The $\delta^{18}O$ signal of the northward flow of Mediterranean waters in the Adriatic Sea

Oxygen isotope composition
Adriatic Sea
Water masses
Levantine Intermediate Water

Composition isotopique de l'oxygène
Mer Adriatique
Masses d'eau
Eau intermédiaire levantine

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ABSTRACT

The sea-water masses in the Adriatic Sea are fairly well known as regards the classical parameters of salinity, temperature and density. By contrast, the distribution of the oxygen isotopic composition is practically unknown apart from a few isolated measurements. The $\delta^{18}O$ values of about 600 water samples from vertical profiles in the Adriatic basin were measured to obtain information on the distribution of these values throughout the basin and, if possible, to correlate this variable to the movements and mixing of water masses.

The salinity and temperature data are also reported here for a direct comparison of these variables to the isotopic values.

Quite positive and homogeneous $\delta^{18}O$ values, ranging from 1.30 to 1.69 ‰ (*vs.* V-SMOW), are found in the Southern Adriatic Sea because of the inflow of Levantine Intermediate Water (LIW). The northward flow of this water, despite the addition of large amounts of continental water, heavily depleted in ^{18}O ($\delta^{18}O$ about –9/–10 ‰), apparently reaches the north-eastern section of the basin, with bottom water still showing high $\delta^{18}O$ values (up to 1.36 ‰) as far north as the Gulf of Trieste. By contrast, the surface water of the Northern Adriatic Sea is almost systematically ^{18}O depleted with a minimum value of –1.49 ‰ measured during Spring 1991, clearly related to the inflow of continental water.

RÉSUMÉ

Le signal $\delta^{18}O$ du courant nord méditerranéen dans la mer Adriatique

Les masses d'eau de la mer Adriatique sont assez bien connues quant à leurs paramètres classiques (salinité, température et densité). Par contre, la composition isotopique de l'oxygène y est pratiquement inconnue, à l'exception de quelques mesures isolées. Les valeurs de $\delta^{18}O$ d'environ 600 échantillons prélevés dans les profils verticaux de l'Adriatique ont été mesurées, afin d'obtenir des renseignements sur la composition isotopique des masses d'eau circulant dans la mer Adriatique et, éventuellement, mettre le $\delta^{18}O$ en corrélation avec la dynamique des masses d'eau dans cette mer.

La salinité et la température sont aussi indiquées pour consentir une corrélation directe avec la composition isotopique.
Des valeurs assez positives et homogènes de $\delta^{18}O$ (de 1,30 à 1,69 ‰ *vs.* V-SMOW) ont été mesurées dans l'Adriatique du Sud à cause de l'afflux de l'eau intermédiaire levantine.
Le courant Nord de cette eau, malgré l'apport de grandes quantités d'eau continentale ayant des valeurs de $\delta^{18}O$ très négatives (environ –9/–10 ‰), atteint apparemment la section Nord-Est du bassin avec des valeurs de $\delta^{18}O$ dans l'eau de fond encore élevées (jusqu'à 1,36 ‰) jusqu'au Golfe de Trieste.
Par contre, l'eau de surface de l'Adriatique du Nord présente presque systématiquement des valeurs faibles des isotopes, avec un minimum de –1,49 ‰ mesuré au printemps 1991 et qui est évidemment à mettre en relation avec l'afflux d'eau continentale.

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INTRODUCTION

The Adriatic basin, oriented in a NW-SE direction with a length of about 800 km and a width of about 200 km, can be divided into three sub-basins:

– the northern one, characterized by shallow depth gradually deepening southward from about 25 to 100 m;

– the central one, characterized by the presence of the Jabuka Pit, with a maximum depth of 280 m, whose southern boundary is the Palagruza Sill;

– the southern one, characterized by a circular shaped pit (South Adriatic Pit), with a maximum depth of 1200 m, separated from the Ionian Sea by the sill of the Otranto Strait (780 m deep).

The classical parameters (salinity, temperature and density), normally used to trace the circulation of sea-water masses, are fairly well known for the whole basin.

