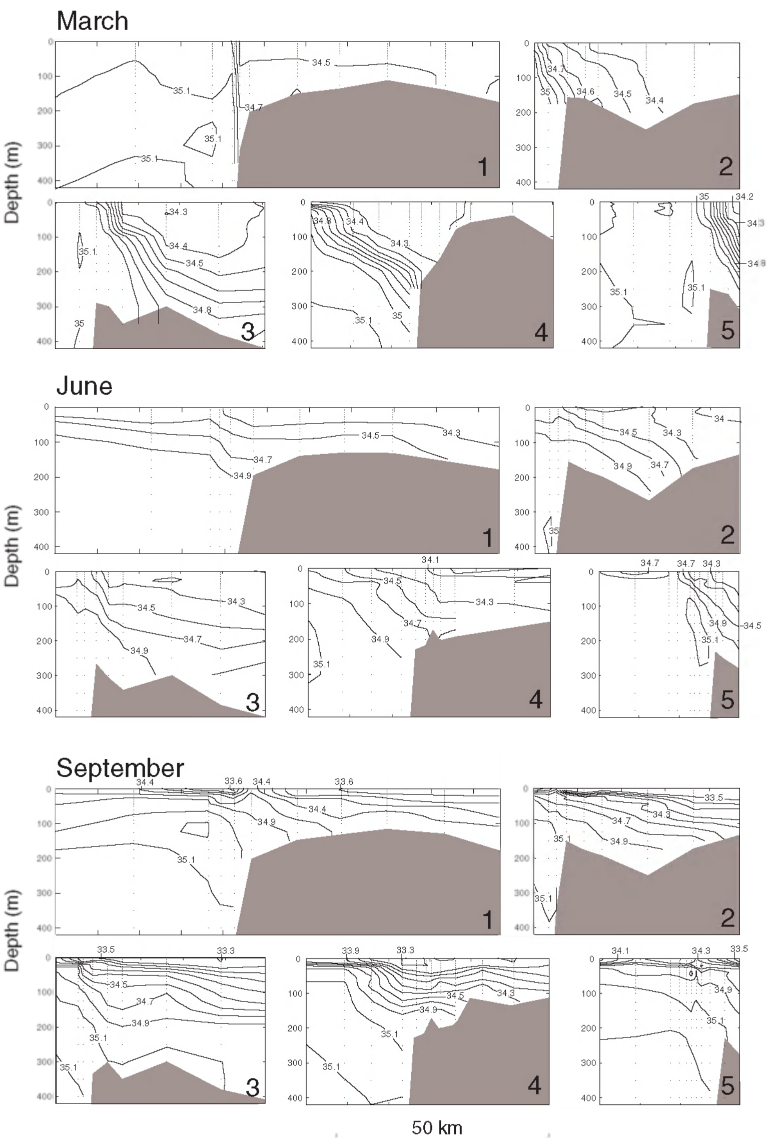

Fig. 3. Salinity isolines from the five transects grouped according to the three sampling periods in March, June and September, respectively.

during spring. Below this "upper layer", seasonal amplitude decreased rapidly, and at 200 m depth and off the shelf break the temperature differed with less than 3 °C from a minimum in March/April (ca 5 °C) and a maximum in October (ca 8 °C), respectively. On the shelf, the temperature increased from approximately 4 to 12 °C in surface waters and 3.7 to 8 °C close to the bottom (ca 150 m). In the intermediate depth (50-200 m) the lowest range in temperature was found close to the shelf break along transect 2. Off the shelf break, cold deep water characterised by temperatures below 0 °C was present beneath 700-1000 m, and no seasonal amplitude was detected at these depths. A strong gradient between 600-700 m (°C/m) indicated a transition zone and thus mixing between AW and NDW. The presence of "isothermal" Atlantic water was prominent all along the shelf slope and in the trench Malangsdjupet, reducing the seasonal amplitude in temperature.

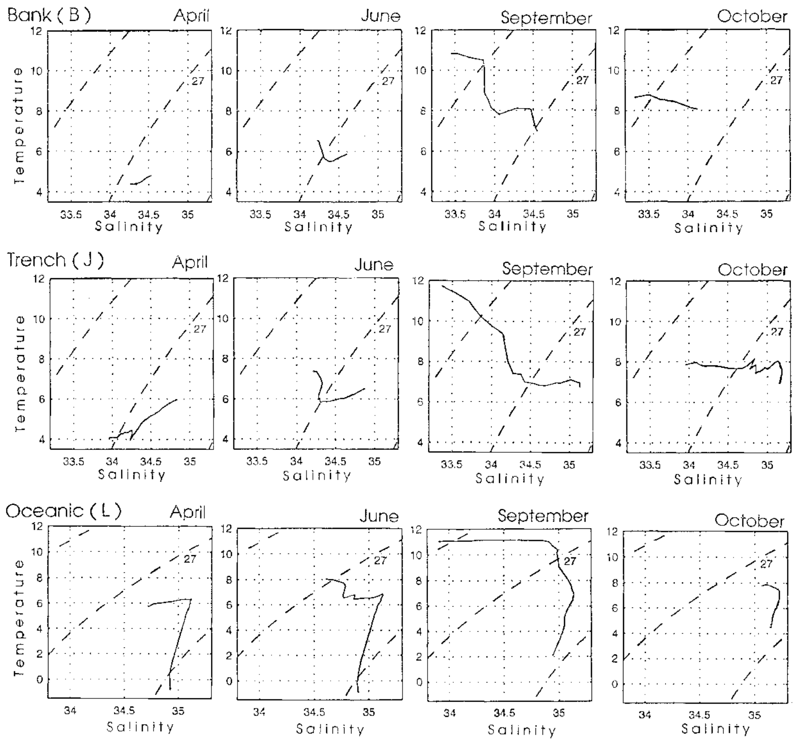

Fig. 4. TS diagrams for March, June, September and October 1994 at Nordvestbanken (Station B), Malangsdjupet (Station J) and off-shelf (Station L).

