Some considerations on neutral surface analysis

Neutral surface
Oceanic circulation
Hydrological data
Atlantic Ocean
Mediterranean Sea

Surface neutre
Circulation océanique
Données hydrologiques
Océan Atlantique
Mer Méditerranée

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ABSTRACT

The development of the concept of a "neutral surface" - an isopycnal surface refined by the introduction of a variable reference pressure - is presented. Problems in approximating such a surface (concerning, for example and *inter alia*, the reference water parcel to be used in starting a neutral surface; or the reference pressure and parcel to be used and path to be followed in extending a neutral surface from station to station) are examined. These problems arise because oceanographic reality only provides data at discrete depths from given station networks. The effects of compressibility dependence on the thermohaline properties of a water parcel in delineating a neutral surface are also considered. A new method of approximating neutral surfaces is presented. Neutral surface analysis, that is to say a technique to infer qualitatively circulation based on hydrographic data, is discussed. Data from the Atlantic Ocean and the Mediterranean Sea are used to obtain a number of neutral surfaces, on which the spreading of various water masses is examined, elucidating some oceanographic problems and thereby vividly demonstrating the versatility of the technique proposed.

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RÉSUMÉ

Quelques considérations sur l'analyse de surface neutre

Le concept de «surface neutre» est développé en associant une pression référence variable à la notion de surface isopycne. La définition d'une surface neutre présente plusieurs difficultés qui concernent, par exemple, les références de volume d'eau et de pression, le trajet à suivre pour étendre la surface neutre d'une station à l' autre. Ces problèmes ont pour origine la pratique hydrologique des prélèvements à des profondeurs discrètes dans un réseau de stations. Les effets de la compressibilité sur les propriétés thermohalines sont pris en considération dans une nouvelle méthode de définition des surfaces neutres. L' analyse de la surface neutre permet de déterminer qualitativement la circulation à partir des données hydrologiques. La méthode est appliquée à l'Atlantique et à la Méditerranée pour définir des surfaces neutres sur lesquelles différentes masses d'eau s'écoulent, et pour résoudre quelques autres problèmes démontrant l'intérêt de la technique proposée.

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INTRODUCTION

The development of the concept of a "neutral surface"

The notion of isopycnal spreading of water characteristics in the ocean (Parr, 1938; Montgomery, 1938) stems directly from the isentropic concept applied to the atmosphere by Rossby (1937). A water parcel that moves adiabatically retains its original potential density, despite changes in its *in situ* temperature and *in situ* density due to the pressure changes. Thus, for an appropriately defined reference pressure, a potential density surface is a surface of movement for a resident water parcel; if the water is stable, any vertical displacement of the parcel from this surface will be counteracted by the buoyancy forces. The ideas of isopycnal flow and spreading have enjoyed widespread acceptance (*e.g.* Reid, 1981), and distributions of conservative tracers (mainly salinity) on isopycnal surfaces, variously defined, have been extensively used to qualitatively infer circulation (*see* Theodorou, 1983, for a summary of such studies). However, the definition of the appropriate isopycnal surfaces on which to follow the spreading of water masses in the ocean interior is far from straightforward. The variation of the *in situ* density in the ocean is dominated by pressure effects, and due to the non-linear nature of the equation of state of sea-water, it is not satisfactory to define density surfaces relative to any single pressure level. Extreme examples to illustrate that σ_θ - surfaces do not represent neutral surfaces in "specific" regions of the ocean (especially where there are strong thermohaline contrasts) are shown in Figures 1 *a* and 1 *b*. Lynn and Reid (1968) pointed out that it is advantageous to choose a reference pressure level, for the definition of density, close to the range of pressure the waters under analysis will experience.

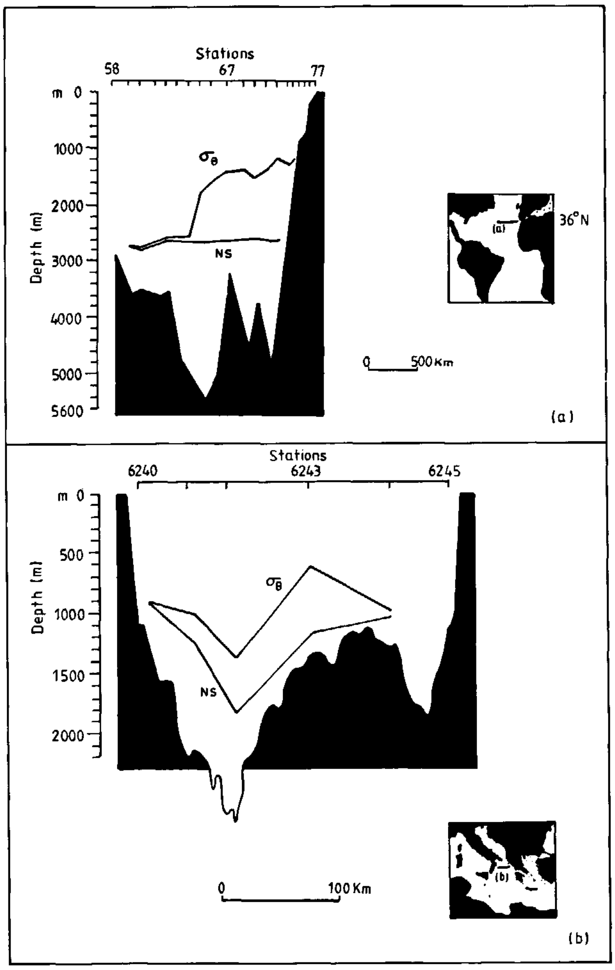


Figure 1
a) Comparison of the neutral surface (NS) delineated by a parcel with $T = 2.99°C$, $S = 34.955$ p.s.u., at depth 2 750 m, with the σ_θ-surface ($\sigma_\theta = 27.871$) defined by the same parcel (data extracted from the Atlas by Fuglister, 1960).

b) Comparison of the neutral surface (NS) delineated by a parcel with $T = 13.57°C$, $S = 38.670$ p.s.u., at depth 1 245 m, with the σ_θ-surface ($\sigma_\theta = 29.160$) defined by the same parcel (data extracted from the Atlas by Miller et al., *1970).*

Pingree (1973) called "neutral surface" an "isopycnal surface «that takes account of all the important terms in the equation of state for sea water when defining a surface of neutral stability». In this respect, determining neutral surfaces is closely related to evaluating "material" surfaces for the calculation of available potential energy, based on energy considerations (Bray and Fofonoff, 1981). However, our approach will be based on buoyancy forces; the latter have also been employed by Ivers (1975), Sheppard (1984), and McDougall (1987 *a*; 1987 *b*); but, as we shall see, the method of approximating neutral surfaces presented in this paper avoids some of the errors involved in their approach.

THE IDEA OF A "PERFECT" NEUTRAL SURFACE

The concept of hydrostatic stability in a vertical direction can be extended to the three-dimensional movement of a water parcel, and in particular to the surface of neutral buoyancy delineated by the locus of all possible neutral paths of the parcel in question. Consider the motion of a parcel on a surface of neutral buoyancy. If the parcel is displaced away from the neutral surface its subsequent behaviour will depend on the value of the local Brunt-Väisälä frequency, N, resulting from the difference between the *in situ* density and the density due to the adiabatic displacement of the parcel. Under conditions of stable stratification, such a displacement gives rise to buoyancy restoring forces whereas for motion confined to the neutral surface no such forces occur, and the parcel is moving with minimum expenditure of energy, provided that:

$$\delta\rho = (\partial\rho/\partial p)_{\theta S}\, \delta p \qquad (1)$$

in situ density change = adiabatic density change
(local environment) (parcel)

(ρ is the *in situ* density and δp is the change in pressure).

The equation above applies only along the neutral surface. Thus, a "perfect" neutral surface is, for a parcel originating on it, a surface of neutral buoyancy and minimum expenditure of energy.

DELINEATING A "PERFECT" NEUTRAL SURFACE

Underlying problems

Moving a parcel from pressure p_A, say, at station A along a neutral surface implies knowledge of the local water properties and in particular the variations of θ and S with pressure, so that for each pressure change δp, equation (1) is satisfied. Then the difference in density between any two points along this path can be easily determined by integra-

