GEOFIZIKA	Vol. 3	1986

Preliminary communication
UDC 551.465

Objective analysis of geostrophic currents in the Adriatic Sea

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Received 16 May 1986, in final form 11 August 1986.

The first results of the objective analysis of geostrophic currents in the Adriatic Sea are presented. Data collected during the „Andrija Mohorovičić" cruise in September and October 1974 are used for computing relative dynamic depths. These are then interpolated on a rectangular grid of points, using a first-order polynomial for approximating the mean depths, and applying both the isotropic and anisotropic autocorrelation functions. The objectively analyzed surface currents, computed relative to those at the 50 dbar surface, show a similarity with the results of subjective analysis only for the anisotropic autocorrelation function. It is concluded that detailed measurements are needed to assess the statistics of relative dynamic depths. Moreover, the problem of aliasing should be considered, and a method for transforming relative into absolute currents should be applied to the Adriatic Sea data.

Objektivna analiza geostrofičkih struja Jadranskog mora

U članku su prikazani prvi rezultati dobiveni objektivnom analizom geostrofičkih struja u Jadranu. Na temelju podataka prikupljenih tijekom krstarenja brodom „Andrija Mohorovičić" u rujnu i listopadu 1974. godine izračunate su relativne dinamičke dubine. Te su dubine interpolirane na pravokutnu mrežu točaka, uz aproksimaciju srednjih dubina polinomom prvog stupnja te uz korištenje izotropne i anizotropne autokorelacione funkcije. Pokazalo se da su objektivno analizirane površinske struje, određene relativno prema strujama na 50-decibarskoj izobarnoj plohi, u skladu s rezultatima subjektivne analize samo za anizotropnu autokorelacionu funkciju. Zaključeno je da su potrebna detaljna mjerenja za procjenu statistike relativnih dinamičkih dubina. Pored toga, valja razmotriti problem prekrivanja u domeni frekvencija i valnih brojeva (engl. aliasing) kao i riješiti pitanje transformacije relativnog toka u apsolutno strujanje za područje Jadrana.

1. Introduction

Geostrophic currents in the Adriatic Sea were first computed by Zore (1956), on the basis of data from the "Najade" and "Ciclope" cruises (1911–1914). Four reference surfaces were selected for the analyses (50, 100, 200 and 500 dbar), and consequently the work was concentrated on the Middle and South Adriatic. The results pointed to the cyclonic surface flow which is modulated seasonally: in winter inflow along the Yugoslav coast prevails, whereas in summer outflow along the Italian coast dominates.

Mosetti (1966/67) as well as Mosetti and Lavenia (1969) extended the analyses to the North Adriatic, by computing surface currents relative tho those at the 20, 30 and 50 dbar surfaces. Their data originated from four Italian cruises (1966–1968). The results showed that occassionally two separated circulation cells may occur in the North Adriatic, one cyclonic and the other anticyclonic.

The results of one of the "Andrija Mohorovičić" cruises were analyzed by Ferenčak et al. (1982). Surface currents were computed relative to the 100 dbar surface. In autumn 1974 inflowing currents were found to prevail in the South Adriatic.

A common feature of all these investigations is *subjective* analysis of relative dynamic depths. During the past ten years *objective* analysis of both scalar and vector fields has been increasingly used in physical oceanography. It has proved to be very successful, for example in meteorology (Gandin, 1965), and has been introduced into physical oceanography by Bretherton et al. (1976). Both subjective and objective analyses imply assumptions about the character or degree of the smoothness of the field analyzed. The advantage of the objective method is its explicitness in stating the assumptions.

In the second section, the "Andrija Mohorovičić" data, to be used in the paper, will be described, and the method will be briefly reviewed. In the third, final section objectively analyzed geostrophic currents will be discussed and compared with the subjective analysis of the same data set.

2. Materials and method

Temperature and salinity data were collected on the cruises of the R. V. "Andrija Mohorovičić", between 1974 and 1976. Altogether five cruises were organized in that period. At each cruise about 50 stations were visited, and measurements were performed at standard depths. Temperature was measured by Richter-Wiese reversing thermometers, with an accuracy of ±0.02° C. Salinity was determined from the Nansen bottle samples with a laboratory inductivity salinometer (Autolab Sample Industries, model 601-MK-III, accuracy ± 0.005). All the data were published by the organizer of the cruises, the Hydrographic Institute of the Yugoslav Navy (1982).

