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Classification of water masses in the Bransfield Strait and southern part of the Drake Passage using a method of statistical multidimensional analysis

ABSTRACT: Classification of water masses in the area investigated during the 1981 FIBEX Expedition and two winter expeditions at the "H. Arctowski" Station using the method of Empirical Orthogonal Functions (EOF) is presented. Four basic water masses (warm and cold Bellinghausen Sea surface waters, surface Weddell Sea waters, Circumpolar Warm Deep Water (CWDW) and the transitional zone) were observed in the area and a significant dependence of water masses distribution ón depth was found. A strong winter increase in the Weddell Sea waters influence was recorded.

Key words: Antarctica, hydrology, water masses classification.

1. Introduction

Marine biologists for many years have been interested in the South Shetlands region, the Bransfield Strait and southern part of Drake Passage. From the hydrological point of view this is an area where the Weddell Sea and Bellinghausen Sea waters meet. It is commonly assumed that the warmer and less saline waters observed in summer in the western and southern part of the area originate from the Bellinghausen Sea (Clowes 1934, Gordon and Nowlin 1978). They flow into the Bransfield Strait through the inlet between Low, Smith and Snow Islands flowing around both sides of Deception Island and finally appearing as a flow directed northeast adhering closely to the coasts of South Shetlands. The southeastern Bransfield Strait seems to be under the influence of cold, strongly saline Weddell Sea water, which may penetrate the Strait over the broad shelf of d'Urville and Joinville Islands. The range of this water mass may highly fluctuate. Presumably, while flowing along the coasts of the Antarctic Peninsula they may approach even the Trinity Island, where they meet with waters inflowing through the Gerlache Strait (Clowes 1934). Detailed measurements of physico-chemical parameters of water masses of this region which were carried out as a part of the international project BIOMASS in 1980—1981 (FIBEX) and 1983—1984 (SIBEX) suggest the occurrence of several to over a dozen water masses there (First Post FIBEX Hydrographic Data Interpretation Workshop, 1982, Sievers 1982, Grelowski and Tokarczyk 1985, Heywood 1985, Silva 1985). All the above mentioned publications analyse the water masses composition without the aspect of depth. In most of works the classification is carried out on the basis of T-S diagrams analysis, whereas informations that could be obtained from the other measured parameters (contents of biogenic substances or dissolved oxygen) were hitherto poorly exploited. For gaining knowledge on the origin and routes along which phyto- and zooplankton are transported the above descriptions seem to be not sufficiently accurate. In the areas of a high dynamic activity as are the southern part of the Drake Passage as well as the Bransfield Strait (Kharitonov 1976, Nowlin, Whitworth and Pillsbury 1977, Joyce, Zenk and Toole 1978, Sievers and Emery 1978, Zykov et al. 1978, Whitworth 1980, First Post FIBEX Hydrographic Data Interpretation Workshop, 1982, Stein and Rakusa-Suszczewski 1983, 1984) those descriptions seem to be not precise enough also from the hydrological point of view.

In the present paper an attempt was made at presenting the composition of water masses in the area as a function of depth. Water mass classification has been carried out on the basis of a complex analysis of temperature, salinity, content of biogenic substances and dissolved oxygen measured during the 1981 FIBEX Expedition. On the basis of the obtained distribution seasonal changes in water masses of the Admiralty Bay (King George I) were analysed and observed tendencies recorded. A comparison of the method accepted by the First Post FIBEX Hydrographic Data Interpretation Workshop with the presently used method of multidimensional analysis was done.

2. Material and methods

2.1. Description of data

For the present investigations temperature, salinity, dissolved oxygen content, phosphates, silicates, nitrites and nitrates measurements collected during the BIOMASS-FIBEX Expedition and IIIrd and Vth Antarctic Expeditions of the P.A.S. to the Polish "H. Arctowski" Station were used. In the course of the FIBEX Expedition measurements were carried out on board of r/v "Profesor Siedlecki" between 14 February and 21 March 1981, in 43 oceanographic stations set in the Bransfield Strait and southern part of the Drage Passage (Fig. 1). Samples were collected at dephts of 0, 10, 20, 30, 50, 75, 100, 200, 300, 400, 500, 750, 1000 m. Data from the IIIrd (M. Lipski) and Vth (R. Tokarczyk) Antarctic Expeditions of P.A.S. to the "H. Arctowski" Station are from the region of the Admiralty Bay (Fig. 2). They were collected at the stations B and F (IIIrd Expedition) and A–H (Vth Expedition) from motor-boats "Dziunia" and "Słoń Morski". Samples were collected over the whole course of the year from one to three times every month at the depths of 0, 25, 50, 100, 200, 300, 400, 500 m. In the winter of 1981 samples were taken from holes cut in the ice cover. The sampling and determination methods were similar in all three expeditions and were described in detail in Atlas of Polish oceanographic observations in Antarctic waters (1981).

2.2. Methodology

2.2.1. Introduction

The still more commonly used methods of multidimensional statistics may be directly applied in classification problems of water masses (Klepikov and Lukin 1972, Klepikov, Smirnov and Božkov 1974). The statistical analysis of spatial-temporal hydrometeorological fields always involves arranging, calculating and interpreting great quantities of experimental data. Consequently, in such a case these multidimensional analysis methods are used which enable the needed information to be quickly extracted from the whole material. These "quick" methods include those in which fields are represented in the form of some series. The idea of the latter methods consists in transforming the initial set of values in an n-dimensional space of physical parameters to obtain a projection of this set into a subspace spanned over a small number of new variables. These variables cannot be chosen at random but have to include in themselves a maximal part of data on the initial field. The utility of the method of transforming of number fields into series with respect to a chosen function system is determined by the rate of convergence of this series and possibilities of physical interpretation of the terms of this expansion. This last procedure frequently turns out to be the most difficult part of the method (Sklarenko and Smirnov 1974). In order that the terms of the series, into which we expand our data, be physically interpretable the basic function system should reflect in ine way or another the features of the investigated process. In other words the distribution should not be purely formal, as it is the case in the Fourrier expansion, for example. In the case when the physical interpretation is not indispensable the rate of convergence of the field representation error to zero becomes of main importance. The higher the rate the more effective information condensation and lower expansion terms are necessary to find out, at a required precision, the information included in the initial data (Sklarenko and Smirnov 1974). Between the different methods of multidimensional analysis, for water mass classification the method of expansion into empirical orthogonal functions (Božkov et al. 1976, Gruza and Reitenbah 1982), frequently called the method of component analysis (Kendall and Stuart 1976) seems to be the most convenient (Sklarenko and Smirnov 1974). It represents a frequent case of linear, orthogonal information processing. The basic function system of this transformation is defined by the correlation structure of the sequence of parametric spaces. The expansion results in the distribution of data on the initial field among linearly independent components. This distribution is characterized by a maximal rate of convergence to zero of field representation error and minimal entropy in comparison with any other distribution of this kind (Fu 1971). This means that it ensures the best (due to the mean square error) aproximation of the numerical field by a finite number of expansion terms (Sklarenko and Smirnov 1974). This method has been used for the analysis of water masses in the Southern Ocean by Klepikov and Lukin (1972), Klepikov, Smirnov and Božkov (1974), Božkov et al. (1976), Kravčuk, Romancov and Smirnov (1978) and Saruchanjan (1981). In the present paper it was used for analysing water masses distribution between the Weddell and Bellinghausen Seans, in the regions of the Drake Passage and the Bransfield Strait which are under their influence.

2.2.2. Method of Expansion into Empirical Orthogonal Functions (principal components)

There is given a matrix of n physical observations in m points of a net defined (as follows).

$$(F)=\begin{bmatrix} F_{11}, & F_{12}, & \dots, & F_{1n} \\ F_{21}, & F_{22}, & \dots, & F_{2n} \\ \dots & \dots, & \dots, & \dots \\ F_{m1}, & F_{m2}, & \dots & F_{mn} \end{bmatrix} \tag{1}$$

Each row of the matrix (1) characterizes a point in an n-dimensional space of observation parameters. Each column of the matrix (1) is a set of values of one of the parameters characterizing this space. We can assume that there is a function.

$F(Y, X)$ in which —
$Y(y = 1, 2, \ldots, m)$ represents the number of the observation point
$X(x = 1, 2, \ldots, n)$ is a function of this parameter's observations.

It is convenient to represent the function F in the form of the series:

$$F(Y, X) = \sum_h Y_h(y) X_h(x) \tag{2}$$

where $X_h(x)$ are unknown base functions, which depend only on x values, while $Y_h(y)$ are functions representing the expansion coefficients (consecutive components).

For an arbitrary element of the matrix (1):

$$F(Y, X) = F_{ij} \quad (i = 1, 2, \ldots, m)$$
$$X_h(x) = X_{hj} \quad (j = 1, 2, \ldots, n)$$
$$Y_h(y) = Y_{ih} \quad (h = 1, 2, \ldots, n)$$

$$F_{ij} = \sum_h Y_{ih} X_{hj} \tag{3}$$

To obtain functions $Y_h(y)$ and $X_h(x)$ optimal in the sense of the criterion of the minimum of the sum of squares of errors of the distribution with an arbitrarily established h the following condition has to be fulfilled:

$$\Delta = \sum_i \sum_j (F_{ij} - \sum_h Y_{ih} X_{hj})^2 = \min \tag{4}$$

this occurs when the partial derivatives fulfil the conditions:

$$\frac{\partial \Delta}{\partial Y_i} = 0; \quad \frac{\partial \Delta}{\partial X_j} = 0$$

and hence

$$\sum_j F_{ij} X_j = Y_i \sum_j X_j^2 \tag{5a}$$

$$\sum_i F_{ij} Y_i = X_j \sum_i Y_i^2 \tag{5b}$$

Substituting in (5a) the index j for index k and determining Y_i we obtain

$$Y_i = \frac{\sum_k F_{ik} X_k}{\sum_k X_k^2} \quad (k = 1, 2, \ldots, n) \tag{6}$$

Substituting Y_i in (5b) we obtain

$$\sum_k X_k \sum_i F_{ij} F_{ik} = X_j \sum_i Y_i^2 \sum_k X_k^2$$

and substituting

$$\sum_i Y_i^2 \sum_k X_k^2 = \lambda$$

and

$$\sum_i F_{ij} F_{ik} = A_{jk}$$

we have

$$\sum_k A_{jk} X_k = \lambda X_j \tag{7}$$

The field of values A_{jk} is represented by a square, symmetric matrix of the form:

$$(A) = \begin{bmatrix} A_{11} \dots A_{1n} \\ ,, \quad ,, \\ A_{n1} \dots A_{nn} \end{bmatrix} \tag{8}$$

This matrix is a variance matrix when the elements of the matrix (F) are in the form of deviations from their mean or a correlation matrix when the elements of the matrix (F) have been additionally standarized.

To solve the equation (7) we represent it in the matrix form

$$|A - \lambda E| \, X = 0 \tag{9}$$

where:
A is the matrix (8)
E is the identity matrix
X is the column vector of unknown base functions.

To have nontrivial solutions

$$|A - \lambda E| = 0 \tag{10}$$

The equation (10) is called a characteristic equation of the matrix (A). When the matrix (A) is positively defined then solving the equation (10) we obtain n positive solutions which are roots of a polynomial in λ of degree n. These roots are called characteristic roots of the matrix (A). The set of all the A matrix eigenvalues forms its spectrum. Let us set the eigenvalues of the matrix (A) is the decreasing order.

$$\lambda_1 > \lambda_2 > \dots > \lambda_n$$

Considering them in the equation (9) we obtain n solutions of an unknown x, in the form

$$\begin{array}{ll} X_1 (x_{11}, x_{12}, \dots, x_{1n}) & \text{for} \quad \lambda_1 \\ X_2 (x_{21}, x_{22}, \dots, x_{2n}) & \text{for} \quad \lambda_2 \\ X_n (x_{n1}, x_{n2}, \dots, x_{nn}) & \text{for} \quad \lambda_n \end{array}$$

Each of the solutions $x_1, \dots, x_n$ is an eigenvector of the matrix (A), while x_{nn} values are the coordinates of a given vector in an n-dimensional space.