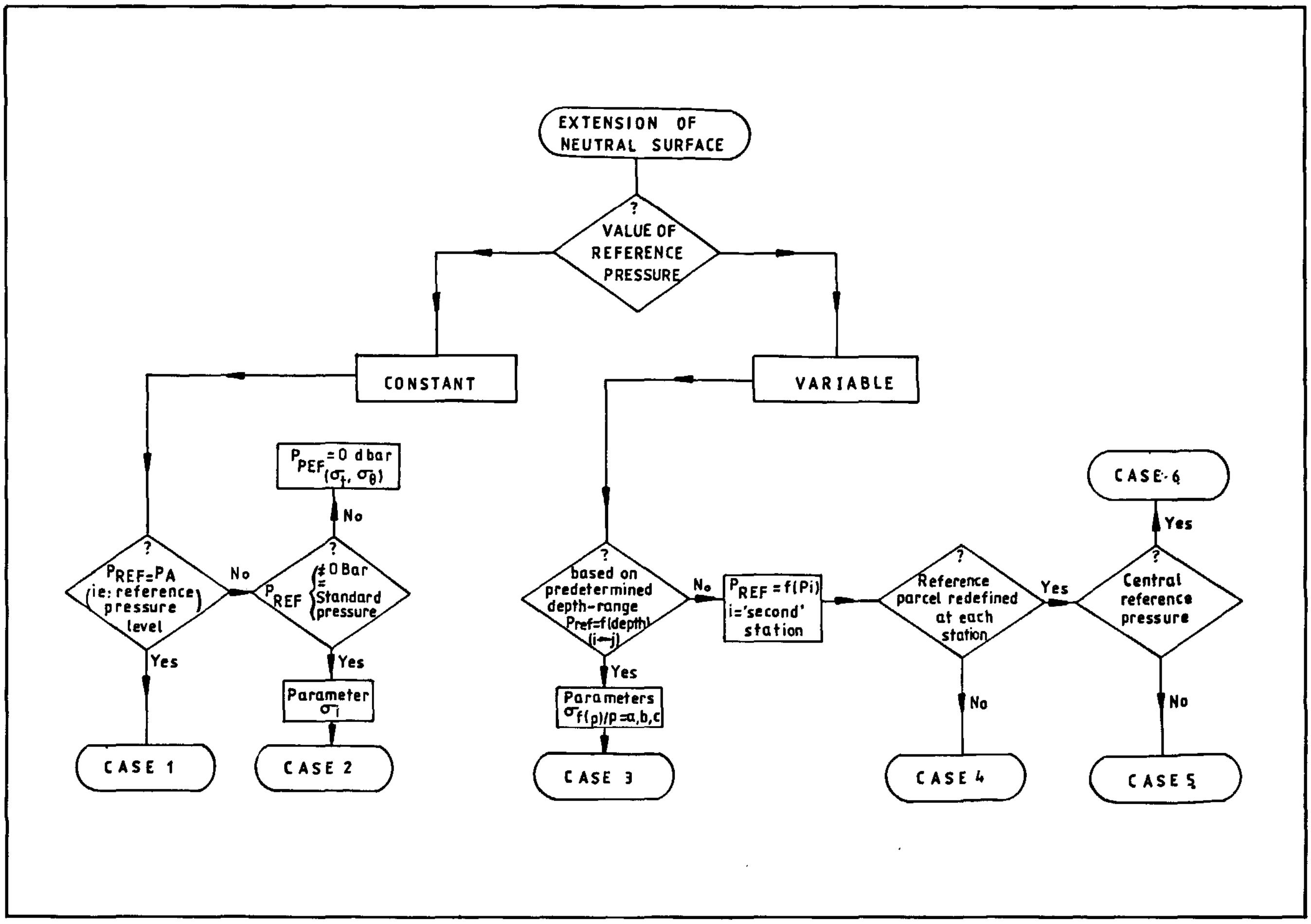


Figure 2

Some possibilities for the selection of the reference pressure in extending a neutral surface from an arbitrary reference station A.

ting the above equation over these limits; and hence the position of the neutral surface at another station B can be obtained, as the pressure p_B ,which satisfies:

$$\Delta\rho_{B-A} = \rho_B - \rho_A = \int_{p_A}^{p_B} (\partial\rho/\partial p)_{\theta S}\, \delta p \qquad (2)$$

However, the above integral cannot be calculated directly, because oceanographic reality only provides data at discrete depths from a given network of stations, sometimes widely spaced. Thus, some approximate approach is needed. This is usually done by calculating an estimator, $\Delta\rho_{B-A}$, at the observational levels at station B. Then, assuming the adiabatic compressibility to remain constant over the pressure change involved, the depth of the extension of the neutral surface at station B can be obtained, by interpolation, as that value which satisfies the equation (2). Implicit in the preceding discussion are the problems of where to start a neutral surface and how to extend it. Any observational level (P_A, S_A ,T_A) of an arbitrary "reference station" A, can be used as a "reference level" to start a neutral surface. However, if our objective is to follow the spreading of a particular water mass, then we should start it from a level at which the presence of this water mass is established. The major question in extending the neutral surface is what reference pressure to use in calculating the densities to be compared; in particular, *in situ* density cannot be used due to the effect of the pressure. Thus, the selection of an "appropriate" reference pressure is crucial and reflects an ambiguity inherent in any method of approximating an "ideal" neutral surface. Another problem in extending the surface is whether to use throughout the originally selected "reference parcel" (S_A, T_A) or to redefine the latter from station to station. Related to that issue is the configuration of the station network available. Some possibilities to overcome these problems exist (*see* Fig. 2). These and their respective utility will be considered next for the general case of three stations A (reference), B and C.

METHODS OF APPROXIMATING A NEUTRAL SURFACE : AN INTERCOMPARISON

In the following examples, the numerical details of the cases to be considered will be outlined; in these calculations only the relevant levels (*i.e.* those bracketing the interval where the extension of the neutral surface pursued lies) are included; in the actual machine computations all lies) are included; in the actual machine computations all levels will be processed and the relevant ones will be selected by the appropriate routine. The neutral surface delineated starts from the level p_A =2787 dbar (S_A=34.985 p.s.u ; T_A =3.03°C) at the "reference" station A (*i.e.* AN 251-121). Stations B and C will be MT 85-10 and AN 251-132 respectively (*see* inset map in Table 1 for station positions). Figures 3, 4, 5, 6, 7 and 8 depict cases 1, 2, 3, 4, 5 and 6 respectively.

Reference pressure constant

Case 1

The extension of a neutral surface at any station B is obtained by that parcel (p_B, S_B, T_B) which is neutrally buoyant when brought adiabatically to the reference level, p_A (Fig. 3); *i. e.* given a reference sample at station A (at 2787 dbar) there may be values on the θ/S curve of station B which would have the same *in situ* density as the reference sample if moved adiabatically to 2787 dbar. Likewise there may be such values at station C. There may also be values at B and C that would not have the same *in situ* density as the reference sample if moved adiabatically to 2787 dbar. Thus, the reference pressure is always equal to that of the original reference level (*i.e.* p_A) at station A, where the neutral surface starts. However, when extending a neutral surface beyond a certain distance, say, 1000 km, over which the potential temperature changes, then this change in potential temperature along the surface causes differences between the neutral surface and the potential density surface, and hence causes inaccuracies in case 1.

Case 2

Reference pressure remains constant irrespective of the pressure changes involved (Fig. 4). For the delineation of surfaces confined within the uppermost 1 000 m or so, p = 0 dbar (or 1 000 dbar) is appropriate; whilst for the deeper water the "success" of the constant reference pressure selected is circumstantial, depending on the relative proximity to the unknown "ideal" local reference pressure. However, moving the reference sample to the other stations by reducing all pressures to 0 dbar, 1 000 dbar, *etc.*, can lead to a wide range along their θ/S curves, as for instance would happen by starting from the high θ/S values near 1 000 dbar off Gibraltar and extending σ_0 (or σ_1) to the cold, low-salinity waters of the Labrador Sea.

Reference pressure variable

Case 3

It lessens the afore mentioned drawback by changing the value of the reference pressure according to a predetermined depth (pressure) range pattern (Fig. 5). Using 1 000-dbar and 1 500-dbar range helps. But Figures 4 and 5 already show that moving reference sample A to station B finds a point on B's θ/S curve that is different from the point at B that would match reference sample A at A's reference pressure.

Case 4

A neutral surface lies at stations, say B and C, at pressures, say, p_B and p_C respectively, at which the reference parcel (S_A, T_A), when brought adiabatically from the reference level, p_A, remains neutrally buoyant (Fig. 6); thus, the reference pressure is continually being redefined on the basis of the currently "second" station, and in this way this case is different from case 1, where the opposite holds. Thus cases 1 and 4 give different results. However, the only difference between them is the direction of motion that is assumed between the reference parcel treated by the algorithm. In case 1 the parcel is moved back to the reference cast, while in case 4, the reference "bottle" is moved to the cast in question.

Case 5

A neutral surface lies at station B, at the pressure, say, p_B , at which the reference parcel (S_A, T_A) when brought adiabatically from the reference level, p_A remains neutrally buoyant; the new parcel thereby defined (S_B, T_B) is used in the same manner to extend the surface to station C (Fig. 7). Thus the reference station A, is used once, thereafter its role is taken by the currently "second" station, and the reference pressure is continually being redefined on the basis of the latter. Hence the sequence in which the stations are taken is important. Based on the above it seems that case 5 is the one that comes closest to a proper algorithm to approximate the stated neutral surface definition [*i.e.* equations (1) or (2)]. Case 5 has in fact been used by Foster and Carmack (1976). Similarly McDougall (1987 *b*) employed this one-sided approach. This procedure is, however, one-sided in that parcels are not referenced to the mid-pressure between the two bottles considered (one of which is a reference bottle).

