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CURRENT MEASUREMENTS IN THE NORTHEASTERN BARENTS SEA.

By

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ABSTRACT

The Institute of Marine Research (IMR) in cooperation with Knipowich Polar Reseach Institute of Marine Fisheries and Oceanography (PINRO), Murmansk, started in autumn 1991 a current measurement program in the strait between Novaya Zemlya and Frans Josef Land. The objectives of the project were:

- to study water masses and the general circulation in the area
- to estimate the outflow of dense bottom water from the Barents Sea
- to obtain data for boundary conditions for numerical models

During late September and the beginning of October 1991, five moorings, with all together 20 current meters were deployed along one section across the strait. The moorings were recovered one year later. During the period of deployment and recovery, hydrographical investications were carried out along five sections in the area. In addition, some other hydrographic observations were carried out.

The present paper describes the results from the hydrographic observations and the current measurements carried out from the end of September 1991 to early September 1992. The results confirm the assumption that this is the main outflow area of water masses from the Barents Sea. The results indicate a marked seasonal variability in the outflow, varying from 0.7 to 3.2 Sv, and with maximum during early winter. At some locations the current is extremely stable, and current stability above 90% is observed. The main driving force of the current is probably the density field. There is also an extremely good accordance between the variability in air pressure over the Barents Sea and the varibility in the current conditions. Low pressure seems to create a strong circulation in the Barents Sea, while high pressure periods seems to decrease the circulation.

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INTRODUCTION

An important process for the climate of the Barents Sea is the formation and outflow of bottom water from the eastern basin. During the winter, water of high density is formed as a result of cooling and ice formation, a process described in detail by Midttun (1985). The bottom water is formed over the shallow bank areas surrounding the eastern basin, and occasionally the basin is entirely filled up with this water. According to the bottom topography of the eastern Barents Sea, most of this dense bottom water probably leaves the Barents Sea through the strait between Novaya Zemlya and Frans Josef Land. The outflowing volume may vary considerably from one year to another, and so will the corresponding infow of Atlantic water to the Barents Sea (Midttun 1985; Midttun & Loeng 1987).

Based on two months of current measurements between Norway and Bjørnøya (Bear Island), Blindheim (1989) calculated the water transport in and out of the southwestern Barents Sea. His results showed a mean transport of 3 Sv in, and about 1 Sv out through this section. The variability in this transport may be considerable. Calculations made by a numerical wind-driven model indicate fluctuations of the same magnitude as the mean transport (3 Sv) in Bjørnøyrenna (Ådlandsvik and Loeng 1991). To balance the net inflow, a corresponding outflow is required. According to available litterature, it is most likely that this transport is located in the area between Novaya Zemlya and Frans Josef Land. In order to observe such fluctuations, long-time current measurements are required.

Knowledge of current patterns from the northeastern Barents Sea is based on hydrographic observations and computations of the dynamical topography. The most detailed current maps from the area are made by Tantsiura (1959) and Novitsky (1961). However, in the area between Novaya Zemlya and Frans Josef Land, the current pattern is rather complicated. Up to now it has been very difficult to make a conclusion on the main current direction in the area.

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- to study water masses and the general circulation in the area
- to estimate the outflow of dense bottom water from the Barents Sea
- to obtain data for boundary conditions in numerical models

The present paper describes the results from the current measurements carried out from the end of September 1991 to early September 1992. The report also includes a description of the hydrographic situation in the area.

MATERIALS AND METHODS

Five moorings with all together 20 Aanderaa RCM-7 and RCM-4 current meters (Aanderaa Instruments 1978; 1987) were deployed from the Norwegian research vessel "Johan Hjort" during a survey lasting from 11 September to 5 October 1991 (Loeng *et al.*, 1991). The position of the moorings are shown in Fig. 1 and in Table 1. The four southernmost moorings were recovered by the same

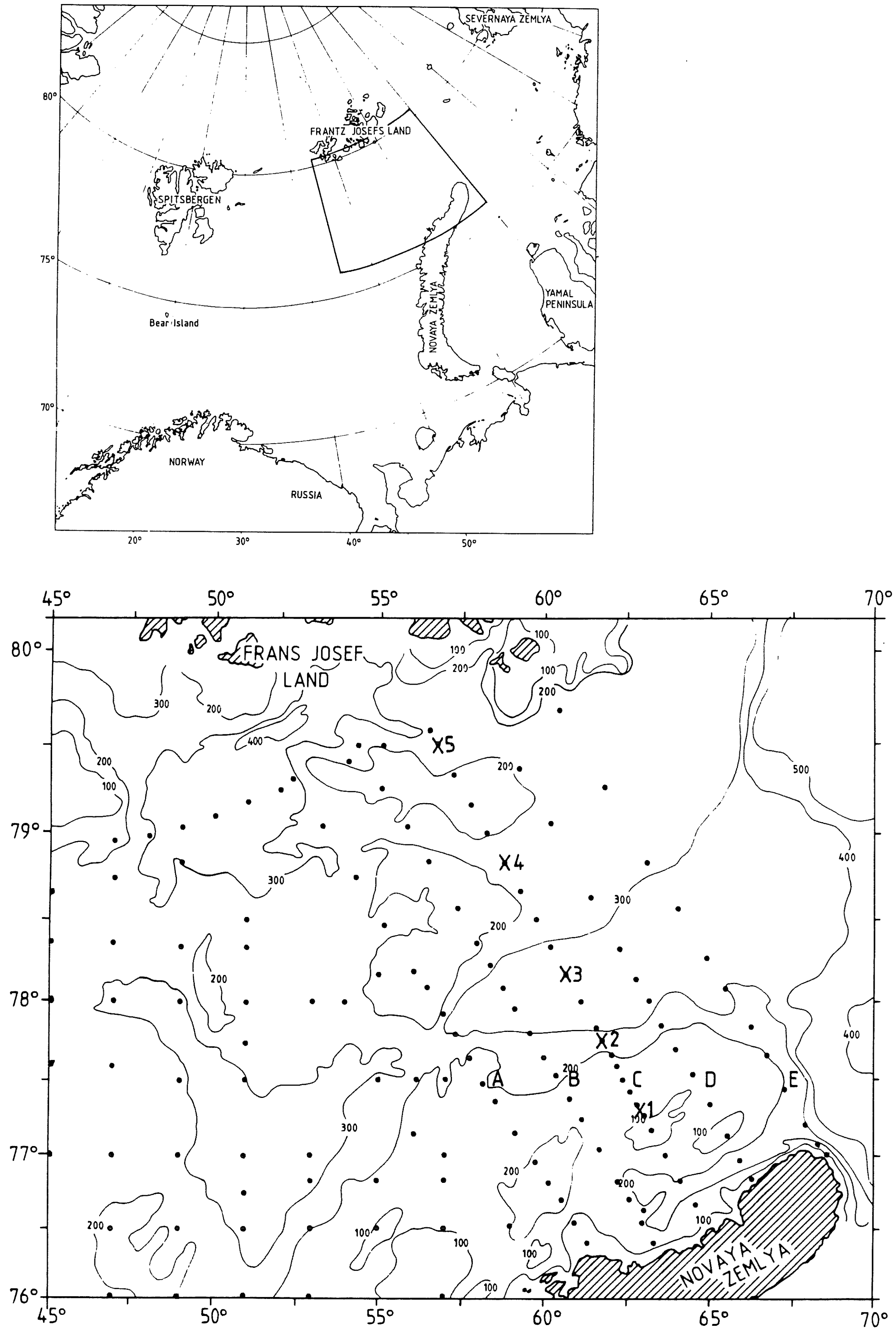


Fig. 1. The obsevation area. Hydrographical stations (•) and positions of the moorings (x). The moorings are given number from 1 to 5. The five cross-sections worked out are marked A, B, C, D and E.

Table 1. The position of moorings , bottom and measuring depths, and date of deployment and recovery.