From the general matrix theory it follows that eigenvectors of a real, symmetric matrix are mutually orthogonal, hence they fulfil the condition:

$$\sum_{g=1}^{n} X_{pj} X_{kj} = \delta_{pk} \qquad \delta_{pk} = \begin{matrix} 0 & \text{for} & p \neq k \\ 1 & \text{for} & p = k \end{matrix}$$

Taking into account the above condition we may formulate the function Y in the form:

$$Y = FX'$$

where X' is the transposed matrix for X or a given Y as:

$$Y_{ih} = \frac{\sum_k F_{ik} X_{hk}}{\sum_k X_{hk}^2} \tag{11}$$

$i = 1, 2, \ldots, m$ (ranges over all the measurement points) $h, k = 1, 2, \ldots, n$ (ranges over all the variables). Thus the distribution has been completed.

The variance of the distribution is described by

$$\Delta = \frac{1}{n}\left(\sum_j A_{jj} - \sum_{h=1}^{H} \lambda_h\right) \tag{12}$$

From the properties of symmetric matrices it follows that for $h = n$ the distribution variance equals zero.

In other words, when the number of components equals the number of classes of measured parameters then the distribution is absolutly precise and no loss of information occurs.

The system of co-ordinates chosen as a result of expansion into empirical orthogonal functions is shifted and rotated by a certain angle with respect to the initial system of coordinates. The directions of the new system coordinates are determined by the eigenvalues of the matrix (A). The co-ordinate values of the eigenvectors are direction cosines of angles between the axes of the new and old coordinate systems. These cosines fulfil the conditions:

$$\sum_k x_{hk}^2 = 1 \qquad \sum_h x_{hk}^2 = 1$$

and supply us with information on the contribution of the parameter h in constructing the component k, or on the distribution of the empirical variable h among given components.

In the case when for some reason the number of components used for describing the distribution (H) is lower than n there occurs inevitable loss of information. The precision of reconstructing of the initial space may be easily determined from the following formula:

$$d = \frac{\sum_{h=1}^{H} \lambda_h}{\sum_{h=1}^{n} \lambda_h} \tag{12a}$$

The number of components which is sufficient for the desired precision of approximation may be found by analysing the sequence of values λ_h ($h = 1, 2, ..., n$).

If the distribution error rapidly tends to zero together with taking into account successive terms of the expansion $Q_1, Q_2, ..., Q_n$, then the number of terms of the expansion which have to be considered to obtain a given precision of the distribution is low.

In general the rate of the convergence depends upon two factors:

1. The statistical structure of the discussed space.
2. The method of data processing.

As regards the field structure both very weak and very strong correlation between parameters (Miesčerskaja et al. 1970) should be avoided. In the former case expansion into empirical orthogonal functions makes no sense, in the latter the solving of the characteristic equation may be difficult and burdened with an error (Miesčerskaja et al. 1970). In this latter case the simplest means of improving the quality of obtained results is to remove one of the two strongly correlated parameters out of the matrix (F).

Of all methods of information processing which are used in multidimensional analysis the method of expansion into empirical orthogonal functions has the highest rate of convergence to zero of distribution error (Kendall and Stuart 1976). This property of the method enables in many cases concentrating the basic data on the field condition in a low number of variables, which are then further analysed. In other words, this method enables limiting the size of space in which the given problem is solved, while information loss which results from such limiting is the lowest of all the possible ones (Kiselev et al. 1979). Geometrically, the method consists in projecting points from an n-dimension space onto a subspace of reduced number of dimensions, the optimal direction being selected for the projection (Sklarenko and Smirnov 1974). In most of the cases of the application of the EOF method for the analysis of oceanographic areas the variance of the initial set of data is described with a 70—90% precision by the first two terms of the expansion series (Klepikov, Smirnov and Božkov 1974). In the present case the precision is 84% (Fig. 3). The final terms of the expansion (Kravčuk, Romancov and Smirnov 1978) usually reflect turbulent properties of fields and their omitting may

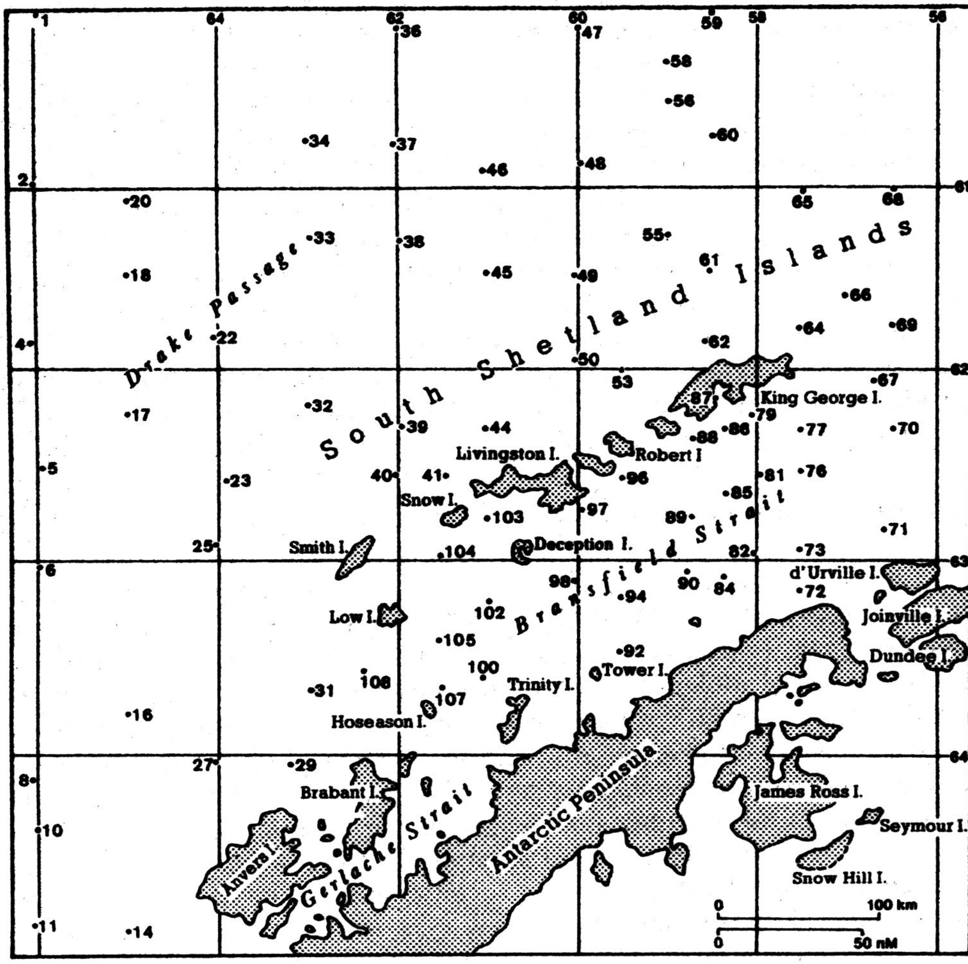

Fig. 1. Position of oceanographic stations of r/v "Profesor Siedlecki" during FIBEX, 14 February — 16 March, 1981

constitute a kind of statistical filtrating, by means of which the part of the spectrum of little importance is cut off. In such cases there is no problem with interpreting the results and the classification of water masses is done by means of isolating the concentrations in the field of points obtained in a system of coordinates determined by the first and second component (Božkov et al. 1976). In the case when the water masses differ in their properties the points which are related to them group in various places of the diagram. The concentration of points in given groups indicates the degree of homogeneity of a distinguished water mass, whereas the distance between the distinguished groups stands for difference in the properties of the distinguished masses. If the distance is larger a high gradient value in the distribution of oceanological characteristics and possibility of the occurrence of frontal zones are to be expected. If, in contrast, the distance is small, it testifies to the high similarity between both groups (Sklarenko and Smirnov 1972, Smirnov and Sklarenko 1974). The distinguishing of isolated groups of points may be troublesome when there occurs a continuous transition of properties (mixing) of two water masses. In such a case, classification is achieved with the discriminating method by introducing into the plane of principal components those points which correspond to control water masses and checking which of the observation points occur within the areas occupied by these masses. The classification cannot be conducted only then when the areas occupied by points belonging to various water masses do not group in various parts of the diagram, but overlap. This means that in the space of parameters chosen for description water masses do not significantly differ in their properties.

2.3. Arrangement of initial data

Initial data were arranged in three sets of common structure and named FIBEX 1981, ADMIRALTY 1979 and ADMIRALTY 1981. As an example, given fragments of the sets are presented in Table 1. Columns 1, 2 and 3 are identifiers (codes) of the observation time. In the FIBEX set the station symbol is concordant with the code accepted in the Atlas of Polish oceanographic observations in Antarctic waters, 1981 (Fig. 1) and the code of the Admiralty sets is concordant with that of Tokarczyk (1986) (Fig. 2). In the columns 4 to 10 the temperature, salinity, dissolved oxygen content, phosphates, silicates, nitrites and nitrates date are presented respectively. The FIBEX set (547 points) was chosen as a basis for determining the projection space. On a subspace determined on this basis both the data belonging to this set (Fig. 4) and data belonging to the Admiralty set (296 and 295 points) (Figs 5 and 6) were projected. Onto this subspace there were also projected parameters determining limits of control sets for surface waters of the Weddell and Bellingshausen Seas, determined on the basis of the literature (Carmack and Foster 1973, 1975, Carmack 1977, Foster and Carmack 1976, Gordon 1971, Kharitonov 1976, Levenčuk and Fedorov 1978, Salamanca and Acuna 1982, Saruchanjan 1980, 1981, Sievers 1982). In this way the classification criterion accepted for the FIBEX experiment was formulated and on its basis seasonal changes in the waters of the Admiralty Bay were estimated.