According to several authors (Franco, 1970; Franco *et al.*, 1982; Mosetti, 1984; Orlic *et al.*, 1992) the Adriatic surficial circulation consists of a general cyclonic gyre including:

– a northward flow, along the eastern coast, of salty water coming from the Otranto Channel and prevailing during the cold semester;

– a southward flow, along the western coast, of moderately salty surface water greatly affected by the contribution of continental water. This southward flow prevails during the warm semester.

As summarized by Mosetti (1984) this general surficial circulation shows several secondary branches of cyclonic currents, probably related to the inflow of river water from both the eastern and western coasts. The first gyre closes towards the Gargano Peninsula (Fig. 1) and may be mainly related to contributions from the Drina and the Bojana rivers (Albania); the second gyre closes towards mount Conero (Ancona) and is mainly related to the Dalmatian river Neretva; the third one closes towards the Venetian Lagoon and Po river, bordering on the Gulf of Trieste between Punta Salvore (Rt. Savudrija) and the mouth of the Tagliamento river.

According to Zore-Armanda (1963, 1969) and to Artegiani *et al.* (1993) the Southern Adriatic circulation exhibits a seasonality in the movements of the water masses that can be summarized as follows:

– a winter situation characterized by a northward flow of Modified Levantine Intermediate Water (MLIW) of Mediterranean origin, with a temperature of 14 °C and a salinity of 38.7 psu mainly present at intermediate depths, and by a deep southward flow of Adriatic Bottom Water (ABW) which outflows into the Ionian Sea. This bottom water, characterized by a temperature of 13 °C and a salinity of 38.6 psu, seems to originate in the South Adriatic Pit as a consequence of a mixing process between MLIW and dense water from the Northern Adriatic cascading from the Palagruza Sill;

– a summer situation characterized by two outflowing water masses, the more important one at the surface consisting of less saline water flowing southward, *i.e.* Adriatic Surface Water (ASW), and the second one at the bottom (ABW), while MLIW inflows at intermediate depths.

The oxygen isotopic composition of Adriatic water has never been studied, apart from a few isolated measurements. Most of the stable isotope work carried out up to now on sea-water has been focused on the interpretation of the dynamics of the great oceans (*e.g.* Craig and Gordon, 1965; Ferronsky and Brezgunov, 1989) but little attention has been paid from this point of view to the Mediterranean Sea. Data on the oxygen isotopic composition of Mediterranean sea-water were reported by Pierre *et al.* (1986) and Stenni and Longinelli (1990), while Cortecci *et al.* (1974) reported data on the $\delta^{18}O$ of the dissolved sulphate and on the tritium content of the Tyrrhenian Sea.

We report here the results of oxygen isotope measurements carried out on a set of 602 sea-water samples from the Adriatic Sea along with the T/S diagrams in order to compare the isotopic results with temperature and salinity.

The aim of this study was to improve our knowledge of this section of the Mediterranean Sea and to obtain detailed information on the existing conditions in the

Gulf of Trieste. We also wanted to confirm, by means of isotopic results, the hypothesis of a direct inflow of Southern Adriatic Water up to the Gulf of Trieste as already suggested by Mosetti (1966; 1984) and Franco (1970).

The variations of the oxygen isotopic composition of sea-water are generally small when compared to those exhibited by meteoric waters. The overall range of variation is of the order of a couple of δ units per mil apart from a few exceptions, as in the case of the northernmost Adriatic Sea, the Baltic Sea and the Black Sea.

The distribution of the isotopic composition of sea-water is mainly related to evaporation and precipitation processes, to mixing between different water masses and to variable contributions of continental water. Evaporation processes tend to enrich surface water in heavy isotopes while a depletion in heavy isotopes is caused by the inflow of continental runoff and atmospheric precipitation. A positive correlation is then observed between salinity and isotopic values. On the basis of these assumptions the isotopic composition of sea-water can be used as an additional tool to characterize different water masses.