Mooring	Position		Bottom depth	Depth of instruments	Instruments	
					deployed	recovered
1	N 77° 19.0′	E 62° 55.8′	154 m	60, 100, 144 m	01.10.1991	08.09.1992
2	N 77° 44.9′	E 61° 48.8′	343 m	65, 105, 240, 333 m	01.10.1991	08.09.1992
3	N 78° 09.8′	E 60° 27.4′	353 m	65, 170, 270, 343 m	01.10.1991	08.09.1992
4	N 78° 50.0′	E 58° 38.9′	241 m	75, 115, 180, 230 m	23.09.1991	09.09.1992
5	N 79° 31.8′	E 56° 30.1′	271 m		23.09.1991	Lost

research vessel during a cruise lasting from 4 to 17 September 1992. The fifth and northernmost mooring had been taken away by an iceberg. The subsurface buoy with one current meter was found by a fisherman in late April 1993, in the vicinity of Bear Island, approximately 1040 km from the mooring site. Unfortunately, the current meter was detroyed, and no data was saved. A detailed description of the mooring system is given by Loeng *et al.* (1993).

From "Johan Hjort" hydrographic observations were carried out along the current measurement section both years, and, in addition, at some stations further west. The grid of stations in 1991 is shown in Fig. 1. The observations were carried out with a Neil Brown CTD-system. The distance between stations along the section varied from 7 to 15 nautical miles, elsewhere the distance between the station varied from 20 to 30 nautical miles. At the same time the Russian research vessel "Akhill" carried out hydrographical investigations with Nansen water bottles in four additional sections in 1991 (Fig. 1). In 1992, only sections B and E were worked out. The distance between stations varied from 5 to 30 nautical miles.

The volume flux through the section is estimated in a simple way. The section between 77°10′N and 79°10′N is divided into rectangles, surrounding each current meter. The average normal component of the current as observed by the current meters are used to calculate to transport within each rectangle and then added for the whole section (Loeng *et al.* 1993).

The variability of the current is often called stability, B, and is usually defined as the ratio of averaged vector velocity to the averaged speed (arithmetic velocity). This ratio is expressed as:

$$B = 100\% \cdot \text{average velocity/average speed}$$

The average vectorial velocity is obtained by taking the vectorial mean value of individually observed current vectors, and the arithmetic mean velocity is obtained by averaging the speeds without regard to current direction.

The relative geostrophic current is given by the *thermal wind equation*

$$\rho f \frac{\partial V}{\partial z} = g \frac{\partial \rho}{\partial x}$$

where the x-axis points south and the z-axis down. V denotes the geostrophic current normal to the section, with positive current out from the Barents Sea.

To find the absolute geostrophic current we need the sea surface elevation or the current at a reference level. This was discussed by Loeng *et al.* (1991), where a reference depth of no current at 60 m, just below the pycnocline, was choosen.

RESULTS

Hydrographical observations

Fig. 2 shows the horisontal distribution of temperature, salinity and σ_t at 10 and 100m in 1991. In the surface layer, the highest temperatures are observed along the coast of Novaya Zemlya, in the low saline coastal current. There was a tongue of warm water penetrating northwards to Frans Josef Land at approximately 55°E. Along this longitude we also found the highest surface salinity. This indicate a water transport from south to north. In the eastern part of the area, water with temperature below -1°C and low salinity was observed, which signalize a westgoing transport along the deep channel (Fig. 1). The main distribution of σ_t follows the salinity distribution. At 100 m, the temperature gives a rather complicated picture. There is some water with t>1°C in the central eastern part of the area. This temperature maximum is found just below the surface minimum. A tongue of cold water is penetrating south along the longitude 50°E, coinciding with a minimum in salinity. The lowest values of salinity, however, were observed in the northeastern areas, while maximum salinity was found in the southern part of the investigated area. At 100 m, also maximum values of σ_t was observed in the southernmost areas. The minimum values observed in the northeastern area indicate a transport of watermasses to the south.

Figs. 3 and 4 show the hydrographic conditions along the current meter section (section C, Fig. 1) between Novaya Zemlya and Frans Josef Land in 1991 and 1992, respectively. In both years there was a 20-40 m thick surface layer with low saline melt water separated from the underlying water masses by a rather sharp transition layer. Below 100 m the salinity varied from 34.6 to 34.9, and there was almost no difference between the two years. Previously, maximum salinity values above 35.0 have been observed (Midttun 1985).

The coldest water was found in a rather thin layer just below the transition layer. The thickness of the cold water layer (t< -1°C) increased considerably from 1991 to 1992 in the area north of 78°N. At the same time, water with t > 1.5°C disapeared, and the rest of the core of "warm water" (t > 1°C) was displaced to the south.

The density distributions along the section C in 1991 and 1992 have many similarities. In the deepest part between 77°30′and 78°30′N the water is less dense at a given depth. North and south of the deep area there are sloping isopycnals more or less following the bottom slope. This indicates an outflow increasing toward the bottom at the southern slope and an inflow increasing toward the bottom about 78°30′N.

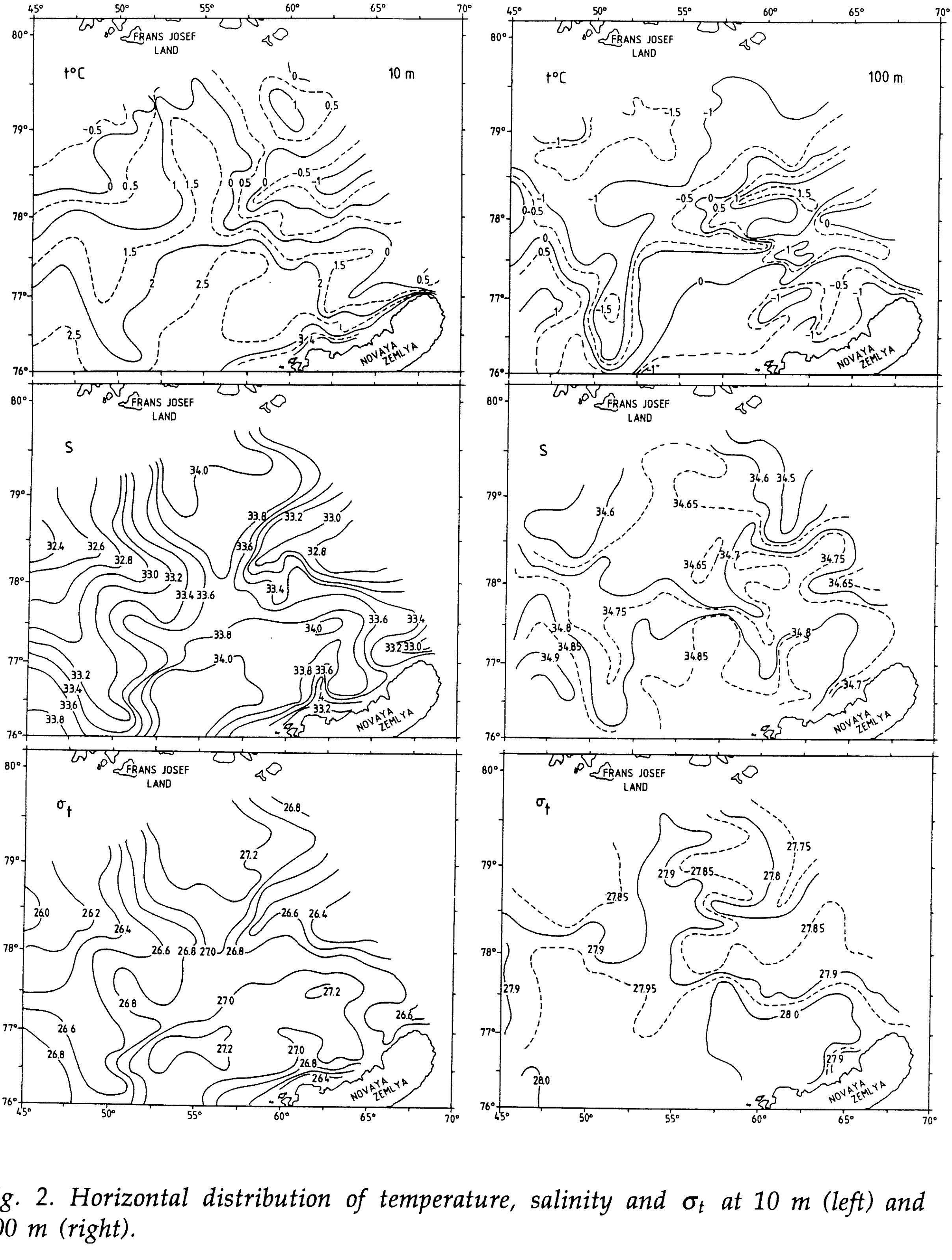


Fig. 2. Horizontal distribution of temperature, salinity and σ_t at 10 m (left) and 100 m (right).