2.4. Calculations and software

Software methods and calculations were prepared and carried out in cooperation with the Institute of Environmental Management of the Warsaw

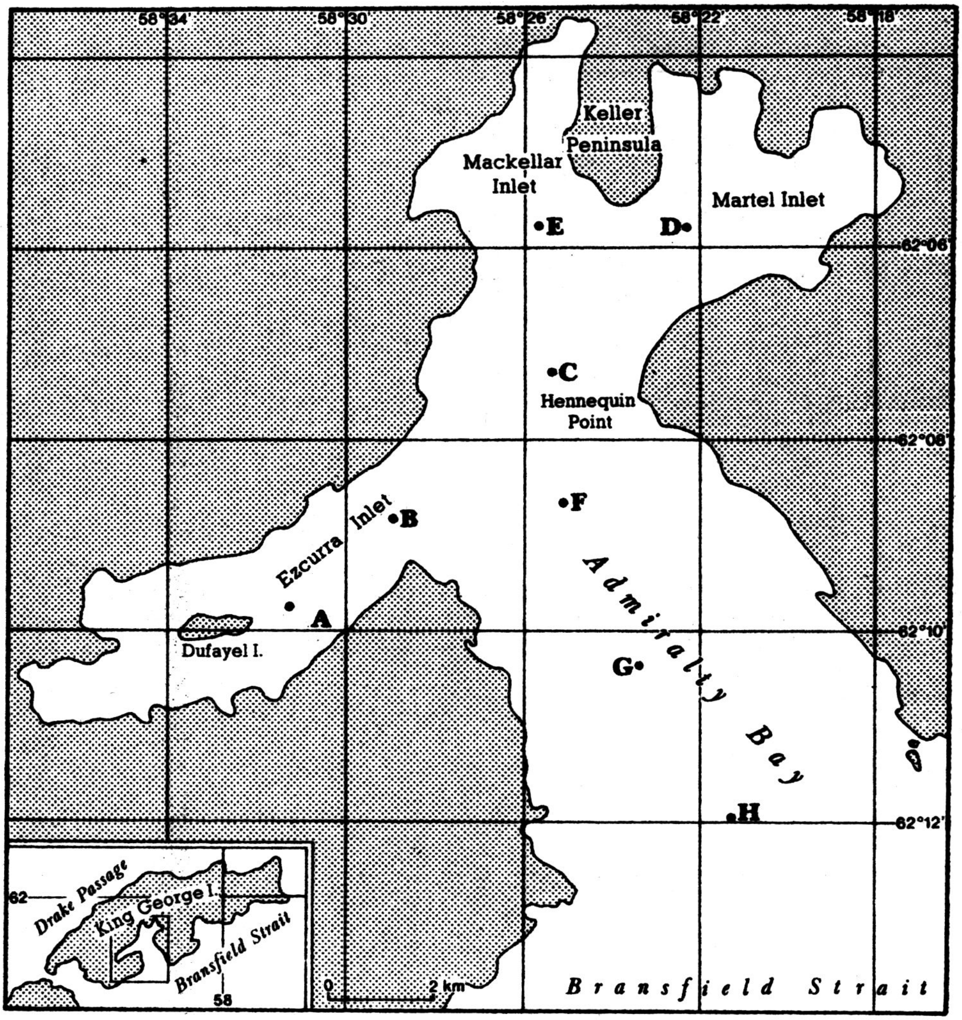

Fig. 2. Positions of oceanographic stations in the Admiralty Bay (King George Island, South Shetlands)

Polytechnic (Łobocki, Madany, Piwkowski and Tokarczyk, unpubl.) using the SM-4 computer working with the operation system RSX-11. The program was prepared in the computer language FORTRAN IV and consisted of three main components:

— subroutine EIGEN which determines the X vectors of the correlation matrix A and transforms a standarized set of observation points into a space determined by these vectors;
— subroutine EXSPA which projects values onto a plane determined by two arbitratily chosen vectors of those determined by the EIGEN subroutine;

Table 1

Exemplary arrangement of initial data sets of observation parameters

---code---			T	S	O_2	PO_4	Si	NO_2	NO_3
					FIBEX — 1981				
1	4	0	1.48	33.65	7.53	0.50	3.69	0.33	25.81
2	4	10	2.88	33.65	7.57	0.50	4.46	0.33	17.21
3	4	20	2.86	33.66	7.62	0.51	5.01	0.32	17.63
547	108	250	0.59	34.58	4.83	0.79	90.70	0.00	24.51
					ADMIRALTY 1979				
1	B	0	0.55	33.99	7.81	2.04	84.60	0.16	14.00
2	B	25	0.52	34.08	7.81	1.97	87.40	0.10	13.30
3	B	50	0.31	34.18	7.39	2.03	88.20	0.11	24.60
296	B	200	−0.41	34.35	6.45	2.40	92.00	0.09	30.80
					ADMIRALTY 1981				
1	B	0	0.02	33.90	7.42	1.83	63.74	0.39	2.96
2	B	25	0.24	34.10	7.32	1.79	67.06	0.37	5.90
3	B	50	0.11	34.20	6.64	1.87	72.46	0.50	12.33
295	F	300	0.39	34.38	6.22	2.09	81.12	0.00	4.24

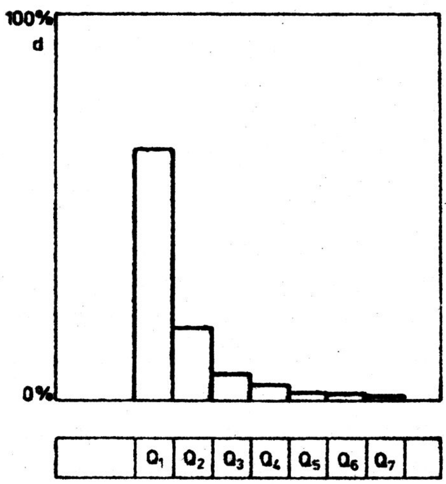

Fig. 3. Arranged distribution of variances (d) along the axis of new variables (Q_1,Q_2,..., Q_7) found by the method

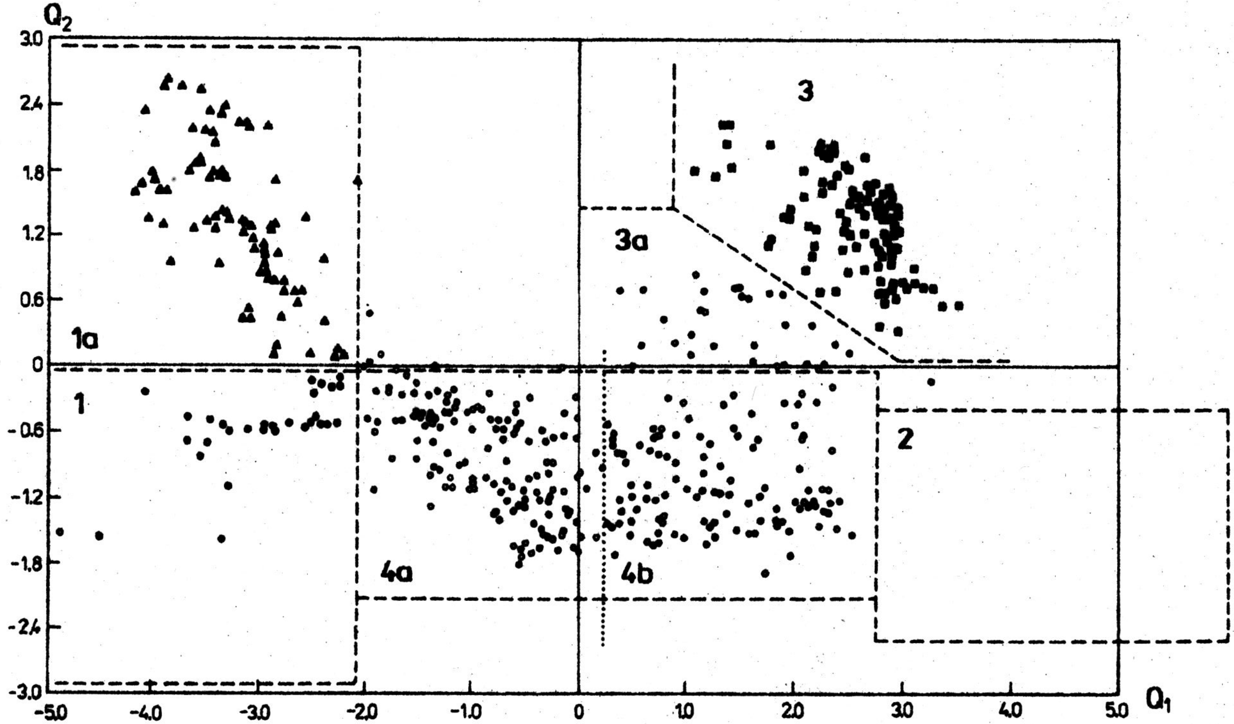

Fig. 4. FIBEX hydrological data projected on the plane of components Q_1, Q_2:
1 — Cold surface waters of the Bellingshausen Sea, 1a — Warm surface waters of the Bellingshausen Sea, 2 — Warm surface waters of the Weddell Sea, 3 — Circumpolar Warm Deep Waters (CWDW) 3a — Area of interaction between waters of types 3 and 4, 4a — Waters of the transitional zone dominated by the typical Bellingshausen Sea features, 4b — Waters of the transitional zone dominated by the typical Weddell Sea features, dotted line — A line distinguishing waters of typical Bellingshausen Sea features and Weddell Sea features

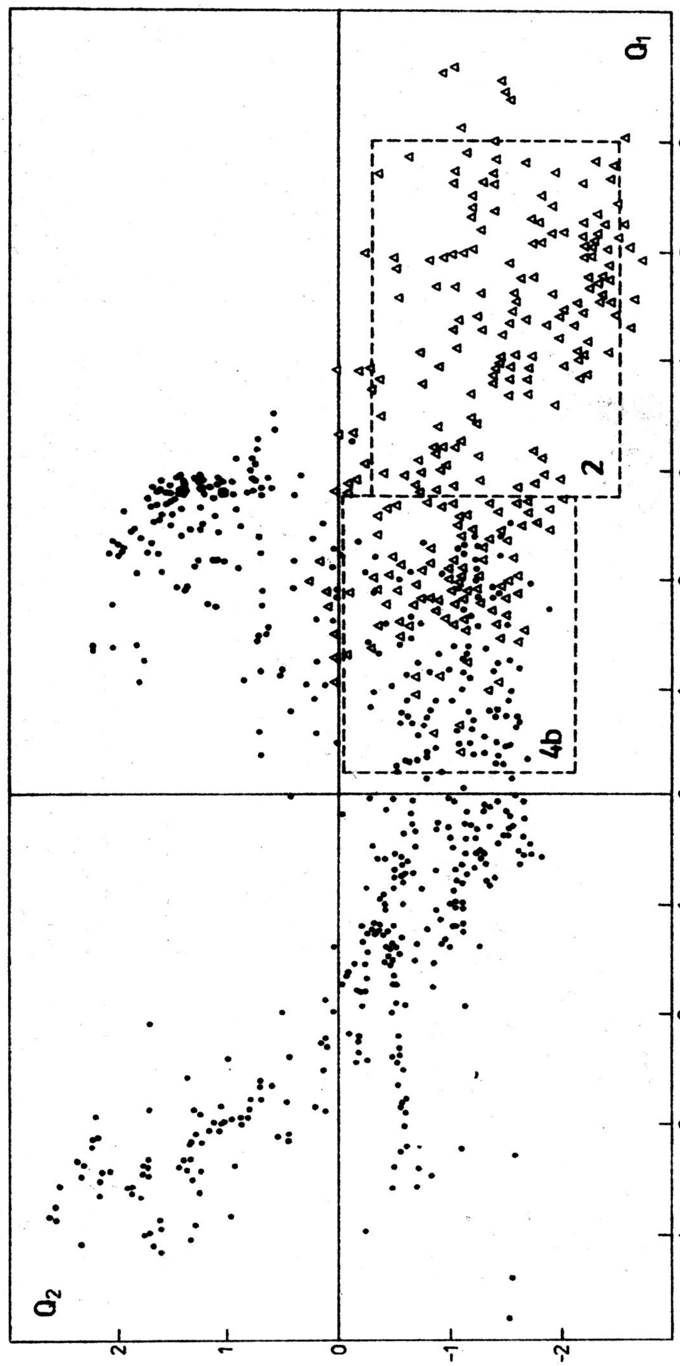

Fig. 5. Data from the Admiralty Bay (December 1978 — December 1979) projected upon the plane components Q_1, Q_2 determined for the FIBEX set;

2 and 4b — as in Fig. 4; triangles — data from the Admiralty Bay; dots — FIBEX data

