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Current measurements in the Iceland Basin

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Abstract

Long term (6 months) current measurements from 5 moorings in the Iceland Basin have been analysed for the mean circulation and the structure of the variable current components. The flow at all 5 moorings had a strong baroclinic character. The mean circulation in the Sub-Polar Mode Water appears to have a general north-eastward direction with maximum mean velocities of 6-7 cm/s. Over the Icelandic slope mean velocities of the order of 10-20 cm/s have been observed where the Iceland-Scotland Overflow water flows westward along the topography. Near the bottom of the slope of the Hatton Bank water entered the Iceland Basin in a branch of the Deep Northern Boundary Current which has a cyclonic rotation sense in the Iceland Basin. The variable part of the current was analysed by means of principal component analysis. The current variations over the Icelandic slope appear to have a mainly barotropic character while variations in the baroclinic flow of Iceland-Scotland Overflow Water contribute 10% or less to the total energy of the variable deep flow. Over the slopes of the Hatton Bank and the Reykjanes Ridge the variable currents had a clear baroclinic character with shear in both speed and direction.

Introduction

The Iceland Basin is a choking point for the global thermohaline circulation. Through this basin Sub-Polar Mode Water (SPMW) from the North Atlantic Current with high temperature and salinity flows to the Faroese waters where it enters the Norwegian Sea, while cold waters, formed in the Nordic seas enter the Iceland Basin through the Faroe Bank Channel and across the Iceland-Faroe Ridge as Iceland Scotland Overflow Water (ISOW) (Schmitz and McCartney, 1993). The circulation in the Iceland Basin is assumed to be influenced strongly by the topography which guides the ISOW along the Icelandic slope toward the slope of the Reykjanes Ridge (McCartney, 1992; van Aken and de Boer, 1993). Along the slope of the Hatton Bank Lower Deep Water (LDW) is assumed to flow into the Iceland Basin in a branch of the Deep Northern Boundary Current (DNBC) (McCartney, 1992). In the Iceland Basin this LDW is entrained in the underlying ISOW and contributes to the total transport of the DNBC along the Icelandic and Reykjanes slopes (van Aken and de Boer, 1993). Because of tracer distributions the DNBC is assumed to have a cyclonic circulation in the Iceland Basin (McCartney, 1992; Tsuchiya *et al.* 1992). Only few current meter observations have been reported from the Iceland Basin, mainly concentrated on the flow of ISOW in the bottom layer (Shor et al., 1977).

In order to study the barotropic and baroclinic structure of the circulation in the Iceland Basin current meter mooring were deployed in 1989 and 1990 at strategic points in the Iceland Basin. (fig. 1, table 1). This current meter programme was additional to hydrographic surveys, carried out in 1990 and 1991 as part of the DUTCH-WARP research programme (van Aken and de Boer, 1993). Over the steep slope south of Iceland moorings IB89/1 and IB90/1 were deployed in 2 consecutive years at approximately the same position. Moorings IB90/3 and IB90/4 were situated over the slopes of the Hatton Bank and the Reykjanes Ridge respectively, while IB90/2 had a position in the deeper central part of the northern Iceland Basin. All moorings contained 4 current meters, of which 2 were mounted at 40 and 200 m from the bottom (table 2).

In this paper the mean currents are described in terms of mean currents, their directional stability and variance. The structure of the variable part of the flow is studied by means of principal component analysis.

The observations

The geographic position of the moorings is shown in fig. 1. The position of the current meters in the temperature field as observed along a nearby CTD section is shown in fig. 2. The uppermost current meters at moorings IB90/2, IB90/3 and IB90/4 were located above the permanent thermocline in the SPMW. The lowest 2 current meters at moorings IB89/1, IB90/1 and IB90/2 were located in the ISOW layer.

For this study NBA DNC-2M current meters were used. Data were recorded every 30 minutes. The data recovery was on average slightly over 6 months per current meter while 3 current meters failed (table 2). A detailed description of the data and data processing is given by van Aken and Ober (1991; 1992).

In order to eliminate tidal motion the velocity components were low-pass filtered by the consecutive application of running averages with widths of 12.5 h, 24 h and 25 h. These low-pass filtered data were used for further processing, described below. Their data statistics are shown in table 2.

The mean currents

The mean current components from the 5 moorings as well as the mean temperature are listed in table 2. Added to this table is also the Neumann/Weyers stability parameter B, defined by:

$$B = 100\,\bar{c}/c\,(\%) \qquad (1)$$

with $\bar{c}$ being the averaged vectorial velocity and c the averaged arithmetical velocity. This parameter can vary between 0% and 100% and is assumed to be a good measure of the directional stability of the current (Neumann, 1968). With a uni-directional flow B will amount 100%.

In fig. 3a the current vectors in the upper 1520 m are shown, while fig. 3b shows the current vectors in the lowest 200 m. It is clear from fig. 3 and table 2 that the mean current is strongly baroclinic at all mooring positions since the shear vector between the lowest and uppermost current meter has a magnitude of the order of the mean current velocity.

In the upper part of the water column the currents have a direction in the north to east quadrant at moorings IB90/2, IB90/3 and IB90/4 (fig.

2a). This indicates a general north-eastward flow of the thermocline water and the Sub-Polar Mode Water (SPMW) over a large part of the deep Iceland Basin. Over the steep South-Icelandic slope at moorings IB89/1 and IB90/1 the current has a mean west to north direction between 1318 and 1520 m. At this position and depth interval the water mainly consists of a mixture of SPMW, Labrador Sea Water (LSW) and Iceland Scotland Overflow Water (ISOW). Probably part of the north-eastward flowing surface water re-circulates in a cyclonic way close to the Icelandic shelf, in agreement with the hydrographic evidence which suggests a westward flow this slope water over the steep Icelandic slope (van Aken and de Boer, 1993). This circulation scheme agrees with the Lagrangean surface drifter tracks, reported by Otto *et al.* (1992) who observed a general north-eastward surface drift as well as some cyclonic re-circulation along the Icelandic and Reykjanes slopes. The direction stability in the upper 1500 m is of the order of 50 % or less (table 2), indicating considerable eddy activity relative to the mean motion.