Maximum temperatures were recorded in surface layers during September when the temperature reached close to 12 °C, where the mean temperature in upper 50 m were approximately 10 °C, both on banks and in offshore areas. Destabilisation of the water column from September to October lead to a more homogenous temperature regime, and a seasonal maximum slightly above 8 °C was recorded in intermediate layers (Fig. 2).

During spring the upper 150 m of the water column covering the banks and the trench Malangsdjupet were generally slightly colder than waters off the shelf break. At intermediate depths (50-150 m) the a horizontal difference in temperature between off-shelf and coastal stations were typically 1.8-2.0 °C. This horizontal gradient in temperature was suppressed close to the shelf break indicating a thermal front along the shelf margins (Fig. 2).

Salinity

Seasonal changes in salinity were most evident in surface layers above banks having an amplitude of 4 psu (Fig. 3). A salinity minimum was found in surface layers during September. At this time a distinct halocline was present and coastal water characterised by the reduced salinity in upper 20 m covered all shelf areas and extended far off the shelf break. However, below this halocline, from ca 50 m and further down, salinity was almost constant at the shelf break sites (35 ± 0.2) in September. Off the shelf break the density field from greater depths (below 200 m) showed that the water masses were almost homogenous. A stratified field in the upper 50 m was recorded from June to September, while more homogenous conditions were found in spring and late autumn (data not shown).

Norwegian Sea Deep Water (NSDW) with salinity below 35 and temperature below 0 °C was found at the depth close to the 700 m isobath throughout the whole investigation period. Within each time window the variation of T and S between stations was as large as variations between months. At the outer station L the uppermost depth strata were influenced by coastal water during most of the productive period of the year. The outer stations at transects 1 and 5 were, however less influenced by coastal waters. The TS plots (Fig. 4) show that there are three different water masses present off the shelf: Norwegian Sea Deep Water (S < 35; T < 0 °C), Atlantic Water (S > 35; T > 3 °C) and coastal water (S < 34.8; 4 < T > 12 °C). Atlantic water was found in the trenches as well.

Fluorescence

Fluorescence profiles indicated a higher standing crop of phytoplankton above the trench Malangsdjupet than above Nordvestbanken (Fig. 5). Even though there was large variation between stations along all transects (1-5), surface integrated fluorescence was in general higher in oceanic areas and trenches than above the banks.

The fluorescence maxima found each month were low throughout the season, and never exceeded values corresponding to more than 6.5 μg Chl *a* l^{-1}. In March and April fluorescence profiles indicated chlorophyll *a* concentrations below 0.5 μg Chl *a* l^{-1}, and sampling did not reveal evidence of spring bloom along any of the transects. Slightly higher fluorescence values were detected in the more saline Atlantic water (at L) in May compared to the shelf. During the spring, highest fluorescence was detected at shelf stations in water of reduced salinity. The vertical distribution of the phytoplankton was according to fluorescence profiles not significantly different at Nordvestbanken compared to Malangsdjupet, but the highest concentrations were in general detected slightly deeper in the latter area. In July, August, and September fluorescence maxima were detected at the base of the pycnocline or beneath (Fig. 5), especially evident in September when high values were found in more saline waters just beneath the halocline.

Comparing the horizontal distribution of fluorescence in the area of study between June and September, clear differences along the transects were found (Fig. 6). In June the fluorescence maximum was found on the shelf, close to the shelf break, along all five transects. In September, maximum levels were recorded off-shelf in oceanic waters, especially prominent along the southern transects 4 and 5.

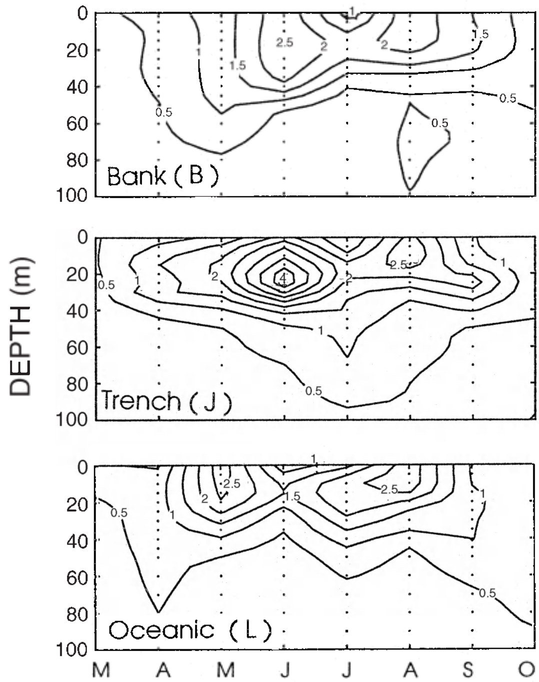

Fig. 5. Fluorescence isolines in upper 100 m for the study period from March to October 1994, at Nordvestbanken (B - depth 100 m), Malangsdjupet (J - depth 300 m) and off-shelf (L- depth 2000 m). The isolines are based on monthly vertical fluorescence profiles sampled (see Table 1 for details in sampling time).

Wind regime

A closer look at data from the hind-cast database demonstrated that the wind regime was highly variable in both speed and direction during the whole year as found during the time periods March-September 1994 (Fig. 7). The wind speed during the period of investigation varied mostly between 7 and 12 m s^{-1}. Short events with wind speed > 15 m s^{-1}, or < 2 m s^{-1} were found during all months from March until October in 1994. In July and August the periods of calm wind regime increased in duration and only occasionally short events of rough wind conditions occurred. Wind direction was as previously mentioned mainly southeasterly, but in both March and September short periods of northern wind were frequently recorded prior to our cruises. Also during the first week of June there was a short period with northeasterly winds of 10-15 m s^{-1}. This wind direction is known to occur frequently during summer months, which might cause Ekman transport and upwelling along the slope.