Computation of geostrophic currents rests on two assumptions, namely, the geostrophic balance of forces in the horizontal plane and the hydrostatic equilibrium along the vertical axis. The equation of horizontal motion in the so-called p-system reads:

$$\mathbf{c}(\mathbf{r}, p) = -\frac{1}{f} \operatorname{grad} D(\mathbf{r}, p) \times \mathbf{k} \tag{1}$$

whereas the hydrostatic equation can be expressed as:

$$\frac{\partial}{\partial p} D(\mathbf{r}, p) = \alpha(\mathbf{r}, p) \tag{2}$$

where p stands for pressure, $\mathbf{r}$ is the radius vector, $\mathbf{c}$ is the horizontal velocity vector, D is the dynamic depth, α is the specific volume, f is the Coriolis parameter, and $\mathbf{k}$ denotes the unit vector orientated vertically downward. The gradient operator implies that pressure is to be held constant for partial differentiation.

By integrating (2) between the sea surface and an isobaric surface, we get:

$$D_r(\mathbf{r}, p) = \int_0^p \alpha(\mathbf{r}, p)\, \mathrm{d}p \tag{3}$$

where subscript r indicates relative value, $D_r(\mathbf{r}, p) = D(\mathbf{r}, p) - D(\mathbf{r}, 0)$. The integral to the right of (3) has been determined numerically, on the basis of hydrographic data collected during the "Andrija Mohorovičić" cruises, and using the International Equation of State of Seawater 1980 (UNESCO, 1981) for computing the specific volume.

The objective analysis or linear least-squares estimation of relative dynamic depths with the data $D_{r,i}(p)$ given at the measuring points $[D_{r,i}(p) = D_r(\mathbf{r}_i, p),\ 1 \leqslant i \leqslant M]$ can be performed if the statistical mean field $m(\mathbf{r}, p)$ of $D_r(\mathbf{r}, p)$ is known as well as its autocorrelation function $C_p(\mathbf{r}, \mathbf{r}')$. Then the estimate of D_r has the form:

$$D_r(\mathbf{r}, p) = m(\mathbf{r}, p) + \sum_{i=1}^{M} \lambda_i(\mathbf{r}, p) D_{r,i}(p) \tag{4a}$$

where λ_i are functions computed from the following linear system:

$$[C]\ [\lambda] = [b] \tag{4b}$$

with $[C]$ being the matrix having the elements $C_p(\mathbf{r}_i, \mathbf{r}_j)$, $[\lambda]$ being the column consisting of λ_j, $1 \leqslant j \leqslant M$, and $[b]$ being the column consisting of $C_p(\mathbf{r}, \mathbf{r}_i)$.

Once the field $D_r(\mathbf{r}, p)$ has been obtained, relative currents may be computed from the expression

$$\mathbf{c}_r(\mathbf{r}, p) = -\frac{1}{f} \operatorname{grad} D_r(\mathbf{r}, p) \times \mathbf{k} \tag{5}$$

which follows from (1) and (3).

3. Results and discussion

In order to illustrate the procedure of objective analysis of geostrophic currents, we have selected data that were collected in the Adriatic Sea during September and October 1974. Moreover, we have restricted the analysis to differences between the sea surface and the 50 dbar surface. Figure 1 shows measuring points, as well as subjectively analyzed relative geostrophic currents. Results obviously agree with those of Ferenčak et al. (1982) in that the inflowing currents predominate in the South Adriatic. In the rest of the basin large cyclonic gyre is formed, reflecting all the previous results obtained for the Adriatic Sea.

Turning now to objective analysis of the same data set, we have to face a difficult problem of construction of both the field m and the autocorrelation function C_p. No theoretical result exists at present indicating the class of functions to which m in (4a) has to belong, so that the choice of m is a guesswork in most cases. In our case it would be reasonable to choose a polynomial of the second order in the horizontal coordinates x and y, for a fixed p, so that the simple ellipse-like circulation along the Adriatic Sea is obtained. As the number of data is too small even for such a simple choice, in case of larger pressures, we have decided to choose m as a polynomial of the first order (three parameters only). Let us point out that our aim is to derive certain general conclusions about the use of the objective analysis in the Adriatic Sea, and the restricted choice of the field m does not limit us in doing this. Of course, a deeper analysis in choosing m is needed if the reliability of estimated D_r is to be the main goal.