Case 6

However, this undesirable one-sided error, described above as an inherent weakness of case 5, is easily circumvented by modifying case 5 and, specifically, by moving parcels at the mid pressure between the reference parcel and the parcel that is being considered by the algorithm (Fig. 8).
Table 1 summarizes the results of all six cases considered and shows that for a "small" station separation (A-B = 43 km) cases 1, 3, 4, 5 and 6 produce fairly similar results, but for "large" station separation (A-C = 260 km), only cases 4 and 6 agree. The disagreement of case 5 is rather unexpected and calls for further investigation. To this end two station networks were selected (*see* Tab. 2): one comprising fairly closely-spaced stations (a); and the other consisting of stations with random spatial distribution (b). These networks were used as inputs to cases 5 and 6. As can be seen from Table 2 for network (a), almost identical results were

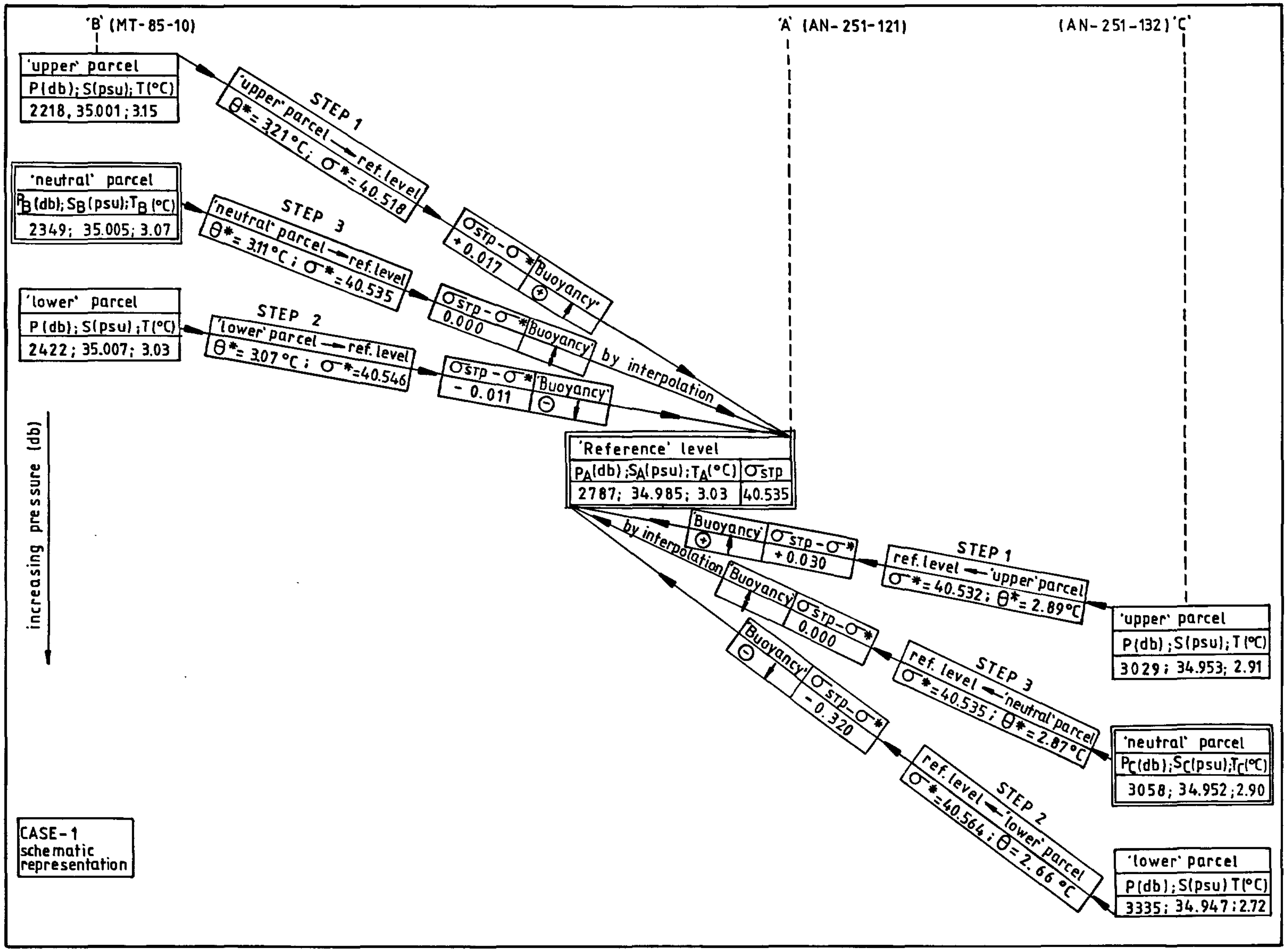
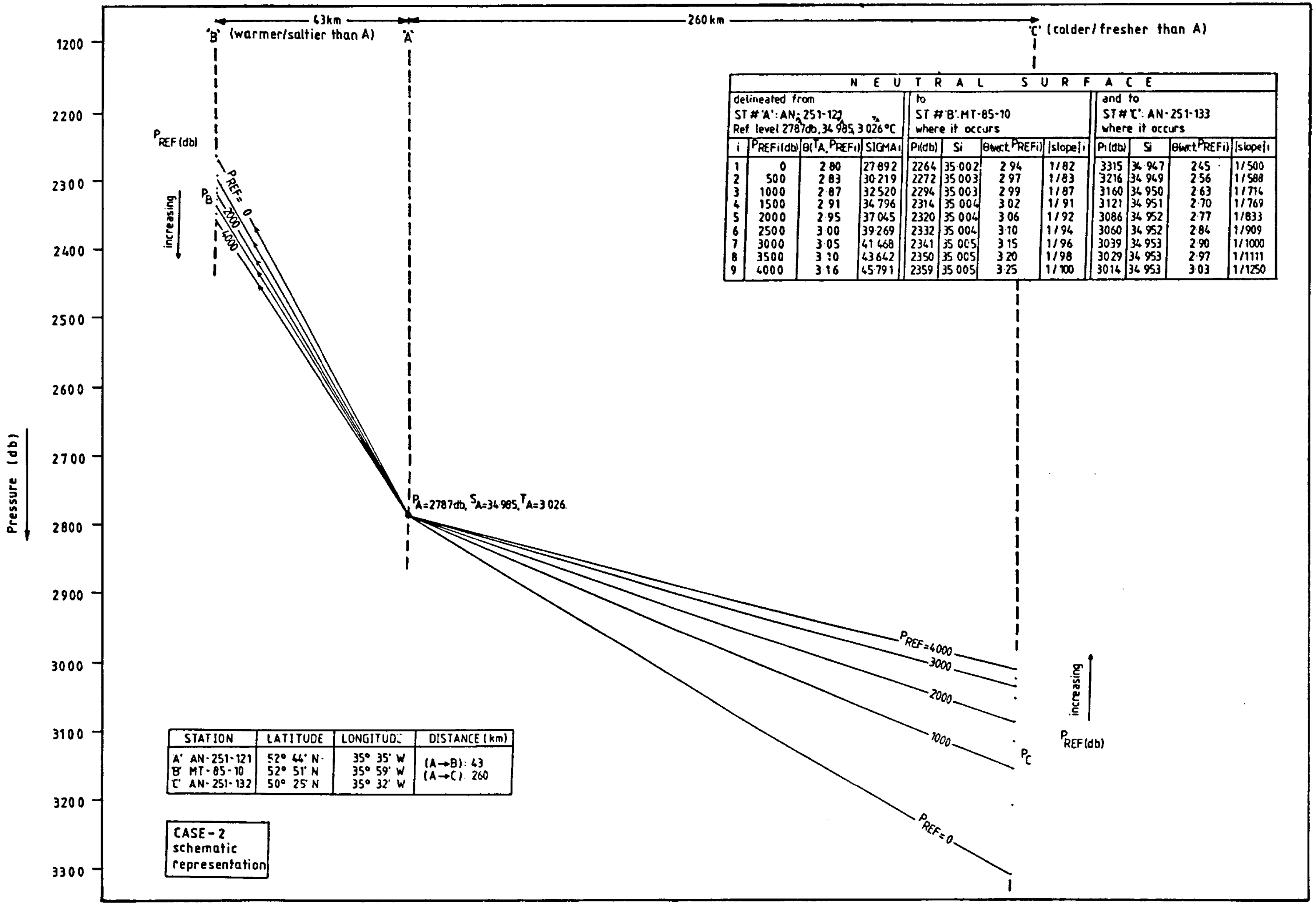


Figure 3

Case 1: schematic representation. 3-step procedure to extend a neutral surface, started from the "reference level" at station "A" to stations "B" and "C". By steps 1 and 2 the interval within which the extension of the neutral surface occurs is identified. The exact position of the latter is obtained by step 3 (i. e. *interpolation). θ^* denotes the potential temperature of the parcel with respect to reference level pressure; σ^* the corresponding potential density; σ_{stp} is the* in situ *density.*



NEUTRAL SURFACE												
delineated from ST # 'A': AN-251-121 Ref level 2787db, 34 985, 3 026°C				to ST # 'B': MT-85-10 where it occurs				and to ST # 'C': AN-251-133 where it occurs				
i	P_{REFi}(db)	θ(T_A, P_{REFi})	SIGMAi	Pi(db)	Si	θ(wrt. P_{REFi})	|slope|i	Pi(db)	Si	θ(wrt. P_{REFi})	|slope|i
1	0	2·80	27·892	2264	35·002	2·94	1/82	3315	34·947	2·45	1/500
2	500	2·83	30·219	2272	35·003	2·97	1/83	3216	34·949	2·56	1/588
3	1000	2·87	32·520	2294	35·003	2·99	1/87	3160	34·950	2·63	1/714
4	1500	2·91	34·796	2314	35·004	3·02	1/91	3121	34·951	2·70	1/769
5	2000	2·95	37·045	2320	35·004	3·06	1/92	3086	34·952	2·77	1/833
6	2500	3·00	39·269	2332	35·004	3·10	1/94	3060	34·952	2·84	1/909
7	3000	3·05	41·468	2341	35·005	3·15	1/96	3039	34·953	2·90	1/1000
8	3500	3·10	43·642	2350	35·005	3·20	1/98	3029	34·953	2·97	1/1111
9	4000	3·16	45·791	2359	35·005	3·25	1/100	3014	34·953	3·03	1/1250

STATION	LATITUDE	LONGITUDE	DISTANCE (km)
'A' AN-251-121	52° 44' N	35° 35' W	(A→B): 43
'B' MT-85-10	52° 51' N	35° 59' W	(A→C): 260
'C' AN-251-132	50° 25' N	35° 32' W	

Figure 4

Case 2. Effects of various constant reference pressures on the movement of a water parcels to stations with contrasting thermohaline properties.