Currents

Tidal strength and direction varied within the study area due to the variable bottom topography. A turn in the flow field is expected when the tide moves over an area with increasing depth or decreasing depth. The modelled tide (Fig. 8) shows the intensifying, and clockwise turn of the tidal currents above banks, while a more or less back and forth flow is found above the trench Malangsdjupet. Strongest currents were found when the tidal forces joined the barotropic current in intensifying the northward flow (> 1m s^{-1}). The strength of the diurnal tidal component was evident from our current meter recording at the shelf break in September (see below) when it occasionally was strong enough to counteract the strong northward current.

In order to substantiate the ADCP measurements, a comparison of ADCP and Aanderaa current meters was carried out. In April in the trench Malangsdjupet there were indications of more or less consistent differences in current direction measured, while the recorded cur-

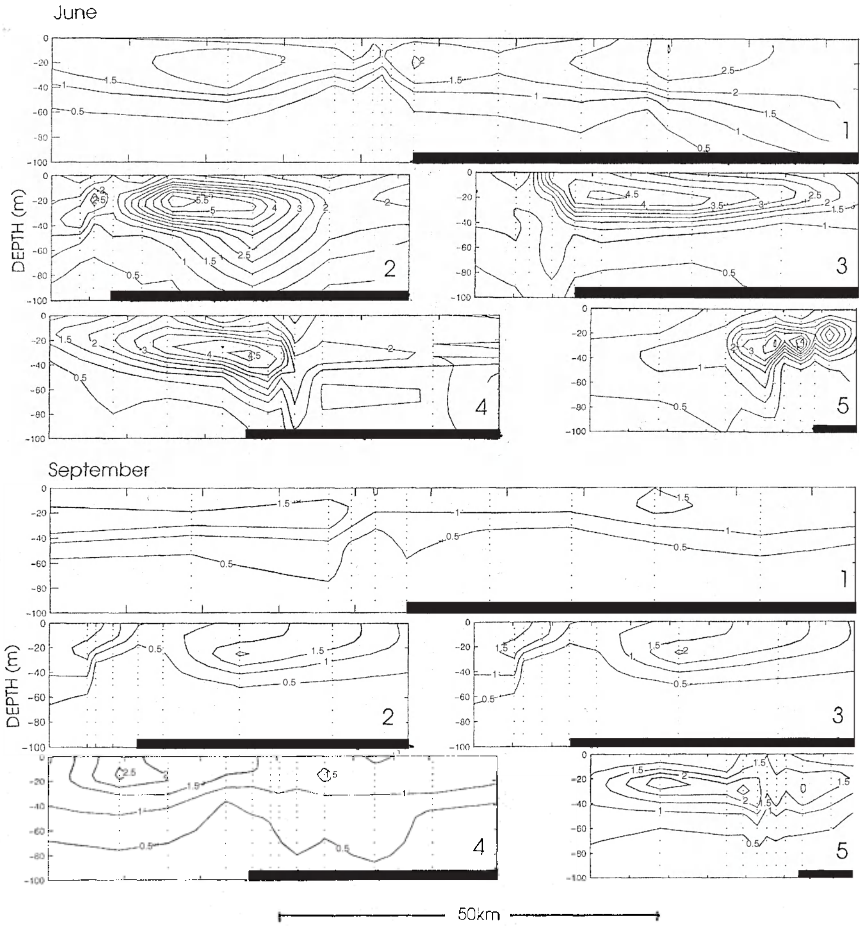

Fig. 6. Fluorescence isolines along the five transects in June and September 1994. The isopleths are based on vertical fluorescence profiles sampled at stations indicated by vertically arranged dots in each figure. Shaded area at the base of each drawing denotes the shelf break at 300 m.

rent speeds were in good agreement (Fig. 9). The differences in current direction were in the order 20-30°, slightly more at 200 m depth then at 50 m. It was also found that the differences seemed to increase with increasing ship velocity, especially when reaching ship speed in the order 8-10 knots. Current speed and directions measured, clearly showed the importance of large-scale physical processes and the influence of the topography in current steering. Strongest currents were recorded at the shelf break of Nordvestbanken in September when it exceeded 1 m s^{-1} (Fig. 9). At this position, the differences in current speed and current direction measured at 50 and 200 m depth were small, showing the importance of the barotropic mode.

Current directions and strength were estimated by ADCP at several cruises, and only selected data are presented in order to substantiate the general patterns. In June currents flow SW at the transect on Nordvestbanken with increasing strength toward the shelf break, where the current turns northwards (Fig. 10). Substantially lower current speeds were observed in Malangsdjupet having a more irregular direction away from the shelf break.

The tides appear as clockwise rotating currents over the whole shelf area as is evident from the modelled M2 tide from 12 March 1994 (see Fig. 9). The current velocities during the cruises in April and September 1994 (Fig. 11) demonstrate a strong off-shelf flow of water along the north side of Malangsdjupet (transects 2 and 3), while a weak and irregular pattern was found at the southern transect of Malangsdjupet (transect 4). The same situation is found for the residual currents calculated. A strong northwestward flowing current was found across the shelf in the southern region of the study area, and the current direction found in September at Nordvestbanken is consistent with the observations found in June.

DISCUSSION

GENERAL DESCRIPTION OF THE WATER MASSES

Temperature measurements along the transects during the time windows of investigation clearly illustrated the cooling of surface waters in spring, a build-up of a thermocline in the upper layer (50 m) during summer and the break-down of the stratification in late autumn (October). The seasonal changes were most evident above the bank areas. The water over the banks has a markedly faster response to changes in air temperature compared to off-shelf waters.

Since the NAC is generally heavier (S > 35) than NCC (S < 35), the less saline NCC would therefore be found above the NAC as a wedge toward the shoreline. The mixing of these two water masses increases north along the Norwegian coast. The separation of the two water masses is most relevant where the differences in salinity are large, which it tends to be during the summer when the freshwater runoff is at its maximum. The distribution of NCC varies seasonally, and the period from May to September represents the maximal offshore extension of coastal water in the upper 50-100 m. NCC retreats during the winter toward land and tends to extend deeper (to about 200 m). The NAC is found deeper than the level of the shelf, but due to the narrow shelf in the study area, it is at its maximum onshore position in the OMEX study area (see also Ljøen 1962).