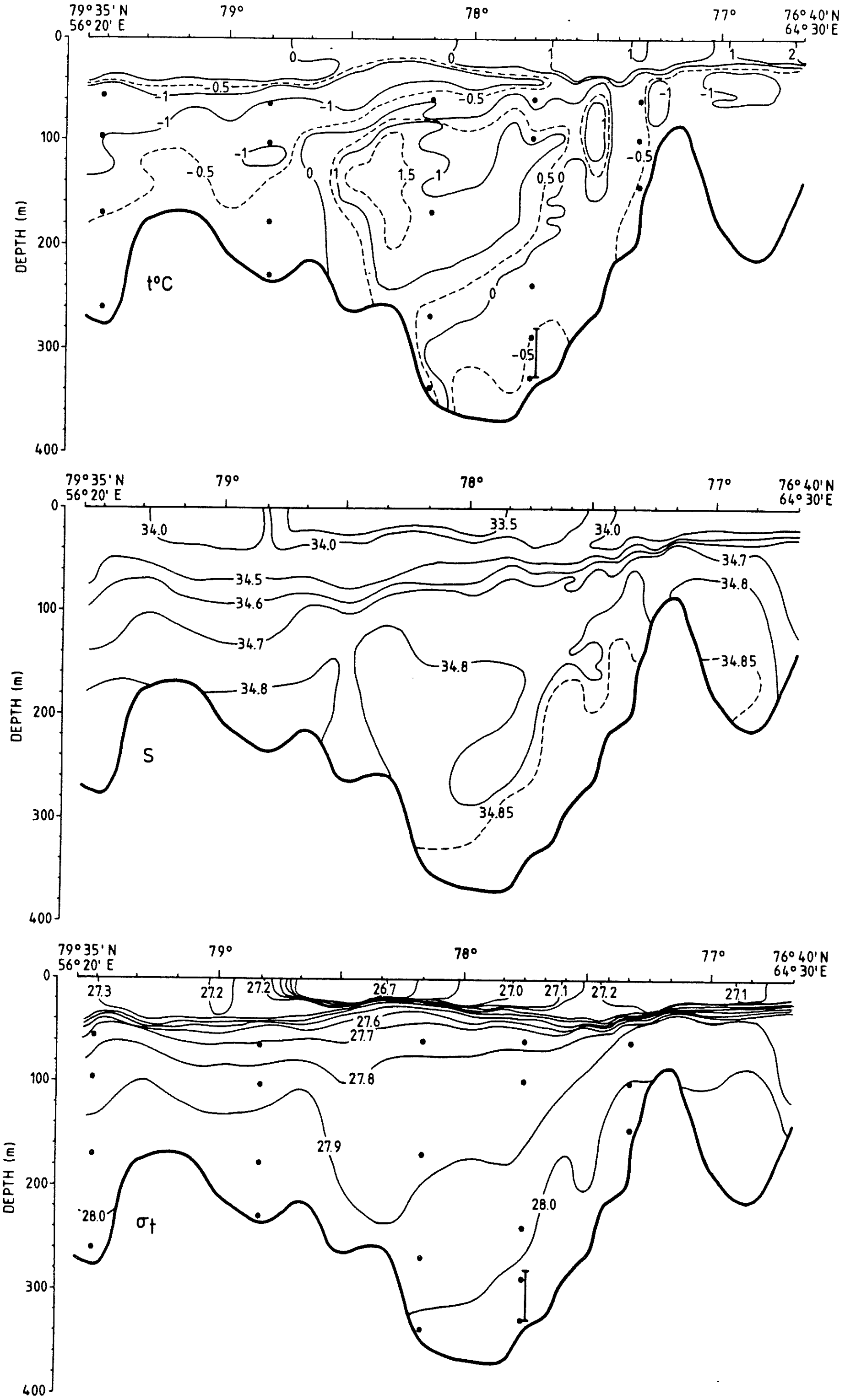


Fig. 3. Distribution of temperature, salinity and σ_t along section C in 1991. The positions of the deployed current meters are indicated by •.

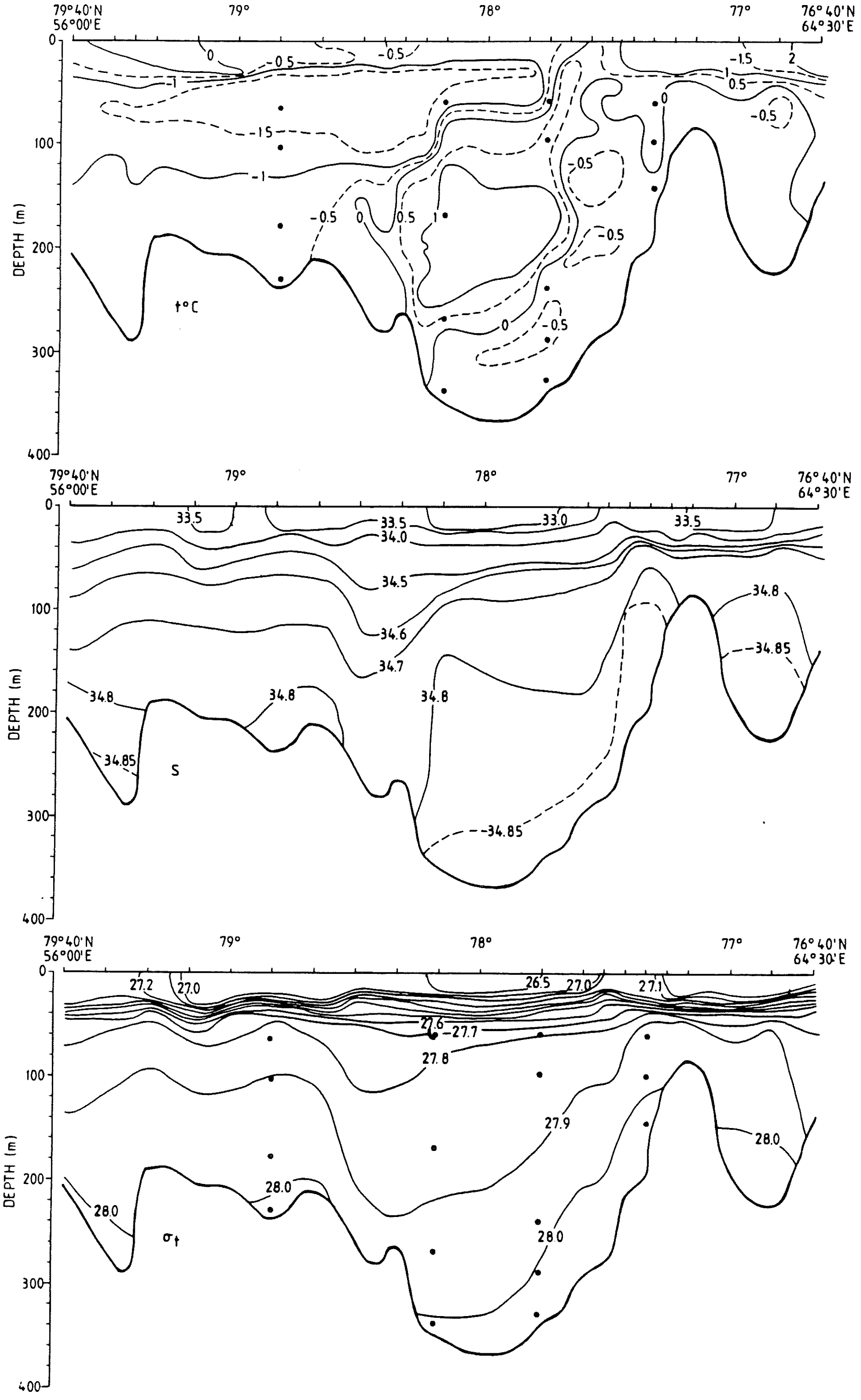


Fig. 4. Distribution of temperature, salinity and σ_t along section C in 1992. The positions of the recovered current meters are indicated by •.