MATERIALS AND METHODS

The location of vertical profiles and of other collection sites is shown in Fig. 1. Samples were collected during the following cruises:

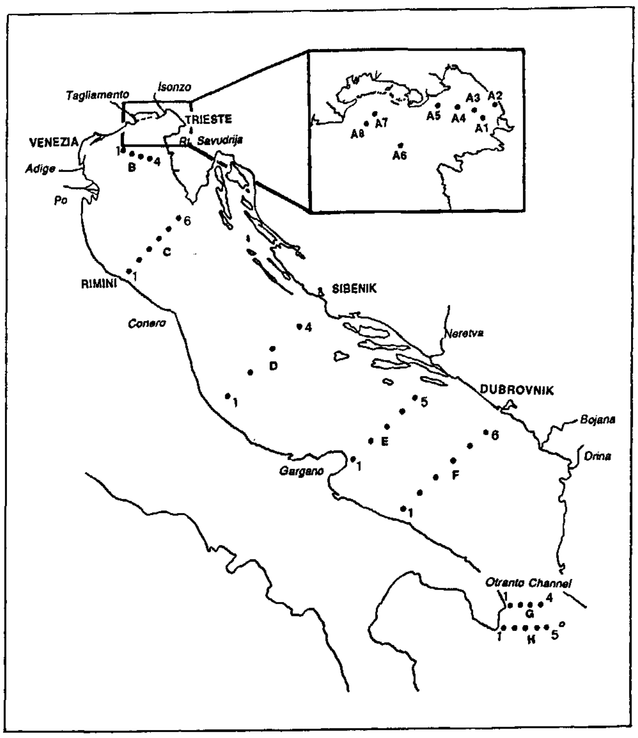

Figure 1

Map of the Adriatic Sea showing the location of the sampling sites.

- POEM-1 cruise in October-November 1985, by the Osservatorio Geofisico Sperimentale of Trieste (O.G.S.) on R.V. *Bannock;* 5 stations (transects G and H) in the Otranto Channel (159 samples);

- AM-01 cruise in April 1990, by the Istituto Talassografico C.N.R of Trieste on R.V. *Bannock;* 11 stations (transects E and F) in the Southern Adriatic (178 samples);

- ASCOP-20 cruise in October - November 1991, by the O.G.S. on R.V. *Bannock;* 14 stations (transects B, C and D) (90 samples);

- 8 stations in the Gulf of Trieste and the nearby area were sampled five times from May 1991 to February 1992 (175 samples) by the Dipartimento di Biologia, University of Trieste.

At each station the positioning was made by means of LORAN C, while the bottom depth was determined by echo sounding, employing an ATLAS KRUPP Deso 20 transceiver.

The thermohaline measurements were carried out with a CTD Neil Brown Mark III B and a CTD Neil Brown Mark V during the ASCOP-20 and POEM-1 cruises and during the AM-01 cruise respectively, connected to a General Oceanics Rosette sampler with 12 Niskin bottles.

The CTD data were collected only during the downcast; the CTD/Rosette system was stopped at sampling depths during the upcast and one or more bottles were triggered at each level to collect samples for chemical and biological determinations.

The processing of the CTD data was carried out on land; salinity was computed from pressure, temperature and conductivity averaged values, according to the UNESCO (1983) algorithm.

The water samples collected for the isotopic analyses were prepared according to the well-established technique of isotopic equilibration of CO_2 with water (Epstein and Mayeda, 1953). The CO_2 samples were measured for their $^{18}O/^{16}O$ ratios by means of a Finnigan Delta S mass spectrometer. All the samples were run at least in duplicate and the reported isotopic data are the mean values of consistent results.

The standard deviation of our measurements is, on average, equal to or better than ± 0.05 per mil. (1σ). The results are reported as δ units ‰, where

$$\delta = [(R_{sample} - R_{standard}) \times R_{standard}^{-1}] \times 1000$$

R being the $^{18}O/^{16}O$ ratio.

The $\delta^{18}O(H_2O)$ values are reported *versus* the V-SMOW isotopic standard (Gonfiantini, 1978).

RESULTS AND DISCUSSION

The Otranto Channel and the Southern Adriatic

All the samples collected from the southern section of the Adriatic and across the Otranto Channel (Tab. 1 and 2) are isotopically heavy and this may be explained by assuming the Eastern Mediterranean to be the source of this water.

Table 1

$\delta^{18}O$ sea-water values (vs. V-SMOW) of the H transect.