HYDROGRAPHY CONDITIONS

In 1994 the temperature in the upper part of the water column was at a minimum during the most biologically productive period in spring, and attained its maximum when the plankton production was about to cease in the autumn. Based on the CTD data obtained from the present study, the calculated mean variation is generally low: 5.0 °C for the upper 0-20 m, 3.5 °C for 20-50 m, 2.0 °C for 50-100 m, and 1.5 °C for 100-200 m for the period from March to September. The stratification in the upper layer starts in June and continues until September. This means that there is a delay in the effect of the increase in thermal insulation and freshwater runoff, which commences in June in these latitudes (Eilertsen & Taasen 1982). The seasonal build-up of the thermocline is found to be modified by the transport of coastal waters from south (Sundby 1976) and the topography in the area. Results from the present surveys in the area indicate that the water above the

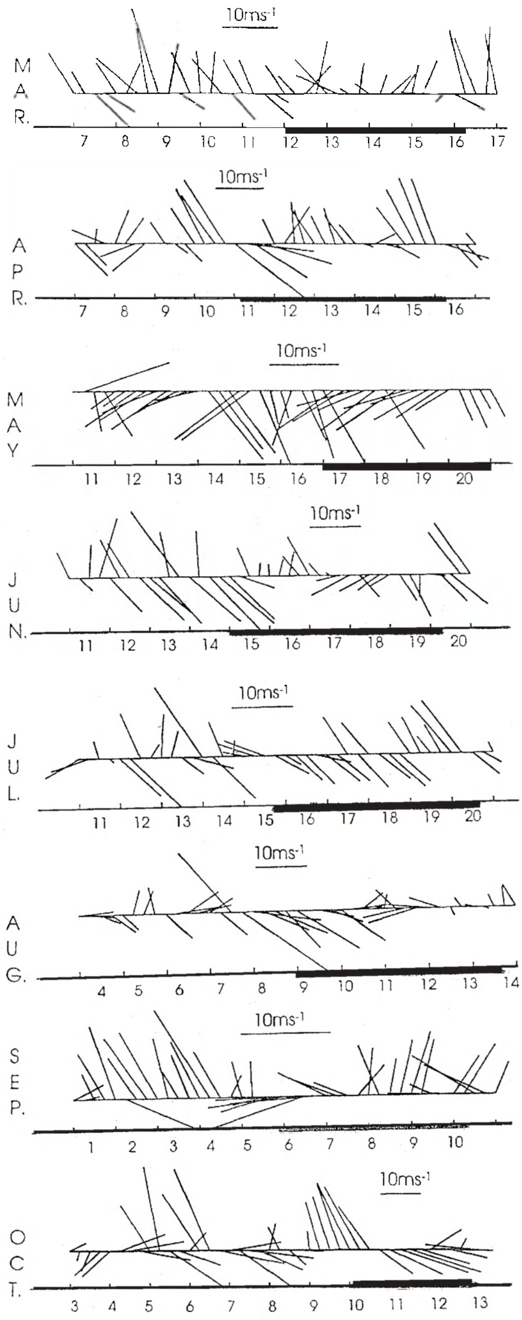

Fig. 7. Wind regime 5 days prior to and during each cruise March-October 1994. Wind, speed and magnitude estimated at station G, 10 m above sea level, based on hind-cast database of the Norwegian Meteorological Institute. Each stick indicates a 6h mean of wind speed and direction. Upright stick indicates wind from south blowing northward (south wind). The periods of the cruises are indicated as heavy lines along part of the abscissa.

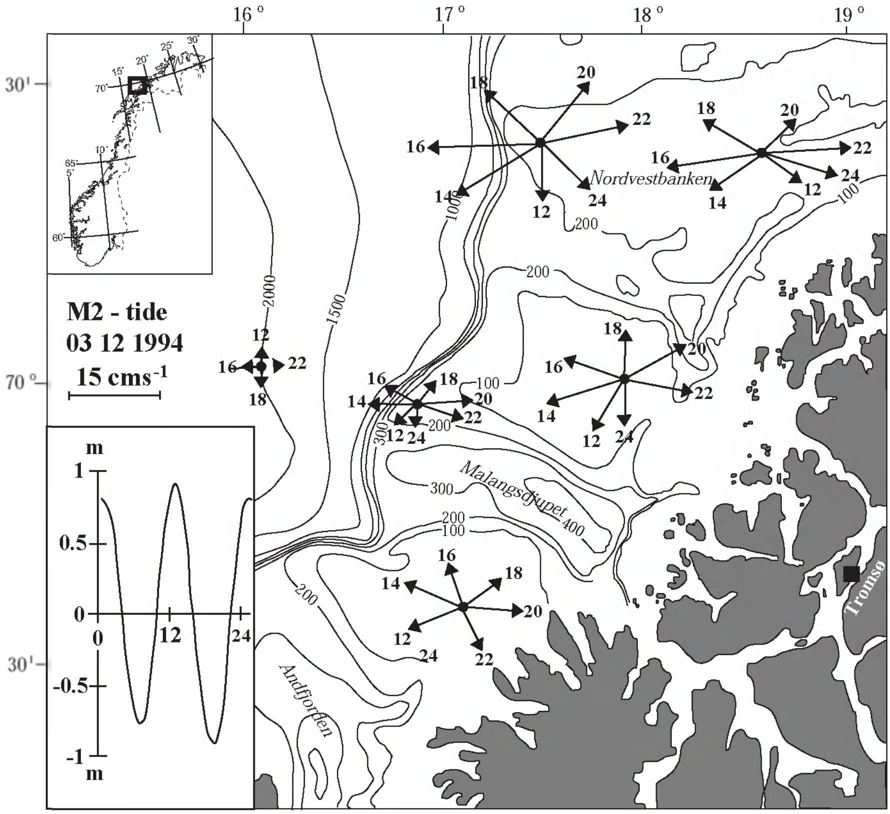

Fig. 8. Tidal ellipses from modelled M2 and tidal amplitude (inserted in figure) in the area of study from 12 March 1994. The tidal amplitude is based on the six major constituents (M2, S2, N2, K2, K1, O1), data from modelling by Gjevik (1989). Current speed and direction of tidal flow at a certain time is indicated by the length and the direction of each vector (modelled by D. SLAGSTAD, see also Moseidjord & al. 1999).

banks is less saline and colder than the water above the trench Malangsdjupet. This has also been confirmed by satellite obtained surface temperatures from June 1994 (U. Normann pers. commn). The topographically generated differences in surface temperatures could be considered a frequently occurring condition.

