International Council for
the Exploration of the Sea

Hydrography Committee
Theme Session O
C.M. 1993/ C:30
Sess. T.

A case study of meso-scale motion patterns off the Portuguese west coast

by

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ABSTRACT

Currents and repetitive sets of CTD- data reveal meso-scale circulation patterns offshore the Portuguese shelf. Besides the presentation of the mean currents the CTD-data analysis refers to local winds, mapped sea surface temperature and salinity, geostrophic flow conditions between potential density surfaces of $\sigma_1=27.1(\approx 200\text{m})$ and $\sigma_7=27.7(\approx 1100\text{m})$, and geostrophic meridional currents during the season of climatic upwelling (September 1991) and "non-upwelling" (April 1991, January 1992) along the coast.

The Tejo Plateau (39°N) subdivides the meridional subsurface currents along the continental slope into a northern and southern flow domain. North of the plateau meso-scale eddy-like subsurface currents controlled by the local slope topography seem to be dominant. South of the plateau the boundary flow is apparently more stable. In particular, the Mediterranean outflow water basically follows the continental slope and bifurcates into two branches with a noticeable west flow component between 37°N/ 38°N (C.S.Vincent) and 39°N / 40°N (Tejo Plateau). Current data provide clear signals of poleward going subsurface flow along the continental slope above, within, and below the layer of the Mediterranean outflow. The results of current measurements at the northern Moroccan continental slope suggest, that there must be a link between the poleward going subsurface flow from the south (Morocco) and along the South-Iberian slope.

Introduction

The objective of our note is to underline the specific nature in the subsurface current regime north and south of the Tejo Plateau. This plateau acts like a barrier by the influence of the bottom topography on the poleward spreading of Mediterranean Water (MW) (baroclinic pressure gradients) along the continental slope, cf MADELAIN (1976) and AMBAR (1982).

Our discussion is based on meteorological and hydrographic data measured during three meso-scale surveys off the Portuguese west coast and on time series of current measurements with a length of few months. Two cruises were carried out during the non-upwelling season while one was performed during the upwelling season. The area of investigation extended between 41° 20′ N and 37° N and between 11° 20′ W and the Portuguese coast. One may expect an energetic link between the northwest African upwelling area and that off Portugal. It is uncertain yet, whether the poleward subsurface flow in depth between 200m and 600m along the Iberian continental slope, above the Mediterranean Outflow (600m-1200m) and below the wind-driven surface layer (down to about 200m), can be linked to the poleward undercurrent existing in the African upwelling area off Morocco. Furthermore there is some evidence that the poleward flowing subsurface current surfaces, especially in autumn and winter, cf FROUIN et al. (1990). Short-term current measurements (few weeks) offshore the Portuguese shelf break in the past suggest a poleward going subsurface eastern boundary flow along the West-Iberian continental slope while long-term current measurements way further offshore indicate fairly variable meso-scale currents in the Iberian Abyssal Plain (west of 13° W).

Hydrographic Data Base

Sections and mooring positions are shown in Fig.1. We carried out three cruises in order to study meridional currents in the system of "Eastern Boundary Currents (EBC)" off the Portuguese west coast. Data result from two cruises with r/v "Heincke" of the" Biologische Anstalt Helgoland" (EBC1 in April 1991, EBC4 in January 1992) and one expedition with r/v "A.v.-

Humboldt" of the "Institut fuer Ostseeforschung Warnemuende" (EBC2 in September/ October 1991).

The hydrographic data have been gathered by means of the CTD-probe OM-87, MÖCKEL (1980). Hydrographic stations follow zonal sections located between the coast and 11.5° W. The station spacing varies between 7 km in the near-shore region and 28 km further offshore. The section spacing was 15′ in latitude for EBC1 and EBC4 but 1° in latitude during the EBC2-survey. The temperature sensor was controlled by three reversing thermometers at each station at different depths. Corresponding comparisons were carried out for salinity (S) between sensor values and laboratory measurements by means of the salinometer.

Using UNESCO-formulas for the equation of state the density was calculated from (S,T,P) values after the procedure of dada validation in pressure steps of 5 dbar. Subsequently anomalies are calculated with respect to the standard ocean (P=0, T=0, S=35 PSU). Resulting values give the input for the calculation of corresponding dynamic depths needed for an estimation of the vertical current shear from the geostrophic momentum balance.

The accuracy of (S,T,P)-measurements justifies to consider geostrophic velocities larger than about 0.04 m/s, FOMIN (1964), only.

According to WOOSTER et al. (1976) results of EBC1 and EBC4 could be representative for a "non coastal upwelling situation" while those from EBC2 should involve effects of upwelling processes.

Methodic aspects

Commonly we have to search for a suitable " zero-motion level" in order to obtain some acceptance for geostrophic velocities. Because its choice involves arbitrary aspects, especially in shelf-slope regions, we propose to accept two assumptions:

- The barotropic motion field with large spatial but small temporal scales is sufficiently separated from baroclinic motions with small spatial but long temporal scales.

- Changes of the baroclinic mass-and current field are locally influenced by barotropic fluctuations, mainly in response to temporal variations in the more large-scale alongshore wind component.

In the following we confine our attention to spatial structures of the meridional current component derived from hydrographic cross-sections. We assume that the baroclinic net volume transport can be neglected in comparison to that from the unknown barotropic motion field. In other words we try to minimize the cross section geostrophic net transport between neighbouring hydrographic stations .

We truncated the CTD-profiles in such a way that the main pycnocline approximately coincides with the middle of profiles. By this approach baroclinic motions in upper layers should be compensated by opposite motions in lower layers. Due to methodic uncertainties we concentrate to current patterns detected in the upper layer because those in the deeper layer are corresponding compensation currents resulting from the minimum concept used. An exception will be made for the intermediate undercurrent transporting MW along the continental slope towards higher latitudes as described, for instance, by ZENK and ARMI (1990).

We state that our procedure cannot be much better than that with a fixed reference level commonly used. Nevertheless there are two additional advantages:

-Our "zero horizon" follows the rising main pycnocline into the direction of the coast due to decreasing water depths.

-We obtain insight into patterns of geostrophic motions in the important shelf-slope region and on the shelf, too.

The most important restriction is that this method cannot provide any conclusions about net volume transports crossing the entire section. Figure.2 compares results from the "minimum method" proposed with those from the fitted reference level according to FIEKAS et al. (1992) and those resulting from fixed levels at 130 bar, 70 bar, and 30 bar. The results from our "minimum method" agree well not only with corresponding patterns calculated by the reference level according to FIEKAS et al. (1992) but also with those resulting from the fixed reference level at 130 bar. However, it seems to be that "zero motion" levels are not suitable at 70 bar (≈700m) and 30 bar (≈300m). Consequently we like to use the "minimum method" in the following.

Winds and T/S at the sea surface

During the "non upwelling season" in April 1991 and January 1992 the CTD observation grids consisted of six zonal sections (z1-z6) between 40° 05′ N and 41° 20′ N in accordance with former measurements carried out by ANDRES and JOHN (1992).

Contours of isobaths, which result from echosoundings at hydrographic stations, are plotted in Fig. 3. The zone of the shelf-edge slope region (200m-2000m depth) roughly runs parallel to the coast line with a southwest-northeast orientation. Therefore the distance between the coast and the 200m isobath increases from section z1 in the north to z6 in the south, about by a factor of two. This region will be denoted "shelf area/ zone" in the following. A deep cañyon-like structure can be detected in the west of 10° W, cf the 4000 m isobath. Its axis roughly runs parallel to the continental slope.

Actual winds are shown by vectors in Fig.4. Favourable winds for upwelling processes were observed by alongshore-offshore components of about 10 m/s in the shelf area during the survey in January 1992. In April 1991, however, the vectors involve onshore components with strong meridional gradients. Such different wind conditions produce a different response in wind-driven currents and, consequently, in temperature and salinity distributions at the sea surface mapped in Fig. 5. Relatively strong zonal gradients in temperature and salinity indicate upwelling processes on the shelf for the case of EBC4. Waters colder than 12°C were locally observed together with salinities lower than 35 PSU. Westward of the continental slope we note a tongue of warm and saline water extending from the southwest to the northeast. On the shelf, very different field distributions are measured during EBC1. Meridional temperature gradients dominate with temperature values between 13.5°C at z6 and 14.5°C at z1 while the sea surface salinity again shows zonal gradients with lower values on the shelf. The isolines suggest a surface frontal zone following the east flank of the deep cañyon, especially between sections z6 and z4. Here drastic wind changes are observed. The frontal zone separates the northeastward spreading of saline ($S>35.9$ PSU) and warm offshore water ($T>14$°C) from cooler and lesser saline waters of the shelf area.

Plumes of low saline water ($S<30$ PSU for EBC1 and $S<35$ PSU for EBC4) over the shelf originate from the fresh water discharge of the river Douro. Obviously such plumes are regionally trapped.

Baroclinic mass-field patterns within the 200/ 1100m layer

Stream lines follow isolines of the constant layer thickness between selected density surfaces. The smaller their separation distance the higher the resulting geostrophic velocity with positive anomalies on the right hand side.