The autocorrelation function C_p is supposed to be homogeneous, i.e., $C_p(\mathbf{r},\mathbf{r}') = K_p(\mathbf{r}-\mathbf{r}')$, where K_p is a function of two real variables. Using the statistical methods with the fluctuations $f_i = D_{r,i}(p) - m(\mathbf{r}_i,p)$, we have obtained experimental autocorrelograms as illustrated in Figure 2 (for the main axis of the Adriatic Sea, x) and in Figure 3 (for the cross-basin direction, y). In computing the experimental autocorrelograms the densest data set – originating from the "Andrija Mohorovičić" cruise of April and May 1975 – has been used. The shapes of experimental autocorrelograms suggest the following choice of theoretical autocorrelation function:

$$K_p(x,y) = \frac{1}{[1+a(y^2+(\frac{x}{b})^2)]^N}\cos\left[c\sqrt{y^2+(\frac{x}{b})^2}\right]$$

with the parameters a, b, c and N to be determined from a curve-fitting procedure. As already underlined, we wish to derive certain qualitative conclusions at present rather than to obtain reliable estimates of D_r. Therefore, we choose c=0, N=1, and a=0.4 (as determined by the least-squares method from the experimental autocorrelograms), and consider two values of b: b=1 and $b=\sqrt{5}$ The theoretical autocorrelation function is also illustrated in Figures 2 and 3.

Figure 4 shows results for the circular autocorrelation function (b=1). The model boundaries are also shown, as well as the 50 m isobath. There is a striking difference between this result and the subjectively analyzed currents (Figure 1). Whereas subjective