Indications of the phytoplankton development (by fluorescence profiles) at three study sites demonstrated a similar temporal development, but with regional differences in the maximum standing crop during 1994. Surface integrated fluorescence (0-100 m) was not correlated to strength of the stratification in surface layer (Spearman rank correlation). During several months fluorescence was more correlated to topographical parameters and both latitude ($-0.7 < r > -0.5$) and longitude. This indicates consistent differences between the bank and the trench area, as well as difference between off-shelf and on-shelf stations. The consistency in the three patterns and the underlying mechanisms for these differences are uncertain, but the pycnocline in June and September indicates a similar stratification at all three stations (for further discussion see Andreassen & al. 1999).

Meteorology

The wind regime was highly variable in both speed and direction during the whole study period, with southeast as the prevailing wind direction with a tendency for longer periods of calm winds during July and August. The coastline from Lofoten to North Cape is in general dominated by northwesterly winds during most of the year, with a high frequency of intensive low-pressure systems (Dannevig 1966). From June to September a northwesterly wind direction prevails, during a period with the lowest frequency of low-pressure systems. Mean wind speed recordings of a ten year period indi-

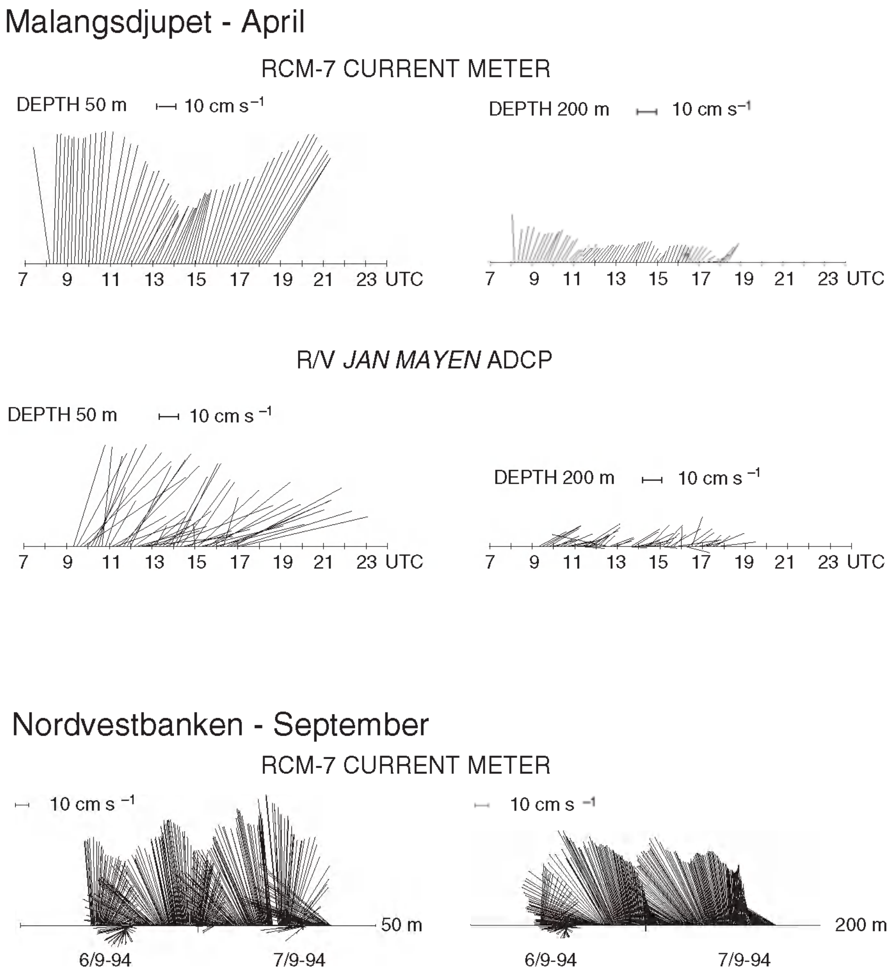

Fig. 9. Current velocities obtained by RCM-7 Aanderaa current meter and ADCP at 50 m and 200 m in Malangsdjupet 14 April 1994 (upper two panels). ADCP recordings were performed while the vessel were cruising westward, eastward, northward, and southward at different ship speeds when passing by a moored rig equipped with the current meters. Average of 10-minute means of current speed and direction recorded are indicated by the length and angle of each stick. Upward line show currents flowing in northward direction and sticks drawn to the right indicate eastward flow. Current meter recordings from Nordvestbanken close to station D at 50 m and 200 m depth from 6 to 7 September 1994 (lower panel).

cate levels varying from 12 to 33 % above 12 m s^{-1} along the coastline in the study area (Sundby 1976). Density driven currents induced by variability in wind field and freshwater runoff from land have only marginal effects on the flow field. The maximum effect of wind is found during periods of stratification, and will therefore have the most pronounced impact on the biology in the area during these periods. For instance, a prevailing wind from SW will favour an onshore transport of water masses, with a tendency for downwelling close to the coastline (Svendsen 1986; Syvitski & al. 1987). The northeasterly winds will generate Ekman currents causing upwelling close to the coastline, with offshore transport of surface water (see Sætre & al. 1988). These processes, which are related to the wind regime will under certain circumstances advect water into coastal areas and fjords of northern Norway (Leth 1995; Falkenhaug & al. 1997) and therefore potentially impose faunal and floral changes (see Ratkova & al. 1999; Halvorsen & Tande, 1999).