The potential density surfaces $\sigma_7 = 27.7$ and $\sigma_1 = 27.1$ are selected in order to describe subsurface conditions. The corresponding reference level for potential temperatures lies at the sea surface. Our selected density surfaces lie near the depth of 1100 m (σ_7) and 200 m (σ_1). The intermediate layer thickness should indicate relative motions between the spreading of MW and currents of the near-surface layer which are not directly influenced by wind-driven motions. In the north of the Tejo Plateau, anomalies of its thickness are shown with respect to its spatial mean thickness of about 82 bar (820 m) in Fig.6. Two meso-scale eddy-like features are depicted along the two northernmost sections of the EBC1 survey. The diameter of the offshore eddy is about 40 km with an anticyclonic rotation sense. The rotation changes further to the east. In the south of section z3 two weak phenomena complete a chess board-like eddy structure. Such structures are typical for very low frequency waves, HUTHNANCE (1978). Corresponding zonal and meridional wave lengths could be about 130 km. Completely different conditions are indicated for the survey of EBC4. Positive anomalies in the west and negative anomalies in the east indicate a geostrophic southward motion continuously flowing along the zero isoline off the continental rise. There is no hint for a similar chess board-like pattern. In both cases shown, the zero-line of local thickness anomalies roughly coincides with the zone bounded by the 3500 m and 4000 m isobath. Moreover there is no clear evidence for a baroclinic poleward current continuously flowing within this intermediate layer off the continental slope during the "non upwelling season".

Local anomalies of the layer thickness, which result from the survey EBC2 in the south of the Tejo Plateau, are depicted in Fig.7a. The CTD measurements were carried out with the 1° section spacing meridionally during September 1991. Due to this poor meridional resolution no eddy-like phenomena of the scale of the Rossby radius can be resolved. Generally the layer thickness between potential density surfaces $\sigma_1 = 27.1$ and $\sigma_7 = 27.7$ increases with increasing latitude. With respect to the mean value of about 67 bar, positive peak values occur in the northeast while negative anomalies were observed in the southwest. Resulting isolines suggest an intermediate current to the northwest starting off C.S.Vincent (37° N). This should be the path of the large-scale spreading of MW. Visually there is a bifurcation into two branches with westward motions in the west of about 10° W. The southern branch is found to be between 37° N and 38° N while the northern one occurs between 39° N and 40° N.

Commonly the barotropic nature of motions dominates in shelf areas where the Rossby radius ($\approx$ 16km according to FIUZA, 1983) is much smaller than the shelf width. The topographic direction tendency for barotropic motions follows from the conservation of the lowest order potential vorticity by $(ß-ß_T)/ ß_{\cdot}$. The water depth is $H=H(x,y)$ in a Cartesian co-ordinate system (x-axis to the east and y-axis to the north). Changes of the Coriolis frequency f with the latitude are given by $ß=2*10^{-11}\ m^{-1}\ s^{-1}$. Meridional gradients of the water depth determine the topographic ß-parameter $ß_T = (f/<H>)(dH/dy)$ while corresponding zonal gradients are considered by $ß_{\cdot} = (f/<H>)(dH/dx)$. The averaged depth is $<H>$, cf SCHEMAINDA and HAGEN (1986).

Vectors of topographic tendencies are shown in Fig.7b. The bottom topography supports a westward motion over the Tejo Plateau (39°) between the coast and about 11° W. A similar zone can be detected between 37°N and 38°N extending offshore to the longitude of about 10° W.

The noted bifurcation should be influenced by the bottom topography. Resulting tendency arrows also suggest the possibility for a permanent generation of meso-scale eddy-like features offshore the continental slope zone, especially off C.S.Vincent.

Geostrophic meridional currents

The geostrophic currents are plotted from the 7-day campaign during April 1991 in Fig.8. Measurements started at 40° 05'. N in the south and were finished at 41° 20' N in the north. The northern most section (z1) indicates a near surface southward flow of about 0.08 m/s over the continental slope while a northward current can be detected with a core velocity of 0.12 m/s at 9.6° W. Its zonal width is about 20 km as it can be estimated from the separation of the 0.04 m/s isoline at the 10 bar pressure level. A narrow southward current seems to exist along the inshore flank of the north flow. Both currents are separated by a frontal zone. The front is visible down to about 500m near 9.4° W. According to the chess board-like anomaly patterns shown in Fig.6, we note a change of sign within the upper 500m layer along section z4. The poleward going flow is replaced by equatorward motions, however, the peak velocities are weaker by a factor of about 2-3. All sections suggest decreasing peak velocities with decreasing latitude during the survey of EBC1. Different conditions are found during EBC4, which are plotted in Fig.9. The strength of the poleward core velocity is smaller than that of the equatorward motion. The southward flowing near-surface current is visible at all sections between 9.6° W and 9.8° W.

Both meso-scale surveys were carried out in the north of the Tejo Plateau. Our measurements only indicate locally weak baroclinic motions to the north

(0.04 m/s). On the other hand the survey of EBC2 covers the region in the south of the Tejo Plateau during the upwelling season. Corresponding plots of geostrophic meridional currents are depicted in Fig.10. A clear poleward flow with core speeds larger than 0.12 m/s is shown for depths between 600 m and 1100 m along the section z4 (37°N) off C.S.Vincent. The zonal extension of the core is about 50 km. The core speed decreases with increasing latitude with a tendency for "offshore stretching".

Current measurements

The current meter moorings were deployed by the "Bundesamt fuer Seeschiffahrt und Hydrographie Hamburg". The data have been collected during different time periods: 1983/84 (P3), 1990/91 (WH), and 1991/92 as compiled in Table 1.

Resulting current averages over the whole recording intervals of different duration are shown in Fig.11. North of the Tejo Plateau, K1 points to a barotropic equatorward flow regime on the mid-shelf during March/ April 1991. Along the continental slope offshore a poleward flow occurs at depths between 260m and 810m at position P3 (40°N) and at 435m at position LO1 (43°N) while weaker northward components are also indicated at 1164m and 1564m depth at position WH (about 40° N). All three moorings were placed in the vicinity of 10° W. The mean westerly deep currents at the position WH (1164m horizon) within the layer of poleward spreading Mediterranean Outflow and there below (1564m level) are most likely poleward motions guided by the bottom topography.

South of the Tejo Plateau, measurements of three moorings are available. Off C.S.Vincent, a topographic eddy-like feature seems to be responsible for the flow observed at A1/ A2. A2 immediately replaced A1. Their positions are approximately one nautical mile apart. Within the layer of the Mediterranean Outflow (811m, 1214m) and below (1715m) the resulting mean current vectors during autumn/ winter 1991 at A1 (solid arrows) suggest (eddy-like?) counter motions to the generally assumed flow towards west at these depths in this region as observed at position CS.

Table 1: Water depths at the mooring locations and periods of current measurements

Location	Water Depth (m)	Measuring Period
LO1	1945	14 March, 1991 to 10 January,1992
K1	105	19 March to 13 April, 1991
WH	3900	15 Aug., 1990 to 27 Aug., 1991
P3	910	30 July, 1983 to 14 January, 1984
CS	1960	28 March to 19 May, 1992
A1	2036	28 Oct., 1991 to 14 January, 1992
A2	1998	14 January to 19 May, 1992
R	1995	20 Oct., 1991 to 15 April, 1992
M3	3979	18 January to 25 May, 1992

The averaged currents have been stronger from October through January 1991 (A1) than during the following four months until May 1992 (A2). Within the core layer of the Mediterranean Outflow ($\approx$1200m depth) the averaged currents are remarkably weak at positions CS, A2, and R. Probably the moorings were deployed in between the main veins of the MW outflow channelled by the bottom topography. Within deeper layers, below 1600m, the flow velocities increase again.

Discussion

Climatological atlases indicate a large-scale wind-stress curl distribution with a nearshore region of cyclonic sign extending about 200 km offshore, parallel to the Portuguese coast. We know from the Sverdrup balance that upward Ekman pumping occurs together with a poleward Sverdrup flow. The curl changes its sign by the influence of the Azores High further offshore. Downward Ekman pumping associated with an equatorward

Sverdrup flow dominates in the open northeastern Atlantic Ocean. A frontal zone follows the isoline of vanishing wind-stress curl at the sea surface in a distance of about 200 km from the coast. For example, at the latitude of 40° N, this surface front should be located between 10.6° W and 10.3° W.

Using climatic data, Mc CLAIN et al. (1986) concluded from numerical approaches that the southward flow over the shelf and along the eastern flank of the near-surface front zone is mainly driven by southward coastal winds, while the northward current along the western flank is associated with the position of the zero-wind-stress-curl. If this scenario for large-scale winds should be also valid at the meso-scale, we can expect a high degree of variability in north-southward currents due to the synoptic-scale of wind fluctuations.

As outlined by PHILANDER (1978), the steady state of the Sverdrup balance breaks down for time scales which are shorter than about ten years between 35° N and the critical latitude of Rossby waves (40-42° N). Dynamics of very low frequency waves dominate for shorter time scales, especially in the meso-scale.

In the north of the Tejo Plateau (39°N), weak upwelling processes with southwesterly wind-driven currents can be also expected during the "non upwelling season" in January. Mean currents at K1 point to an equatorward flow regime covering the entire water column on the mid-shelf during March/ April 1991. Analogous conditions are reported by SILVA (1992) from current measurements carried out on the shelf at about 41° N during May to September, 1987. Between about 41° N and 39° N, our geostrophic current estimates show dominating southward motions on the shelf. Therefore we may conclude that these nearshore equatorward currents involve a significant baroclinic component although they should be mainly wind-generated. In the shelf area, the wind-driven currents produce the high variability in space and time. The surface frontal zone, which zonally meanders along the continental slope, separates this onshore flow regime from offshore motions near the longitude of about 10° W. This front extends down to about 500/ 600m depth. In the north of the Tejo Plateau

(39 ° N) the northeastward spreading of warm and saline water is indicated in the near-surface layer, probably controlled by a deep canyon-like structure. Generally the geostrophic currents are intensified with increasing latitudes during the EBC1 and the EBC4 campaign. Furthermore meso-scale plumes are observed trapping mixed Douro waters on the shelf off Leixoes/ Porto.