The flow in the bottom layer (fig. 3b) shows large mean currents, O(10-20 cm/s), over the steep Icelandic slope, where ISOW flows westwards in the DNBC. This order of magnitude is comparable with the order of magnitude of the short-term mean currents, reported by Shor *et al.* (1977) from positions 100-150 km up-stream. The current direction more or less agrees with the direction of the isobaths, indicative for topographic steering of this strong baroclonic flow. The difference in direction between the mean currents 200 m from the bottom at moorings IB89/1 and IB90/1, only a few miles apart (table 1), is probably due to small-scale local topographic features. A considerable mean shear is observed between 40 and 200 m from the bottom at mooring IB90/1. The shear in velocity is assumed to be due to local horizontal density gradients. In order to check whether the southward veering of the current direction is due to friction effects, the thickness of the bottom Ekman layer was estimated according to Weatherly and Martin (1978) to be of the order of 20 to 30 m. This agrees with observations by Williams and Armi (1991) in the deep boundary current near Newfoundland and rules out frictional effects as cause of the observed directional shear. Most probably local density gradients in the flow direction, caused by the containment of the baroclinic flow in the irregular topography of the Icelandic slope causes the vertical veering of the mean current direction.

If we take the mean near bottom velocities, observed at IB89/1 and IB90/1 as characteristic for the steep slope between 60°30'N and 60°45'N, we can derive a westward transport of water below σ_Θ=27.8 kg m^{-3}, that is the ISOW below the LSW, to be 1.5 Sv for this narrow stretch of only 15 n. miles. Given the temperature and therefore density gradients between 60°45'N and 60°15'N (280 and 360 km in fig. 2a) we can expect the total transport of ISOW to be at least double this estimate.

The near-bottom current from mooring IB90/2, about 65 km south of IB89/1 & IB90/1 shows a mean south-eastward flow (fig. 3b). Because of the larger bottom depth (table 1) and the lower bottom temperature at mooring IB90/2 (table 2), it can be concluded that at mooring IB90/2 also ISOW is transported in the bottom current, in an even less diluted form than at IB90/1. This is confirmed by the hydrographic surveys, described by van Aken and de Boer (1993). The lateral veering of the flow direction is attributed to topographic steering by an extension of the West Katla Ridge (Malmberg, 1975). A similar, although less extensive lateral veering was observed by Shor *et al.* (1977) near the East Katla Ridge. Tracer distributions in the ISOW, as described by van Aken and de Boer (1993) confirm the flow of ISOW around the extension of the West Katla Ridge rather than across it.

The different orientations of the observed near-bottom baroclinic flow directions at IB89/1, IB90/1 and IB90/2 are probably due to a change in orientation of the near-bottom horizontal density gradient. The isopycnals and isotherms in the lowest 500 m follow the bottom contours quite closely (fig. 3a).

At mooring IB90/3, positioned on the north-western slope of the Hatton Bank, a mean north-eastward current with the maximum velocity close to the bottom was observed, closely following the isobaths (fig. 3b). The mean directional shear between 40 and 200 from the bottom was small, compared to the moorings over the Icelandic slope, discussed above. Probably the flow along the more regular topography of the north-western Hatton Bank is less well able to generate density gradients in the flow direction compared to the South Icelandic slope with it's many ridges and canyons. The north-eastern flow along the Hatton Bank is probably part of the DNBC which transports water of southern origin, among which LDW, into the Iceland Basin. This deep boundary current has also been observed along the edges of the Purcupine Abyssal Plain (Dickson *et al.* 1985). LDW transported in this eastern boundary current is assumed to re-circulate in the Iceland Basin and to modify ISOW properties (McCartney, 1992; van Aken and de Boer, 1993). With an inflow along the Hatton Bank and a westward flow along the Icelandic slope the deep circulation of the Iceland Basin has a cyclonic character.

The deep flow observed at mooring IB90/4 is extremely small (table 2) and does not show any southward flow as expected by van Aken and de Boer (1993). Probably the south flowing bottom waters originating from ISOW mixed with SPMW, which follows the topographic contours, was diverted here, due to the rough topography of the Reykjanes slope, with numerous isolated peaks and ridges.

The directional stability B (table 1) appears to be highest where strong baroclinic currents are found, subject to topographic steering. In the bottom layer at moorings IB89/1 and IB90/1 B is of the order of 90%. The lowest B values (O[20-30%]) are found over the Reykjanes Ridge (mooring IB90/4) and between 1318 and 1520 m over the steep Icelandic slope (moorings IB89/1 and IB90/1). There the flow is irregular with no clearly prevailing flow direction. The B values from the other current meters are of the order of 50 %.

The vertical distribution of the magnitude of the mean flow velocity (fig. 4) suggests a minimum in the energy of the mean flow to be found between close to 1000 m in between the main thermocline and the layer of Labrador Sea Water (van Aken and de Boer, 1993). For dynamic computation of the geostrophic circulation the reference level should be chosen at about this level.