Currents

The direction of the current vectors in the shelf area show small changes with depth, (see Fig. 9) thus indi-

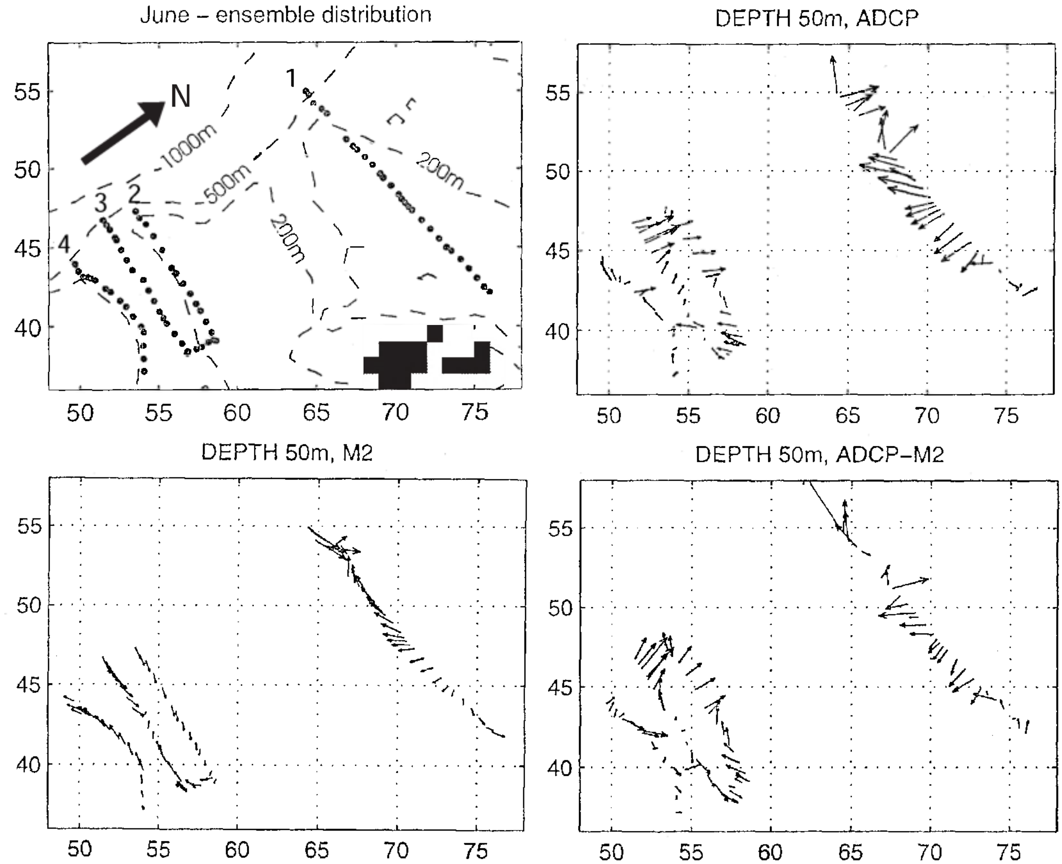

Fig. 10. Position of the four northern transects (upper left panel), current speed and direction measured at 50 m depth by ADCP (upper right panel), where each arrow represents an average of 15 minutes continuous recording while steaming. Modelled M2-tide at the same time and position as the averaged ADCP measurement (lower left panel) and residual current after removing modelled M2 from the total current obtained (lower right panel). Vertical and horizontal axes are gridpoint numbers. 1-4 are the transect numbers given in Fig. 1.

cating the importance of a strong barotropic signal. During all cruises this pattern was more or less consistent, and thus found both during the vertically unstratified (October-May) and during the most stratified periods (July-September). The current meter measurements carried out in September underlined the influence of the barotropic signal, thus indicating a stratification not strong enough to induce strong baroclinic signal in the major flow.

It is well known that data sampled with an ADCP may be encumbered with errors, which for a ship mounted ADCP, could be due to a combination of factors: inadequate navigation system, unfavourable ship movements (speed, waves), irregular bottom topography etc. Validations of ADCP data using current measurements from moored rigs for comparison show usually small differences concerning the speed of the current, while the data on the current direction may show considerable deviations. In this respect the results from our calibration experiment carried out during the cruise in April is no exception. There is reason to expect that all directions are affected in about the same degree by the causes for errors mentioned above. The tide will of course modify the flow pattern. However, both the modelled tide (Fig. 8), and measurements from the current meters show a relatively weak tidal signal (10 cm s^{-1}) at the position of the rig in the trench Malangsdjupet, while the measured current was in the order 40-80 cm s^{-1} towards north-northeast. The tide has a much stronger signal (30-40 cm s^{-1}) on the Nordvestbanken. However, also here the measured current was very strong towards north-northwest, with a maximum of ca. 100 cm s^{-1}. At the shelf break the steep continental slope and variable bottom topography probably increased the variability in our ADCP measurements due to the use of bottom track mode in our recording. Variations in current speed and direction within short tracks of 1-2 nm will also tend to reduce the coherence between ADCP and current meter recordings. It is therefore expected that the deviation in current direction between ADCP and current meter is actually caused by topographic steering of the main flow. Although our ADCP data do not include several tidal cycles at the shelf break, the data indicate that the tidal component occasionally was strong enough to counteract the prevailing mean flow along the sampled transects. The flow at Nordvestbanken follows a consistent pattern according to our measurements: A conspicuous clockwise turn in the current direction from eastern to western part of the shelf, was evident during all our cruises, a pattern which appeared irrespective of the tidal cycle. The impact of tide on the flow patterns will increase with decreasing depth, which is evident in the modelled M2 tide from 12 March 1994 (Fig. 8). Conservation of potential energy causes a clockwise turn in current direction on Nordvestbanken. Due to a time lag in tide from north to south, there will also be a small difference from south to north. Results from the tidal model of M2-tide, show an anticlockwise turn west of the shelf break at depth of 2000 m, with a generally low tidal current. In the northern part of the investigated area also diurnal oscillation (K1) may take place as topographic Rossby waves (Gjevik & Straume 1989).