Depth (m)	H1	H2	H3	H4	H5
0		1.35	1.32	1.37	1.39
5	1.31	1.30	1.32	1.34	1.37
10	1.27	1.32		1.32	1.37
20	1.28	1.30	1.24	1.34	1.34
30	1.32	1.30	1.32	1.29	1.34
40	1.35	1.34		1.31	
50	1.36	1.35		1.37	1.34
75	1.31	1.36		1.41	1.38
100	1.38	1.35		1.37	1.36
125	1.36	1.43		1.41	1.42
145		1.37			
150				1.41	1.41
200			1.39	1.44	
250			1.41	1.43	1.42
300			1.45	1.50	1.38
350			1.39		1.48
400			1.42	1.43	1.44
450			1.45		1.47
500			1.41	1.44	1.51
550			1.40		1.43
600			1.41	1.37	1.43
650			1.42		1.49
670			1.41		
700				1.38	1.40
750					1.41
800				1.45	1.45
850					1.45
900					1.40
905				1.42	
950					1.46
1000					1.44
1030					1.43

Table 2

$\delta^{18}O$ sea-water values (vs. V-SMOW) of the G transect.

Depth (m)	G1	G2	G3	G4
0	1.34	1.32	1.33	1.31
5		1.27	1.44	1.32
10	1.32	1.39	1.33	1.35
20	1.31	1.29	1.31	1.32
30	1.38	1.26	1.27	1.35
40	1.52	1.56	1.41	1.35
50	1.38	1.42	1.47	
75	1.60	1.41	1.40	1.31
90	1.36			
100		1.48	1.58	1.37
125		1.50	1.66	1.44
150		1.43	1.47	1.41
200		1.47	1.47	1.39
250			1.43	1.47
300		1.50	1.48	1.48
350		1.44	1.50	
400		1.41	1.44	
450		1.46	1.43	1.50
500		1.34	1.48	1.48
550		1.45	1.50	1,47
600		1.46	1.47	1.46
650		1.34	1.47	
700			1.45	1.41
750				1.58
800			1.46	1.55
850			1.45	1.61
870			1.47	
900				1.42
950				1.49
960				1.47

Zore-Armanda (1963, 1969) and Mosetti (1984) suggest an inflow of salty Mediterranean water in the Southern Adriatic and refer it to Levantine Intermediate Water (LIW). Isotopically heavy waters, at depths between 150 and 500 m, have already been found in the central and eastern Mediterranean (Pierre *et al.*, 1986) and referred to LIW. This is a layer of fairly homogeneous water with $\delta^{18}O$ values of the order of + 1.5 to + 1.6 ‰ in the central Mediterranean and even heavier values in the eastern Mediterranean where LIW originates.

The salinity and temperature data of H and G transects are reported graphically as T/S diagrams (Fig. 2 and 3) in order to compare them with the $\delta^{18}O$ values.

A general trend can be observed for both the H and G transects, where two water masses are identified by means of $\delta^{18}O$ values:

– the water mass from the surface to the thermocline, (about 40 m depth) shows mean $\delta^{18}O$ values ranging from 1.30 to 1.36 ‰ for the various stations of the H transect and from 1.33 to 1.37 ‰ for the stations of the G transect; this surficial layer exhibits mean salinity values varying from 38.40 to 38.53 psu and from 38.33 to 38.51 psu respectively for the H and G transects while mean temperature values for the same stations range from 18.61 to 19.92 °C and from 18.70 to 19.08 °C (H and G transects respectively).

– the water mass from the thermocline to the bottom displays mean $\delta^{18}O$ values ranging from 1.35 to 1.43 ‰ for the stations of the H transect and from 1.43 to 1.46 ‰ for the G transect. If we consider the salinity data of the subsurface waters it is possible to distinguish, in the central and eastern parts of both transects, a core of saltier water with salinity values well above 38.70 psu and a temperature of around 14 °C.

The isotopic difference (0.1 ‰) between the two water masses is almost negligible: however, if we want to explain such a small difference we can ascribe it to a southward flow of less saline water related to river influence as regards the surface layer and to the inflow of salty and isotopically heavy Mediterranean sea water as regards the remaining part of the water column. As already observed by Artegiani *et al.* (1993) the saltier core found at the intermediate depth (200-600 m) could be related to the presence of MLIW. Furthermore, as suggested by the same authors, the less saline surface water flowing southwards seems to be spread more widely in autumn (the water column still being stratified) than in spring, when the fresher water flow is confined near the Italian coast. Nevertheless, a slight eastward ^{18}O enrichment of both surface and subsurface waters is apparent only in the stations of H transect, suggesting the occurence of a southward flow of isotopically light water along the western coast. The mean salinity and temperature values, reported above, display a similar pattern, the eastern section of the Otranto Channel being slightly saltier and warmer than the western one.