The structure of low frequency variations

The low-pass filtered currents were de-trended by subtracting a least squares approximation. The resulting currents present the variable part of the current with time scales of 1 day to about half a year. Not any significant correlation was observed between the variations of the current components of current meters, mounted in different moorings, not even between moorings IB90/1 and IB90/2, only 65 km apart. This indicates that the variability of the currents is mainly caused by eddies with horizontal scales less than 65 km.

In order to study the vertical structure of the current variations, principal component analysis (Preisendorfer, 1988) was performed on the variable current components within a single mooring. Several methods exist for the principal component analysis of vector series (Kundu *et al.*, 1975; Mercier and Colin de Verdiere, 1985; Owens, 1985; Lippert and Briscoe, 1990). Here we have incorporated the velocity components as individual real valued scalar quantities, $q_i(t)$ (i=1-2N), where N is the number of current meters in a mooring. With principal component analysis an empirical orthogonal presentation of the data is generated, where the original data are represented by:

$$q_i(t) = \sum_{j=1}^{2N} e_{ij}\lambda_j(t) \quad . \tag{2}$$

Here e_{ij} are the empirical orthogonal functions (EOF) and $\lambda_j(t)$ are the corresponding amplitudes. Since the amplitudes are not correlated, that is

$$\langle \lambda_i \lambda_j \rangle = l_j \delta_{ij} \tag{3}$$

where the angle brackets represent the ensemble average over t, l_j is the variance of amplitude λ_j, and δ_{ij} is the Kronecker delta. This implies that the variance of a scalar parameter can be written as

$$\langle q_n q_n \rangle = \sum_{j=1}^{2N} l_j e_{nj}^2 \quad . \tag{4}$$

From (4) it appears that the variance of q_n is formed by the addition of the contributions of the different EOFs. If there is some structure in the relation between the variables q_n usually a few EOFs can account for most of the variance of q. Therefore the EOFs are ordered for decreasing variance. For this study the EOFs and their amplitudes were determined according to the methods described by Preisendorfer (1988).

An EOF, based on a series of N current vectors, can be represented as a vector in a 2N-dimensional space, but also as a series of N 2-dimensional vectors. Each of these 2-D vectors can be related to one of the current meters. We will use this property to present the structure of each EOF as a series of N 2-D vectors.

Mooring IB90/2 in the centre of the northern Iceland Basin and mooring IB90/3 over the Hatton slope covered a large part of the water column (fig 3a). The current components from IB90/2 and IB90/3 (N=4) were developed into EOFs.

The cumulative contribution of the EOFs to the total variance or energy at the levels of the current meters at IB90/2 (fig. 5, full line) shows that the first 2 EOFs account for 81% (EOF1 56%, EOF2 25%) of the total energy while the remaining EOFs each contribute only a few percent to the total energy. EOF1 of IB90/2, when plotted as a series of 4 current vectors (fig. 6a), shows nearly parallel vectors with only a small shear. Also EOF2 is presented by nearly parallel vectors with low shear, more or less perpendicular to the vectors representing EOF1 at all 4 current meter levels (fig. 6a, dashed lines). By determining the variable barotropic current from an average of the current components of all 4 current meters the contribution of the barotropic current to the total eddy energy was determined to be 75%. This suggests that the current variance at the site of mooring IB90/2 mainly is formed by nearly barotropic eddies or waves, generating a NW-SE oriented variance ellipse. No predominant rotation sense of the barotropic current vector could be determined by means of a rotary-component spectral analysis (Gonella, 1972).

For mooring IB90/3 it appeared, from the cumulative contributions to the total energy (fig. 5, dashed line) that the first 2 EOFs contributed 66% to the total energy. But for IB90/3 both EOF1 and EOF2 showed a strong shear in direction as well as in velocity, concentrated in the main thermocline (fig 6b). This implies that along the Hatton Bank not only the mean current, but also the variable part of the current has a mainly baroclinic character.

The variable current at IB90/4 (N=3), shows an EOF structure with a maximum shear in both EOF1 and EOF2 in the permanent thermocline (fig. 7b). These 2 empirical modes explain 70% of the total eddy energy (fig.

7a). This implies that the eddy energy over the Reykjanes slope mainly can be attributed to baroclinic eddies, similar to the slope of the Hatton Bank.

In order to study the structure and relative importance of the variations in the flow of ISOW, the data from the deepest 3 current meters from moorings IB89/1, IB90/1 and IB90/2 were analysed by means of principal component analysis. Since here no data from the permanent thermocline or shallower levels are involved it is expected that the analysis will combine the barotropic mode and the first baroclinic mode into single EOFs, while the EOFs with baroclinic character are expected to be caused by variations in the overflow. The resulting EOF1 and EOF2 represent in all 3 cases well over 80% of the total energy (fig. 8), while their structure is mainly barotropic with low shear in direction and velocity (fig. 9a, c, e). EOF3 and EOF4 had a clear baroclinic character with the shear concentrated above 200 m from the bottom at moorings IB89/1 and IB90/1 and at about 200 m at mooring IB90/2 with EOF3 more or less perpendicular to EOF4 (figs. 9b, d, f). These EOFs are clearly connected with the baroclinic variations in the flow of ISOW relative to the overlying water. However, the total energy, involved in these baroclinic modes contributes only of the order of 10% or less to the total energy (fig. 8), as measured with the lowest 3 current meters.

Summary & conclusions.

Current observations from 5 moorings in the Iceland Basin have been analysed to determine the structure of the mean circulation as well as the structure of the variable or eddy part of the motion.