The residual current shown in the present study demonstrated slightly lower current speeds, more pronounced on the shelf in June than in September. The mean current speed calculated for the period 1976 to 1981 obtained from moorings at the NW part of Tromsøflaket decreased steadily towards depth, from 13.0 cm s^{-1} at 25 m to 5.7 cm s^{-1} at 225 m. The maximum residual current velocity is found in the range from 85.0 to 43.0 cm s^{-1} in the same period. Drift speed of satellite tracked drogues drifting (between 12 and 76 hours duration) from Sveinsgrunnen to Malangsgrunnen from 30 April to 4 May 1981, indicated mean speed in the range from 15 to 29 cm s^{-1}, with maximum speed of 50 cm s^{-1} along the shelf break (Sundby 1984). Current measurements obtained at Malangsgrunnen during several time windows from 1972 to 1975 demonstrate large monthly variations in residual current, with a mean from 0.2 to 14.6 cm s^{-1} over a 15 days period at 50 m with a bottom depth of 70 m (Sundby 1976). The data obtained from 1976 to 1981 indicate a seasonal variation in the speed, with maximum in the autumn (September-November) and a minimum in March and April. The above observations are within the range of the residual currents calculated from the ADCP measurements obtained in our study during 1994.

An intensifying of the current speed appears to take place at Nordvestbanken and Malangsdjupet. This is contrary to the expected relaxation of the currents found

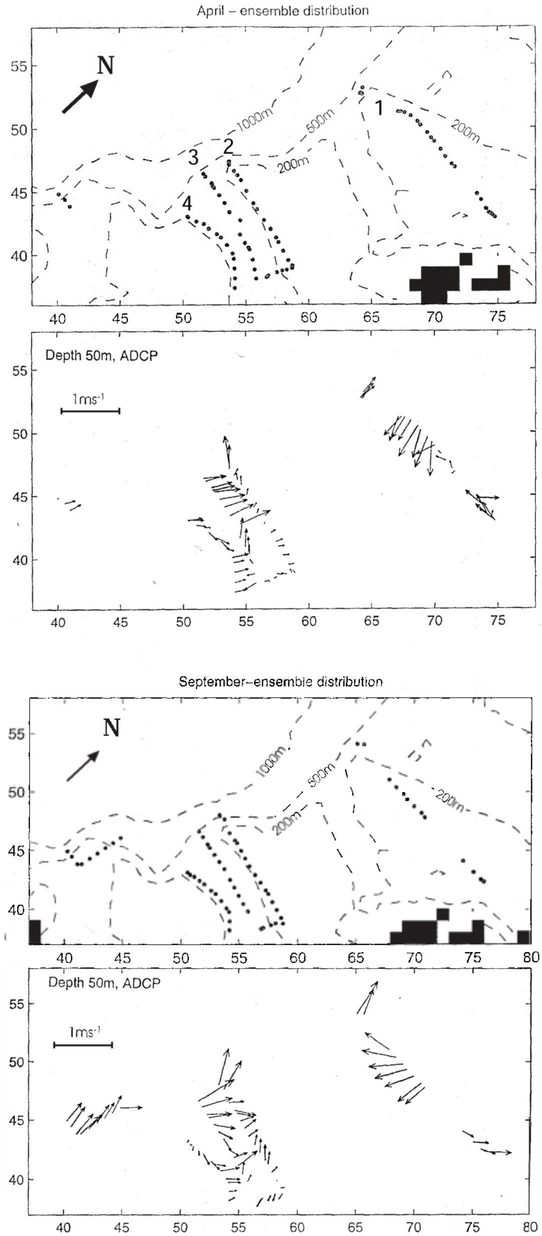

Fig. 11. Current velocities and direction measured at 50 m depth along the transects in April (next upper panel) and September (lower panel) obtained by ADCP. Position of each average is indicated as dots in the two panels with the depth topography, and the length of a vector indicate current speed and velocities obtained by average of 15 minutes of continuous recording while steaming. Note the arrow which gives the north direction. Vertical and horizontal axes are gridpoint numbers. 1-4 are the transect numbers given in Fig. 1.

over banks due to friction (Sundby 1976). In the study area outside Troms, the NCC follows the coastline with the maximum speed along the shelf break at a depth around 50 m (Sætre & Ljøen 1971). Although the mixing of the two water masses occurs south of Vesterålen (Orvik & al. 1995), the border between the NAC and NCC gives rise to strong horizontal and vertical gradients, with gyres and lateral transport in the area of study (Sundby 1976). The two bodies of water vary strongly with regard to thickness, broadness, depth and velocity, which ultimately modulates the current speed in the area.

Front dynamics

Detailed analysis of the current data showed that the front at the shelf break moved laterally during the sampling period of a cruise. Although our sampling programme was not designed to reveal front dynamics, the data indicate that within a few hours, on-shelf lateral movement of at least 5 km was observed in April. This movement may also be a result of oscillations driven by the NAC in this area. In the data set from the current study, both northward and southward flowing currents, give rise to off-shelf transport on the upstream side of the bank, and on-shelf transport on the downstream side. Gjevik & Moe (1994) argued that cross-shelf flow depends of current speed, the width of the shelf and the slope of bank topography in the alongshelf direction.

CONCLUSIONS

Variations in both vertical and horizontal distribution of the three distinct water masses present in the study area mirrored the meteorological changes taking place from March to October. Wind regime during the last 12 hours prior to the current measurements had no detectable influence on the main flow regime. We were also unable to detect any flooding, ebbing or spring-neap influence in the currents obtained by ADCP. Variations in these parameters found between each station during each cruise seemed overruled by large-scale physical processes. Shelf waves, intrusion of wind induced density currents on the shelf, as well as lateral movements in NCC and AC have great influence on the hydrography and the current regime in the Norwegian shelf waters (Sætre & Ljøen 1971; Gjevik & Moe 1994; Orvik & al. 1995), and these processes are probably the major impetus causing short time variation in physical conditions in the study area. Coastal Water (CW) was found covering the shelf during the whole period of study, but only reached the bottom of bank areas in spring. Increased strength of stratification in surface layers during summer, decreased the vertical distribution, but widened the horizontal distribution of CW, and thus facilitated inflow of dense, more saline Atlantic Water (AW) into trenches and onto bank areas. AW was always present along the shelf break and close to the bottom in the trench Malangsdjupet, indicating the importance of the Norwegian Atlantic Current on the current regime in the trench. The increased current velocity found at the shelf break was caused by the Norwegian Atlantic Current. The lack of correlation between variations in hydrography, wind regime, tidal strength and current regime obtained by ADCP, underlined the importance of topography and large physical processes on spatial and temporal variations in the environmental conditions on the north Norwegian Shelf.