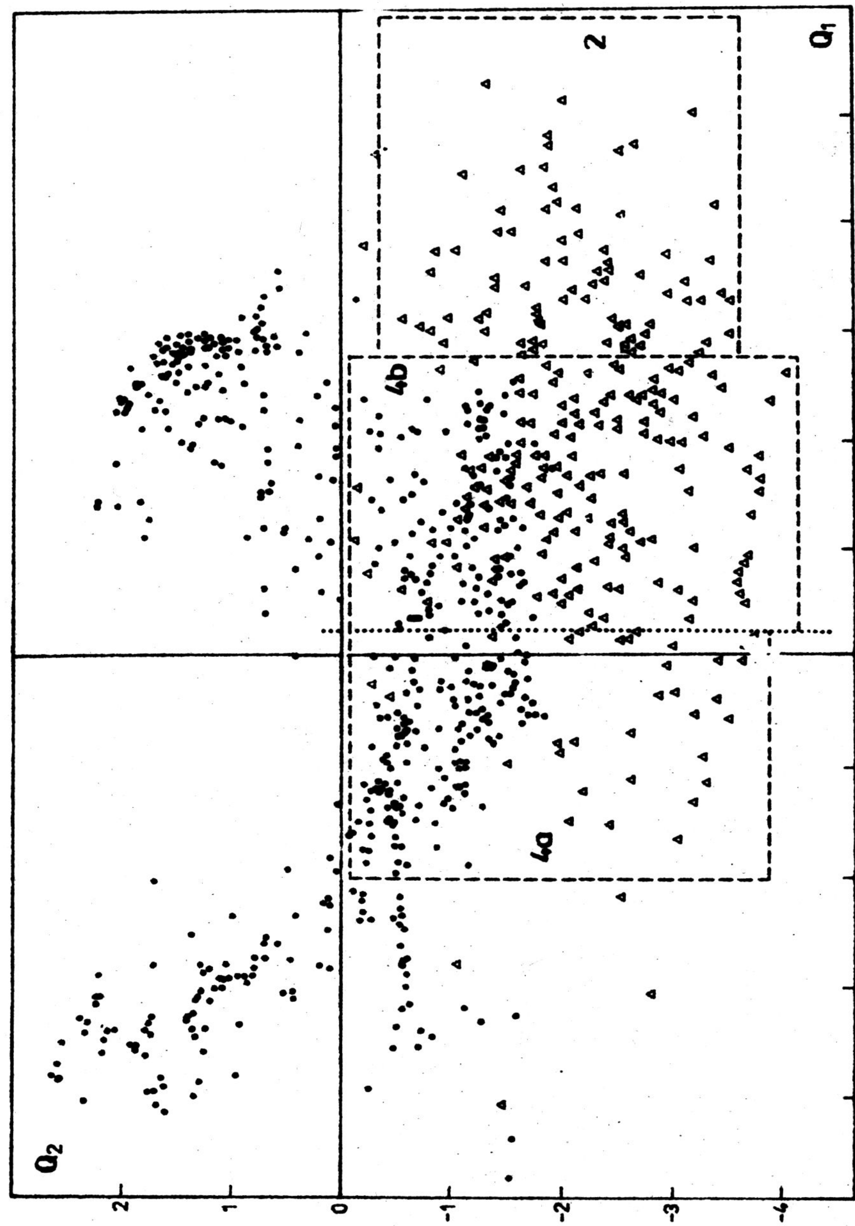

Fig. 6. Data from the Admiralty Bay (March 1981 — March 1982) projected upon the plane of components Q_1, Q_2 determined for the FIBEX set;
2, 4a and 4b — as in Fig. 4; triangles — data from the Admiralty Bay; dots — FIBEX data

— subroutine PLOT making graphs of projections realized by the EXSPA program using a typical plotter, the 1204 (Czechoslovakia).

A detailed description of the program together with mathematical procedures is presented in Łobocki, Madany, Piwkowski and Tokarczyk (unpubl.).

3. Results

In the proiection of observation points upon the plane of components Q_1, Q_2 (FIBEX set — Fig. 4) characteristic areas were distinguished, which belonged to water masses of specific characteristics (Table 2).

Area 1 — comprises cold, surface waters of the Bellingshausen Sea, situated at the south-western limits of the investigated region, close to the Anvers and Brabant Islands. These waters range from the surface to the depth of 30—50 m (Fig. 7, 8) and are of relatively low temperature and salinity and low content of biogenic substances and of a high content of dissolved oxygen.

Area 1a — comprises warmed surface waters of the Bellingshausen Sea ranging from the surface to the depth of about 50—75 m (Fig. 7—9). These waters are of relatively high temperature and dissolved oxygen content and of relatively low salinity and low content of biogenic substances. They extend to the north from the South Shetlands and their southern limits are rather well indicated by the isobaths 500 and 1000 m which lie on the slope of Antarctic continental shelf (compare Bathymetric chart 3, Szeliga 1985).

Area 2 — comprises the surface waters of the Weddell Sea. Its limits (Fig. 4) were determined by the projection of literature data on the Q_1 Q_2 plane (see chapter 2, 3). For Polish data collected in the course of the FIBEX experiment this set is an empty one (Fig. 4), i.e. there was no observation point located in this area.

Area 3 — comprises Circumpolar Warm Deep Waters (CWDW). These relatively warm, strongly saline waters of high (except nitrites) content of biogenic substances and low content of dissolved oxygen were recorded on the northern side of the South Shetland Islands at depths ranging from 200 to 1000 m (Figs. 12—14).

Area 3a — (Fig. 4) comprises intermediate waters, between waters of types 3 and 4. These waters do not constitute a separate group but reflect only the interaction between the CWDW and waters of the transitional zone (Figs. 10—12).

Area 4 — comprises waters of the characteristics changing gradually from those which are typical of the Bellingshausen Sea to those close to the Weddell Sea and this is the reason why they are named the transitionalzone.

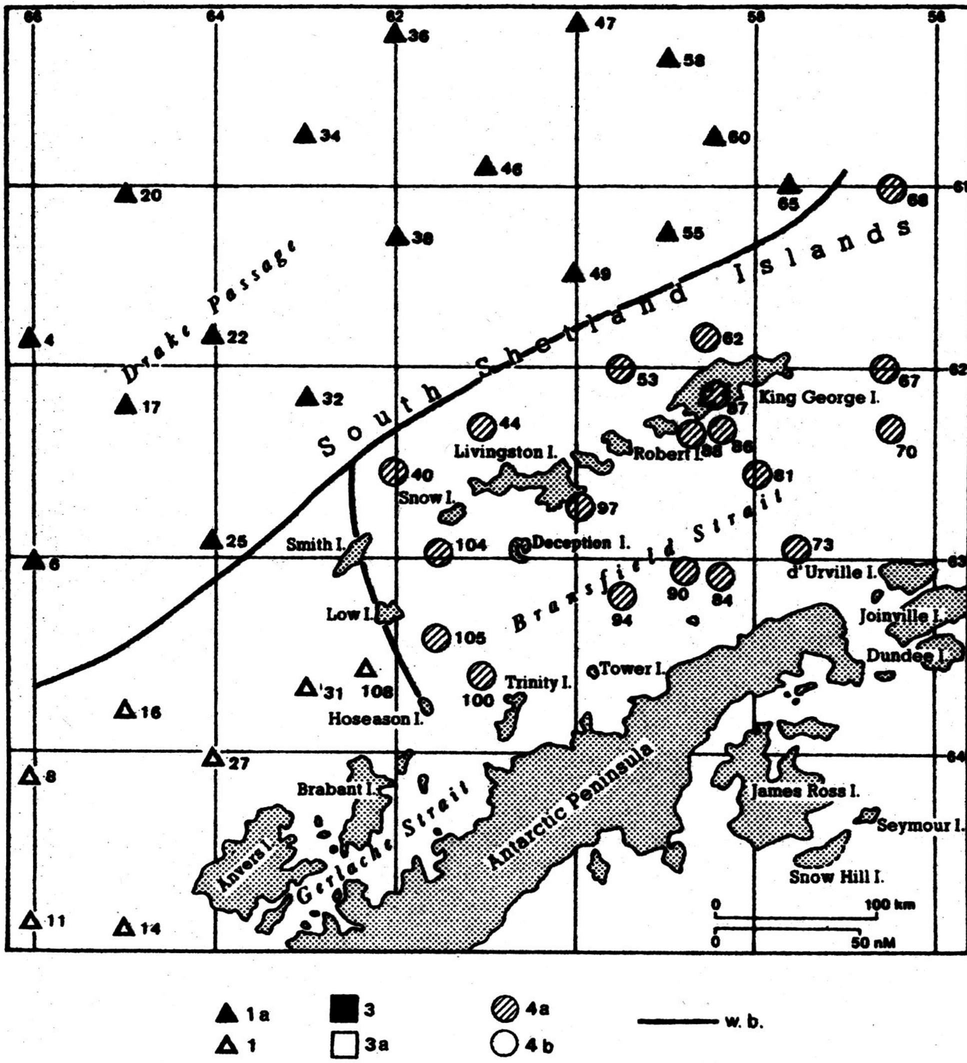

Fig. 7. Boundaries of water masses in the layer 0—30 m

1a — Warm surface waters of the Bellingshausen Sea (type 1a), 1 — Cold surface waters of the Bellingshausen Sea (type 1), 3 — Circumpolar Warm Deep Waters (type 3), 3a — Interaction zone between waters of types 3 and 4, 4a — Waters of the transitional zone doygnated with features sypical of the Bellingshausen Sea (type 4a), 4b — Waters of the transitional zone dominated with features typical of the Weddell Sea (type 4b), w.b. — water boundaries

Points situated within this set do not form any distinct clusters. Except of the layer extending from 50 to 100 m this area is limited to the region of the Bransfield Strait and of the shelf of the South Shetlands (Figs. 7—14). The observed distribution of points (Fig. 4) indicates that within this area

Table 2

Range of fluctuations of physico-chemical parameters within the distinguished water masses

type	temp. °C		salinity 10^{-3}		oxygen cm^3/dcm^{-3}		phosphates $mmol/m^{-3}$		silicates $mmol/m^{-3}$		NO_2^- $mmol/m^{-3}$		NO_3^- $mmol/m^{-3}$	
							FIBEX — 1981							
1a	0.5	3.3	33.1	33.9	7.4	8.2	0.3	1.8	1.7	27	0.1	0.4	9	26
1	0.1	0.8	32.9	33.9	7.5	8.7	0.2	1.6	20	61	0.1	0.2	2	16
3	0.9	2.1	34.3	34.8	4.0	5.6	0.5	2.0	25	105	0.0	0.1	23	28
4a	−1.3	1.5	33.6	34.4	6.0	8.1	0.4	1.9	11	75	0.0	0.3	10	25
4b	−1.5	1.0	33.8	34.6	5.0	7.7	0.7	2.1	40	103	0.0	0.2	13	27
							ADMIRALTY 1979							
4b	−1.7	1.0	33.4	34.5	6.1	8.3	0.7	2.1	73	95	0.0	0.6	6	33
2	−1.8	1.3	33.9	34.6	5.1	8.0	1.2	2.6	75	102	0.0	0.5	11	34
							ADMIRALTY 1981/82							
4a	−1.8	3.1	32.0	34.3	7.0	9.1	0.7	2.0	63	81	0.1	0.8	4	24
4b	−1.8	2.4	33.0	34.5	6.2	9.0	1.3	2.3	63	88	0.0	0.6	10	30
2	−1.9	1.5	33.4	34.6	5.2	7.9	1.6	2.8	64	91	0.0	0.5	10	34

1a — Bellingshausen Sea warm surface waters, 1 — Bellingshausen Sea cold surface waters, 2 — Weddell Sea surface waters, 3 — CWDW (Circumpolar Warm Deep Waters), 4a — transitional zone waters dominated with the Bellingshausen Sea features, 4b — transitional zone waters dominated with the Weddell Sea features

Table 3

Mean and standard deviation values for particular classes of parameters in the FIBEX, ADMIRALTY 1979 and ADMIRALTY 1981 sets