The mean flow, as observed with the current meter moorings in the Iceland Basin has a strong baroclinic character with shear in direction as well as in velocity. The mean currents in the SPMW above the permanent thermocline have a general north-eastward direction. At deeper levels, in the DNBC, the flow is cyclonic, with a north-eastward inflow along the slope of the Hatton Bank and a westward outflow over the steep Icelandic slope. Especially in the lowest 200 m at moorings IB89/1 and IB90/1 the mean flow transports cold ISOW with mean velocities of the order of 10-20 cm/s and with very high (>90%) directional stability. Irregularities in the topography like ridges appear to guide the baroclinic near bottom flow by influencing the density field. Such a topographic effect is assumed to be responsible for the south-eastward flow of ISOW as observed at IB90/2, in the centre of the northern Iceland Basin. Over the slope of the Reykjanes Ridge the mean currents were very weak and had a low directional stability.

The current variations, analysed by means of a principal component analysis, appear to be mainly barotropic in the centre of the Iceland Basin (IB90/2) while over the slopes of the Hatton Bank and the Reykjanes Ridge these variations have a strong baroclinic character with maximum shear in the permanent thermocline. Over the Icelandic slope, where ISOW is found near the bottom, the main variations of the current below the permanent thermocline presented by EOF1 and 2 reveal a low shear in direction and velocity. There EOF3 and 4 represent variations in the baroclinic flow of ISOW along the bottom. However these baroclinic modes only contribute of the order of 10% to the total eddy energy.

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Table 1

geographical mooring information

mooring	latitude	longitude	water depth
IB89/1	61° 33.1' N	20° 00.8' W	2120 m
IB90/1	61° 34.1' N	19° 57.8' W	2118 m
IB90/2	60° 59.6' N	19° 59.3' W	2388 m
IB90/3	59° 16.1' N	18° 24.7' W	1906 m
IB90/4	58° 45.1' N	28° 39.6' W	1923 m

Table 2

mean currents meter readings (standard deviation in brackets), direction stability B and number of days, recorded

mooring ident.	depth (m)	distance to bottom (m)	east comp. (cm/s)	north comp. (cm/s)	stability (%)	days recorded
IB89/1	1320	800	-1.2 (7.8)	1.6 (7.2)	19	147
IB89/1	1520	600	-2.3 (7.9)	0.7 (7.7)	21	145
IB89/1	1920	200	-12.8 (7.4)	1.4 (5.7)	85	140
IB89/1	2080	40	no data recorded			
IB90/1	1318	800	no data recorded			
IB90/1	1518	600	-3.9 (9.0)	1.0 (8.3)	36	173
IB90/1	1918	200	-15.2 (7.8)	-1.5 (3.1)	96	198
IB90/1	2078	40	-17.7 (8.0)	-7.2 (5.0)	96	212
IB90/2	488	1900	6.1 (7.7)	2.6 (8.7)	54	213
IB90/2	1388	1000	6.2 (8.0)	1.7 (11.2)	48	183
IB90/2	2188	200	4.6 (6.6)	-2.9 (7.7)	49	182
IB90/2	2348	40	3.1 (6.3)	-4.7 (6.4)	52	210
IB90/3	306	1600	1.9 (7.8)	5.9 (9.2)	52	202
IB90/3	1006	900	-0.4 (3.7)	1.4 (3.2)	28	186
IB90/3	1706	200	2.4 (4.6)	2.2 (4.6)	48	198
IB90/3	1866	40	3.9 (4.8)	3.0 (3.9)	58	192
IB90/4	323	1600	0.4 (5.2)	0.5 (5.1)	14	205
IB90/4	1023	900	1.4 (4.5)	1.3 (2.9)	34	192
IB90/4	1723	200	-0.5 (2.2)	0.4 (1.5)	19	169
IB90/4	1883	40	no data recorded			

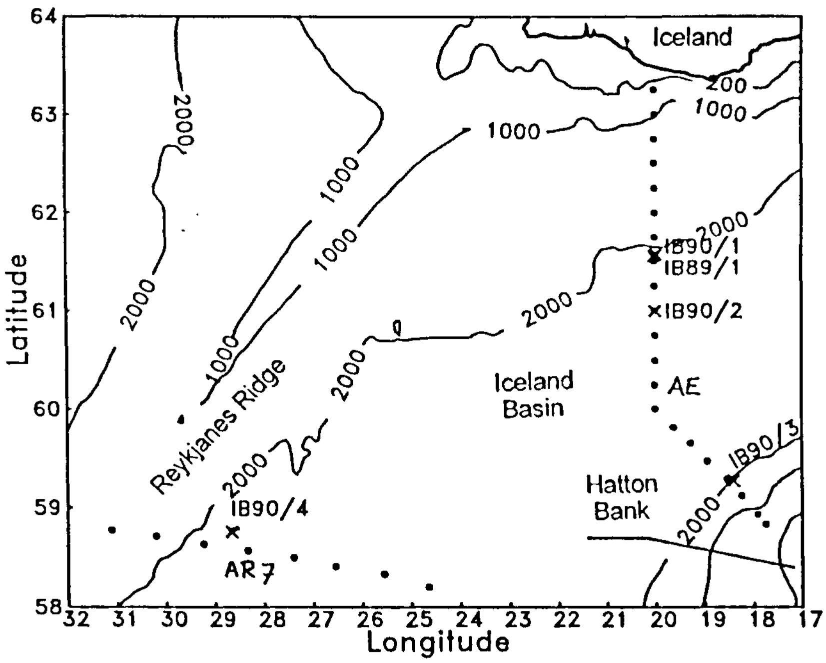

Fig. 1 Topography of the Iceland Basin (depth in m) with the positions of the moorings indicated with crosses (x). The dots indicate the positions of CTD stations along 2 hydrographic survey lines (AE and AR7), occupied in April 1991.