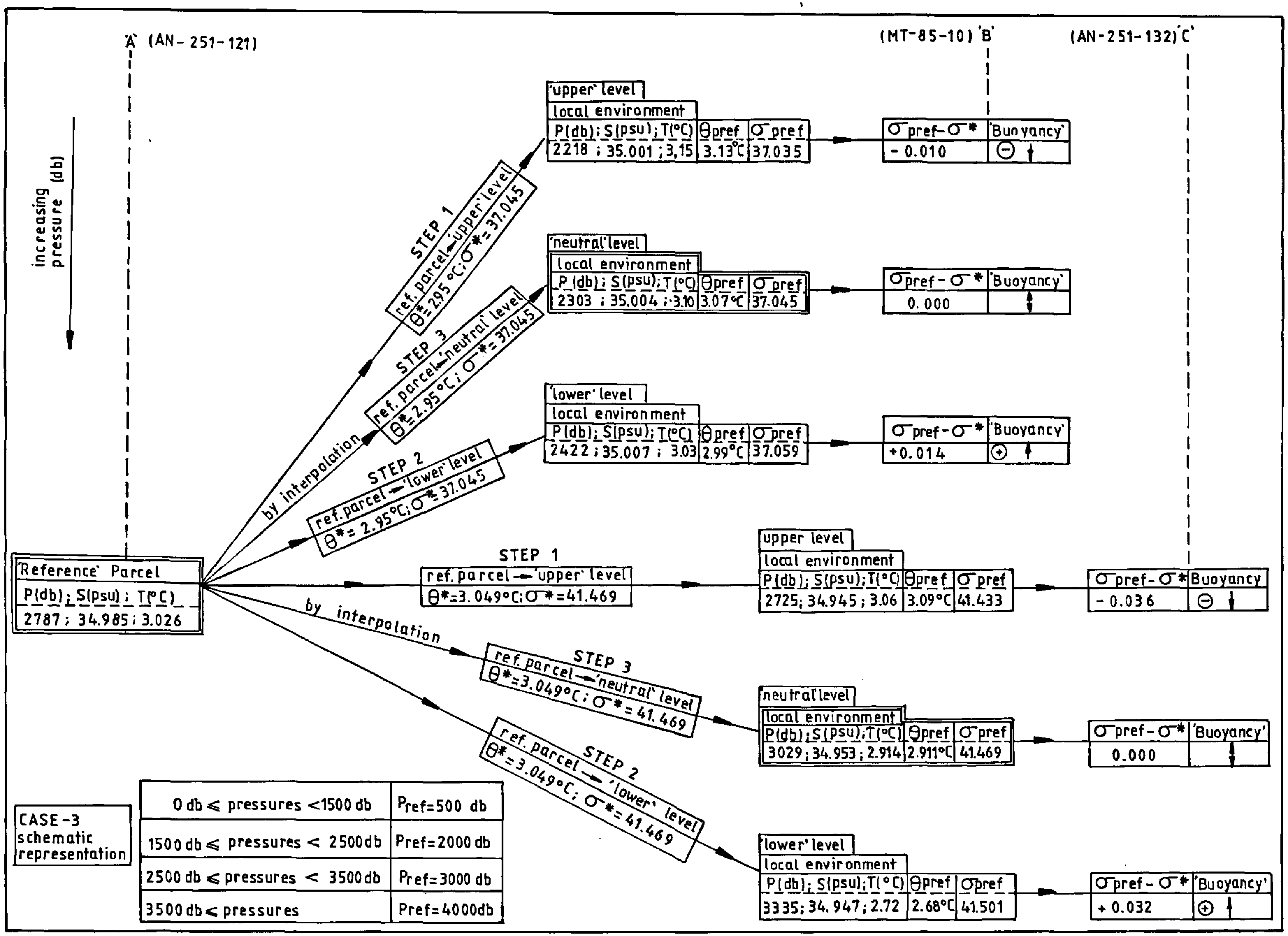


Figure 5

Case 3: schematic representation (see *caption Fig. 3*).

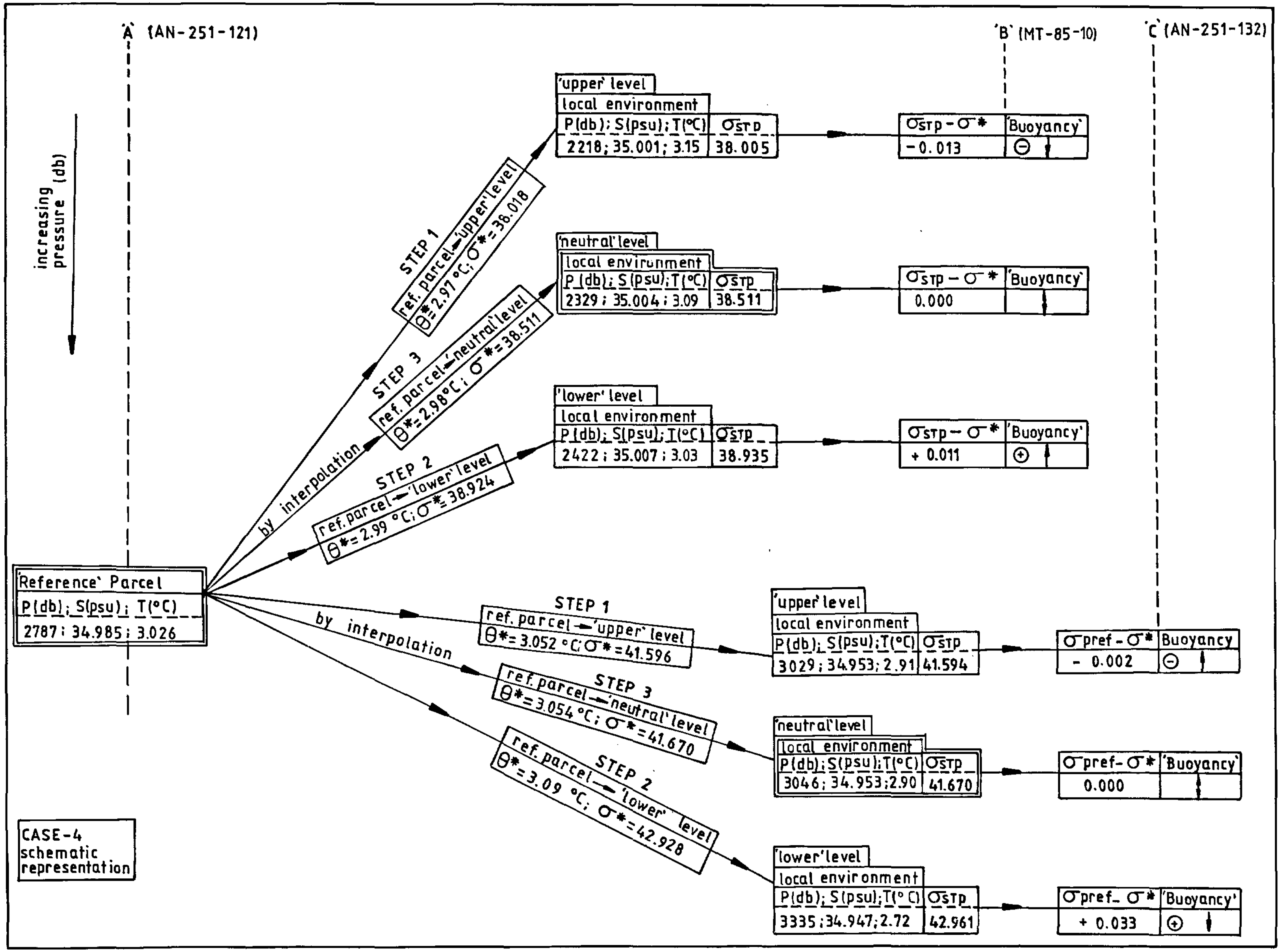


Figure 6

Case 4: schematic representation (see *caption Fig. 3*).