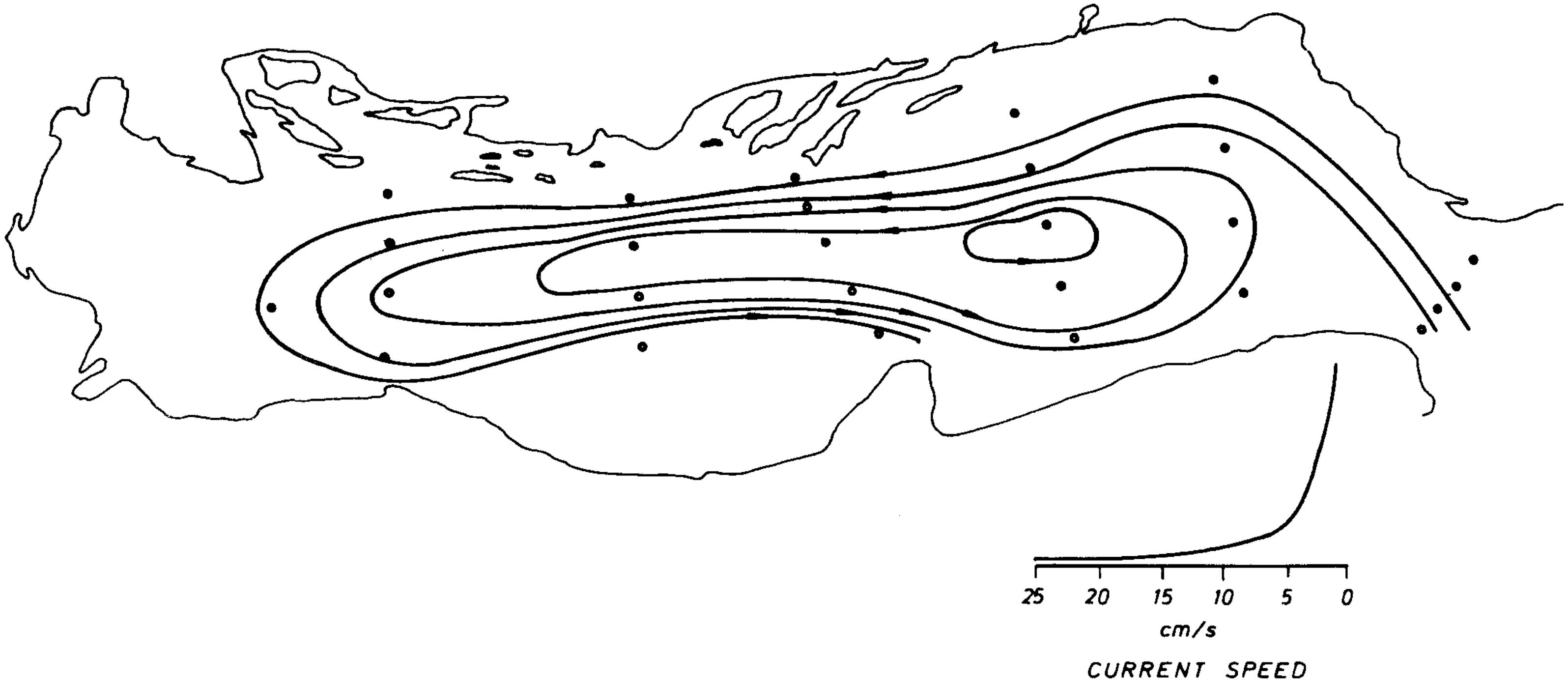

Figure 1. Subjectively analyzed surface geostrophic currents, expressed relative to the 50 dbar currents, for the "Andrija Mohorovičić" cruise of September and October 1974. Also shown are measuring points.

analysis points to a single cyclonic gyre, objective analysis with the circular autocorrelation function shows a number of smaller, mostly cyclonic cells. A better agreement with the subjectively analyzed relative geostrophic currents is obtained if the elliptical autocorrelation function ($b=\sqrt{5}$) is taken into account. Now the great cyclonic gyre appears (Figure 5), but it is modified by a series of smaller circulation cells. There is no inflow in the Otranto Strait, which indicates that the autocorrelation function is still of smaller eccentricity than the one implied by the subjective analysis.