According to HINRICHSEN et al. (1993) the depth of the salinity maximum indicates a meandering frontal zone in intermediate layers (≈ 1200m) along the continental slope. Its extension lies between 37/ 42 °N and about 10/ 11° W. The western most position is shown on the Tejo Plateau (39° N). There must be an adjustment of the baroclinic mass- and current field to the bottom topography. Furthermore, we know from HOLLOWAY et al. (1989) the topographic stress causes undercurrents in terms of intrinsic poleward propagating shelf waves along eastern boundaries. The poleward subsurface flow is an ingredient of coastal upwelling dynamics. With respect to structures of the subsurface motions, there is a clear evidence that the current regime off the Portuguese west coast is separated by the Tejo Plateau at about 39° N. Characteristic geostrophic motion patterns, which include poleward currents at depths between 600m and 1100m, are drastically disturbed and/ or completely vanish in the north of the Tejo Plateau. Here the surfacing of poleward currents is more probable than in the south. Our data of the subsurface layer thickness between about 200m-1100m suggest the existence of very low frequency wave-like fluctuations. Possible candidates could be topographically trapped baroclinic Rossby waves travelling along the topographic wave guide towards north. Visually zonal and meridional wave lengths are estimated to be about 130 km. On the other hand, no continuous poleward flow could be detected by our geostrophic calculations in layers deeper than about 600m although the averaged observational data of currents clearly indicate a northward component at positions P3, WH, and LO1 in the vicinity of 10° W. In this way we may conclude subsurface poleward currents are more barotropic in the north of the Tejo Plateau. It seems to be that the topographic direction tendency of the lowest order potential vorticity supports the bifurcation in two westward currents bands between 39° N and 40° N and between 37° N and 38° N but west of about 10° W.

According to Fig.9 in ZENK and ARMI (1990), both flow branches describe the northwestward spreading of the intermediate Mediterranean Water (MW) at depths between about 800m and 1200m between the Tejo Plateau and C.S.Vincent. The layer thickness between selected surfaces of potential density $\sigma_1 = 27.1$(200m) and $\sigma_7 = 27.7$(1100m) increases with increasing latitude. This fact indicates the existence of intermediate meridional large-scale pressure gradients. Consequently our geostrophic currents show a clear poleward current core (0.04-0.12 m/s) in layers between 600m and 1200m off the continental slope while southward motions (0.04-0.20 m/s) dominates in upper layers. These results support the conclusion of ZENK and ARMI (1990) that the MW passes through a broad "gateway" between C.S.Vincent and Gettysburg Bank and shows a strong tendency to follow the contours of the Portuguese continental slope up to the Tejo Plateau (39° N). However no clear evidence could be obtained for any vertical core displacement between the Tejo Plateau and C.S.Vincent. Moreover we know from float trajectories in between layers of 629 dbar and 847 dbar that there are also anticyclonic eddy-like features with diameters of about 50 km between 38° N and 39° N, as reported by ZENK et al. (1992). Such phenomena could not be resolved by our meridional section spacing. This zone with a tendency for subsurface eddy-like events is placed between our two well separated branches of westward motions in the west of about 10° W.

In the vicinity of C.S.Vincent (37° N), current measurements suggest a divergence indicated by westward currents in the southwest and an eastward flow in the southeast within layers between about 250m and 1900m. Poleward directions are only obtained for depths beneath and under the Mediterranean Outflow. These current records could be also associated to an eddy-like feature, which is topographically trapped in the south of C.S.Vincent. For instance, SWALLOW (1969) reported an anticlockwise eddy by neutrally buoyant float tracks at depths between 1000/ 1400m where the maximum salinity layer of MW is placed in the south of C.S.Vincent. The mean flow vectors at position R (6 months records) provide an indication of a subsurface poleward going flow along the northern Moroccan slope. We assume, that this result represents a continuation of the poleward undercurrent along the northwest African slope at lower latitudes. However we cannot exclude, that the northward current component at position R also results from a similar meso-scale eddy-like feature, which is topographically trapped. Furthermore it seems to be likely that the slope areas off Morocco and the South-Iberian peninsula are linked energetically by the poleward propagation of low frequency, topographically trapped waves. The proximity of the position R to the South-Iberian continental slope let us believe/ speculate, that there must be a link between the poleward going subsurface boundary flows off northwest Africa and southwest Europe.

Acknowledgments: We are grateful to the officers and crew of r/v "HEINCKE" and "A.v.Humboldt". This work has been supported by the "Bundesministerium fuer Forschung und Technologie", Grant 03F0050G/H

References

Ambar, I.L.; 1982: General review of the Mediterranean influence in the N Atlantic. In: Actual Problems of Oceanography in Portugal; Proceedings of a seminar held in Lisbon on 20-21 November 1980, Investigacao Cientifica e Tecnologica, Lisbon, 73-87.

Andres, H.G.; H.Ch. John; 1992: Fish larvae and Gammaridea plankton off northern Portugal during autumn 1987. Senckenbergiana marit., 22, 179-201.

Fiekas, V.; J.Elken; T.J.Müller; A. Aitsam; W. Zenk; 1992: A view of the Canary Basin thermocline circulation in winter. J.Geophys.Res., 97, 12495-12510.

Fiuza, A.F.G.; 1983: Upwelling patterns off Portugal. In: Coastal Upwelling, Editors: E.Suess and J.Thiede, Plenum Publishing Corporation, 85-98.

Fomin, L.M.; 1964: The dynamic method in oceanography. Elsevier Publishing Company, 211 p.

Frouin,R.; A.F.G. Fiuza, I.L. Ambar, T.J. Boyd; 1990: Observations of a poleward surface current off the coasts of Portugal and Spain during winter. J.Geophys. Res., 95, 697-691.

Hinrichsen,H.H.; M. Rhein, R.H.Käse; W.Zenk; 1993: The Mediterranean water tongue and its chlorofluoromethane signal in the Iberian Basin in early summer 1989. J.Geophys.Res., 98, 8405-8412.

Holloway, G.; K. Brink; D.Haidvogel; 1989: Topographic stress in coastal circulation dynamics. In: Coastal and Estuarine Studies 34, Poleward flows along eastern boundaries, Editors: S.J.NESHYBA et al.; Springer Verlag, 315-330.

Huthnance, J.M.; 1978: On coastal trapped waves: Analysis and numerical calculation by inverse iteration, J.Phys.Oceanogr., 8, 74-92.

Laughton,A.S.; D.G.Roberts, R.Graves; 1975: Bathymetry of the northeast Atlantic: Sheet 3, Hydrographer of the Navy, Taunton

Mc Clain, C.R.; S. Chao; L.P. Atkinson; J.O.Blanton; F. Castillejo; 1986: Wind-driven upwelling in the vicinity of Cape Finistere, Spain. J.Geophys. Res., 91, 8470-8486.

Madelain,F. ; 1976: Circulation des eaux d´origine Mediterraneenne au niveau du Cap St.Vincent. Hydrologie et courants de densite. CNEXO Ser. No.24, p. 73.

Möckel,F.; 1980: Die ozeanologische Meßkette OM-75, eine universelle Datenerfassungsanlage für Forschungsschiffe. Beitr.Meereskd., H.43, 5-14.

Philander S.G.H.: 1978. Forced oceanic waves. Rev. Geophys. and Space Phys., 16, 15-46.

Schemainda,R.; E.Hagen; 1986: Zur topographischen Richtungstendenz barotroper Strömungen im östlichen Zentralatlantik. Beitr. Meereskd., 54, 69-74.

Silva da, A.J.; 1992: Dependence of upwelling related circulation on wind forcing and stratification over the Portuguese northern shelf. ICES Hydrographic Committee, C:17, 12 p.

Wooster,W.S.; A.Bakun; D.R. Mc Lain; 1976: The seasonal upwelling cycle along the eastern boundary of the North Atlantic. J.Mar.Res., 34, 131-141.

Swallow, J.C.; 1969: A deep eddy off Cape St. Vincent. Deep Sea Res. Suppl. 16, 285-296.

Zenk,W.; L.Armi; (1990): The complex spreading pattern of the Mediterranean Water off the Portuguese continental slope. Deep-Sea Res., 37, 1805-1823.

Zenk,E.; K.Schultz-Tokos; O.Boebel; 1992: New observations of meddy movement south of the Tejo Plateau. Geophys. Res. Letters, 19, 2389-2392.

Figures:

Fig.1. Mooring positions and sections during the campaign "Eastern Boundary Currents (EBC)": EBC1 (2-10 April, 1991), EBC4 (22-29 January, 1992) along cross-sections z1-z6 (solid lines) in the north of the Tejo Plateau, and EBC2 (3-8 September, 1991) along four cross-sections z1-z4 (dashed lines) in the south of the Tejo Plateau, (Isobaths in fathoms, LAUGHTON et al.1975)

Fig.2. Vertical patterns (pressure units in bar) of geostrophic meridional currents (poleward motions are stippled) along the z1-section of EBC1 resulting from the minimum method, fitted reference levels proposed by FIEKAS et al.(1992), and reference levels fixed at pressure levels of 130, 70, and 30 bar, (Note the unsuitable reference level at 30 bar which was selected by FROUIN et al. (1990))

Fig.3. Bottom topography from the station grid. The region of the continental slope is hatched between the 200 m and 2000 m isobath

Fig.4. Vectors of the wind velocity (V_w) resulting from the surveys of EBC1 and EBC4

Fig.5. Mapped distribution of the temperature (T) and salinity (S) at the sea surface

Fig.6. Pressure anomalies of the layer thickness (units in bar) between surfaces of potential density [p(27.7)-p(27.1)]' with respect to the spatial mean values $<\Delta P>$ =82.8 bar and 81.1 bar, respectively
(Total geostrophic motions follow the isolines with positive values on the right hand side).