Figs. 5 and 6 show the vertical distribution of t, S and σ_t along sections A and E in 1991 (see Fig. 1). The conditions have several similarities to those observed along section C. In both sections there is a well mixed surface layer with melt water. The thickness of this surface layer seems to decrease eastwards. At the same time the surface salinity also decreases eastwards probably due to heavier ice melting. The vertical gradients in the temperature became less pronounced eastwards. Below the transition layer the cold arctic water was observed in the northern part. The temperature in the core with warm water, seems to increase eastwards. The corresponding salinity is close to 34.8 with decreasing values westwards. The changes in the distribution of temperature, salinity and σ_t from 1991 to 1992 in sections B and E, were similar to those observed in section C (Figs. 3 and 4).

Geostrophic current

In order to get an impression of the density driven current in the area, we calculated the geostrophical current through the section. Contour plots of the resulting geostophic current normal to the section are shown in Fig. 7. Here positive values denote currents out from the Barents Sea.

The strongest currents are calculated to be the outflow between 77°20′and 78°00′N. This outflow had in 1991 a maximum velocity of more than 5 cm s^{-1} and was stronger than in 1992 when the maximum velocities were between 3 and 4 cm s^{-1}. The outflow increases toward the bottom. An interesting observation is that the outflow was split in two cores both years. The moorings no. 1 and 2 were situated in these cores, and as described below these current meters showed a consistent outflow and, for most of the year, strongest outflow close to the bottom.

In the northern slope, at about 78°40′N the geostrophic computations give an inflow of more than 1 cm s^{-1} for both years. Also here the inflow increased with depth as expected. Unfortunately there were no moorings in this area to confirm the result. Mooring 4 at 78°50′N is about the position of the vertical zero velocity contour. All current meters at this mooring report a mean outflow each month. Further south in the steepest part of the slope mooring 3 was the most variable with respect to in- and outflow. The geostrophic calculations indicate very small current activity in this area.

Current observations

All the data from the current meters are presented in a data report (Loeng *et al.*, 1993). In the present paper only a few summarizing figures are presented.

Fig. 8 shows the progressive vector diagrams from the four moorings. At moorings 1, 2 and 4 the current direction was extremely stable, and the direction of the current was almost the same at all depths. The monthly mean values of current stability in some month exceeded 90%. The highest stability, 97.6% was found in February close to the bottom at mooring no. 2. At that location, the stability exceeded 90% in eigth months. At mooring no. 3, the situation was a bit different with a much more variable current. At the two uppermost current meters, a weak ingoing current was observed. Closer to the bottom, the current direction was eastwards. The figures also show increasing speed toward bottom,

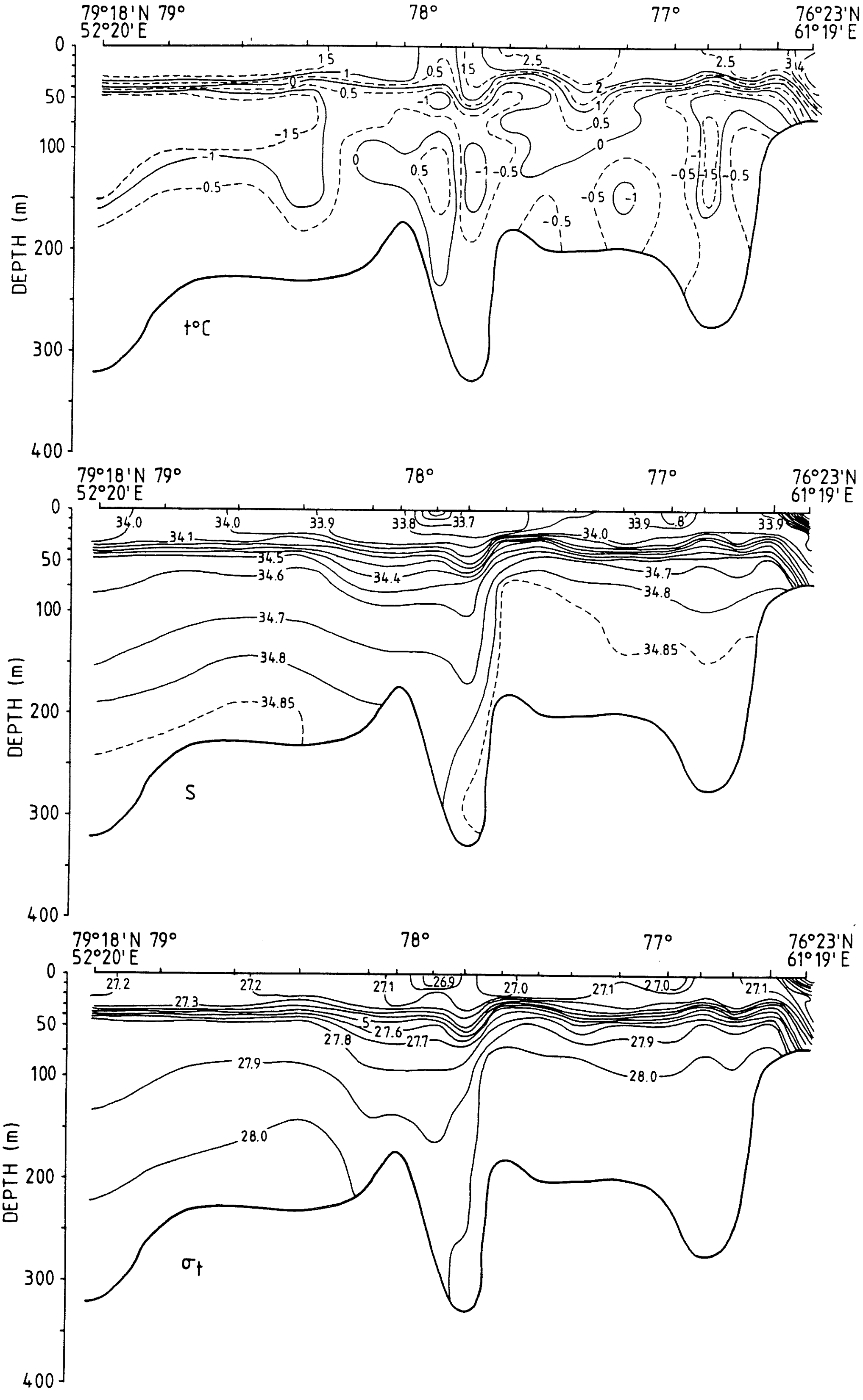


Fig. 5. Distribution of temperature, salinity and σ_t along section A in 1991.