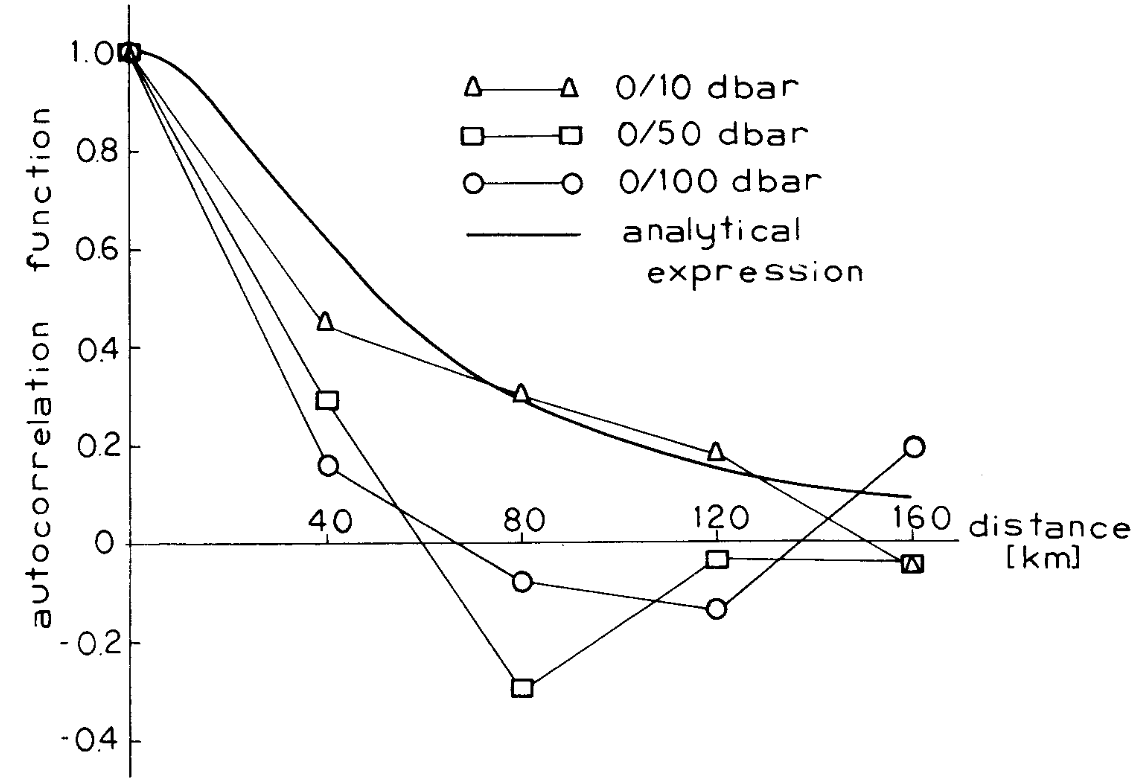

Figure 2. Experimental autocorrelograms and fitted autocorrelation function for the main axis of the Adriatic Sea. Data were collected during the "Andrija Mohorovičić" cruise in April and May 1975.

Although inconclusive about the true nature of geostrophic currents in the Adriatic Sea, the present investigation clearly defines the main problems that should be solved if objective analysis is to be successfully performed. The data were collected over some--weeks intervals, on the network of widely spaced stations, so that the problem of aliasing in space and time should be considered. Furthermore, special measurements are needed for an accurate determination of the field m and the autocorrelation function C_p (which may even be inhomogeneous). Finally, we should recall that the results presented here give *relative* currents (Figures 1, 4 and 5). There is a number of methods for transforming relative into absolute fields. However, the method based on the sea-surface altimetry (Wunsch and Gaposchkin, 1980) as well as the method utilizing vertically-averaged currents (Limić and Orlić, 1986) should be ruled out, since the additional