Fig.7. Comparison between baroclinic mass field structures as in Fig.6 with topographic conditions for the EBC2 area

a) Anomalies of the layer thickness between potential density surfaces selected with respect to the spatial mean value of 67.1 bar

b) Arrows of the topographic direction tendency for unforced barotropic motions given by $(\beta-\beta_T)/\beta_*$, values are taken from a personal communication by METZNER (1992), (Further explanations in the text)

Fig.8. Geostrophic currents calculated by means of the minimum method along the six zonal sections (z1-z6) from the campaign of EBC1

Fig.9. Similar plots as in Fig.8 but for the survey of EBC4

Fig.10. Corresponding plots as in Figs.(8,9) but for the survey of EBC2

Fig.11.Vector-averaged flow (Number at vector heads denote measuring depth. The measuring duration is given in Table 1.)

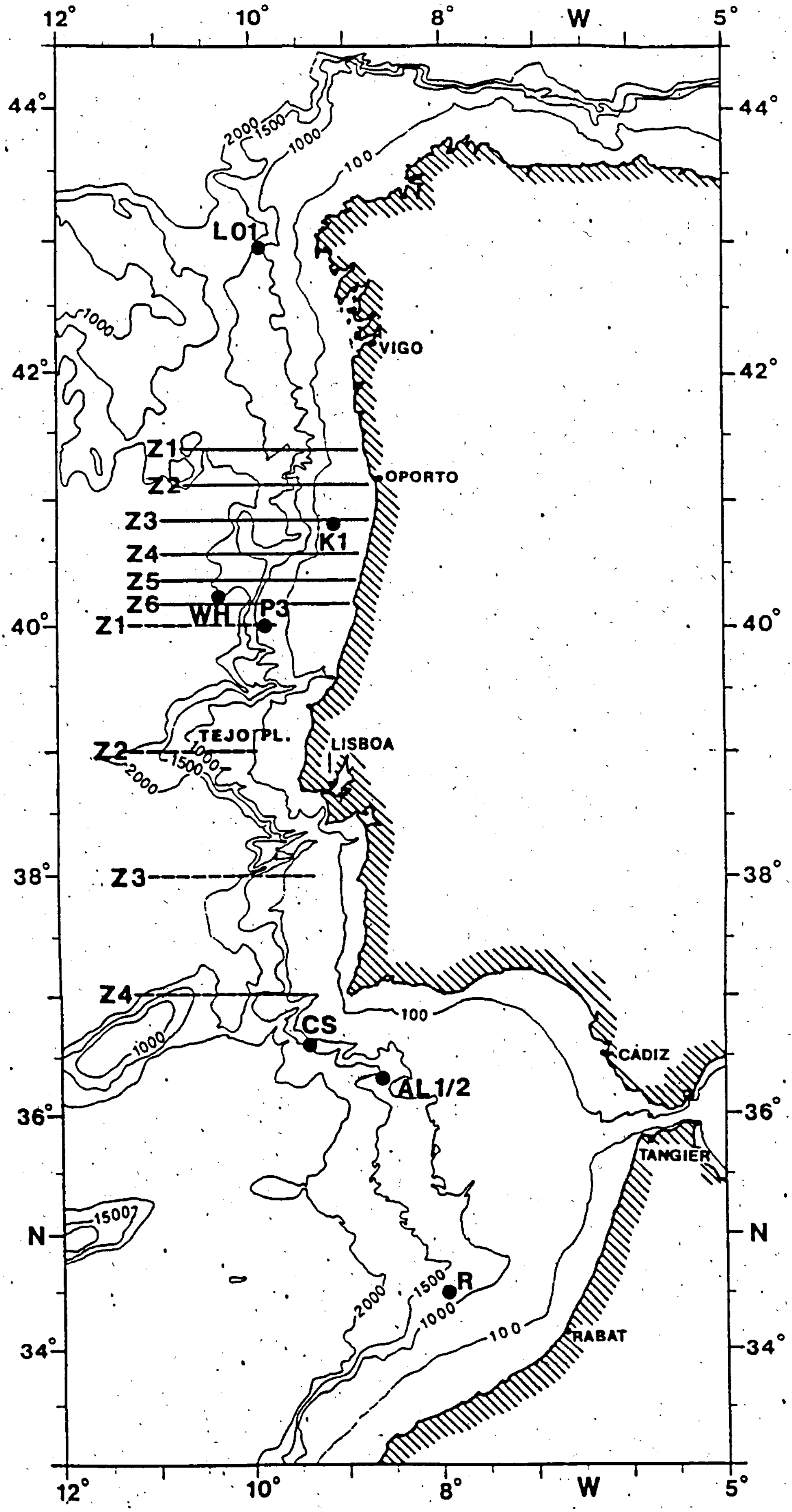

12°
10°
8°
W
5°
44°
42°
40°
38°
36°
N
34°
2000
1500
1000
100
L01
VIGO
Z1
Z2
OPORTO
Z3
K1
Z4
Z5
Z6
WH
P3
Z1
TEJO PL.
LISBOA
Z2
Z3
Z4
CS
AL1/2
CÁDIZ
TANGIER
R
RABAT

Fig.1

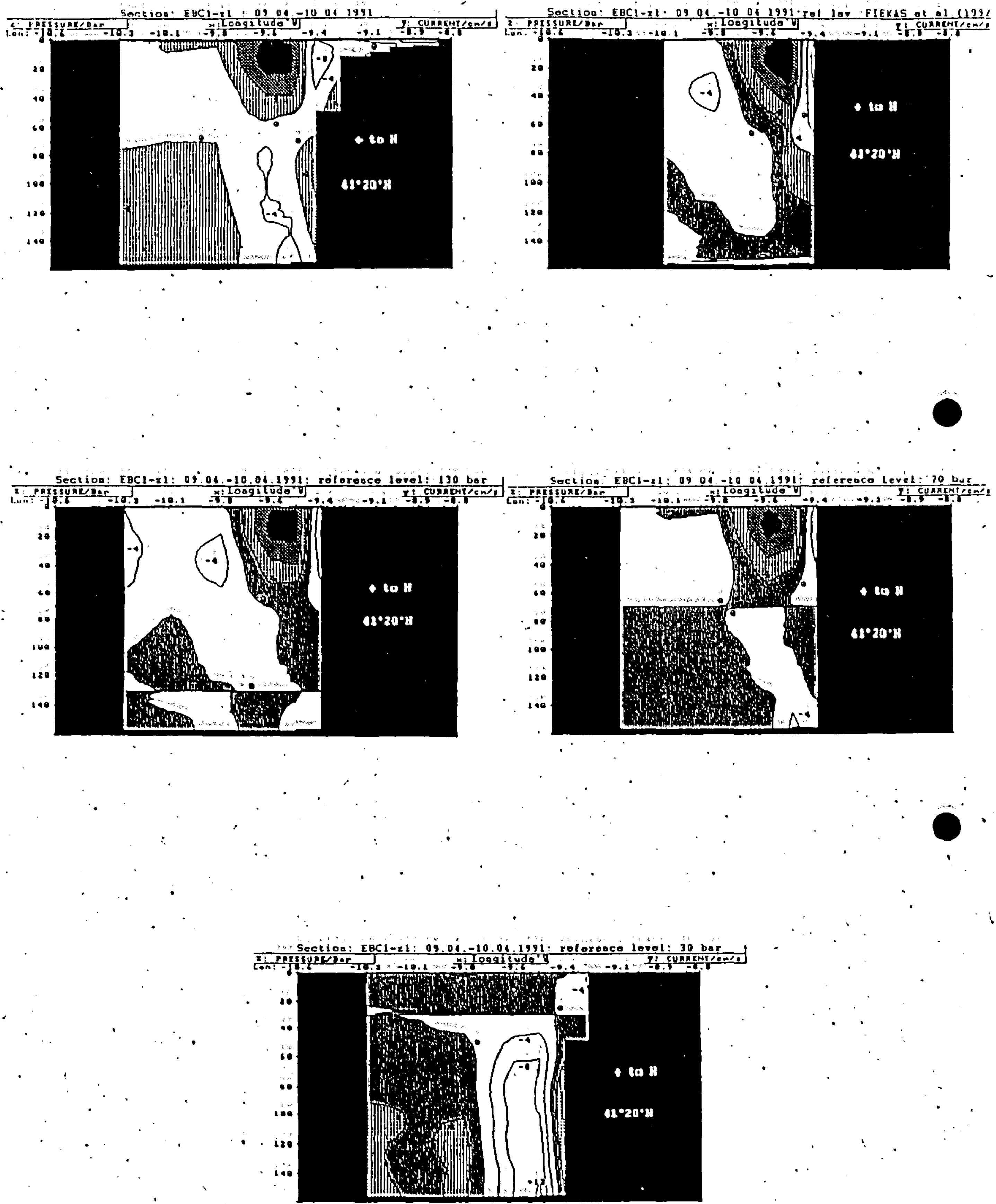

Section: EBC1-z1 : 09.04.-10.04.1991
z: PRESSURE/Bar
x: Longitude W
y: CURRENT/cm/s
Lon: -10.6 -10.3 -10.1 -9.8 -9.6 -9.4 -9.1 -8.9 -8.8
0
20
40
60
80
100
120
140
-8
-4
-4
+ to N
41°20'N
Section: EBC1-z1: 09.04.-10.04.1991 ref lev FIEKAS et al (199
z: PRESSURE/Bar
x: Longitude W
y: CURRENT/cm/s
Lon: -10.6 -10.3 -10.1 -9.8 -9.6 -9.4 -9.1 -8.9 -8.8
0
20
40
60
80
100
120
140
-4
-4
+ to N
41°20'N
Section: EBC1-z1: 09.04.-10.04.1991: reference level: 130 bar
z: PRESSURE/Bar
x: Longitude W
y: CURRENT/cm/s
Lon: -10.6 -10.3 -10.1 -9.8 -9.6 -9.4 -9.1 -8.9 -8.8
0
20
40
60
80
100
120
140
-4
-4
+ to N
41°20'N
Section: EBC1-z1: 09.04.-10.04.1991: reference level: 70 bar
z: PRESSURE/Bar
x: Longitude W
y: CURRENT/cm/s
Lon: -10.6 -10.3 -10.1 -9.8 -9.6 -9.4 -9.1 -8.9 -8.8
0
20
40
60
80
100
120
140
-4
+ to N
41°20'N
Section: EBC1-z1: 09.04.-10.04.1991: reference level: 30 bar
z: PRESSURE/Bar
x: Longitude W
y: CURRENT/cm/s
Lon: -10.6 -10.3 -10.1 -9.8 -9.6 -9.4 -9.1 -8.9 -8.8
0
20
40
60
80
100
120
140
-4
-4
-8
-12
+ to N
41°20'N