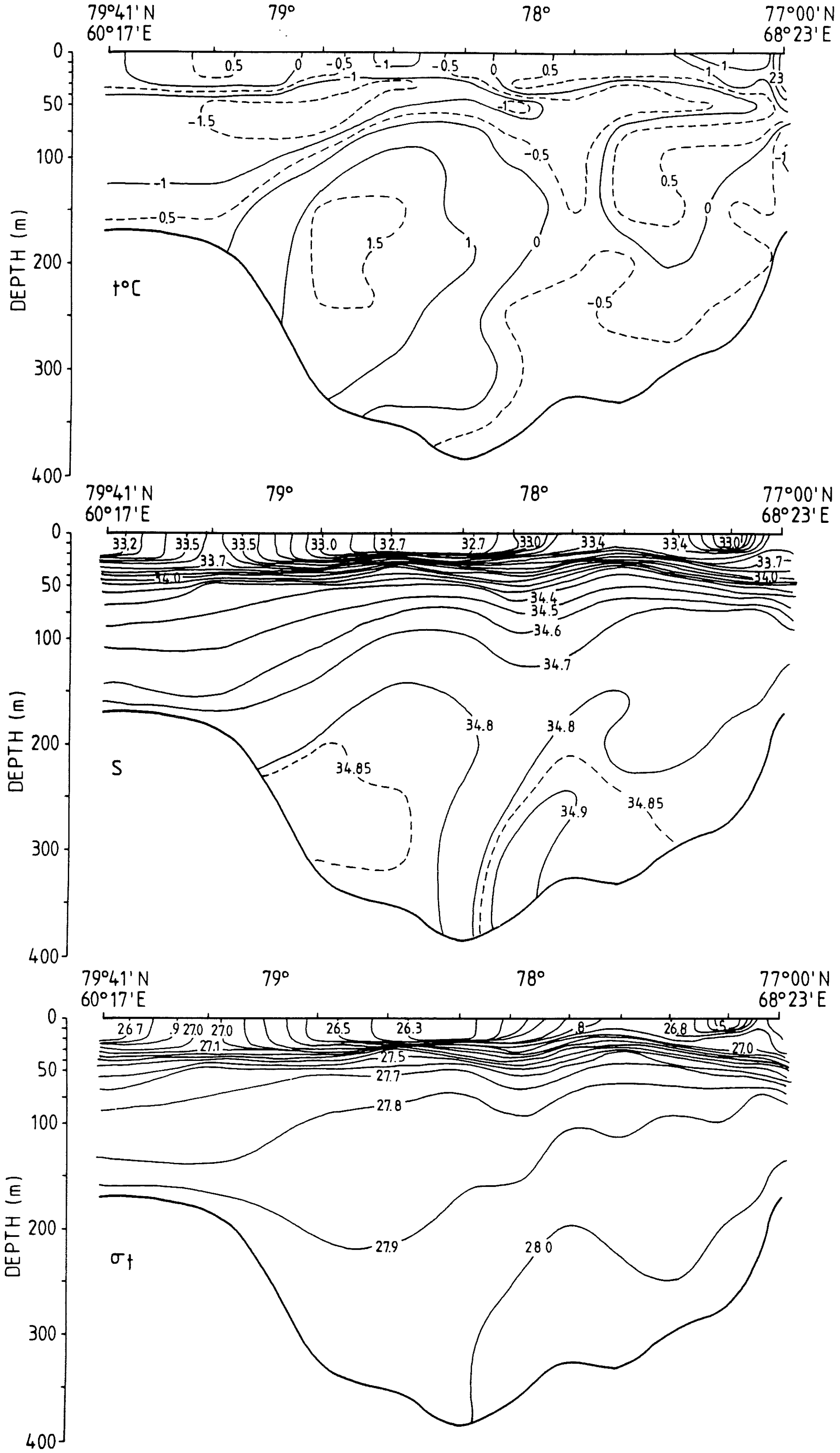


Fig. 6. Distribution of temperature, salinity and σ_t along section E in 1991.

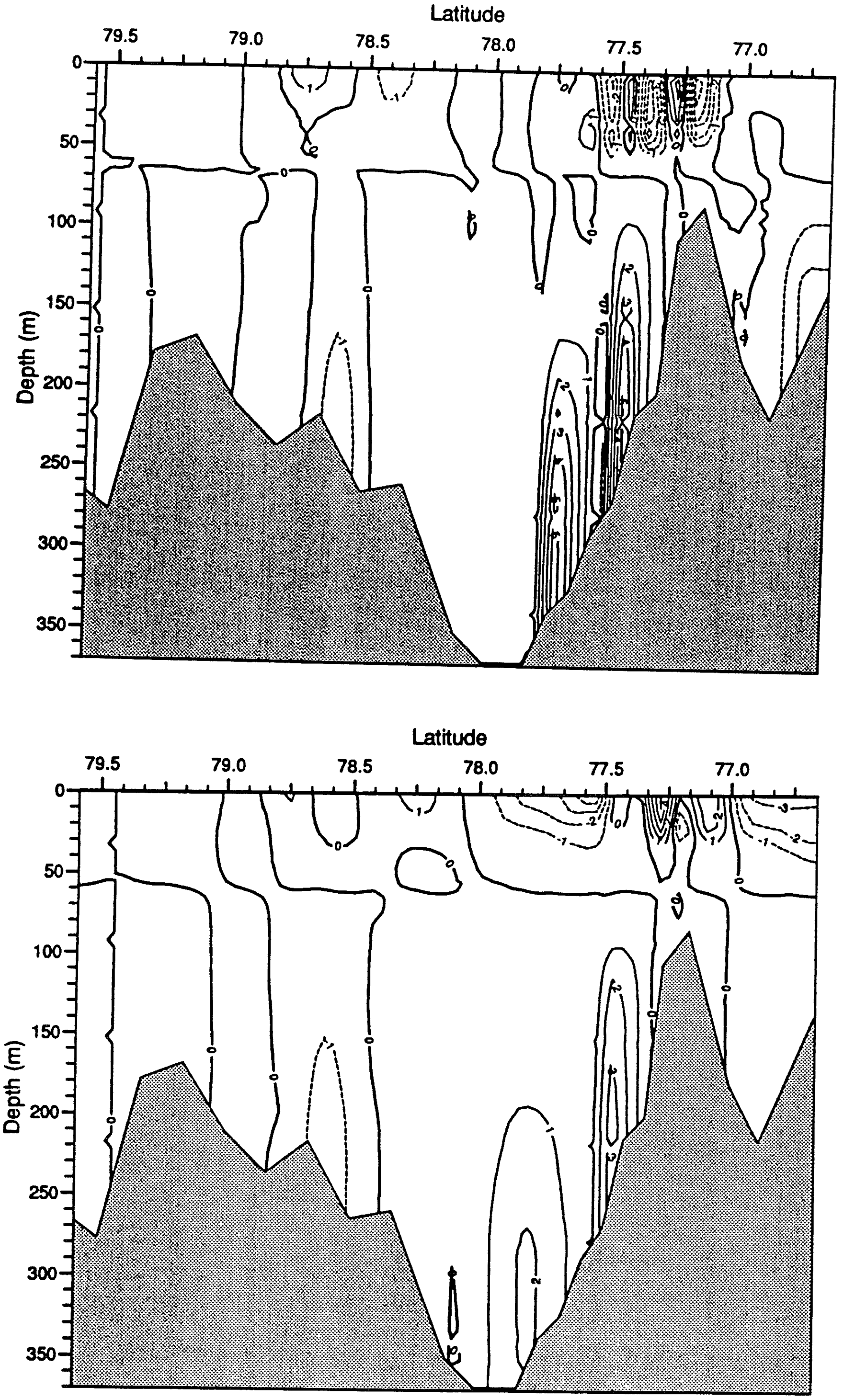


Fig. 7. Geostrophic current velocity (cm s-1) normal to section C in 1991 (upper) and 1992. Positive values denote current out of the Barents Sea. The level of no motion is chosen at 60 m.