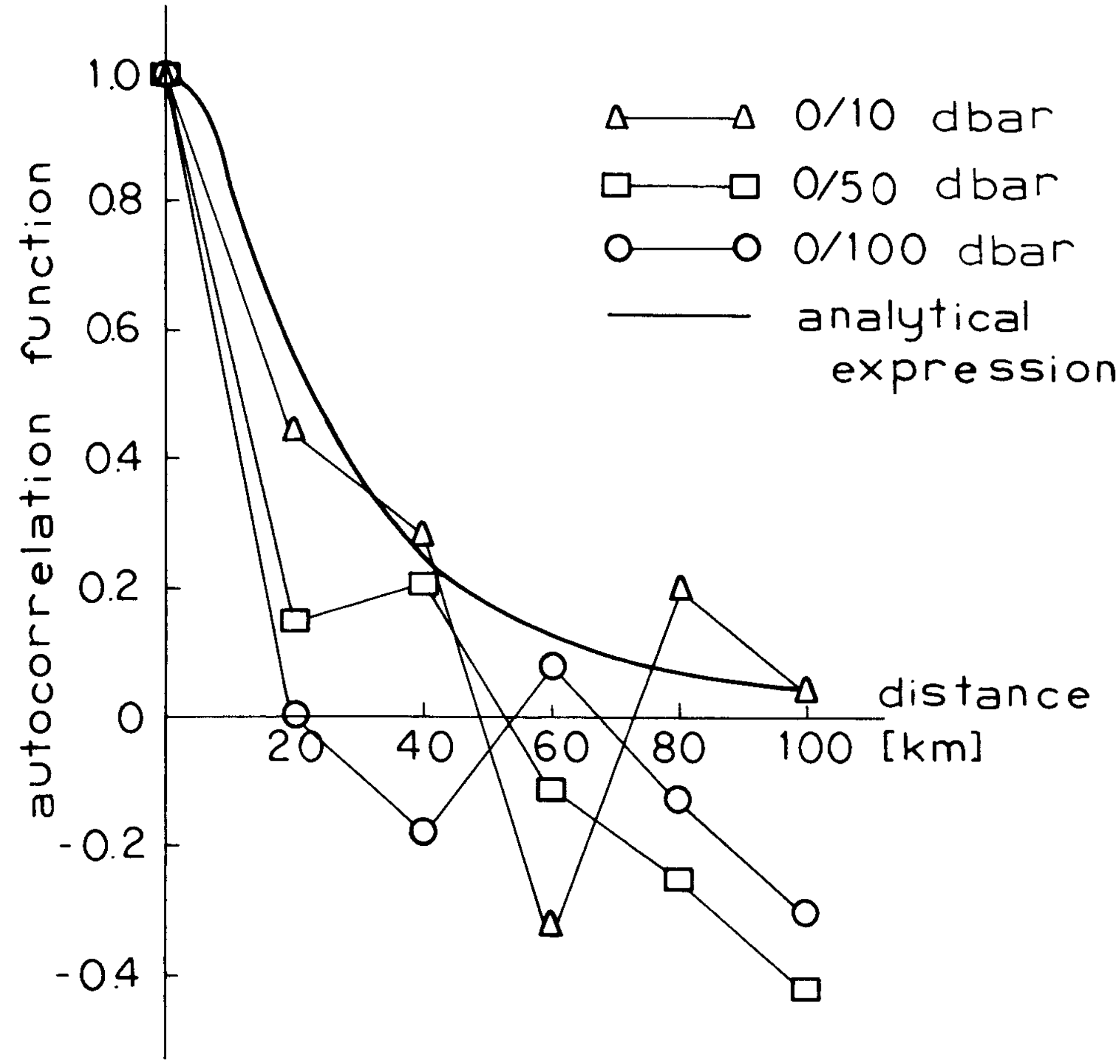

Figure 3. As in Figure 2 except for the cross-basin direction.

data needed are not available for the Adriatic Sea. That implies that an effort should be made in extracting all the information from hydrographic data, along the lines suggested by Stommel and Schott (1977) and by Wunsch (1977).