Fig.2

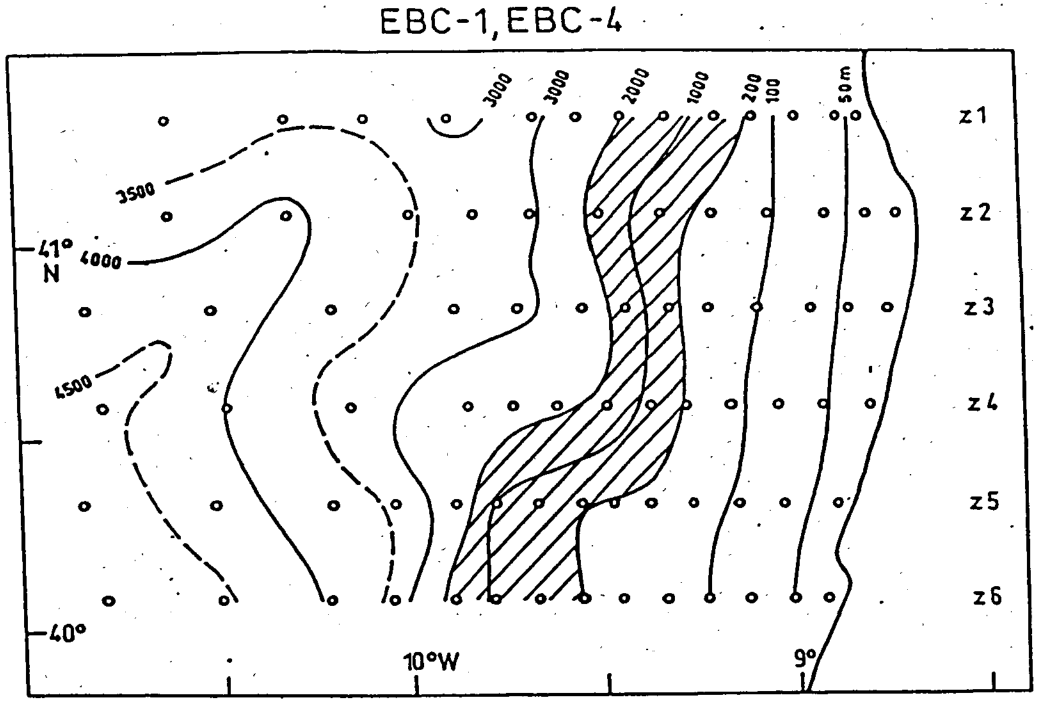

EBC-1, EBC-4
3000
3000
2000
1000
200
100
50 m
3500
4000
4500
z1
z2
z3
z4
z5
z6
41°
N
40°
10°W
9°

Fig.3

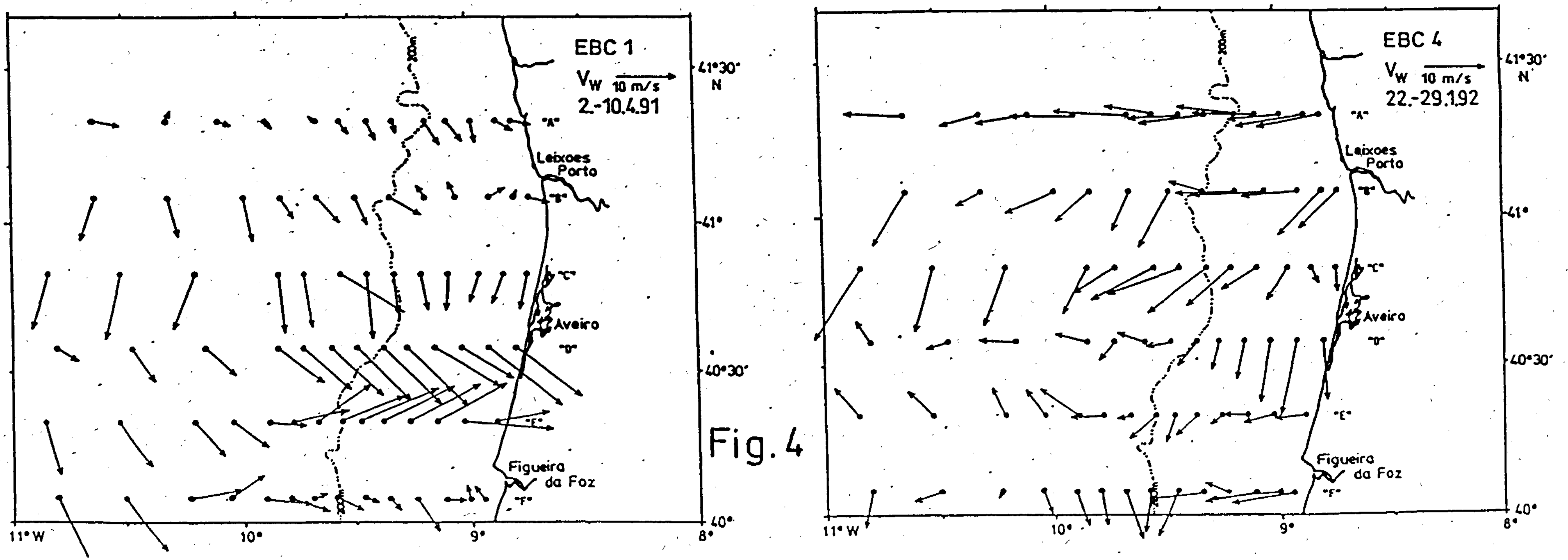

EBC 1
V_W 10 m/s
2.-10.4.91
200m
"A"
Leixoes
Porto
"B"
"C"
Aveiro
"D"
"E"
"F"
Figueira
da Foz
41°30'
N
41°
40°30'
40°
11°W
10°
9°
8°
EBC 4
V_W 10 m/s
22.-29.1.92
200m
"A"
Leixoes
Porto
"B"
"C"
Aveiro
"D"
"E"
Figueira
da Foz
"F"
41°30'
N
41°
40°30'
40°
11°W
10°
9°
8°