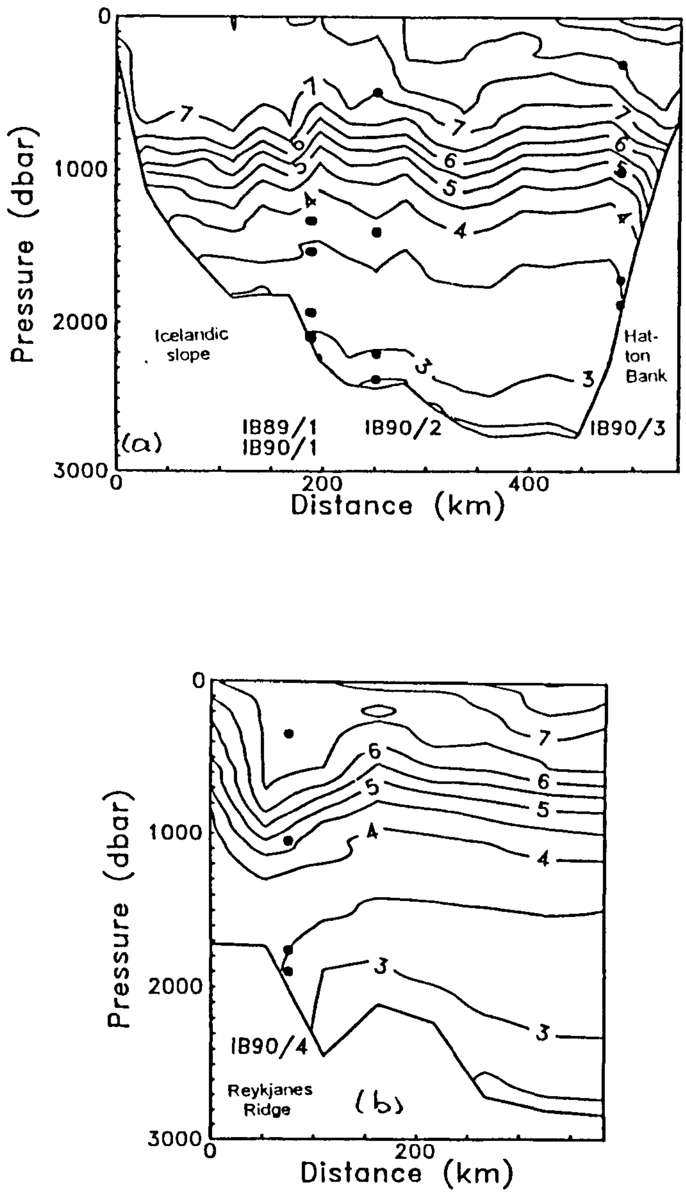

Fig. 2 Position of the moored current meters, projected on the potential temperature field from the nearby CTD sections. a) section AE; b) section AR7.