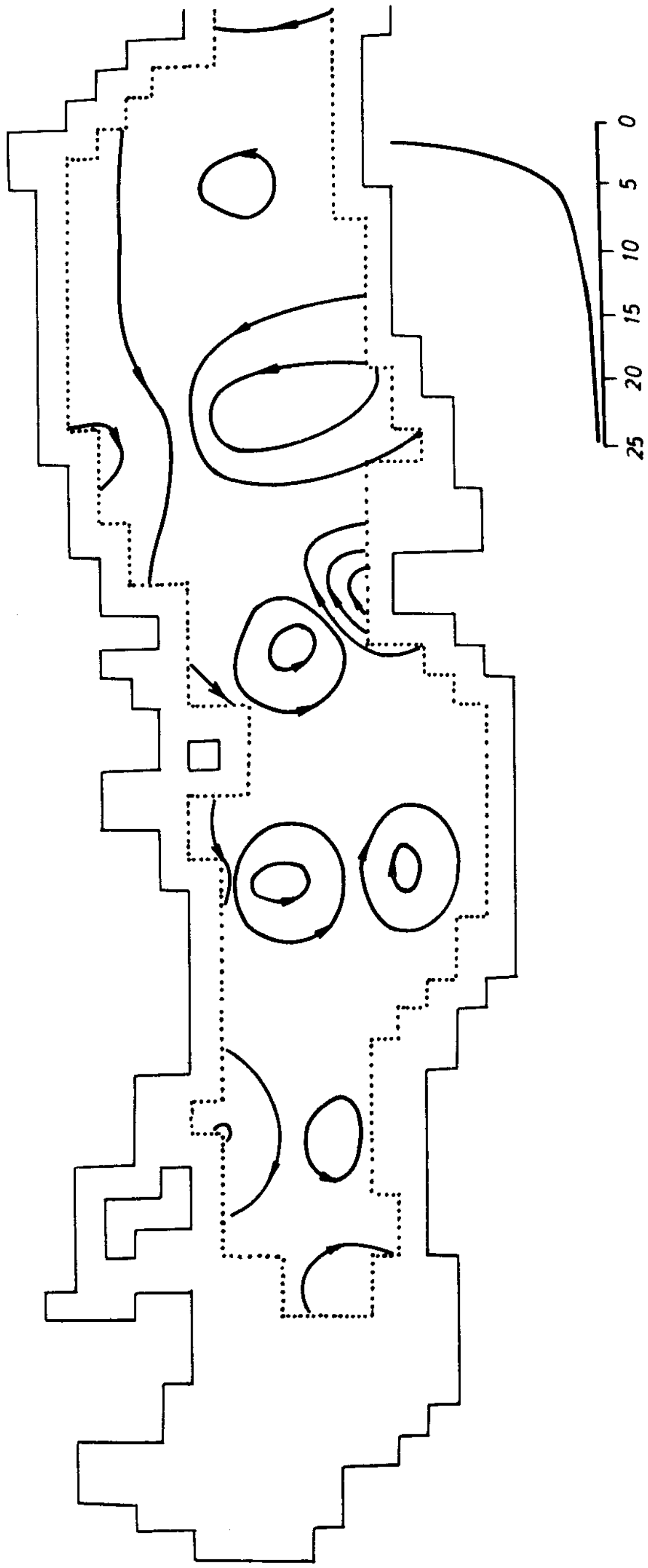

Figure 4. Results of objective analysis with the circular autocorrelation function: surface geostrophic currents, expressed relative to the 50 dbar currents, for the "Andrija Mohorovičić" cruise of September and October 1974. Also shown are model boundaries and the 50 m isobath.

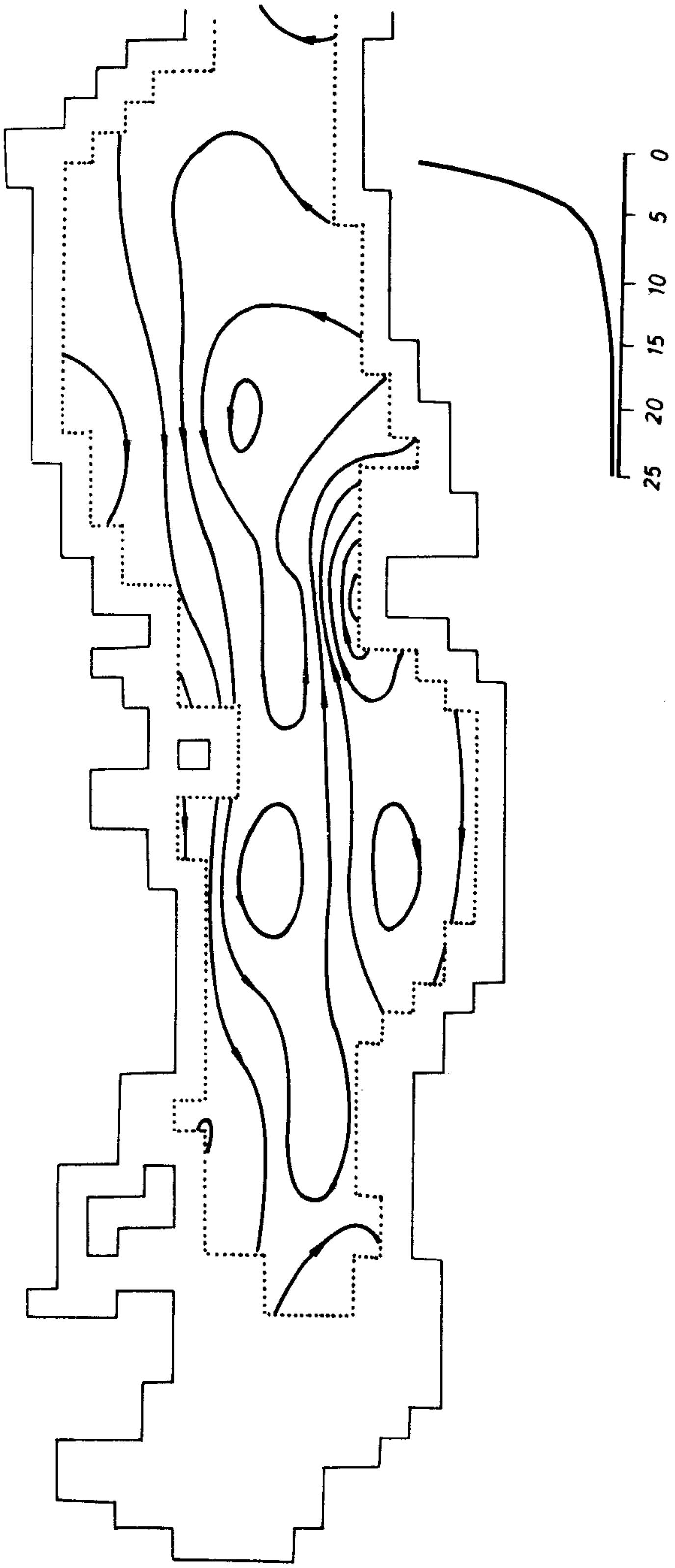

Figure 5. As in Figure 4 except for the elliptical autocorrelation function.

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