	T	S	O_2	P	Si	NO_2^-	NO_3^-
			FIBEX				
$\bar{x}$	0.58	34.18	6.51	0.69	57.68	0.09	20.13
sd	1.17	0.41	1.35	0.15	25.75	0.08	4.89
			ADMIRALTY 1979				
$\bar{x}$	−0.42	34.17	7.21	1.76	86.92	0.18	27.71
sd	0.94	0.18	0.63	0.32	4.76	0.11	6.06
			ADMIRALTY 1981				
$\bar{x}$	−0.70	34.10	7.37	1.77	73.65	0.26	13.19
sd	1.04	0.30	0.56	0.29	5.40	0.18	7.85

T — temperature (°C), S — salinity (10^{-3}), O_2 — dissolved oxygen (cm^3/dcm^{-3}), P, Si, NO_2^-, NO_3^- — biogenic substances ($mmol/m^{-3}$), $\bar{x}$ — mean value, sd — standard deviation

we deal with a mixture of waters originating from the neighbouring water areas. The only factor which can be determined is the domination of characteristics typical of a given area which is observed at particular observation point. From the analysis of the distribution of observation

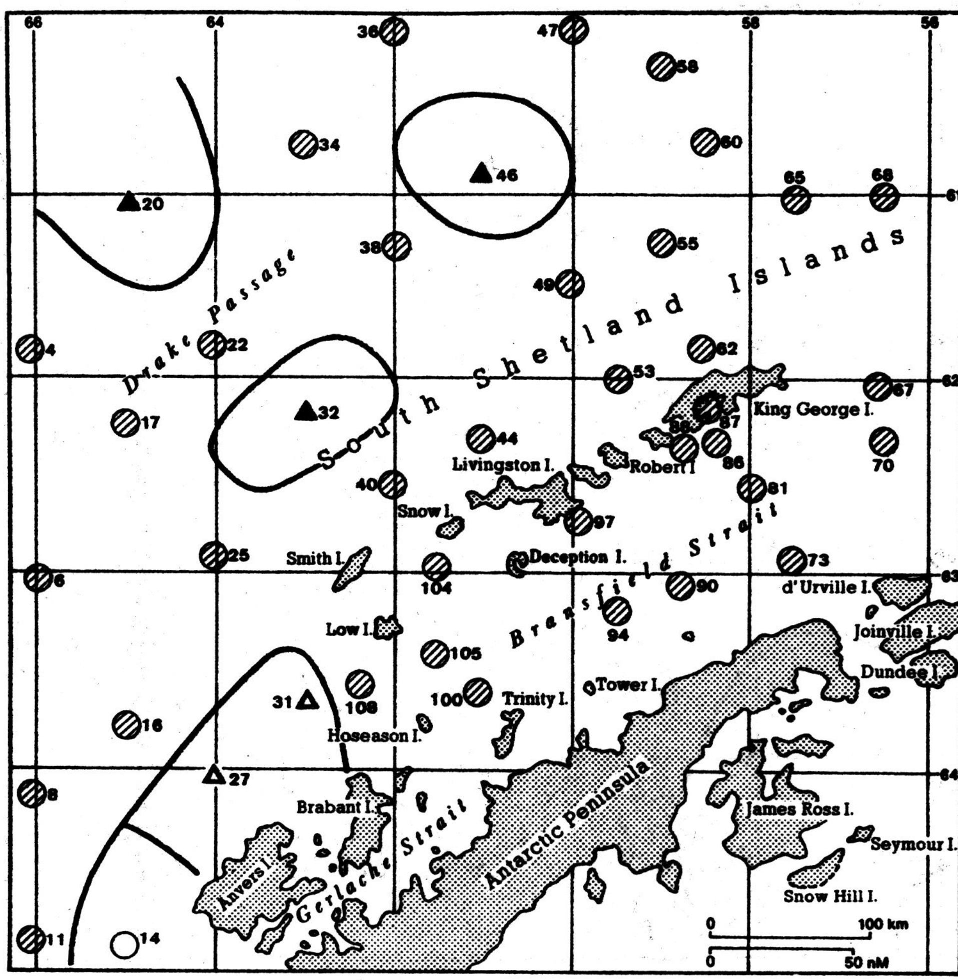

Fig. 8. Boundaries of water masses at the depth of 50 m; Legend as in Fig. 7

points and of the situation of pattern sets on the plane of components Q_1 Q_2 it follows, that the separation line between the waters of the Weddell and Bellingshausen Seas (i.e. line at which the influences of both seas are coarsely equal) may be a line described by the equation $Q_1 = 0.25$ (Fig. 4). With such an assumption water masses described by points situated to the left of this line, within the negative Q_2 values, were under the dominating influence of cold, surface waters of the Bellingshausen Sea (4a, Fig. 4); whereas waters described by points situated to the right of this line, within the range of negative Q_2 values, are mostly influenced by the Weddell Sea (4b, Fig. 4). The result of such a division is shown in Figs. 4—14, whereas the ranges of changes of physico-chemical parameters observed within the separated zones are presented in Table 2.

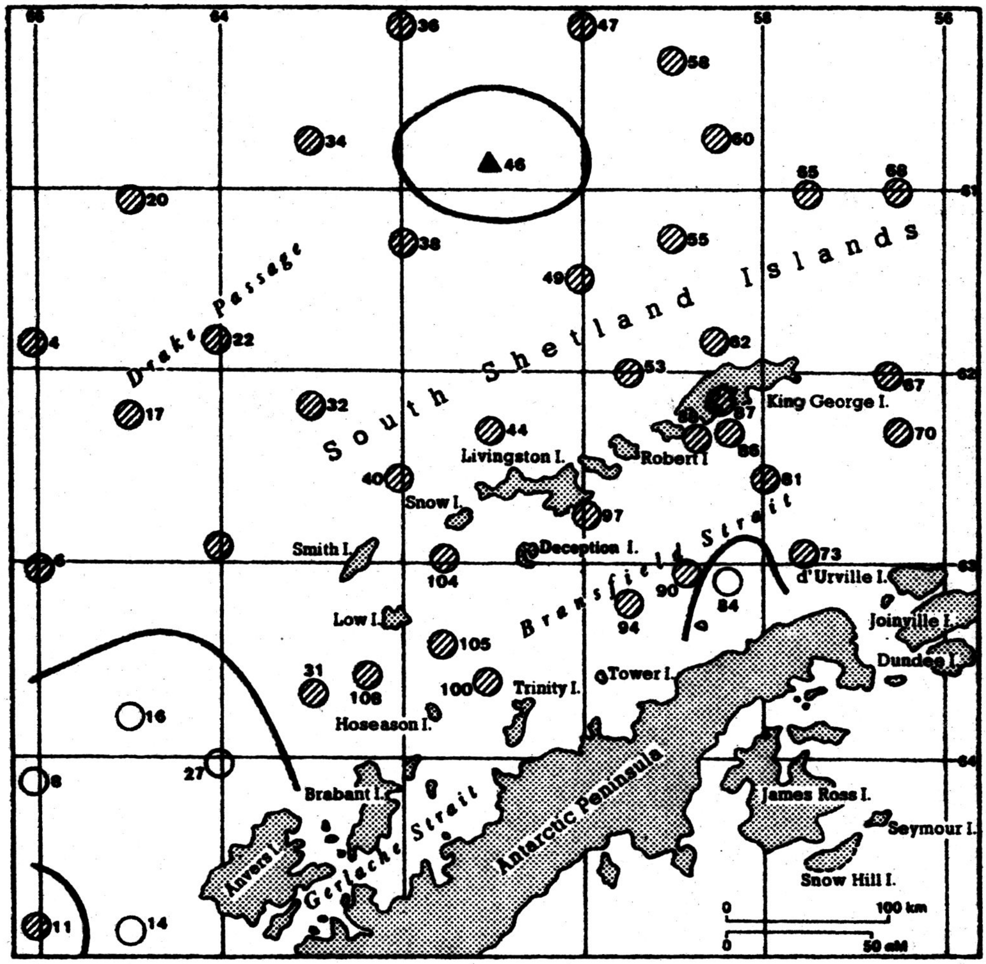

Fig. 9. Boundaries of water masses at the depth of 75 m; Legend as in Fig. 7

— Water layer ranging from the surface to the depth of 30 m (Fig. 7) remained completely under the influence of the Bellingshausen Sea. The northern part of this region as far as to the slope of the continental shelf determined by the 500—1000 m isobaths was occupied by warm surface waters of the Bellingshausen Sea (type 1a). The southwestern part of the region, comprising the extensive shelf of the Anvers and Brabant Islands was filled up with cold surface waters of the Bellingshausen Sea (type 1). The Bransfield Strait and the shelf of the South Shetland Islands was filled up with waters of the transitional zone, which were affected by cold surface waters of the Bellingshausen Sea (type 4a).

— At the depth of 50 m (Fig. 8), pure Bellingshausen Sea waters were met only at several stations, close to the Anvers and Brabant Islands

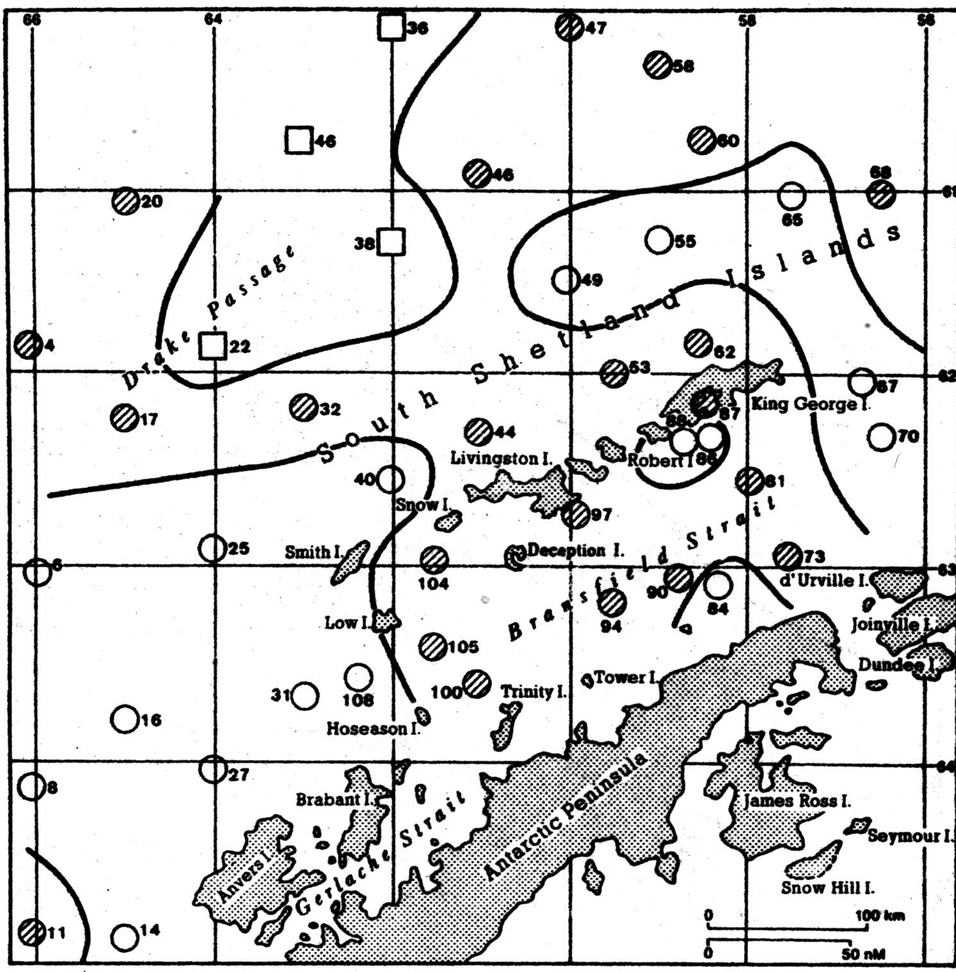

Fig. 10. Boundaries of water masses at the depth of 100 m; Legend as in Fig. 7

(type 1), and in the northern part of this region (type 1a). The major part of this region was occupied by waters of the transitional zone (type 4a). Waters with the domination of the Weddell Sea features first appeared to the south-west of the Anvers Island (type 4b).