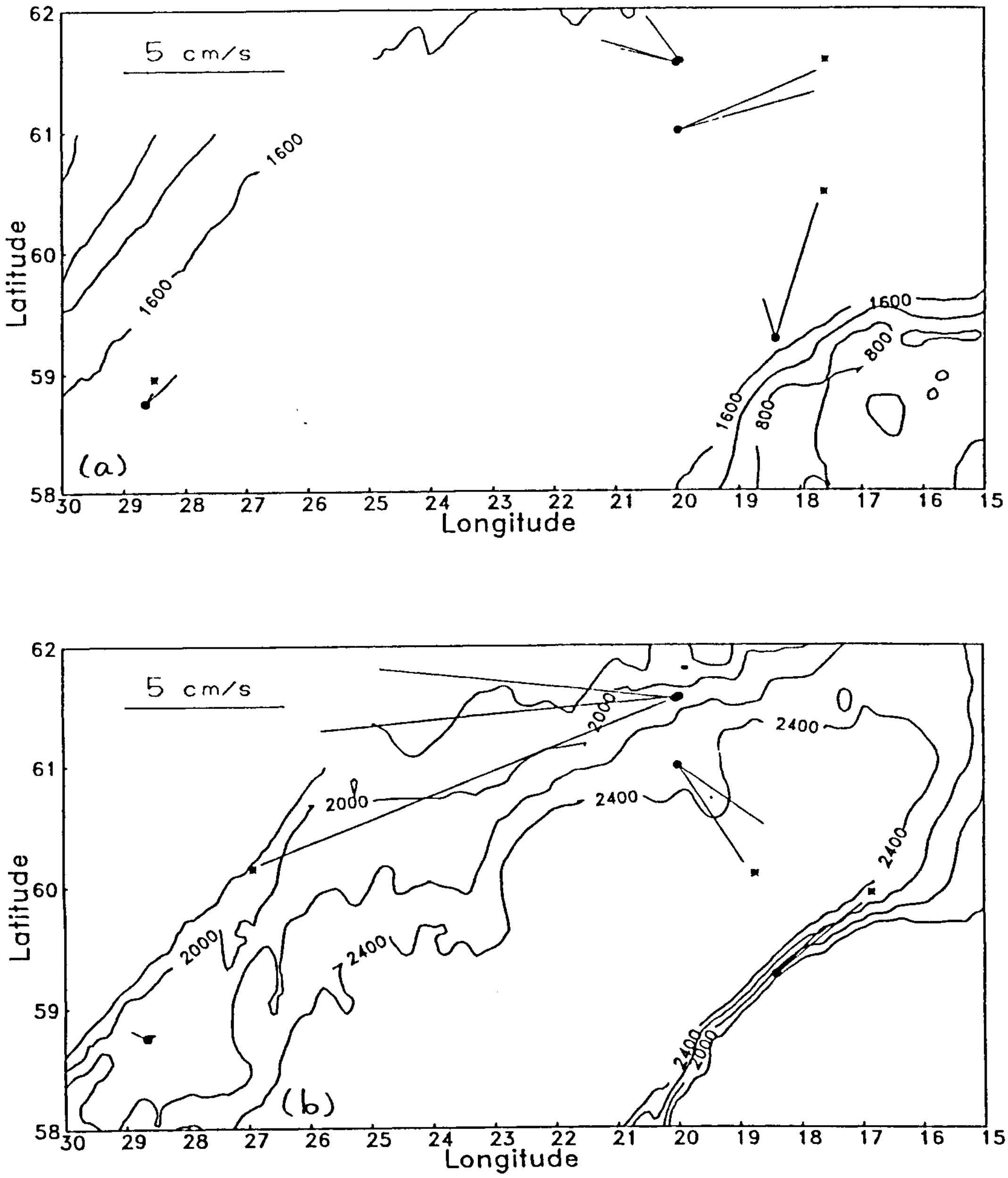

Fig. 3 Mean current vectors with the surrounding topography. a) current vectors in the upper 1520 m, The current vectors in the SPMW are marked with and asterisk (*); b) current vectors from the lowest 200 m above the bottom. The currents at 40 m from the bottom are marked with an asterisk (*).

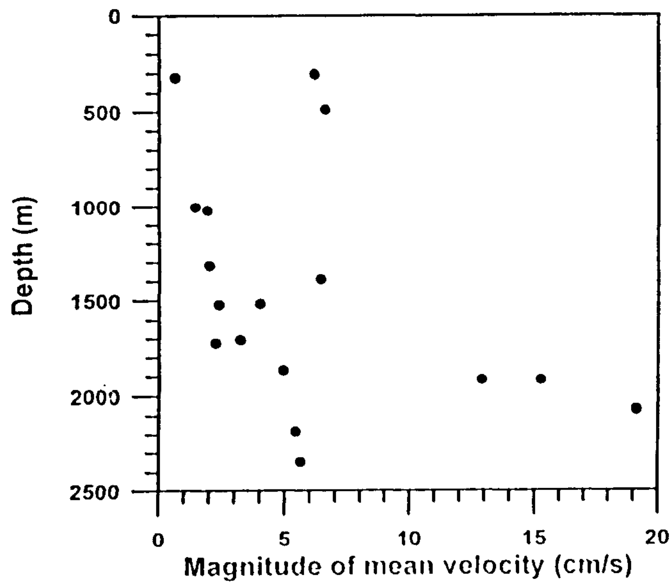

Fig 4 Magnitude of the mean current vectors, plotted versus the depth.

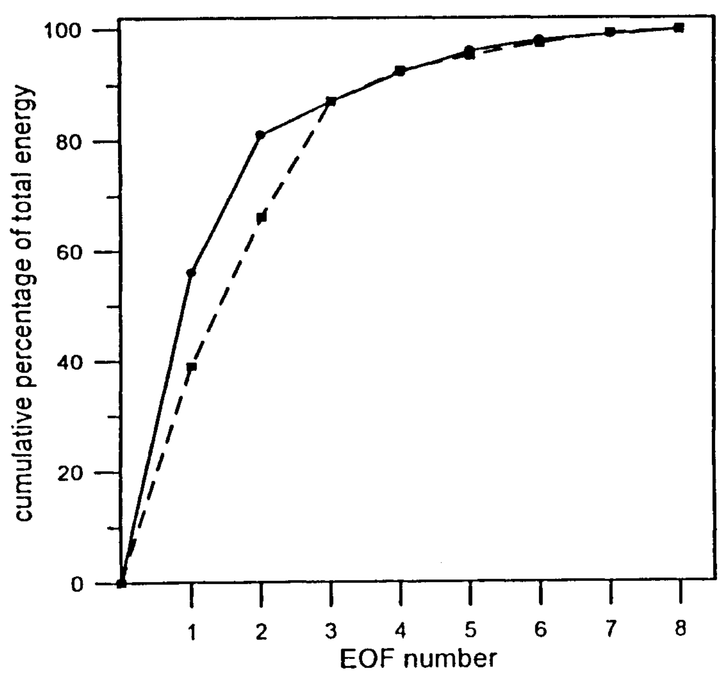

Fig. 5 Cumulative contribution (%) of the EOFs to the total energy of the variable motion. IB90/2 full line, IB90/3 dashed line.