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REFERENCES

Andreassen IJ, Wassmann P, Ratkova TN. 1999. Seasonal variation of vertical flux of phytoplankton and biogenic matter at Nordvestbanken, north Norwegian shelf in 1994. *Sarsia* 84:227-238.

Dannevig P. 1966. *Weather, wind and sea at the Norwegian coast*. Bergen, Norway: Nordangers Nautiske Håndbøker. 54 p.

Eide LI, Reiestad M, Guddal J. 1985. *Database av beregnede vind og bølgeparametre for Nordsjøen, Norskehavet og Barentshavet, hver 6 time for årene 1955-81*. Oslo/Bergen, Norway: The Norwegian Meteorological Institute. 38 p.

Eilertsen HC, Taasen JP. 1982. Investigations on the plankton community of Balsfjorden, northern Norway. The phytoplankton 1976-1978. Environmental factors, dynamics of growth, and primary production. *Sarsia* 69:1-15.

Falkenhaug T, Tande K, Timonin A. 1997. Spatio-temporal patterns in the copepod community in Malangen, Northern Norway. *Journal of Plankton Research* 19:449-468.

Flather RA. 1981. Results from a model of the north east Atlantic relating to the Norwegian Coastal current. In: Sætre R, Mork M, editors. *The Norwegian Coastal Current*. Proceedings from the Norwegian coastal current symposium; 1980 Sep 9-12; Geilo, Norway. p 427-458.

Gjevik B, Moe H. 1994. Steady and transient flow around banks located near a shelf edge. *Continental Shelf Research* 14:1389-1409.

Gjevik B, Straume T. 1989. Model simulations of the M2 and K1 tide in the Nordic Seas and Arctic Ocean. *Tellus* 41A:73-96.

Halvorsen E, Tande KS. 1999. Physical and biological factors influencing the seasonal variation in distribution of zooplankton across the shelf at Nordvestbanken, northern Norway, 1994. *Sarsia* 84:279-292.

Leth OF. 1995. *Circulation in Malangen, a north Norwegian fjord* [Cand.scient. thesis]. Copenhagen: University of Copenhagen, Niels Bohr Institute of Astronomy, Physics and Geophysics; Bergen, Norway: University of Bergen, Department of Geophysics. 112 p.

Ljøen R. 1962. The waters of the western and northern coasts of Norway in July-August 1957. *Fiskeridirektoratets Skrifter Serie Havundersøkelser* 13(2):1-39.

Martinsen EA, Engedahl H. 1987. Implementation and testing of a lateral boundary scheme as an open boundary condition in a barotropic ocean model. *Coastal Engineering* 11: 603-627.

Moseidjord H, Svendsen H, Slagstad D. 1999. Sensitivity studies of circulation and ocean-shelf exchange off northern Norway. *Sarsia* 84:191-198.

Orvik KA, Lundberg L, Mork M. 1995. Topographic influence on the flow field off Lofoten-Vesterålen. In: Skjoldal HR, Hopkins C, Erikstad KE, Leinaas HP, editors. *Ecology of Fjords and Coastal Waters*. Elsevier Science B.V. p 165-175.

Ratkova TN, Wassmann P, Verity PG, Andreassen IJ. 1999. Abundance and biomass of pico-, nano-, and microplankton on a transect across Nordvestbanken, north Norwegian shelf, in 1994. *Sarsia* 84:213-225.

Sætre R, Aure J, Ljøen R. 1988. Wind effects on the lateral extension of the Norwegian Coastal Water. *Continental Shelf Research* 9:239-253.

Sætre R, Ljøen R. 1971. The Norwegian coastal current. In: *Proceedings of the first international conference on port and ocean engineering under Arctic conditions*. Trondheim, Norway: University of Trondheim. p 514-536.

Sætre R, Mork M. 1981. *The Norwegian Coastal Current*. Volume 1 and 2. Proceedings from the Norwegian coastal current symposium; 1980 Sep 9-12; Geilo, Norway.

Schwiderski EW. 1980. On charting global ocean tides. *Revue Geophysical and Space Physics* 18:243-268.

Slagstad D. 1987. A 4-Dimensional physical model of the Barents Sea. *SINTEF report* STF48 F87013:1-34.

Slagstad D, Støle-Hansen K, Loeng H. 1990. Density driven currents in the Barents Sea calculated by a numerical model. *Modeling, Identification and Control* 11:181-190.

Støle-Hansen K, Slagstad D. 1991. Simulation of currents, ice-melting and vertical mixing in the Barents Sea using a 3-D baroclinic model. *Polar Research* 10:33-44.

Sundby S. 1976. Oceanographic conditions in Malangen-Fugløybanken-Tromsøflaket. An overview. *Fisken og Havet serie B* 1:1-53.

Sundby S. 1984. Influence of bottom topography on the circulation at the continental shelf off northern Norway. *Fiskeridirektoratets Skrifter Serie Havundersøkelser* 17:501-519.

Svendsen H. 1986. Mixing and exchange processes in estuaries, fjords and shelf waters. In: Skreslet S, editor. *The role of freshwater outflow in coastal marine ecosystems*. Berlin: Springer-Verlag. p 13-45.

Syvitski JPM, Burell DC, Schei JM. 1987. *Fjords: Processes and products*. New York: Springer-Verlag. 379 p.

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