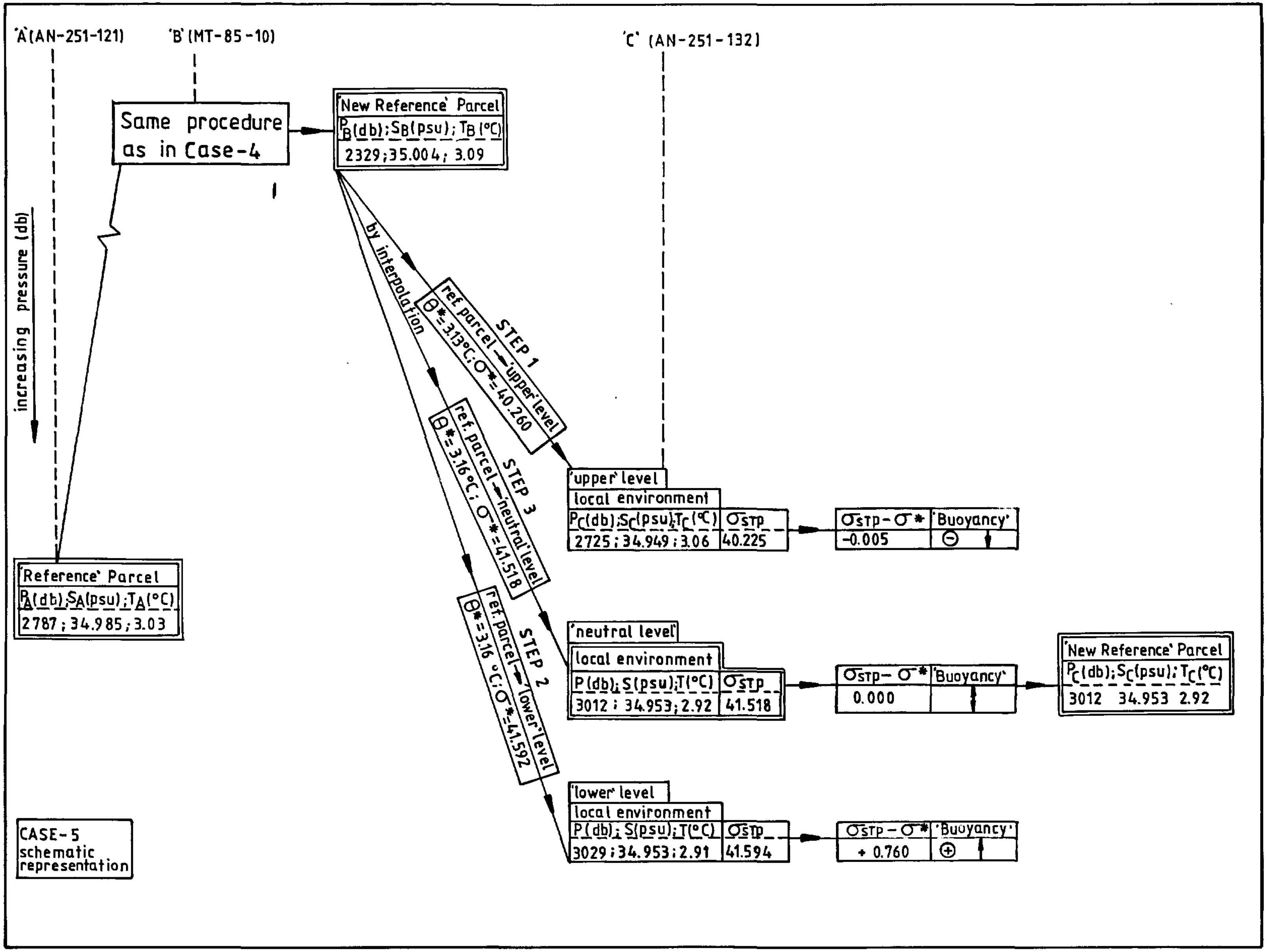


Figure 7

Case 5: schematic representation (see *caption Fig. 3*).

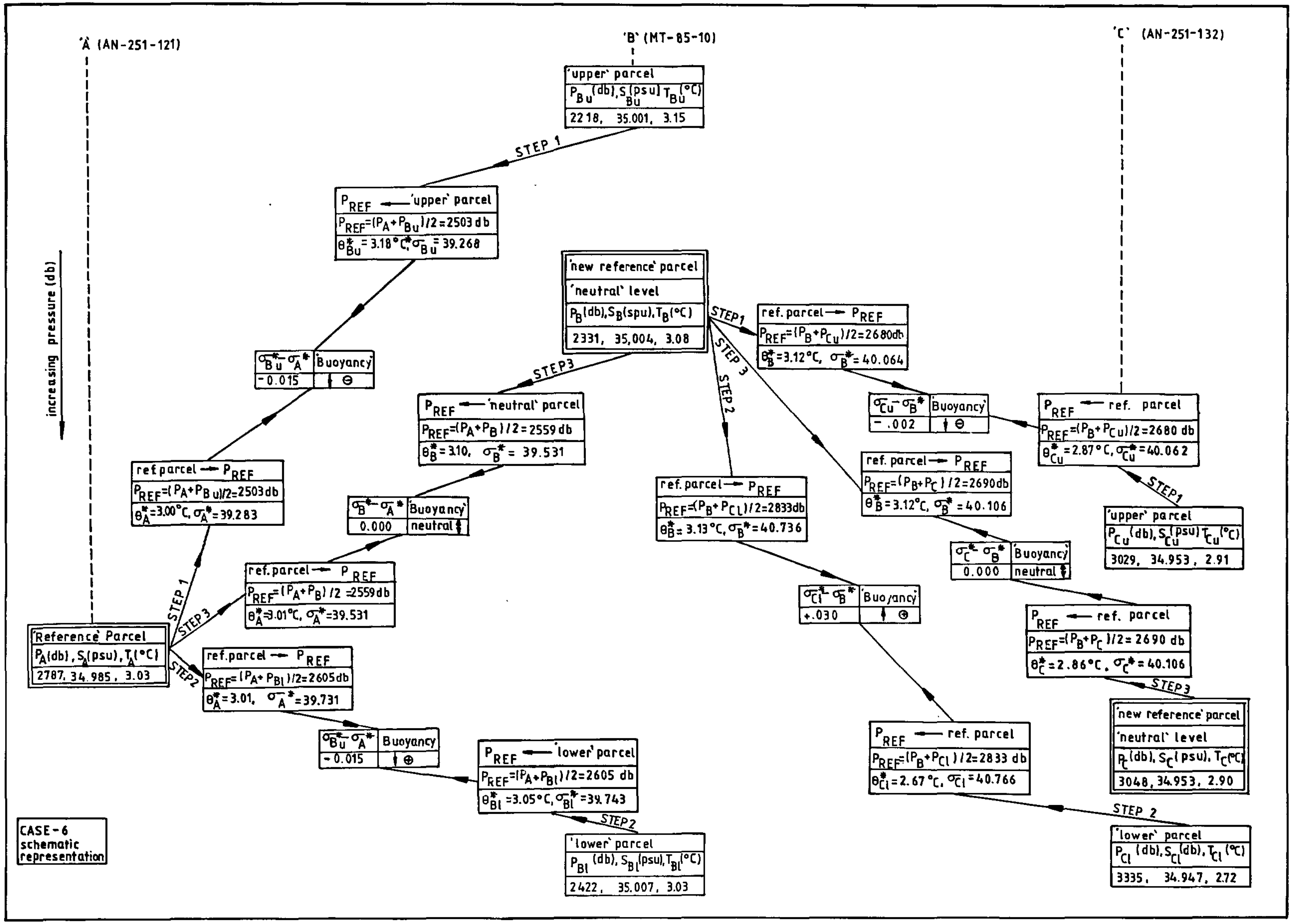


Figure 8

Case 6: schematic representation (see *legend Fig. 3) [pref = reference pressure. The upper-case subscripts refer to stations; the lower-case ones to observational levels (u=upper, l=lower);* e.g. P_{Bu} *denotes the pressure (P) at the upper observational level (u) at station B].*

Table 1

Results of calculations for selection of method.

Neutral surface delineated from station "A" (AN-251-121). "Reference " level: p_A = 2 787 db; S_A = 34.985; T_A = 3.03°C.								
Case	Station "B" (MT-85-10)				Station "C" (AN-251-132)			
	P_1 (dbar)	P_1-P_6 (dbar)	S (p.s.u.)	T (°C)	P_1 (dbar)	P_1-P_6 (dbar)	S (p.s.u.)	T (°C)
1	2 349	18	35.005	3.07	3 058	10	34.952	2.90
2	2 264	- 67	35.002	3.12	3 315	267	34.947	2.45
3	2 320	- 11	35.004	3.09	3 086	38	34.952	2.77
4	2 333	2	35.004	3.08	3 047	- 1	34.953	2.90
5	2 329	- 2	35.004	3.09	3 012	- 36	34.953	2.92
6	2 331	0	35.004	3.08	3 048	0	34.953	2.90

Data source: World Data Center A. Oceanography, National oceanic and Atmospheric Administration, Washington D.C., 20235 USA.

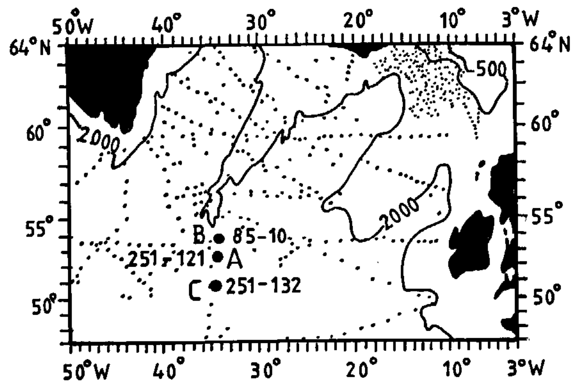


Table 2

Comparison of cases 5 and 6 using (a) closely-spaced (b) randomly spatially-distributed station-inputs.

Neutral surface delineated					
(a) from station 716-*Chain*-12 at the level: D = 1 659 m, S = 34.997 (p.s.u.), T = 2.27°C			(b) from station 98-HU-134 at the level D = 1 659 m, S = 34.997 (p.s.u.), T = 2.27°C		
Station input fairly-closely spaced			Station input randomly spaced		
Depth (m) of neutral surface			Depth (m) of neutral surface		
at stations	**by case 5**	**by case 6**	**at stations**	**by case 5**	**by case 6**
EX-10-284	1 461	1 461	AN-251-32	2 881	2 889
SH-6-233	1 253	1 253	AN-251-33	2 920	2 927
SH-6-231	1 524	1 524	6N-2 718-6	2 712	2 726
SH-6-234	1 240	1 240	HU-101-52	2 665	2 678
SH-6-235	1 324	1 324	ER-170-177	2 572	2 591
EX-6-223	1 564	1 564	MT-85-5	1 920	1 934
EX-10-285	1 298	1 298	HU-101-98	2 360	2 386

Data source: World Data Center A. Oceanography, National Oceanic and Atmospheric Administration, Washington D.C., 20235 USA.