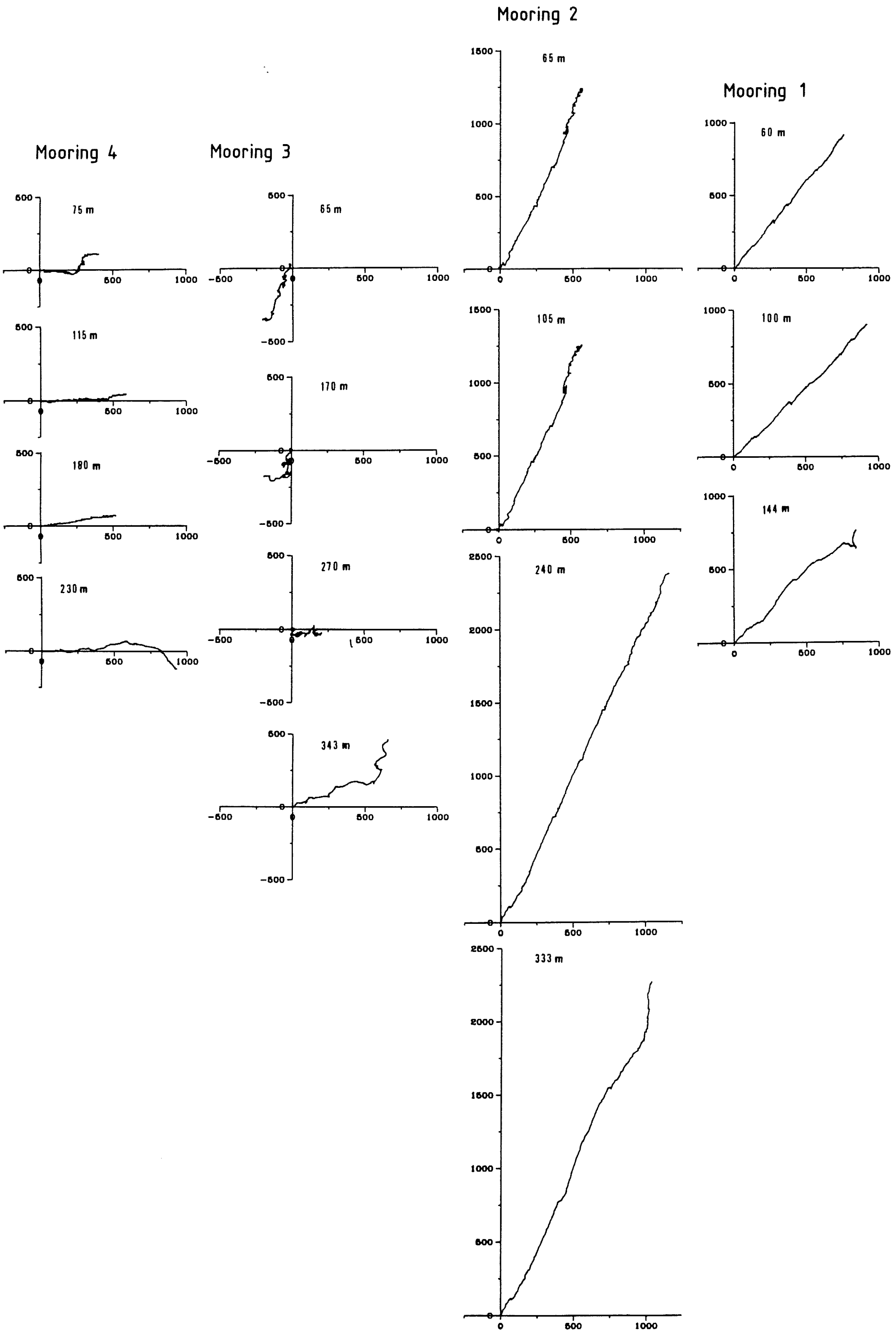


Fig. 8. Progressive vector diagrams for all current meters during the observation period (see Table 1).

especially at moorings 2 and 4. Another typical feature in the current observations, was some sudden changes in the speed (Loeng *et al.* 1993). Those changes were most often related to changes in temperature and salinity, indicating that at least some of the "high speed" periods are connected to passages of eddies with different water masses.

Table 2 shows the mean speed and mean direction in each month during the observation period. The mean current direction is very stable up to March/April. Later on, the conditions seem more variable. The average current speed is highest during the first half year, thereafter the values are lower. Also the current stability shows the same trend (Loeng *et al.*, 1993).

All current meters in the main outflow area (mooring no. 1 and 2) showed the same variability in current speed through the year, as demostrated in Fig. 9. From October, the average speed increased to a maximum in December. Then there was a decrease toward a minimum in April, before some higher mean values observed in May and also partly June. The variability in air pressure is shown in Fig. 10. The pressure decreases to a minimum in December, and then increases to a small maximum in April before another minimum.

The tidal current was much less dominant in this area than in the southern and western parts of the Barents Sea. Only in the results from the two uppermost current meters at mooring 3 and 4, there is a marked influence of the tidal current. At the position of the two southernmost moorings, the residual current was the dominating current component. Also close to the bottom at the two northernmost moorings, the residual current was dominating. The harmonic analysis revealed only a few tidal components. Among the semi-diurnal components the principal lunar component (M_2) was dominating, but also the principal solar component (S_2) appeared. The luni-solar diurnal (K_1) and principal lunar diurnal (O_1) component were the only diurnal ones. In addition, fortnigthly (Mf and MSf) and monthly (Mm and MSm) components appeared in the results from the harmonic analysis (Loeng *et al.*, 1993)

Flux estimation

Table 3 gives the calculated average transport for every month during the observation period. These values are of the same order as reported by Blindheim (1989) for the inflow between Bear Island and Norway. Our results support the hypothesis that the area beetween Frans Josef Land and Novaya Zemlya is the main outflow area in the Barents Sea. The results also indicate a seasonal cycle with high flux values during the late autumn and early winter, with a maximum in December. It should be noted, however, that we did not get any observation from the northernmost part of the section, which is expected to be the area with the highest inflow.

DISCUSSION

The hydrographic observations revealed a rather complicated picture of the physical oceanograhpic situation in the area. The conditions are strongly

Table 2. Mean velocity, V (cm s-1), and direction (°) of the current for each month.

		October		November		December		January		February		March		April		May		June		July		August		September	
Mooring	Depth	V	Dir.	V	Dir.	V	Dir.	V	Dir.	V	Dir.	V	Dir.	V	Dir.	V	Dir.	V	Dir.	V	Dir.	V	Dir.	V	Dir.
	m	cm/s		cm/s		cm/s		cm/s		cm/s		cm/s		cm/s		cm/s		cm/s		cm/s		cm/s		cm/s	
1	60	4.4	039	4.1	045	7.3	037	5.5	041	4.4	041	6.4	041	3.8	044	4.7	034	3.2	039	4.2	035				
	100	5.5	046	5.6	051	9.4	043	5.6	049	4.6	053	6.8	043	3.3	040	4.2	045	2.9	041	2.8	048				
	144	5.6	046	5.8	053	10.7	037	6.6	051	4.4	066	5.9	057	1.7	108	1.1	108	1.4	327	1.3	014				
2	65	2.5	040	8.0	025	9.6	028	8.6	024	6.5	026	4.0	010	3.8	019	3.9	022	4.4	029	0.1	048				
	105	2.5	035	7.7	025	10.4	027	8.4	026	6.0	028	4.5	015	2.7	006	4.6	018	4.5	031	1.2	033	1.1	285		
	240	7.8	032	9.8	026	15.0	026	11.9	024	9.3	025	8.3	025	7.6	026	8.0	028	7.5	027	6.3	028	7.4	017	6.1	055
	333	8.8	033	11.1	027	15.5	026	11.6	018	10.3	024	8.1	031	7.0	033	8.1	037	3.5	014	4.2	005	6.5	002	5.9	028
3	65	1.8	242	1.0	197	1.1	205	0.7	162	0.1	205	2.9	213	1.1	158	3.4	208	2.0	195	3.0	238				
	105	1.4	221	1.1	154	1.3	217	1.0	262	1.2	072	1.5	213	2.0	072	1.9	211	1.0	120	1.5	248	4.0	265	6.1	267
	270	0.8	176	1.3	094	0.7	142	0.6	285	2.2	077	1.0	170	1.8	048	1.0	072	1.2	120	1.0	086	1.4	314	2.2	256
	343	3.7	073	3.3	065	2.9	079	3.1	047	5.4	074	2.7	111	2.2	080	3.9	024	1.1	326	3.6	036	3.6	008	1.3	344
4	75	2.5	097	1.2	084	2.4	098	1.3	095	2.0	094	1.3	030	1.5	036	0.4	056	1.3	354	1.7	053	3.0	087		
	115	3.5	093	2.1	082	4.2	088	2.0	081	2.9	097	0.7	109	1.2	062	0.5	121	0.3	062	1.8	061	3.0	085	1.6	070
	180	3.7	085	2.4	083	4.5	081	2.7	077	3.1	084	1.5	086	1.8	078	1.9	093	1.2	080	2.0	073	3.0	083	1.5	061
	230	5.0	089	3.0	094	5.6	087	2.7	073	4.1	075	3.0	090	3.3	096	3.7	104	2.7	130	2.3	144	2.0	138	2.0	122