Fig. 4

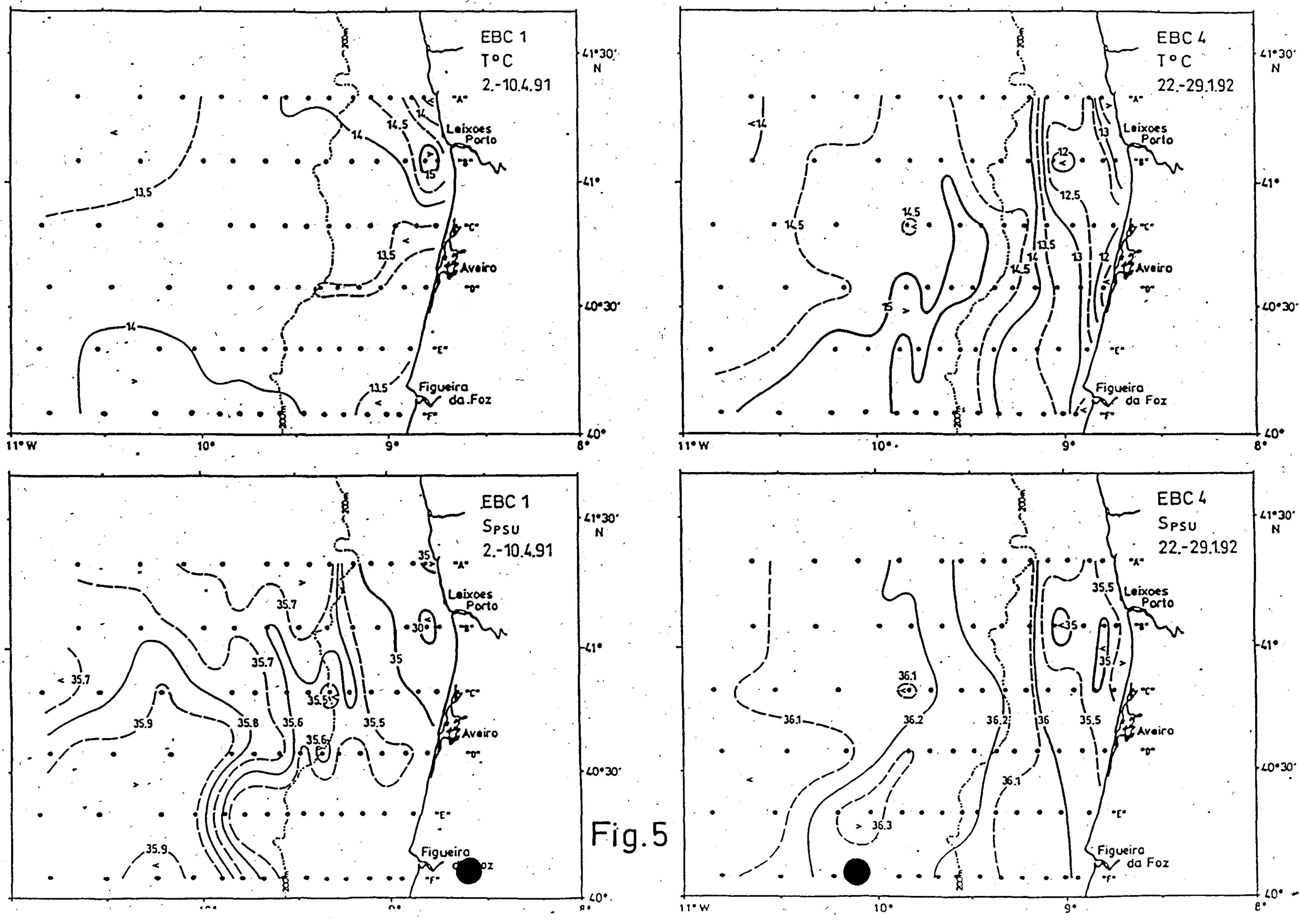

EBC 1
T°C
2.-10.4.91
EBC 4
T°C
22.-29.1.92
EBC 1
S PSU
2.-10.4.91
EBC 4
S PSU
22.-29.1.92
Leixoes
Porto
Aveiro
Figueira da Foz
"A"
"B"
"C"
"D"
"E"
"F"
200m
41°30' N
41°
40°30'
40°
11° W
10°
9°
8°
13.5
14
14.5
15
12
12.5
13
<14
35
35.5
35.6
35.7
35.8
35.9
36
36.1
36.2
36.3
30

Fig. 5

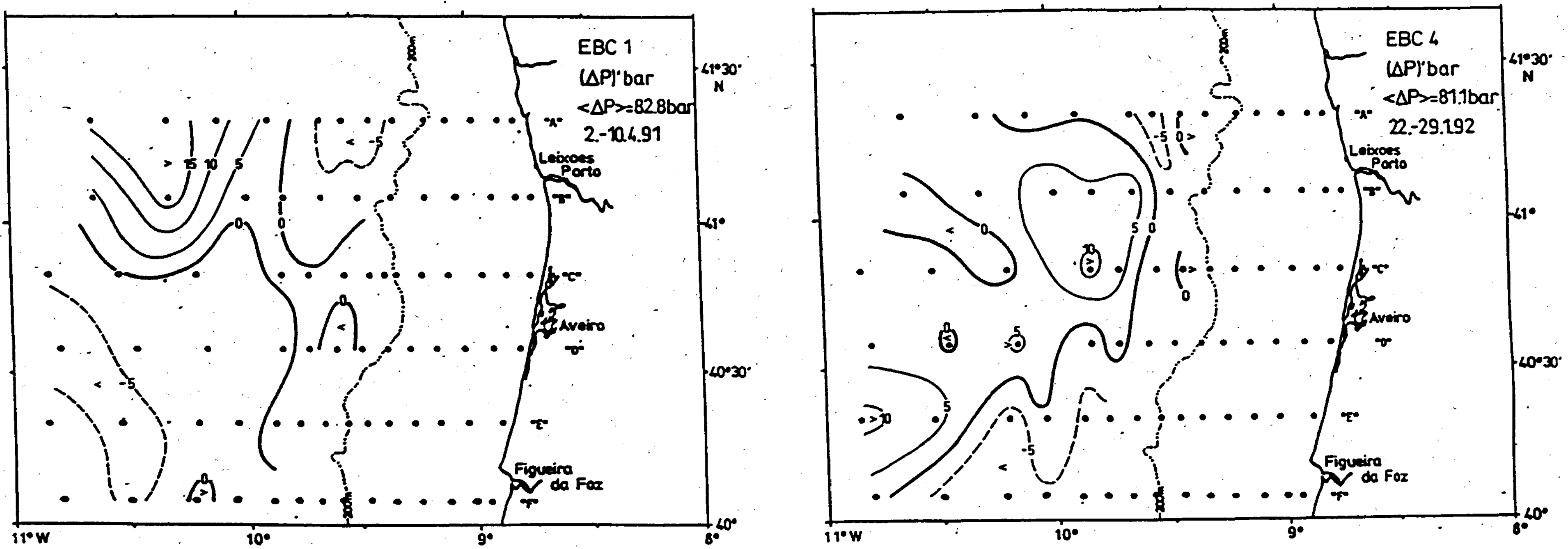
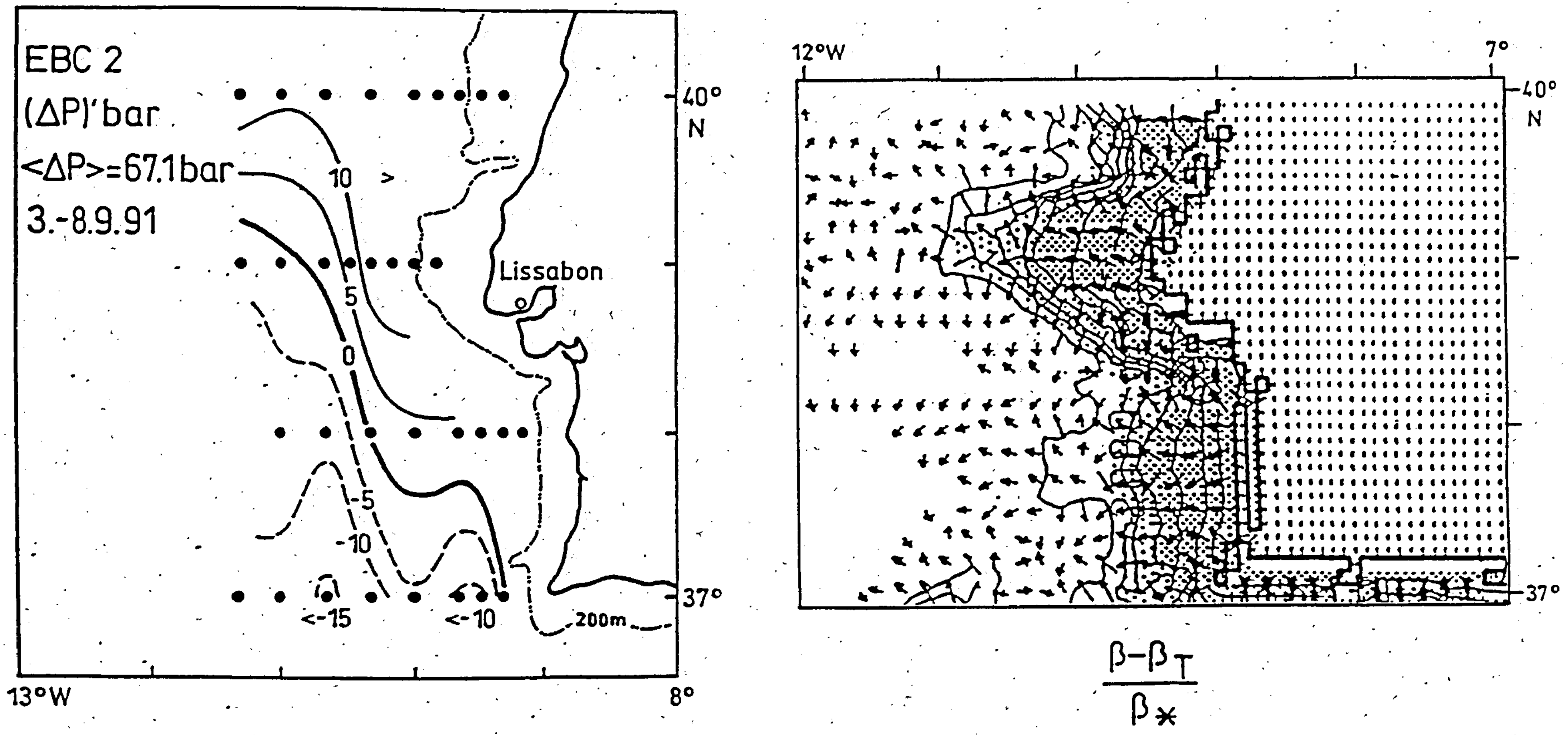

EBC 1
(ΔP)' bar
<ΔP>=82.8bar
2.-10.4.91
Leixoes
Porto
Aveiro
Figueira da Faz
"A"
"B"
"C"
"D"
"E"
"F"
200m
15
10
5
0
-5
41°30' N
41°
40°30'
40°
11°W
10°
9°
8°
EBC 4
(ΔP)' bar
<ΔP>=81.1bar
22.-29.1.92
Leixoes
Porto
Aveiro
Figueira da Faz
10
5
0
-5
41°30' N
41°
40°30'
40°
11°W
10°
9°
8°

Fig.6


EBC 2
(ΔP)'bar
<ΔP>=67.1bar
3.-8.9.91
10
>
5
0
-5
-10
<-15
<-10
Lissabon
200m
40°
N
37°
13°W
8°
12°W
7°
40°
N
37°
β-β_T
β_*

(a) Fig.7 (b)