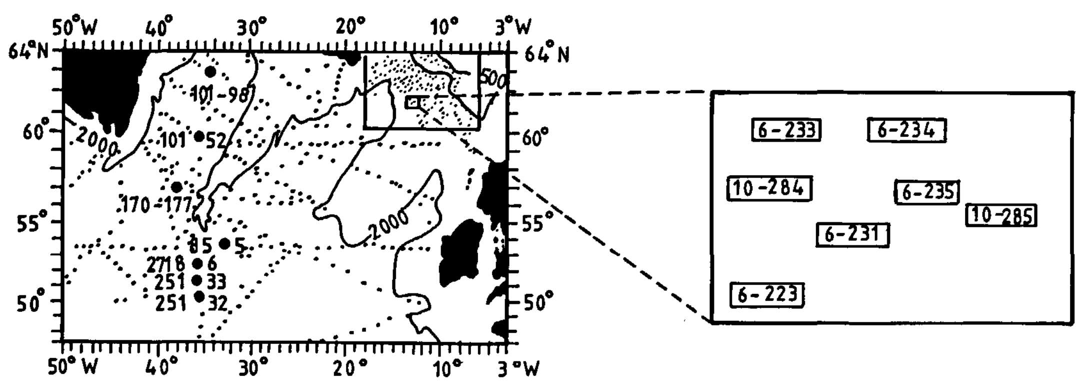
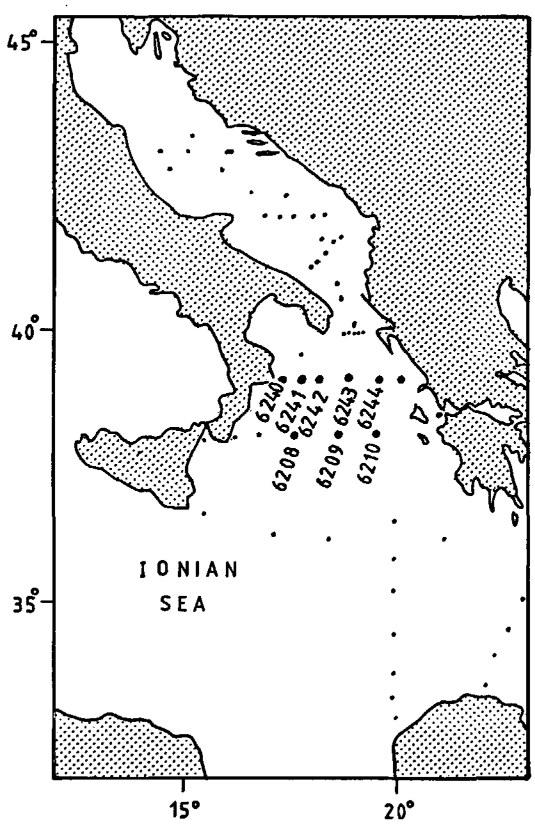


Table 3

Path-dependency test.

Neutral surface delineated from a parcel with S = 38.670 (p.s.u.), T = 13.570°C, at D = 1 245 m (reference station 6 292).						
by case 5				**by case 6**		
Station	D (m)	S (p.s.u.)	T (°C)	D (m)	S (p.s.u.)	T (°C)
6 240	865	38.731	13.717	869	38.731	13.715
6 241	1 172	38.705	13.681	1 209	38.704	13.679
6 242	1 615	38.695	13.721	1 698	38.689	13.709
6 243	1 108	38.711	13.691	1 143	38.709	13.684
6 244	1 033	38.739	13.774	1 049	38.737	13.763
6 210	1 530	38.689	13.701	1 667	38.681	13.682
6 209	1 724	38.666	13.661	2 047	38.647	13.640
6 208	1 432	38.687	13.681	1 583	38.682	13.671
6 240	840	38.729	13.729	865	38.731	13.717

Data source: Atlas by Miller et al. *(1970).*



Caption: see table 3.

obtained. However, for network (b) their results were sometimes widely different. This is probably not so much due to the "reference parcel" being redefined between widely spaced stations, with sometimes contrasting thermohaline properties, but mainly due to the error involved in this one-sided approach. The latter will accumulate on going around a loop, so that the loop will be helical and path-dependence will be implicated, even though the vertical pitch of the helix may be caused by this one-sided numerical error rather than by true, unavoidable, and physically present path-dependence, as we shall see next.

PATH-DEPENDENCY: AN INHERENT AMBIGUITY

To clarify the above and to assess the effects of the compressibility dependence on the thermohaline properties of a water parcel, a "path-dependency" test was conducted, *i.e.*

a neutral surface was traced in a network of closely-spaced stations arranged in a closed loop, so that the neutral surface in question was started and in the absence of "path-dependency" was expected to return to the same level at the original station. The regions selected to demonstrate here "path-dependency" and associated phenomena are rather small in extent, nevertheless, they are most appropriate, due to the strong thermohaline contrasts that occur there. The results are shown in Table 3 and taken in conjunction with those of Table 2, indicate that redefining a "reference parcel" from station to station in extending a neutral surface does not return the surface in question to its original level. Hence, diminishing the effects of "path-dependency" requires sequential, in terms of proximity, station input from a closely-spaced and preferably symmetrically arranged station network. Thus, since McDougall's (1987 *b*) data were spaced just 1° of latitude or longitude apart, the errors due to his one-sided approach were almost certainly small. The results in Table 3 show that the centralized approach (case 6) has the advantage of exhibiting the least path-dependency, whilst the main cause of the 25 dbar pitch of the helix in Table 3 (865 dbar - 840 dbar) is due to the one-sided errors of the algorithm described by case 5. The path-dependency of case 6, however, is an expression of the inherent ambiguity concerning the depth (pressure) at which a neutral surface occurs, and is ultimately a manifestation of the dependence of the (adiabatic) compressibility of sea water on temperature and salinity. In particular, colder and fresher water is more compressible than warmer and saltier. Figure 4 examplifies the effects of various constant reference pressures on the movement of a water parcel from station A to stations B and C. The parcel at A is "colder and fresher" relative to its "new" position at B, but it is "warmer and saltier" relative to that at C. The parcel, brought adiabatically and at a constant reference pressure, is neutrally buoyant at a more shallow (B) /deeper (C) level than the one from which it originated (A). Moreover, its relative position, at either B or C, depends on the reference pressure used: the higher the latter is, the deeper (B)/more shallow (C) the "new" position of the parcel will be. Hence, there is a "thickness" associated with each neutral surface. However, provided the assumptions for neutral flow and mixing are not violated, this "fuzziness of neutral surfaces" (Sheppard, 1984, which is due to the dianeutral advective process known as thermobaricity; McDougall, 1987 *a*), is insufficient to cause ambiguity in the position of the neutral surface in question (Theodorou, 1983; Harvey and Theodorou, 1986; McDougall and Jackett, 1988). Thus, the "central-reference-pressure" approach (case 6) will now form the basis of a neutral surface analysis.

NEUTRAL SURFACE ANALYSIS

The three-dimensional depth configuration of a neutral surface coupled with the spreading on it of a resident conservative property (salinity) constitutes the essence of the "neutral surface analysis". The latter is based on equation (3) below:

$$K_H (\partial^2 S/\partial x^2 + \partial^2 S/\partial y^2) = u\, \partial S/\partial x + v\, \partial S/\partial y \qquad (3)$$

where: the x and y coordinates are taken parallel to the neutral surface; u and v are the corresponding velocity components; and, K_H is the coefficient of turbulent diffusion along the neutral surface.

Equation (3) has been derived from the advection-diffusion equation, which itself stems directly from the salt conservation equation. In this context, its simplified form above lends itself to a tractable formulation of an inverse problem: qualitative inference of the flow field on the basis of the salinity distribution on various neutral surfaces. This estimation is facilitated by the fact that the stably stratified waters of the world ocean are layered, with the various water masses segregated to their own level. Otherwise there would have been an immensely complicated three dimensional tracer distribution. However, advection is mainly confined to the layer under study, and lateral stirring, within each layer, is isotropic due to the effects of stratification. Thus, patterns in the map of salinity, say, on a neutral surface indicate the paths of spreading and flow of a water from a particular source. Flow patterns suggested by the distribution of salinity on a neutral surface can be supported by its topography assuming geostrophy; since, the neutral surface isobaths provide the direction of the thermal wind vector (McDougall, 1988).

Neutral surface analysis provides answers to questions:

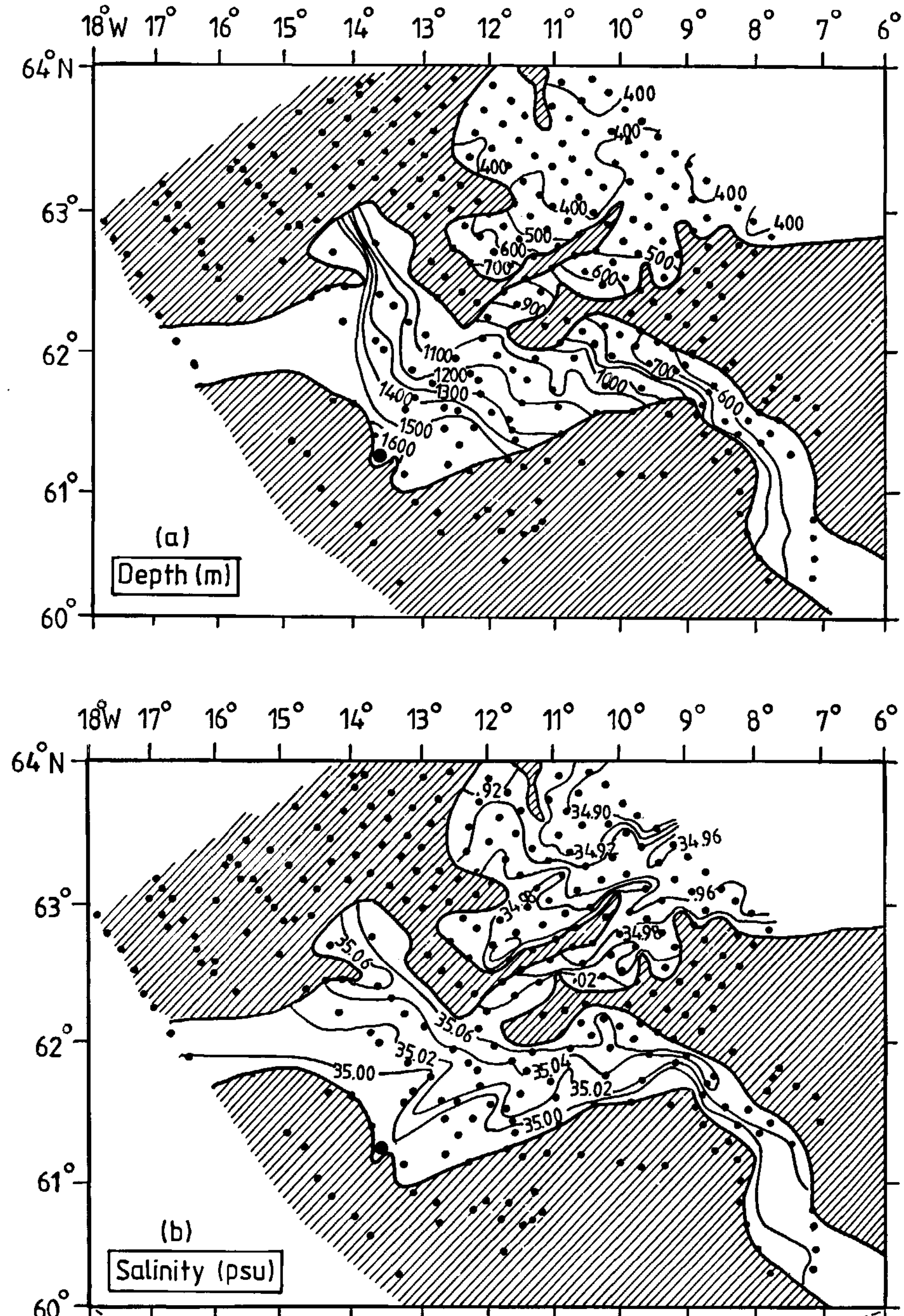
- What is the direction of spreading (and flow) as deduced from the distribution of salinity on neutral surfaces ?
- How can the occurrence of salinity gradients be accounted for ?
- Are there any "distortions" in the flow, and if so, are they related to bathymetric features ?
- Can we distinguish the water masses occurring on each neutral surface on the basis of their different salinities ?
- What is the sense of flow and under what assumptions ?
- How is the flow related to the pattern of salinity distribution ?
- Are the inferred spreading and flow related to bottom bathymetry ? and if so, to what extent ?

The versatility of the neutral surface analysis will now be demonstrated based on data from the Atlantic Ocean and the Mediterranean Sea.

Applications: some regional case studies

The case of the Lousy Bank water

Steele *et al.* (1962) reported the presence of a somewhat isolated "overflow" water at the western side of the Lousy Bank (station 716-12 of R/V *Chain*; for position *see* inset map in Tab. 2). Figure 9 *a* shows the topography of the neutral surface delineated from the characteristics of this water (T = 2.27°C, S = 34.997 p.s.u., at D = 1 659 m). The distribution of salinity on the same neutral surface (Fig. 9 b) shows two "tongues", which presumably indicate axes at flow. Thus, it seems that a relatively unmixed branch of the Faroe Bank outflow, steered by the bathymetric



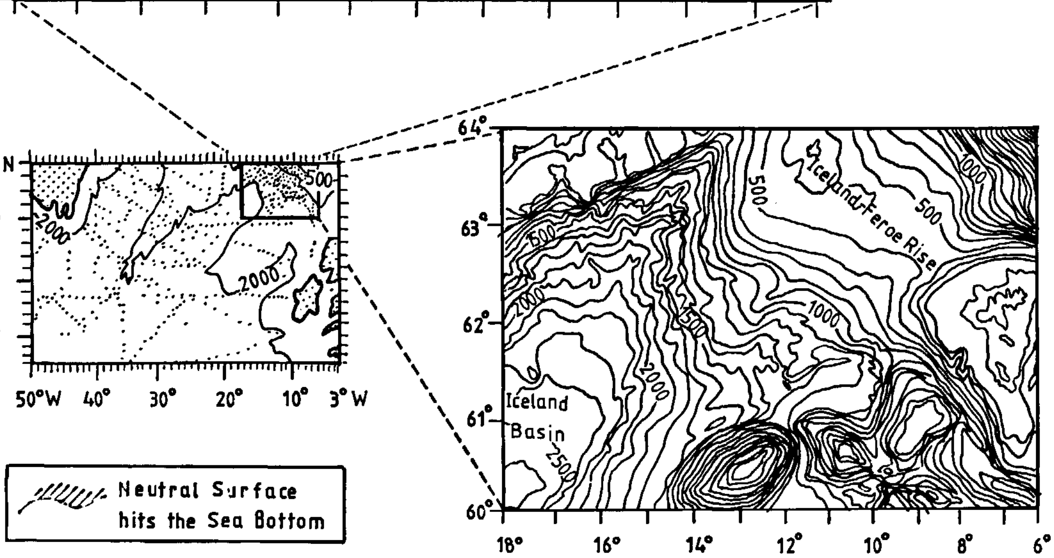
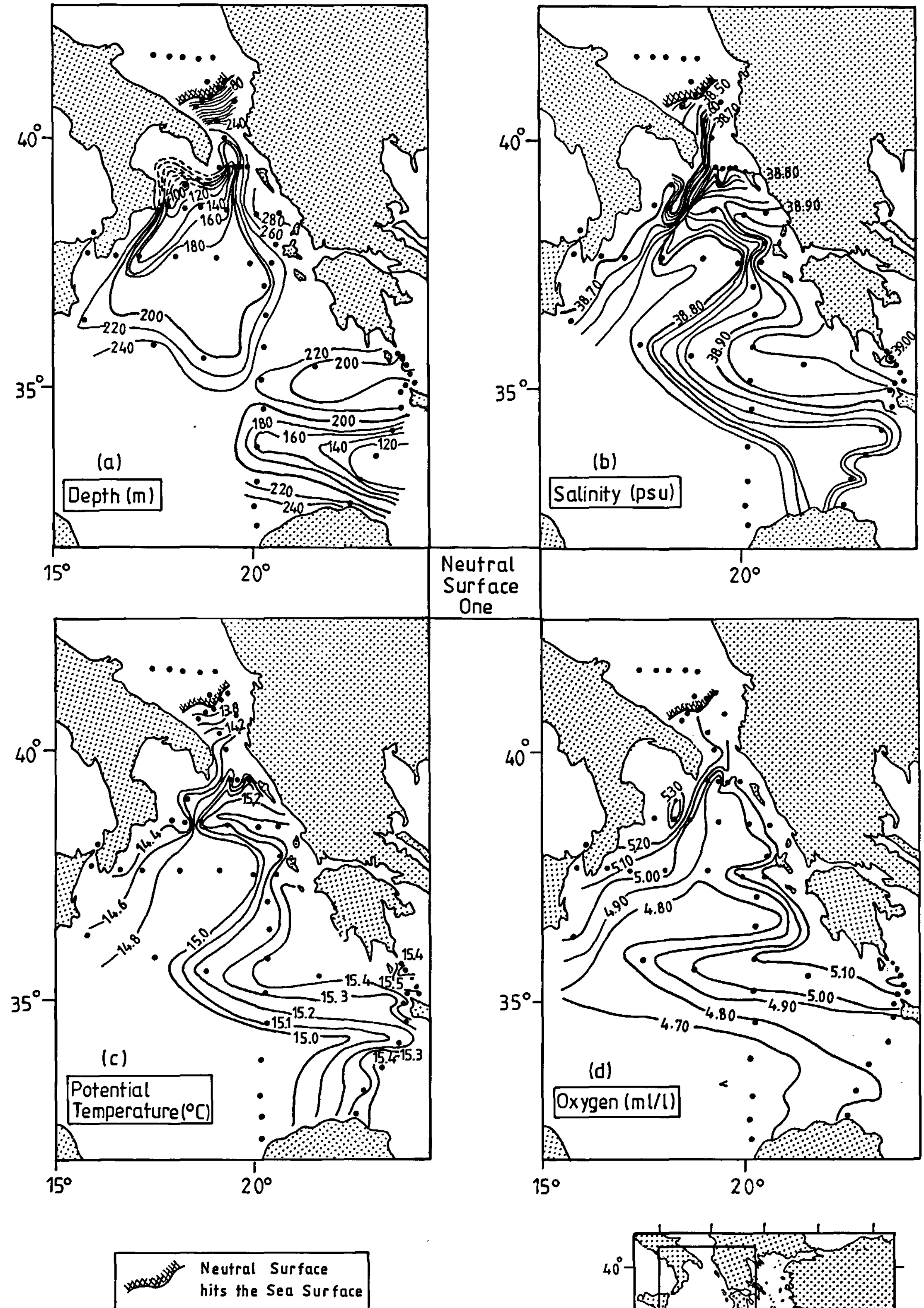


Figure 9

Depth (a) and salinity (b) of the neutral surface delineated from the level with T= 2.27 ° C, S= 34.997 p.s.u. at D= 1659 m, of the reference station 716-12 of R/V Chain *(denoted by ●)*



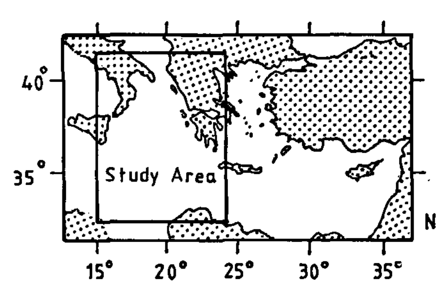


Figure 10

Depth (a), salinity (b), potential temperature (c) and oxygen (d) of the neutral surface delineated by a parcel, defined by T= 15.61°C, S=38.984 p.s.u., at depth 296 m, of the reference station 6295 of R/V Atlantis *(indicated by *).*