— At the depth of 75 m (Fig. 9) the Bellingshausen Sea waters (type 1a) were recorded at one station in the northern part of the region. The remaining area was occupied by the transitional zone waters (type 4), which were affected in general by the Bellingshausen Sea (type 4a). Only in the region of the Anvers Island and close to the end of the Antarctic Peninsula waters of the domination of Weddell Sea features were observed (type 4b).

— At the depth of 100 m (Fig. 10) the investigated area was filled up

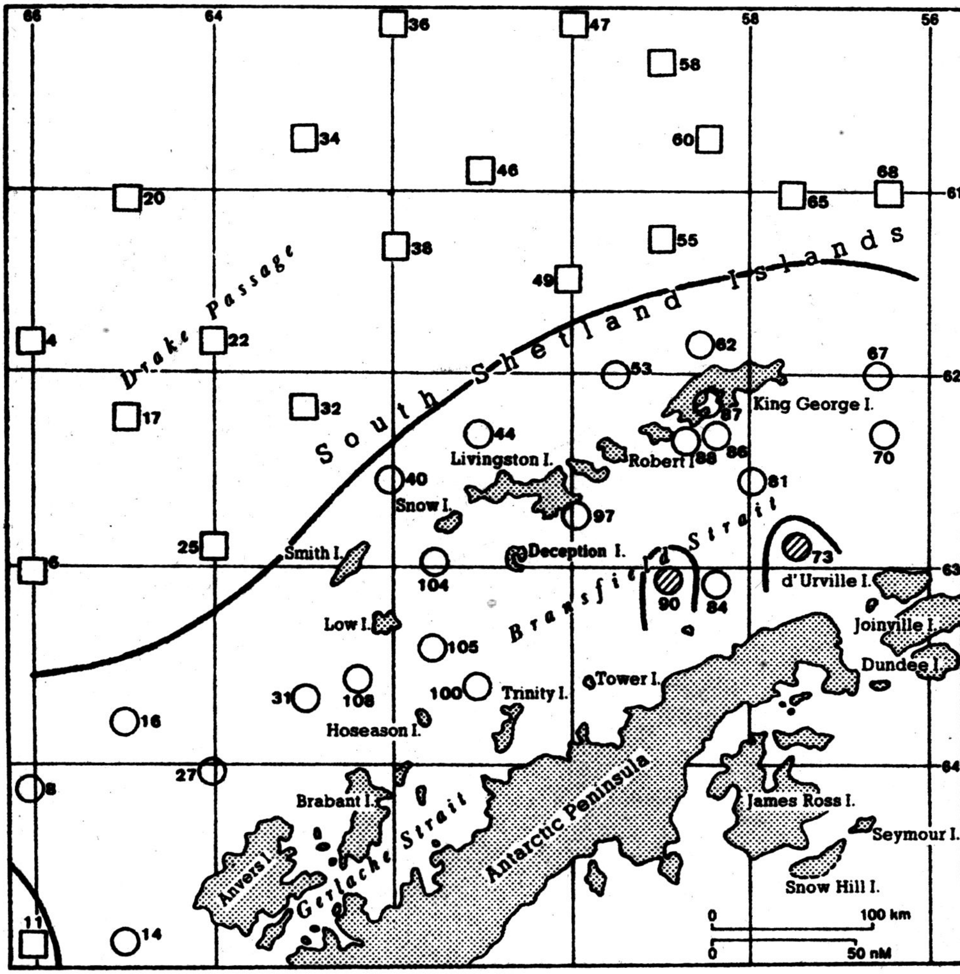

Fig. 11. Boundaries of water masses at the depth of 150 m; Legend as in Fig. 7

with waters of the transitional zone. The shelf of the Anvers and Brabant Islands as far as to the Smith Island to the north was occupied by waters dominated by the Weddell Sea features (type 4b). A thin tongue of these waters was also observed in the eastern part of this region, running from the region of the Joinville Island to the north and north-east along the line determined by stations 70, 67, 65, 55 and 49. Within the Bransfield Strait these waters were observed to the west of the end of the Antarctic Peninsula and at the south coasts of the Robert and King George Islands. The remaining part of the Bransfield Strait, similarly as the area situated to the north of the slope of the continental shelf, were occupied by waters dominated by the Bellingshausen Sea features (type 4a). In the

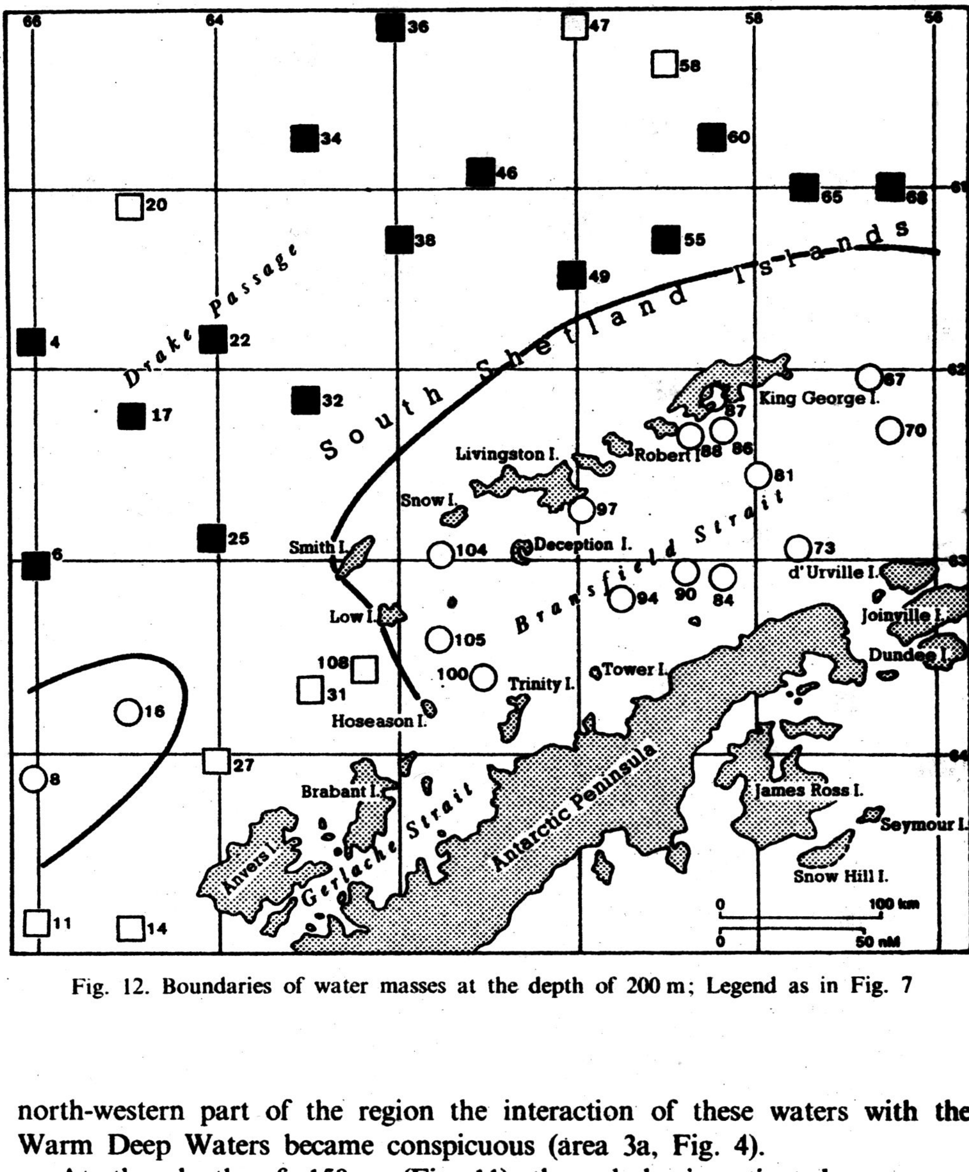

Fig. 12. Boundaries of water masses at the depth of 200 m; Legend as in Fig. 7

north-western part of the region the interaction of these waters with the Warm Deep Waters became conspicuous (area 3a, Fig. 4).

— At the depth of 150 m (Fig. 11) the whole investigated area was filled up with waters of the transitional zone. The region situated to the north of the slope of the continental shelf was occupied by waters dominated by the Weddell Sea features (type 4b), except the stations 73 and 90 where the dominance of Bellingshausen Sea features continued. To the north of the slope of the continental shelf the interaction of transitional zone waters with the CWDW occurred (area 3a, Fig. 4).

— At the depth of 200 m (Fig. 12) the area situated to the north of the slope of the Antarctic shelf was occupied by warm deep waters (CWDW,

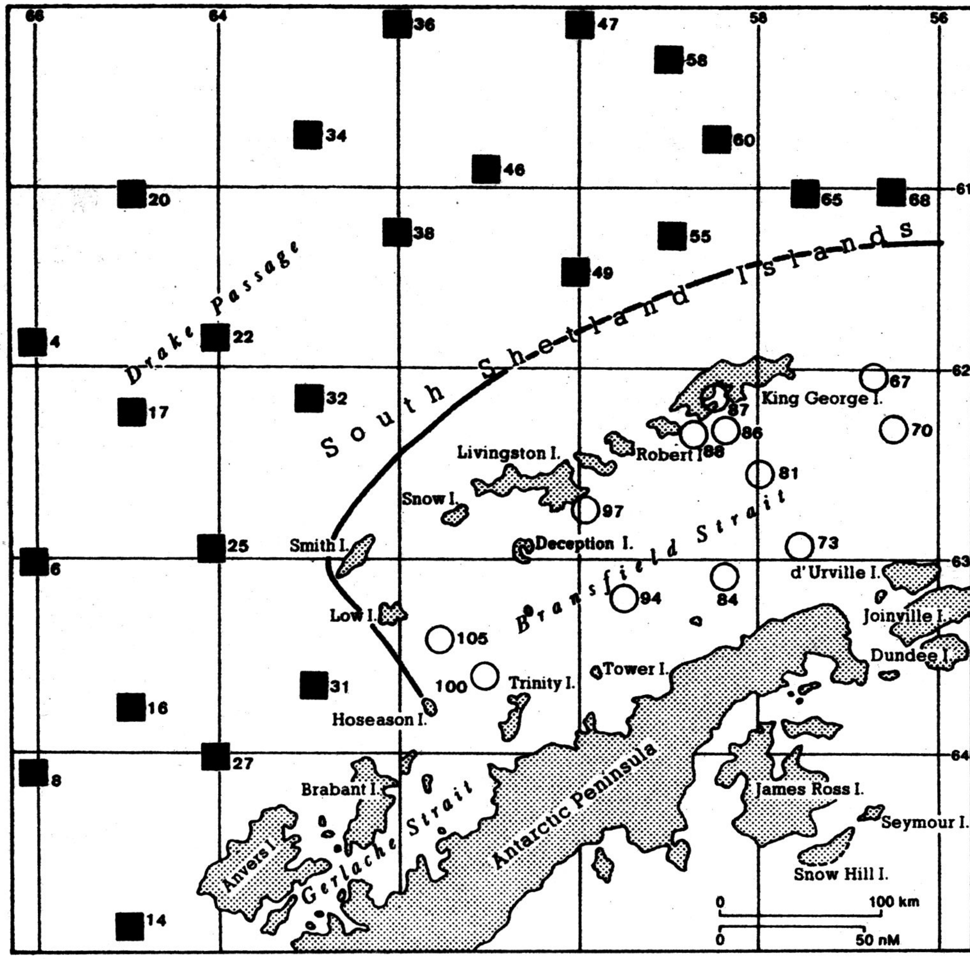

Fig. 13. Boundaries of water masses at the depth of 300 m; Legend as in Fig. 7

type 3), the influence of which extended to the vicinity of the Anvers and Brabant Islands. The Bransfield Strait was filled up with waters of the transitional zone with the dominance of Weddell Sea features (type 4b). — From the depth of 300 m downwards (Fig. 13) the hydrological situation in the investigated region seems to be stabilized. The Bransfield Strait was filled up with waters of the transitional zone affected by the Weddell Sea (type 4b). The remaining area was occupied by Circumpolar Warm Deep Waters (type 3). In subsequent cross-sections down to the depth of 1000 m the number of stations decreased; the distribution of water masses did not change (Fig. 14).