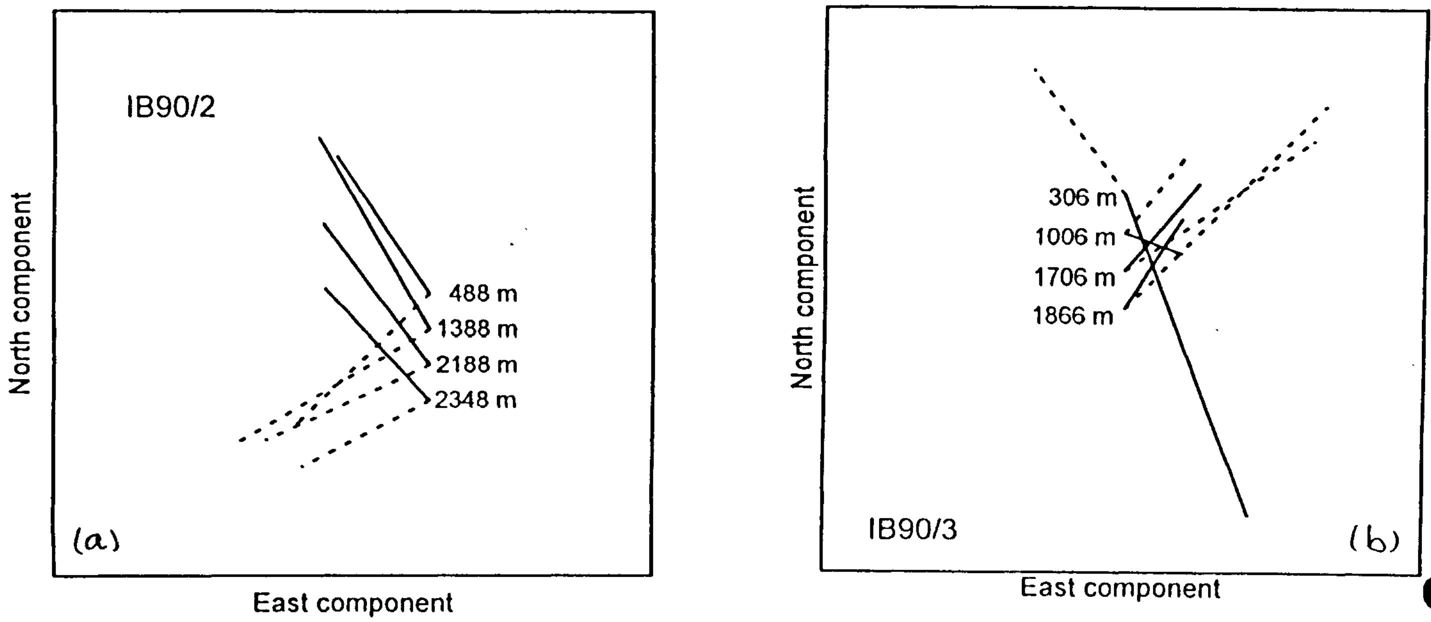

Fig 6 Vectors at 4 levels, representing EOF1 (full line) and EOF2 (dashed lines) for IB90/2 (a) and IB90/3 (b)

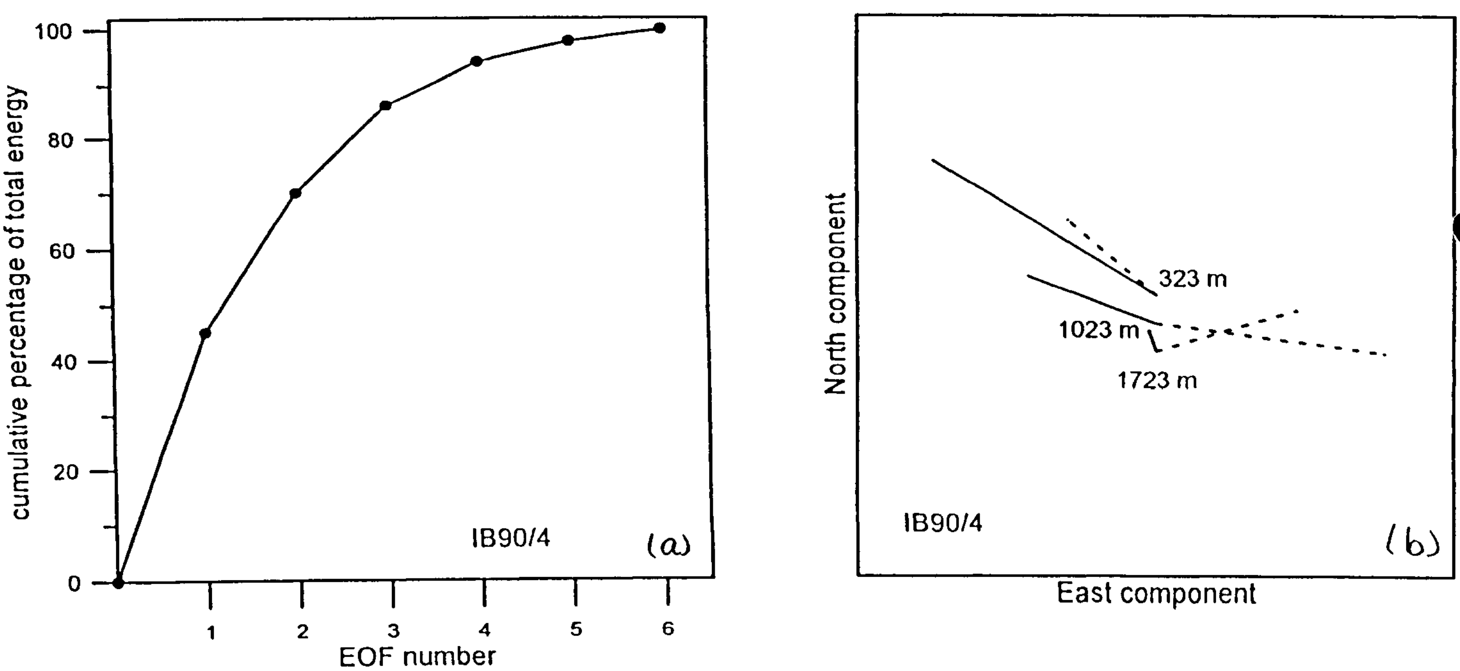

Fig. 7 EOF properties for IB90/4. a) cumulative contribution (%) of the EOFS to the total energy of the variable motion; b) vectors at 3 levels, representing EOF1 (full lines) and EOF2 (dashed lines).