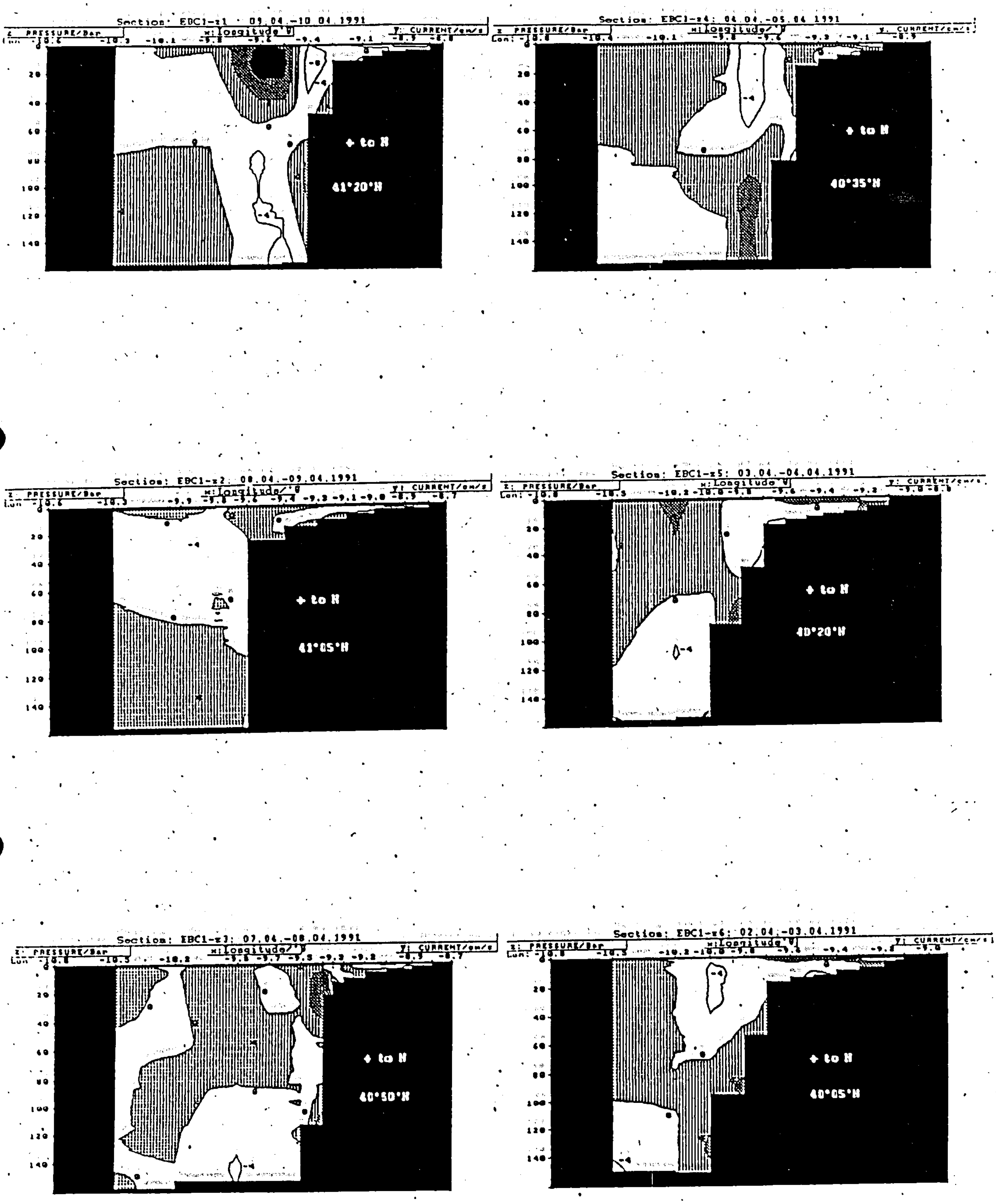

Section: EBC1-x1 : 09.04.-10.04.1991
z: PRESSURE/Bar
x: Longitude/°
y: CURRENT/cm/s
Lon: -10.6 -10.3 -10.1 -9.8 -9.6 -9.4 -9.1 -8.9 -8.8
0
20
40
60
80
100
120
140
-8
-4
0
+ to N
41°20'N
Section: EBC1-x4: 04.04.-05.04.1991
z: PRESSURE/Bar
x: Longitude/°
y: CURRENT/cm/s
Lon: -10.8 -10.4 -10.1 -9.8 -9.6 -9.3 -9.1 -8.9
-4
0
+ to N
40°35'N
Section: EBC1-x2: 08.04.-09.04.1991
z: PRESSURE/Bar
x: Longitude/°
y: CURRENT/cm/s
Lon: -10.6 -10.3 -9.9 -9.8 -9.6 -9.4 -9.3 -9.1 -9.0 -8.9 -8.7
-4
0
+ to N
41°05'N
Section: EBC1-x5: 03.04.-04.04.1991
z: PRESSURE/Bar
x: Longitude/°
y: CURRENT/cm/s
Lon: -10.8 -10.5 -10.2 -10.0 -9.8 -9.6 -9.4 -9.2 -9.0 -8.8
-4
0
+ to N
40°20'N
Section: EBC1-x3: 07.04.-08.04.1991
z: PRESSURE/Bar
x: Longitude/°
y: CURRENT/cm/s
Lon: -10.8 -10.5 -10.2 -9.8 -9.7 -9.5 -9.3 -9.2 -8.9 -8.7
-4
0
+ to N
40°50'N
Section: EBC1-x6: 02.04.-03.04.1991
z: PRESSURE/Bar
x: Longitude/°
y: CURRENT/cm/s
Lon: -10.8 -10.5 -10.2 -10.0 -9.8 -9.6 -9.4 -9.2 -9.0
-4
0
+ to N
40°05'N

Fig.8

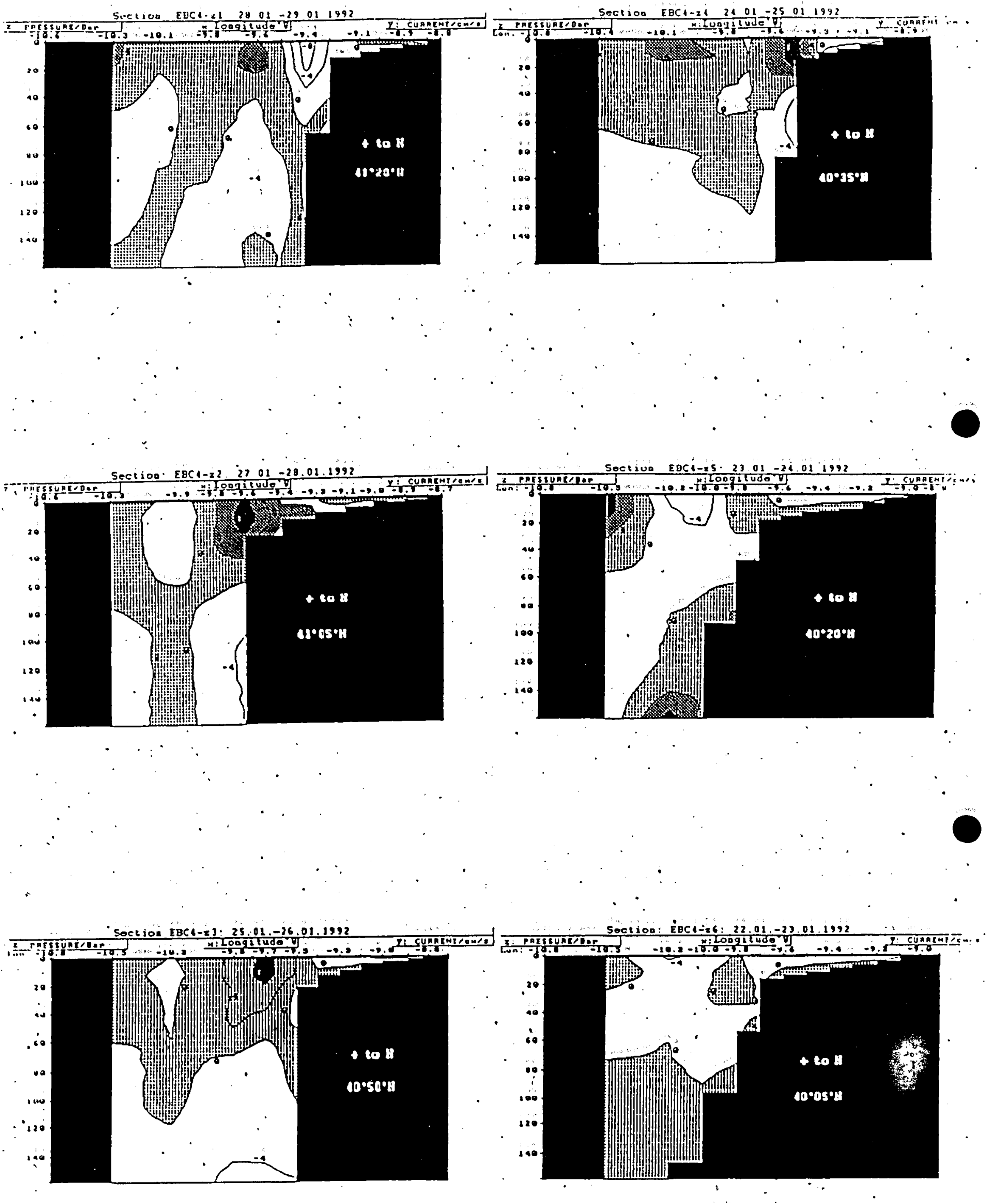

Section EBC4-z1 28 01 -29 01 1992
z PRESSURE/Dbar
x Longitude W
y: CURRENT/cm/s
-10.6 -10.3 -10.1 -9.8 -9.6 -9.4 -9.1 -8.9 -8.8
0 20 40 60 80 100 120 140
-8
-4
0
+ to N
41°20'N
Section EBC4-z4 24 01 -25 01 1992
z PRESSURE/Dbar
x Longitude W
y CURRENT/cm/s
Lon. -10.6 -10.4 -10.1 -9.8 -9.6 -9.3 -9.1 -8.9
0 20 40 60 80 100 120 140
-4
0
+ to N
40°35'N
Section EBC4-z2 27 01 -28.01.1992
z PRESSURE/Dbar
x Longitude W
y: CURRENT/cm/s
-10.6 -10.3 -9.9 -9.8 -9.6 -9.4 -9.3 -9.1 -9.0 -8.9 -8.7
0 20 40 60 80 100 120 140
-4
+ to N
41°05'N
Section EBC4-z5 23 01 -24.01 1992
z PRESSURE/Dbar
x Longitude W
y CURRENT/cm/s
Lon. -10.6 -10.5 -10.2 -10.0 -9.8 -9.6 -9.4 -9.2 -9.0 -8.8
0 20 40 60 80 100 120 140
-4
0
+ to N
40°20'N
Section EBC4-z3 25.01.-26.01.1992
z PRESSURE/Dbar
x Longitude W
y: CURRENT/cm/s
Lon. -10.6 -10.5 -10.2 -9.8 -9.7 -9.5 -9.3 -9.0 -8.8
0 20 40 60 80 100 120 140
-4
0
+ to N
40°50'N
Section EBC4-z6 22.01.-23.01.1992
z PRESSURE/Dbar
x Longitude W
y CURRENT/cm/s
Lon. -10.6 -10.5 -10.2 -10.0 -9.8 -9.6 -9.4 -9.2 -9.0
0 20 40 60 80 100 120 140
-4
0
+ to N
40°05'N