From the distributions presented above (Figs. 7—14) it follows that the limits of water masses in the whole investigated area change with

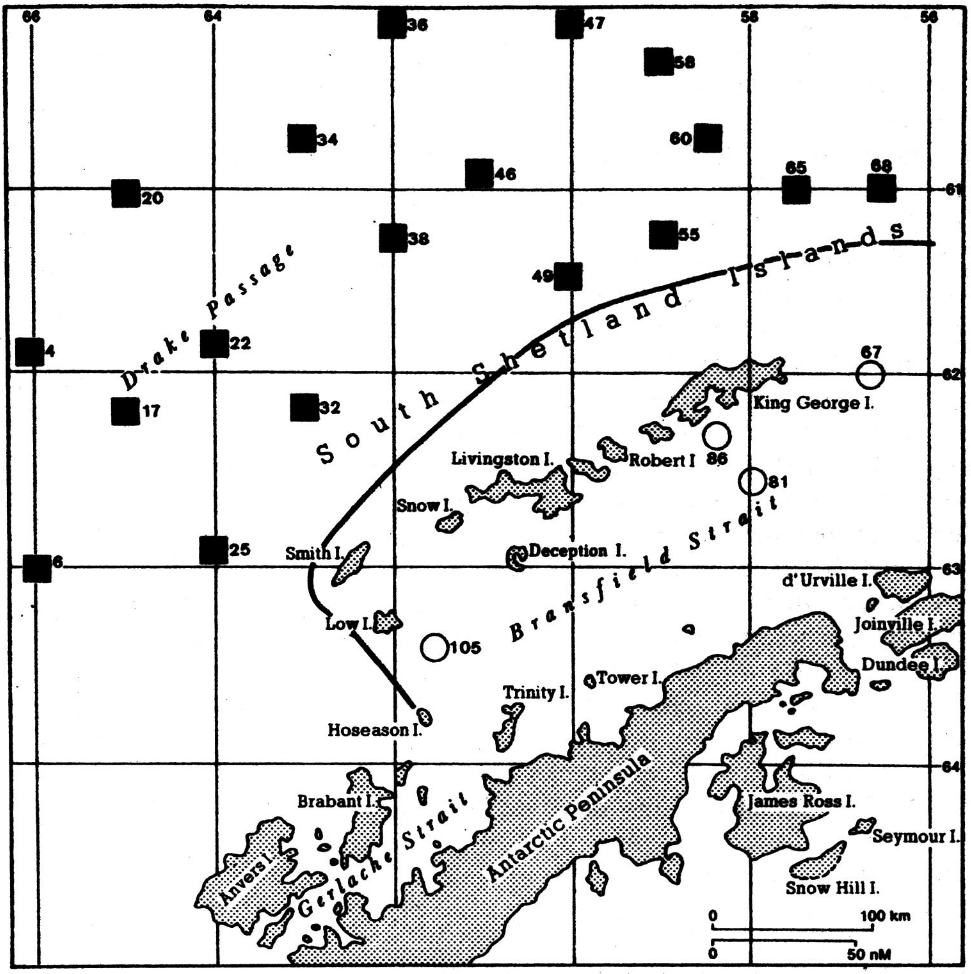

Fig. 14. Boundaries of water masses at the depth of 1000 m; Legend as in Fig. 7

depth. The active layer, in which a high variability of the limits of particular water masses was observed, was the layer occurring at depths ranging from 0 to 300 m. Waters ranging from the surface to the depth of about 50—75 m (Figs. 7—9) had mostly the features of the Bellingshausen Sea (types 1, 1a, 4a). In the layer ranging from 75 to 150 m (Figs. 9—11) this dominance decreased, whereas the share of Weddell Sea features increased which is related to the appearance of waters of the type 4b. At the same time in the region situated to the north of the slope of the continental shelf the influence of Circumpolar Warm Deep Waters became more pronounced (type 3). In this layer a conspicuous upwelling of waters of the Weddell Sea type (4b) was observed in the region of the Anvers Island (Figs. 9—11). The maximal range of these waters was observed at the depth of 150 m (Fig. 11), at which these waters extended outside of the Bransfield Strait, occupying the shelf of the Anvers and Brabant Islands. At the depths of 200—300 m their penetration was hindered by Circumpolar Warm Deep Waters (Figs. 12—13).

In the Bransfield Strait and over the shelf of South Shetlands two types of waters were observed. The upper layer, ranging from the surface down to the depth of about 1000 m was occupied by waters with the majority of Bellingshausen Sea features (type 4a, Figs. 7—10). However, at the depth of 150—200 m waters dominated by Weddell Sea features occurred (type 4b, Figs. 11—14). In this region, similarly as in the rest of the area, the dynamically active layer was that ranging between 0 and 300 m depths.

To estimate the seasonal changes occurring in the Admiralty Bay the ADMIRALTY 1979 and ADMIRALTY 1981 sets were projected together with the FIBEX set upon the plane of components Q_1 and Q_2 (296 and 295 measurement points respectively) (Figs. 5, 6). It appeared that the obtained distribution extends outside the space described by the FIBEX set. Beside the seasonal variability of waters filling the bay an increase in the variability range of physico-chemical parameters characterizing particular water types was observed (Table 2). This is especially conspicuous for the 1981—1982 season (Fig. 6). When comparing the mean values and standard deviations of observation parameters in three analysed sets (Table 3) one can see that four of the seven measured parameters changed approximately within the same limits. These parameters were salinity, silicates, nitrates and dissolved oxygen contents. The remaining three parameters differed significantly from one another. The mean annual temperature values were much lower than the FIBEX set mean calculated for the Antarctic summer. This parameter accounts for the downward shift of the results, in relation to the FIBEX set, towards the negative Q_2 values. The increased mean phosphates value in comparison with that observed in the FIBEX set connected with its low standard deviation value in this set causes a far shift of points belonging to the ADMIRALTY set towards positive Q_1 values. The nitrites content was higher than that of the FIBEX set, which affects the Q_1 component in an opposite direction. The above differences considered against the background of the situation recorded during the FIBEX investigations allow to indicate the following seasonal trends:

1. Waters of the transitional zone typical of the Bransfield Strait (type 4a, 4b; Table 2, Figs. 4—6) dominate in the bay throughout most of the year. In 1979 from February to July they either filled up all of the bay's volume or constituted its upper, about 200 m thick, layer. In the rest of the year these waters were recorded in the bay mainly close to the surface. In the 1981—1982 season these waters dominated in the bay in 1981 from March to July, in October and from December to February

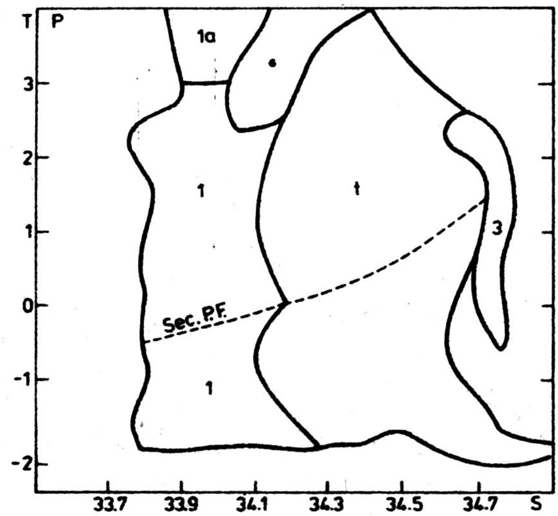

Fig. 15. Temperature-salinity diagram for Antarctic waters of the Pacific sector (according to Gordon 1971);
P — Pacific sector, Sec. P. F. — Secondary Polar Front, 1 — Antarctic surface waters, 1a — warmed Antarctic surface waters, t — transitional zone waters, s — Subantarctic surface waters, 3 — deep and bottom waters, T — temperature (°C), S — salinity (10^{-3})

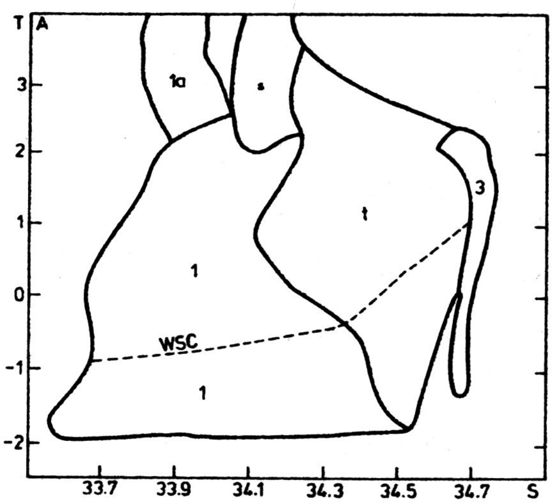

Fig. 16. Temperature-salinity diagram for Antarctic waters of the Atlantic sector (according to Gordon 1971)
A — Atlantic sector, WSC — Weddell-Scotia Confluence, 1 — Antarctic surface waters, 1a — warmed Antarctic surface waters, t — transitional zone waters, s — Subantarctic surface waters, 3 — deep and bottom waters, T — temperature (°C), S — salinity (10^{-3})

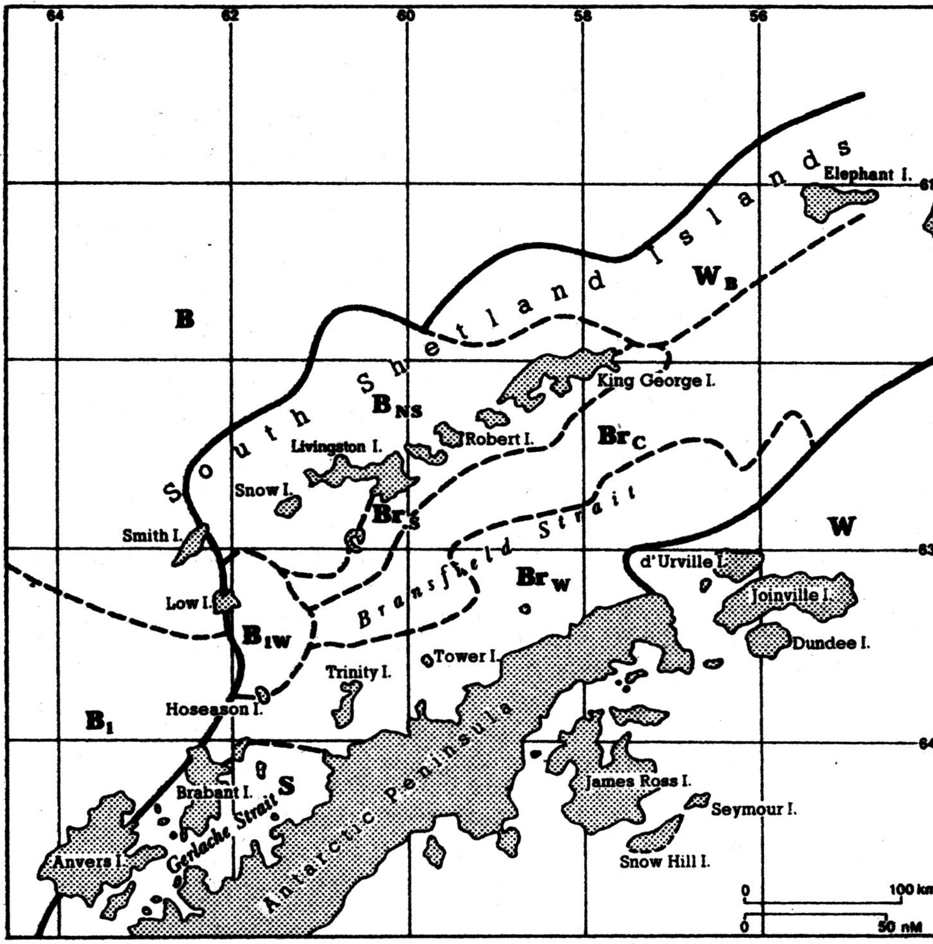

Fig. 17. Boundaries of water masses according to the First Post FIBEX Hydrographic Data Interpretation Workshop