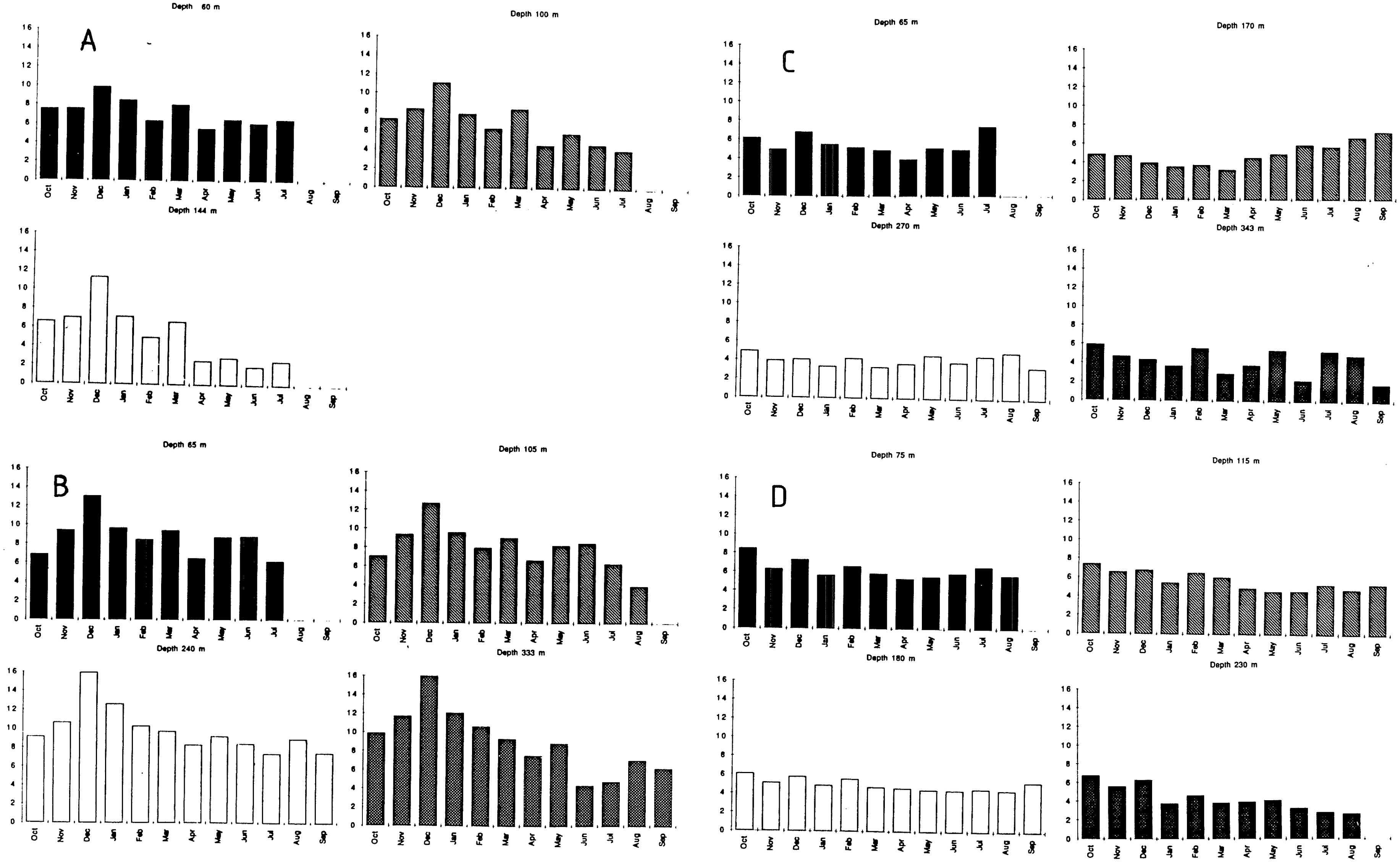
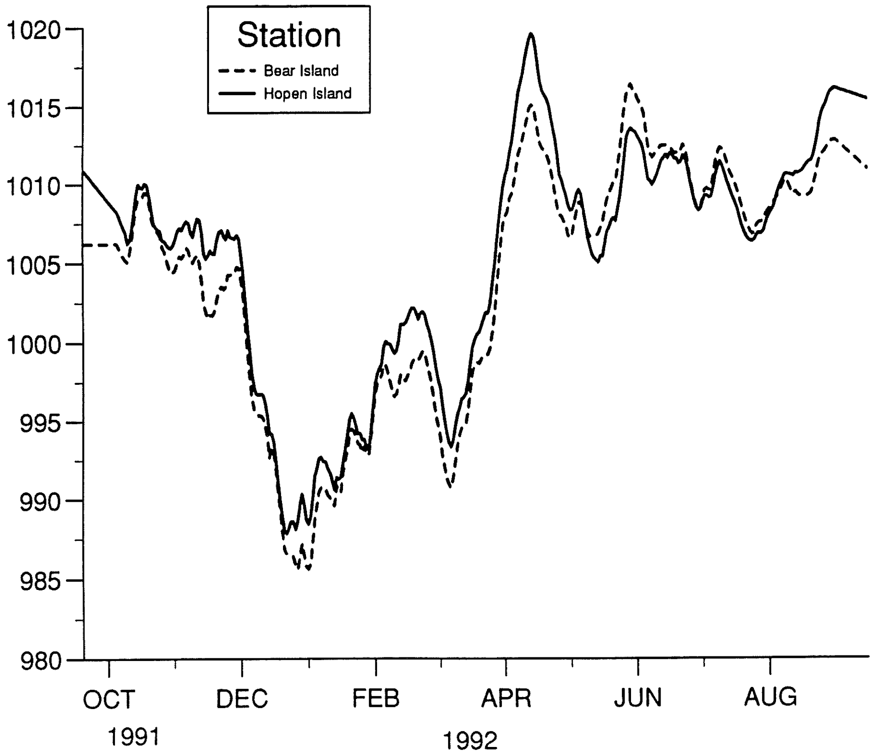


Fig. 9. Monthly mean speed (cm s-1) at mooring 1 (A), 2 (B), 3 (C) and 4 (D).



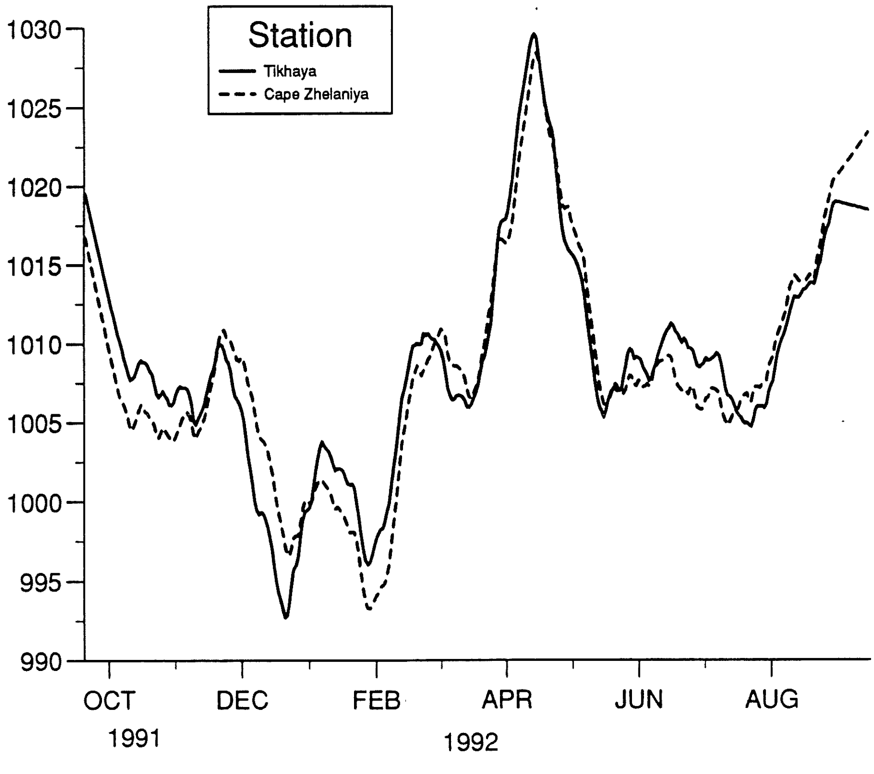


Fig. 10. Air pressure (mbar) at Bear Island and Hopen (upper) and at Tikhaya (Frans Josef Land) and Cape Zhelaniya (Novaya Zemlya).

*Table 3. Mean monthly volume transport (Sv) through the strait between Novaya Zemlya and Frans Josef Land calculated from the mean current velocity observed by the current meters. Values marked with * are based on very few observation points, and are therefore more uncertain than the other values.*

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Flux out	1.9	2.3	3.3	2.4	2.4	1.7	1.7	1.6	1.2	1.2	1.0*	1.9*
Flux in	0.3	0.1	0.2	0.1	0.0	0.3	0.0	0.4	0.1	0.4	0.7*	1.0*
Net flux	1.6	2.2	3.1	2.3	2.4	1.4	1.7	1.2	1.1	0.8	0.3*	0.9*

influenced by the bottom topography, which influences both the water mass distribution and the movement of the water masses.