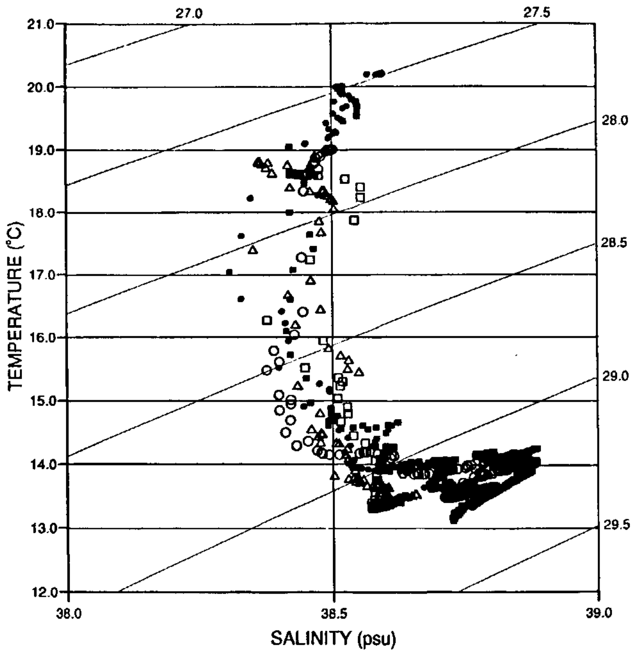

Figure 2

Temperature-salinity diagram for the H transect data (H1: open triangle; H2: open square; H3: open circle; H4: full circle; H5: full square). Isopycnals are also reported.

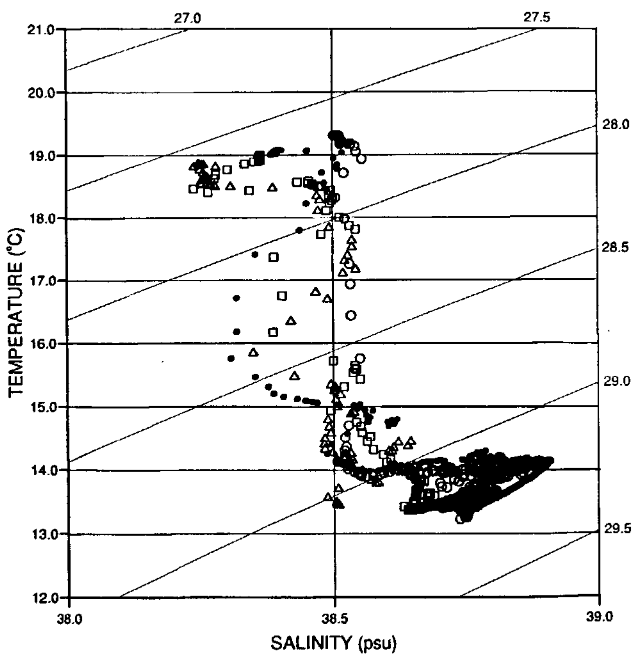

Figure 3

Temperature-salinity diagram for the G transect data (G1: open triangle; G2: open square; G3: open circle; G4: full circle). Isopycnals are also reported.

In the Southern Adriatic (Tab. 3 and 4) the $\delta^{18}O$ values from the E and F transects are quite heavy; the mean $\delta^{18}O$ values for the stations of transect F range from +1.54 to +1.69 ‰ while transect E exhibits lower mean $\delta^{18}O$ values (1.27 to 1.40 ‰). The salinity and temperature data of the F and E transects are reported in Figures 4 and 5. These two transects generally exhibit more homogeneous salinity and temperature values than those found in the

Table 3

$\delta^{18}O$ sea-water values (vs. V-SMOW) of the F transect.