Fig.9

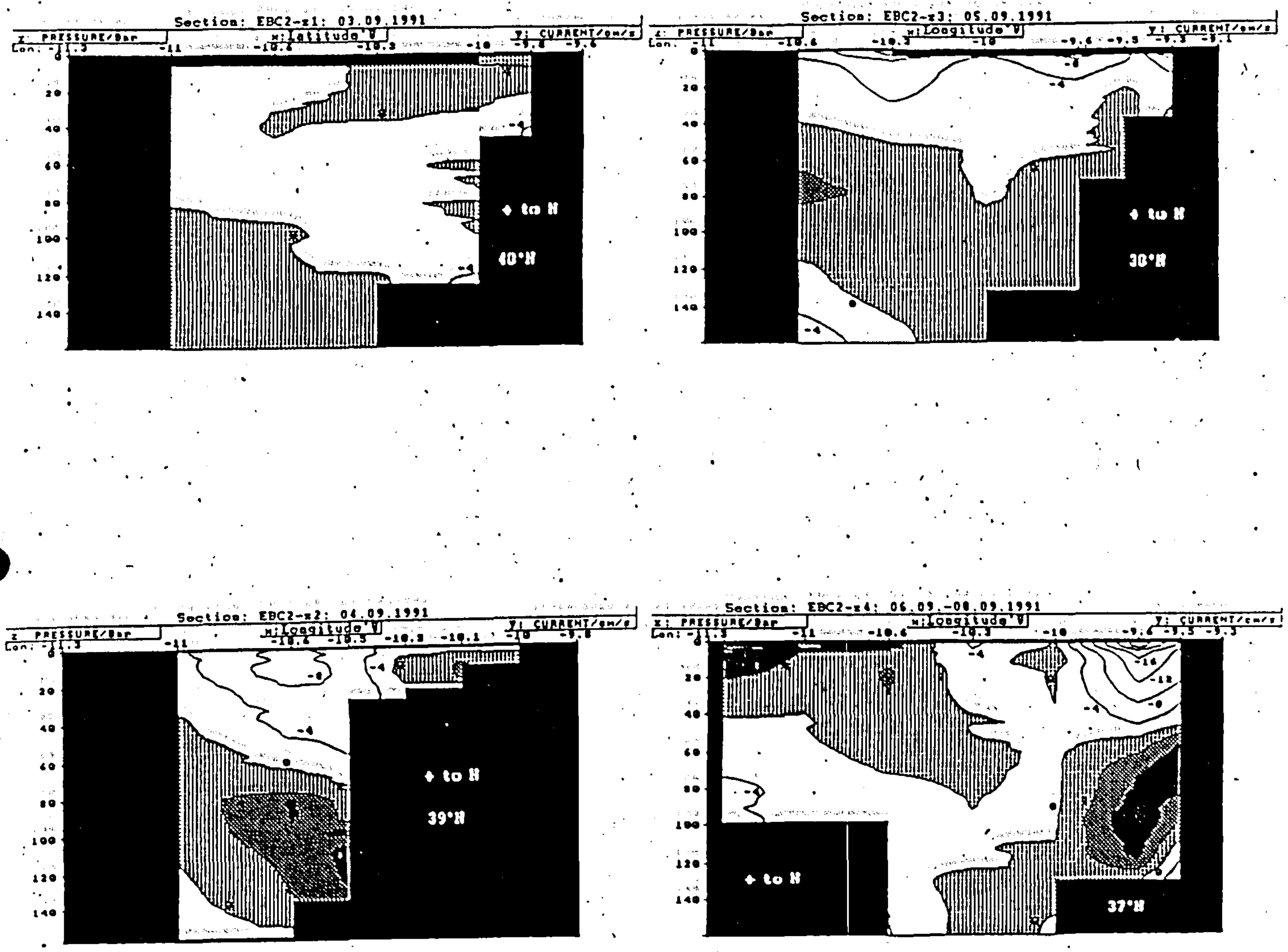

Section: EBC2-x1: 03.09.1991
z: PRESSURE/Bar
x: Latitude °N
y: CURRENT/cm/s
+ to N
40°N
Section: EBC2-x3: 05.09.1991
x: Longitude °W
+ to N
38°N
Section: EBC2-x2: 04.09.1991
x: Longitude °W
+ to N
39°N
Section: EBC2-x4: 06.09.-08.09.1991
x: Longitude °W
+ to N
37°N

Fig.10

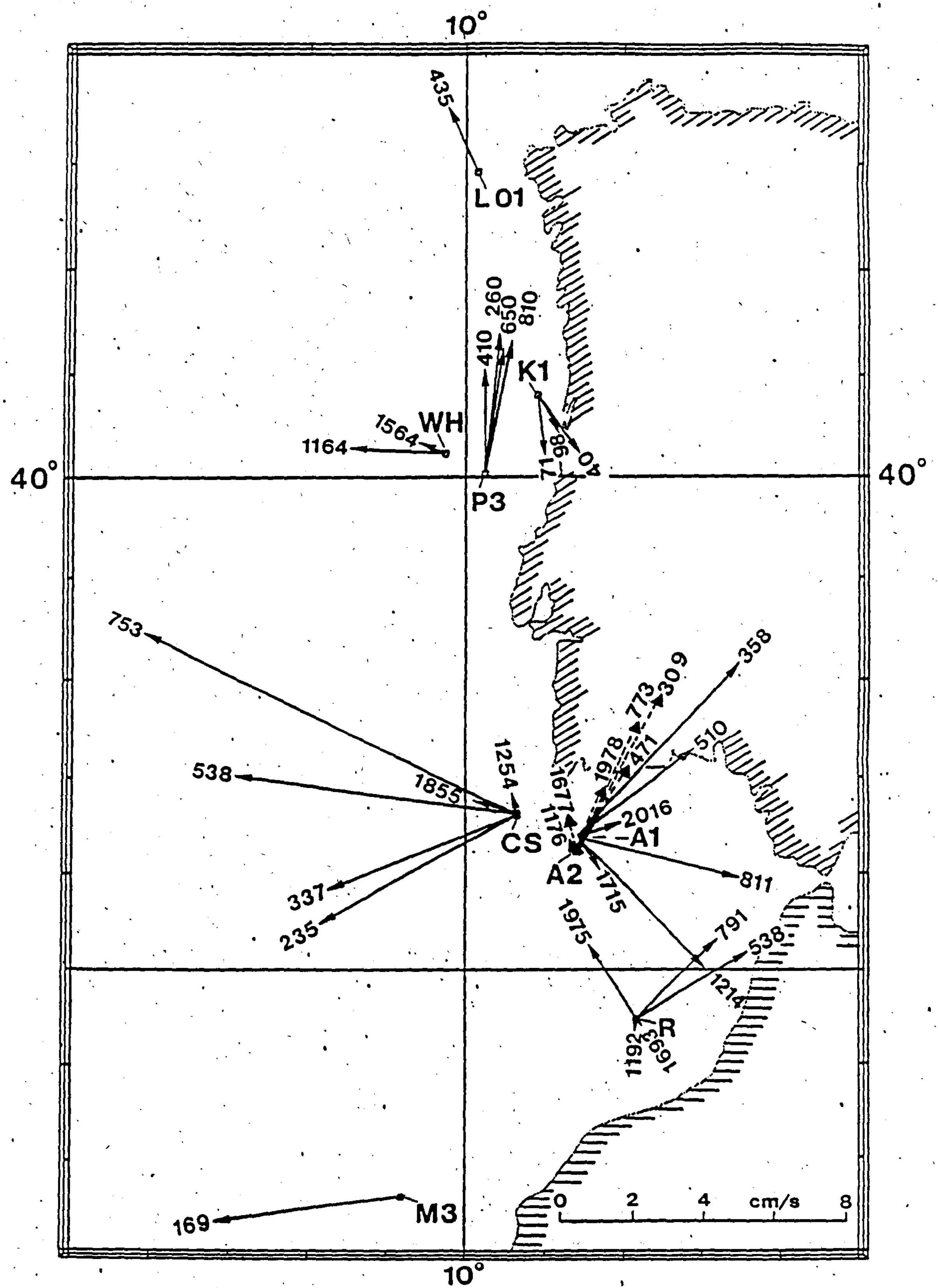

10°
435
L 01
260
410
650
810
K1
WH
1564
1164
71
98
40
40°
40°
P3
753
358
309
773
510
471
1978
538
1855
1254
1677
1176
2016
A1
CS
A2
1715
811
337
235
1975
791
538
1214
R
1192
1693
0
2
4
cm/s
8
M3
169
10°

Fig.11