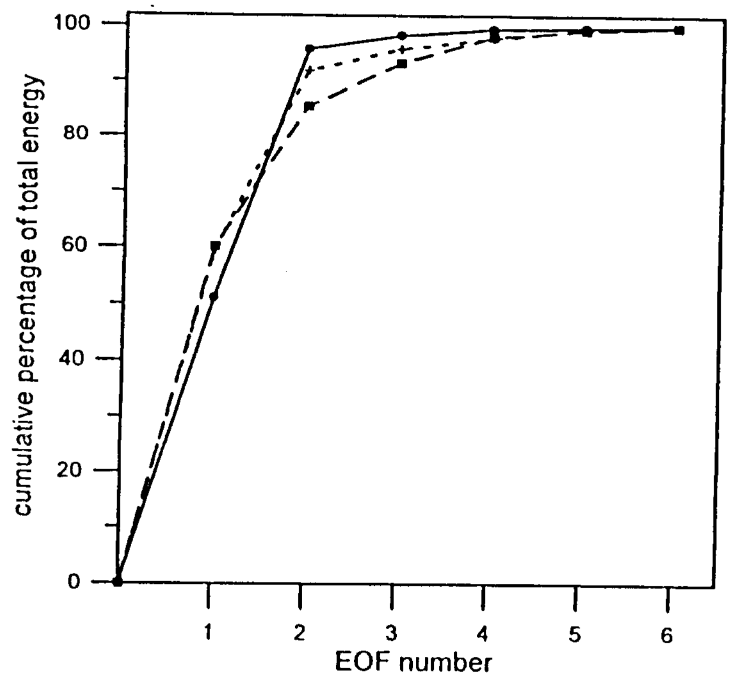

Fig. 8 Cumulative contribution (%) of the EOFs to the total energy of the variable motion. IB89/1 full line, IB90/1 short dashes, and IB90/2 long dashes.

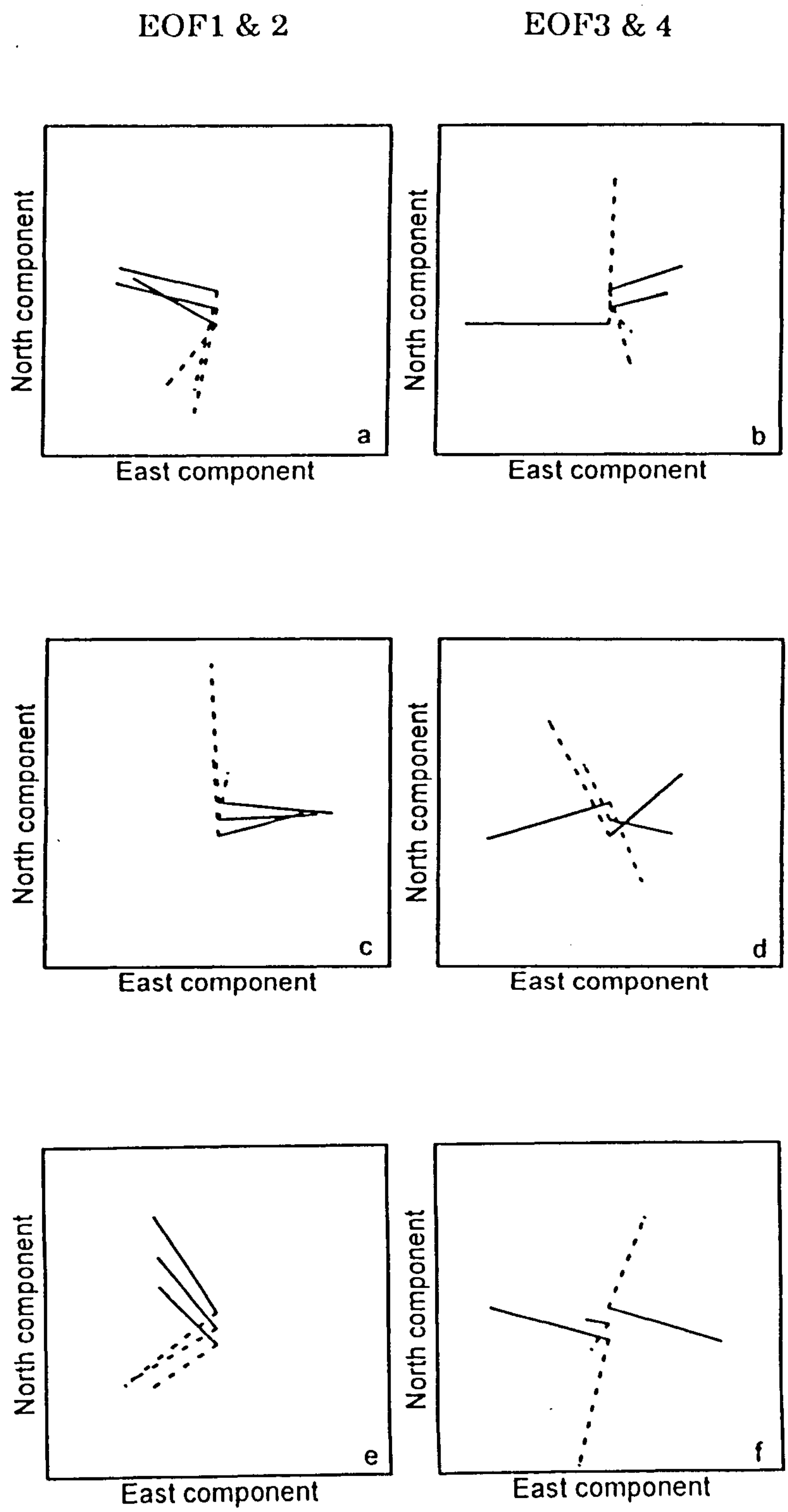

Fig. 9 Vectors at 3 levels, representing the EOF structure for the lowest 3 current meters at IB89/1 (a, b), IB90/1 (c, d) and IB90/2 (e, f). EOF1 and EOF3 are drawn in full lines, EOF2 and EOF4 are dashed.