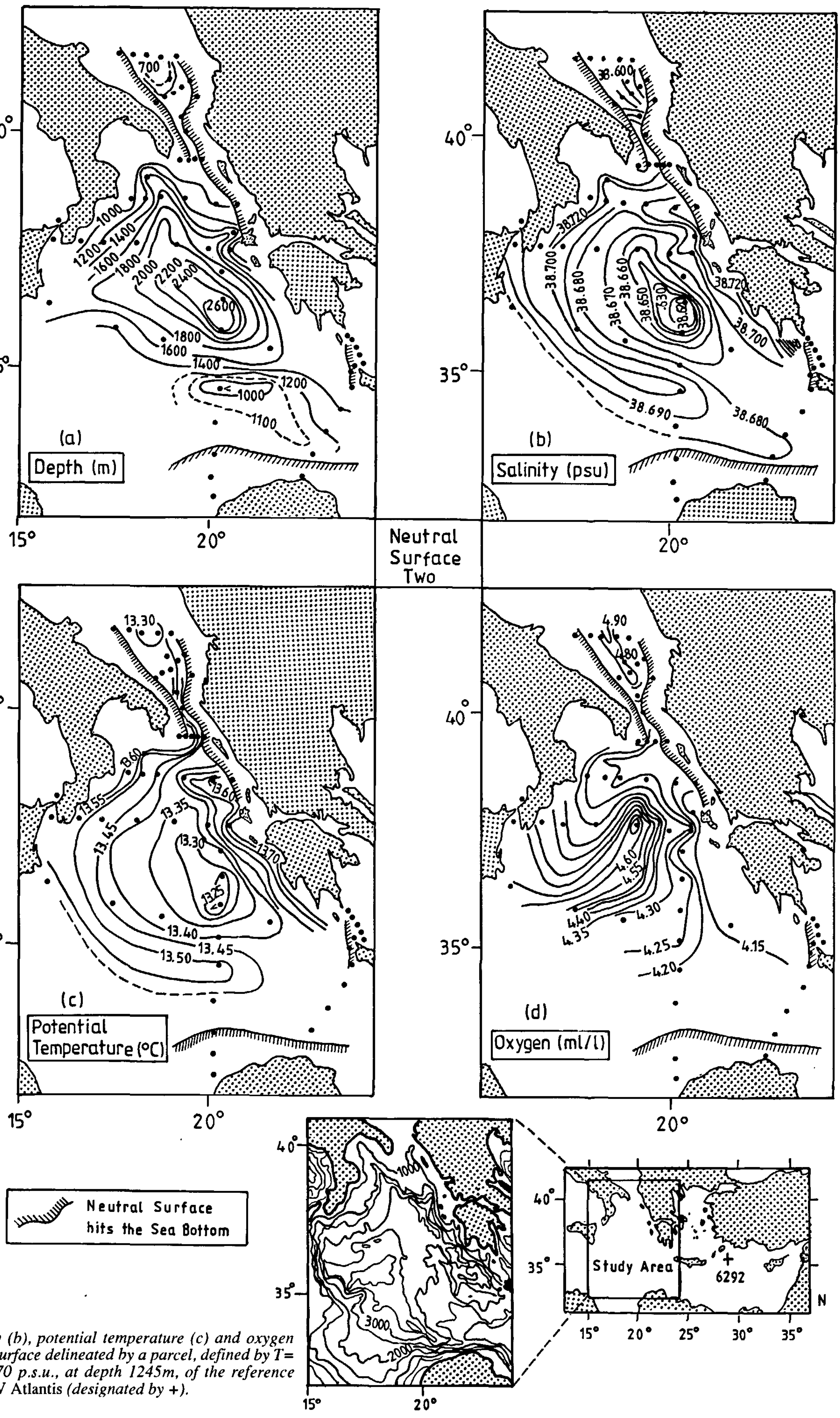


Figure 11

Depth (a), salinity (b), potential temperature (c) and oxygen (d) of the neutral surface delineated by a parcel, defined by T= 13.570°, S= 38.670 p.s.u., at depth 1245m, of the reference station 6292 of R/V Atlantis *(designated by +).*

contours, follows the course of a gully, extending from about 61°40'N, 10°10'W to about 61°35'N, 11°30'W (*see* inset map in Fig. 9), at the latter position the gully changes direction, which may cause the outflow to be divided to two branches, the northernmost of which, in a flow influenced by gravity and friction, reaches the station in question. This result does not support the suggestion, based on marine geological data, by Bowles and Jahn (1983; Fig. 12) that this flow is a continuation of the Hatton Drift current (McCave *et al.*, 1980; Fig. 1).

The Ionian Basin gyre

Historical data (collected by R/V *Atlantis* in the Ionian Sea during February-March 1962), extracted from the Atlas by Miller *et al.* (1970), were used to obtain two neutral surfaces delineated from the parcels with observed temperatures and salinities T_1=15.610° C, S_1=38.984 p.s.u. at depth 298 m (NS1) and T_2= 13.57°C, S_2= 38.670 at depth 1245 m (NS2) at the reference stations marked by * and + respectively in the inset maps. The two reference stations were selected on the basis of their characteristics, which were such as to allow, in the case of NS1, the delineation of the westward spreading of LIW, whilst in the case of NS2, the demarcation of the source area of the eastward spreading Eastern Mediterranean deep water (Hopkins, 1978). Figures 10 and 11 depict, for these two neutral surfaces respectively, the distributions of depth, salinity and dissolved oxygen (as supporting evidence, though not discussed here); and also of potential temperature (although the latter contains no more information than the respective salinity distribution on the same neutral surface), and vividly portray the spreading patterns of Levantine intermediate water (Fig. 10) and Eastern Mediterranean deep water (Fig. 11) in the Ionian Sea. Many features stand out clearly:

Neutral Surface One (NS1)

- Although the differences in depth (Fig. 10 *a*) are rather small, nevertheless, assuming geostrophy relative to the "deeper" water, a broadly defined cyclonic flow appears (Fig. 10 *a*) to occupy the greater part of the Ionian Sea.
- Two saline tongues can be seen (Fig. 10 *b*), spreading northwards-northwestwards and westwards. Their salinity decreases in the directions of their spreading, due presumably to lateral stirring and mixing with the relatively fresher waters that occur in the northern and western Ionian sea.
- In the northernmost part (Otranto Strait), where a strong thermohaline front is evident (Fig. 10 *b*), and also further to the north, where the surface encounters the sea surface, diapycnal processes are expected to occur (Armi, 1978).

Neutral Surface Two (NS2)

- The topography of the NS2 (Fig. 11 *a*) broadly reflects the bottom bathymetry (*see* inset map in Fig. 11) and, assuming geostrophy relative to the "upper" water, implies the presence of a cyclonic gyre occupying most of the central Ionian basin.

The afore mentioned cyclonic gyre, tentatively deduced from the neutral-surface topography, can be seen (Fig. 11 *b*) to consist of relatively low-salinity water embedded within a matrix of more saline water.

- To the south of the above gyre a tongue can be seen (Fig. 11 *b*) extending eastwards, its salinity decreasing in the direction of spreading.
- Evidently, the same cyclonic pattern is observed throughout the depth of the central Ionian basin -a region considered as a potential source of deep water formation (Ovchinnikov and Plakhin, 1965)- thereby implying that the thermohaline effects are dominant there. However, whether this wintertime gyre constitutes a yearly feature of the circulation has not yet been proven.
- Under the geostrophic assumption a cyclonic circulation can be seen to occupy the Southern Adriatic Sea (Fig. 11 *a*).
- A low salinity (Fig. 11 *b*) and high oxygen (Fig. 11 *d*) water bounded by the bottom to landward can be traced from the southern Adriatic -a region of wintertime deep water formation (Buljan and Zore-Armanda, 1976)- into the Ionian Sea through the Otranto Strait around the continental margin of Southern Italy.

In conclusion, the main features agree well with previous results [*see* Malanotte-Rizzoli and Hecht (1988) for a review], but here we presented the spreading patterns in considerably more detail.

Thus, our results confirmed Pollak's (1951) hypothesis of a deep cyclonic gyre, occupying the central Ionian basin during winter, also hinted at by El-Gindy and El-Din (1986; *see* their Fig. 9 *a*, 10 *a*) and not the "main eastward spreading" that Wüst (1961) has deduced.

CONCLUSIONS

Spreading of water masses in the ocean interior occurs mainly along neutral surfaces (*e.g.* large-scale stirring brought about by baroclinic eddies), although certain diapycnal processes, such as double diffusive mixing, breaking of internal waves, boundary mixing and the final stages of baroclinic instabilities (*e.g.* McDougall, 1984), certainly occur. These neutral surfaces can be defined as normal at every point to the gradient of potential density which is referenced to the pressure at the point in question, and thus along which water parcels can be interchanged without any work being done against buoyancy forces. A set of water parcels with observed temperatures and salinities can be used to start a set of neutral surfaces. Based on the "central-reference-pressure" method outlined above, the levels at which the adiabatic density gradients for each of these water parcels intersect the corresponding adiabatic density profile at each station in a data set determine the levels of each of the neutral surfaces at that station. However, the results depend upon the path of integration between any two points chosen, but as was shown earlier, the errors due to this path-dependence are small. Neutral surface analysis based on the "central-reference-pressure" method was applied to data from the Atlantic Ocean and the results revealed the origin of a somewhat isolated Norwegian Sea "overflow" water at the western side of the Lousy Bank.

Moreover, application of the same method in the Ionian Sea portrayed vividly the spreading patterns of the Levantine intermediate water and of the Eastern Mediterranean deep water, and confirmed, for the latter water mass, Pollak's (1951) hypothesis of a deep cyclonic gyre occupying the centre of the Ionian basin during winter.

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