B — Bellingshausen Sea surface waters B_1 — Bellingshausen Sea cold surface waters, W — Weddell Sea surface waters, Br — Bransfield Strait waters (Br_s, Br_c, Br_w) S — waters formed as a result of the interaction of Br_w and B_1 types of waters W_b — waters formed as a result of the mixing of B_{ns} and W types of waters B_{ns} — Bellingshausen Sea waters modified over the shelf of South Shetlands B_{lw} — waters formed as a result of interaction of waters filling the Bransfield Strait with the Bellingshausen Sea waters

1982. In March, October and December 1982 they totally filled up the bay, whereas between April and July 1981 and from January to February 1982 they constituted its upper, about 200 m thick layer.

2. In winter for three to five months the Admiralty Bay remains under the influence of waters of characteristics identical with those of the Weddell Sea (type 2; Table 2, Figs. 4—6). These waters were represented by a layer of water relatively cold, saline, abundant in

biogenic substances, of low mean nitrites and of lower dissolved oxygen contents in comparison with typical surface waters from the Bransfield Strait region. These waters filled up the most part of the bay from August to December 1979 and from August to November 1981. In other periods they were recorded sporadically, usually in the bottom layers. It follows from this fact that they may fill up the bay in winter, but in summer they are pushed out by the transitional zone waters typical of the Bransfield Strait (type 4; Table 2).

3. In the 1979 season the influence of the Weddell Sea waters in this region was slightly stronger than that observed in the 1981—1982 season.

4. Discussion

On the basis of the methodology applied in the present investigations there was obtained a variable, dynamic pattern of four main water masses occurring in the region: surface warm and surface cold Bellinghausen Sea waters, surface Weddell Sea waters and Circumpolar Warm Deep Waters. Warm surface Bellingshausen Sea waters (type 1a) are those Bellinghausen Sea waters which occur in the Drake Passage to the north of the third most southern ACC stream (Kharitonov 1976, Zykov et al. 1978). The course of this stream (Nowlin, Whitworth and Pillsbury 1977, Whitworth 1980) is relatively stable in this region and is connected with the edge of the continental shelf. Cold surface Bellingshausen Sea waters (type 1) are situated to the south of this stream and are influenced by the ice-covered continent. They belong to a comprehensive class of coastal waters (Whitworth 1980) met above the shelf surrounding Antarctic; in the Bellingshausen Sea they are recorded to the south of the Secondary Polar Front (Gordon 1971). The comparatively high (above 0°C) temperature, low salinity (Table 2) and relatively small depth of occurrence (Figs. 7—9) indicate that the both distinguished water masses may belong to the waters of the so called summer modification. Circumpolar Warm Deep Waters (type 3) in concordance with earlier observations (Božkov et al. 1976, Kravčuk, Romancov and Smirnov 1978) were recorded, from the depth of about 200 m downwards, mainly outside the continental shelf. Their influence on the composition and distribution of other water masses is significant. The upwelling of CWDW observed on the slope of the continental shelf. (Figs. 11—12) constitutes a dynamic barrier limiting the outflow of water from the shelf region to the north. In this way, beginning from the depth of 150 m, the CWDW limit the spreading of waters dominated by the Weddell Sea features (Figs. 11—14). Inside the Bransfield Strait it is difficult to distinguish water masses. None of the four main water masses (types 1, 1a, 2 and 3) was observed in the course of the FIBEX expedition in its pure form. The transition between surface layers and deeper layers is not sharp. This is caused by the lack of flow of the Circumpolar Warm Deep Waters along the Bransfield Strait on one hand (Clowes 1934, Gordon and Nowlin 1978) and by refreshing of deeper layers by winter convection on the other. Surface waters reflect the mixing effect of Weddell Sea and Bellingshausen Sea waters (Clowes 1934, Gordon and Nowlin 1978, First Post — FIBEX Hydrographic Data Interpretation Workshop, 1982, Sievers 1982, Grelowski and Tokarczyk 1985, Heywood 1985, Silva 1985). Accordingly, the Bransfield Strait may be considered a typical transitional zone, in which gradual water mixing takes place. In the composition of such mixture one of the water masses becomes dominant and waters of a given point may be attributed to particular water mass. The distribution obtained with the presently used methods appears to be significantly correlated with depth in the Bransfield Strait. In the observed mixture of waters the dominance of the Bellingshausen Sea features was observed from the surface downwards to the depth of about 100 m (Fig. 7—10). Change in water properties occurred in a relatively narrow layer observed during the FIBEX expedition at depths between 100 and 150 m (Figs. 10—11). In lower layers the dominance of the Weddell Sea features was observed (Figs. 12—14). Such a picture clearly differs from that proposed by the First Post — FIBEX Hydrographic Data Interpretation Workshop (Hamburg, 1982; Fig. 15) and by the others based on the same methods. These differences come first of all from methodological differences. The above mentioned works are based on the analysis of T-S diagrams and discuss their results within an integrated (usually 0—500 m) depth scale. In other words, an arbitrary assumption was done that in the water column several hundred of meters thick only one waters mass is present. The ranges of particular water masses become then the functions of only geographical position of oceanographic stations. This leads (Fig. 15) to the division of the investigated area with vertical planes determining borders between subsequent water types. The results of the present paper indicate that this assumption is an improper one. In the investigated region the 0—300 m layer is that of the highest dynamics. The range of a particular water mass clearly depends here on the depth and thus the proper distribution should have a spatial character. This is obtained from distributions presenting the course of borders at subsequent levels distinguished. The other doubtful feature of distributions based upon the data of the First Post — FIBEX Hydrographic Data Interpretation Workshop is the description of water masses made only by means of relation between temperature and salinity. In this method classification of waters is carried out on the basis of the distribution of observation points within areas considered typical in the T-S diagram for chosen was masses. Defining such areas is necessary and their mutual distinction (impenetrability of one another) is the condition of the classification. In the T-S space (Figs. 16, 17) Gordon (1971) distinguished such areas for the Pacific and Atlantic sectors. From their comparison it follows that in the surface Weddell Sea waters and Bellingshausen Sea waters situated to the south of the so called Secondary Polar Front (Gordon 1971) this condition is only partly fulfilled. Because these very waters are present in the Bransfield Strait and South Shetlands region the T-S method does not have to give unequivocal results in this area. In this situation it semms to be proper to include a higher number of features in the classification. The analysis of subsequent pairs of binomial diagrams like temperature — salinity, temperature — phosphates, temperature — silicates, etc. becomes a work-consuming task at a higher number of variables. It is more convenient to use the methods of multidimensional analysis. Their idea consists in such change of the system of coordinates in the n-dimensional space of empirical variables that an accidental variance distribution among variables found out with such a method. If the new, arranged variance distribution rapidly tends to zero part of the new variables may be deleted with little information loss and thus reduce the dimension of space in which the results are interpreted. For example, in the present paper the information loss resulting from the reduction of the 7-dimensional system of empirical coordinates to a 2-dimensional system of synthetic variables discovered with this method amounted to 16% (Fig. 3). The complex use of empirical parameters is retained here, because they are used for constructing each of the new variables to a degree proportional to their actual significance. Among various statistical methods the one proposed in this paper is considered optimal for water classification (Klepikov, Smirnov and Božkov 1974) because it allows to reduce maximally the number of space dimensions with minimal (Sklarenko and Smirnov 1974) information loss in comparison with other methods.

Using the data from two years of observations in the Admiralty Bay (King George Island, South Shetlands) an assessment of seasonal changes in this region's water masses was carried out in the present study. The FIBEX set was used as a background. It was found that in summer the Admiralty Bay is filled up by waters of the transitional zone, typical of the Bransfield Strait (type 4, Table 2). In these waters the Bellingshausen Sea influence decreased and the one of the Weddell Sea increased with depth. In summer these influences become equal at the depths about 200—300 m. In winter the influence of the Wedded See increased. At the beginning of winter a clear shift of the points characterizing the waters of the Bay towards areas typical of the Weddell Sea was observed (Figs. 4—6). This was caused by the decrease of temperature, and of nitrites and dissolved oxygen contents which are connected with an increase of the salinity and of the contents of the other biogenic substances. This situation might be explained by an inflow of the Weddell Sea waters into the Bransfield Strait. This phenomenon was recorded in both winter seasons (1979 and 1981) while in the summer of 1981 no penetration of the Bransfield Strait waters into the area typical of the Weddell Sea waters was detected, despite the measurements being conducted down to the depth of 1000 m; that would suggest that the inflow of the Weddell Sea waters into the Bransfield Strait is much stronger in winter, which, in turn, may be related to a change in the range of katabatic continental winds which occur in this period (Gordon 1971).

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6. Streszczenie

W oparciu o pomiary temperatury, zasolenia, zawartości krzemianów, fosforanów, azotynów, azotanów i rozpuszczonego tlenu przeprowadzono klasyfikację mas wodnych w rejonie Cieśniny Bransfielda i południowej części Cieśniny Drake'a. Do celów analizy wykorzystano metodę Empirycznych Funkcji Ortogonalnych (EOF) zwaną też met. składowych. W opracowaniu wykorzystano dane zebrane podczas ekspedycji FIBEX-BIOMASS (14 luty — 16 marca 1981) oraz III (grudzień 1978 — grudzień 1979) i V (marzec 1981 — marzec 1982) Wyprawy Antarktycznej PAN na stację im. Arctowskiego. Określono zasięg wpływów powierzchniowych wód bellingshausenowskich, weddellowskich i Okołopolarnych Ciepłych Wód Głębinowych na poziomac„bgłębokości od 0 do 1000 m (Rys. 7—14). Wykazano, że rozkład mas wodnych jest w tym rejonie silnie związany z głębokością. W górnych warstwach od 0 do 150 m dominują wody o przewadze cech bellingshausenowskich, zaś wody o przewadze cech weddellowskich napotyka się zwykle poniżej, z wyjątkiem obszarów położonych po zewnętrznej stronie szelfu kontynentalnego, gdzie ich miejsce zajmują CWDW. Rozpatrując sezonowe zmiany mas wodnych w Zatoce Admiralicji stwierdzono w obu sezonach zimowych wyraźny wzrost wpływu wód weddellowskich w porównaniu do sytuacji obserwowanej podczas FIBEX-u.