One of the most characteristic features observed was the core of warm water (t>1°C), which was traced in all sections crossing the strait between the Novaya Zemlya and Frans Josef Land. Since the temperature decreased from east to west, we assume that this is transported into the area from the north. Probably it is the last rest of the Atlantic water which has been tranported along the northern slope of the Barents Sea, and then turned south along the St. Anna Trough.

The current conditions showed clear seasonal variations, with the strongest and most stable currents during the winter time. There is maximum outflow during the period November-February. This in good accordance with the result obtained by Moretskiy and Stepanov (1974), Potanin and Korotkov (1988) and Orlov and Poroshin (1988), calculating the geostrophical transport in the Atlantic inflow between North Cape and Bear Island. Their results showed maximum transport between September and January (Fig, 11). Also Ådlandsvik

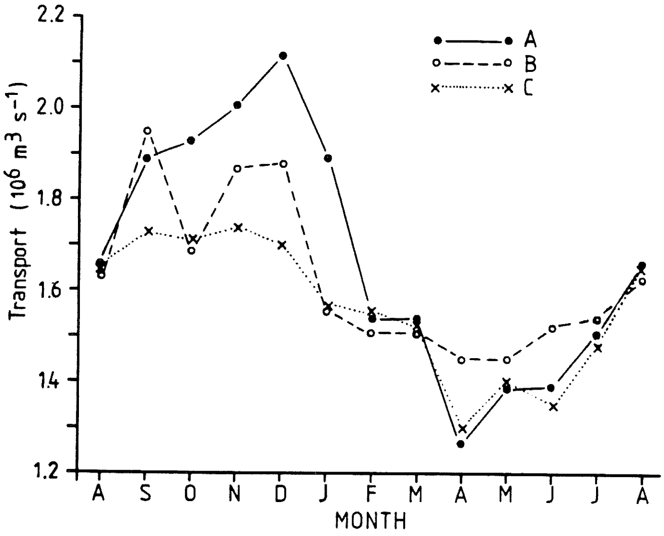


Fig. 11. Geostrophic transport in Atlantic inflow to the Barents Sea as calculated by Potanin and Korotov (1988) (A), Orlov and Poroshin (1988) (B), and Moretskiy and Stepanov (1974) (C).

(1989), found the highest transports in the inflowing Atlantic current to the Barents Sea during winter time, using a wind driven numerical model. All these results show that the most intensive circulation in the Barents Sea take place during winter time. This may be caused by the internal density field as indicated by the geostophical computations, but also by the wind field. The atmospheric pressure during the observation period showed a low pressure period at Bear Island from December to mid-March, and at Frans Josef Land/Novaya Zemlya from December to February. According to Ådlandsvik and Loeng (1991), low pressure is favourable for high inflow of Atlantic water to the Barents Sea. Since the most intensive circulation occurs with only a couple of months delay from the western to the eastern Barents Sea, the process is rather instantaneous.

Based on the results from the current measurements and the hydrographical observations, we have prepared a map for the current circulation in the area (Fig. 12). This map are a bit different from earlier Russian maps, based on dynamics computations, which assumed that the current is zero at the bottom. The current measurements showed that this assumption is wrong in this area. The most pronounced difference between the older current maps and what is shown in Fig. 12, is that we have a marked outflow in large areas of the strait.

Based on the results presented in the present paper and the data report by Loeng *et al.* (1993), we may draw the following conclusions:

- There was no major outflow of dense bottom water from the Barents Sea during the observation period.

- There were small changes in the hydrographic conditions between the two years. The results from the current meters revealed that the largest variability occurred during the cooling period in early winter.

- The geostrophic computations may give a good picture of the main current direction in the area if one choose the right level of no motion. However, the computed current velocities were much lower than the observed ones.

- At some locations, the current conditions were extremly stable. Current stability above 90 % is observed at several localities.

- There is a net volume transport out of the Barents Sea. The transport varies between 0.8 to 3.1 Sv with maximum in late autumn and early winter. This confirm the hypothesis that this is the main outflow area in the Barents Sea.

- The residual current is rather strong in the area. The main driving force is probably the density field. The tidal component is much weaker than other places in the Barents Sea.

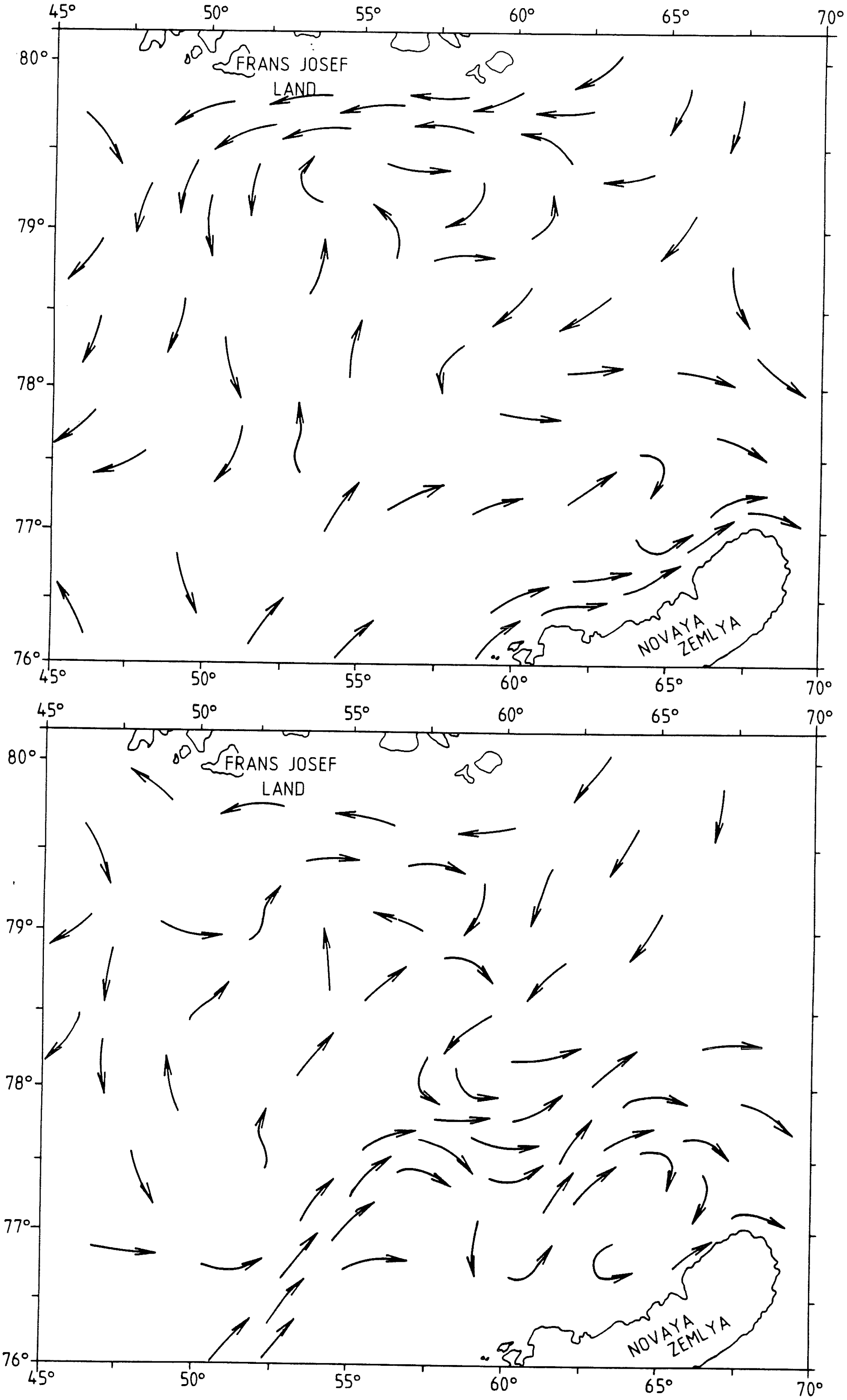


Fig. 12. Current circulation at the surface (upper) and at the bottom.

- There is an extremly good accordance between the variability in air pressure over the Barents Sea and the variability in the current conditions. Low pressure seems to create a strong circulation in the Barents Sea, while high pressure periods seems to lower the circulation.

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