Depth (m)	F1	F2	F3	F4	F5	F6
0	1.48	1.55	1.46	1.54	1.58	1.45
10	1.54	1.58	1.47	1.46	1.70	1.45
20	1.50	1.49	1.60	1.64	1.63	1.55
30	1.54	1.56	1.55	1.51	1.57	1.58
40		1.53	1.54	1.55		1.59
50	1.61	1.60	1.52	1.56	1.64	1.58
75	1.57	1.47	1.46	1.44	1.82	1.56
100	1.50	1.64	1.52	1.45	1.60	1.55
125	1.54	1.58	1.53	1.58	1.65	1.49
150	1.60	1.50	1.46	1.47		1.58
175				1.50	1.56	
200		1.55	1.75	1.50		1.48
225				1.64	1.59	
250		1.56	1.60	1.67	1.53	1.55
300		1.53	1.46	1.57	1.72	1.60
350				1.55		
400		1.62	1.62	1.64	1.66	1.81
450				1.50		
500		1.55	1.66	1.54	1.66	1.53
550				1.67		
600		1.58	1.55	1.70	1.51	1.59
650				1.58		
700		1.52	1.51	1.53	1.51	1.44
750				1.49		1.61
800		1.60	1.50	1.68	1.48	
850				1.49		
900		1.52	1.52	1.41	1.54	
950				1.46		
1000		1.56		1.43	1.51	
1050		1.48		1.60		
1100			1.49	1.50	1.56	
1150				1.73	1.44	
1200				1.52	1.53	

Table 4

$\delta^{18}O$ sea-water values (vs. V-SMOW) of the E transect.

Depth (m)	E1	E2	E3	E4	E5
0	1.15	1.31	1.38	1.31	1.21
10	1.22	1.25	1.48	1.27	1.32
20	1.19	1.31	1.43	1.30	1.19
30	1.34	1.25	1.48	1.27	1.25
40	1.38	1.37	1.40	1.15	1.22
50	1.34	1.27	1.33	1.39	1.33
75		1.35	1.38	1.25	1.42
100		1.34	1.42	1.19	1.44
125		1.23	1.34	1.43	1.45
150			1.43	1.42	1.38
175			1.35		
200			1.46	1.41	1.43
225			1.38	1.32	
250				1.29	
300				1.48	
400				1.34	
500				1.30	
600				1.27	

Otranto Strait, probably in relation to the lack of stratification during the early spring. Also in this case a core of relatively saltier water (38.74 psu) is apparent at intermediate depth in the central and eastern sections, while it is more extensive in the F transect. This water mass could be ascribed to an inflow of MILW, even if dilution processes affected the original salinity and temperature values. A water mass with salinity of about 38.66 psu and temperature of about 12.8 °C can be distinguished at the bottom of the F transect, while the E2 and E3 sites show even lower values (38.60 psu and 12.2 °C) at their bottom.

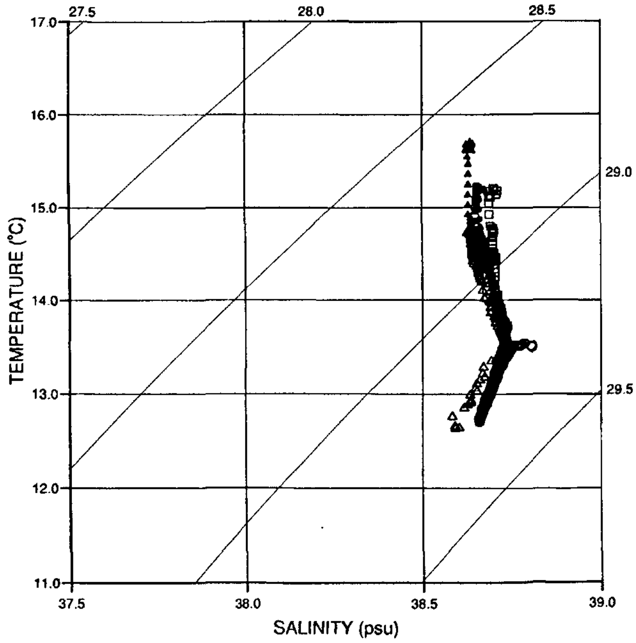

Figure 4

Temperature-salinity diagram for the F transect data (F1: open triangle; F2: open square; F3: open circle; F4: full circle; F5: full square; F6: full triangle). Isopycnals are also reported.

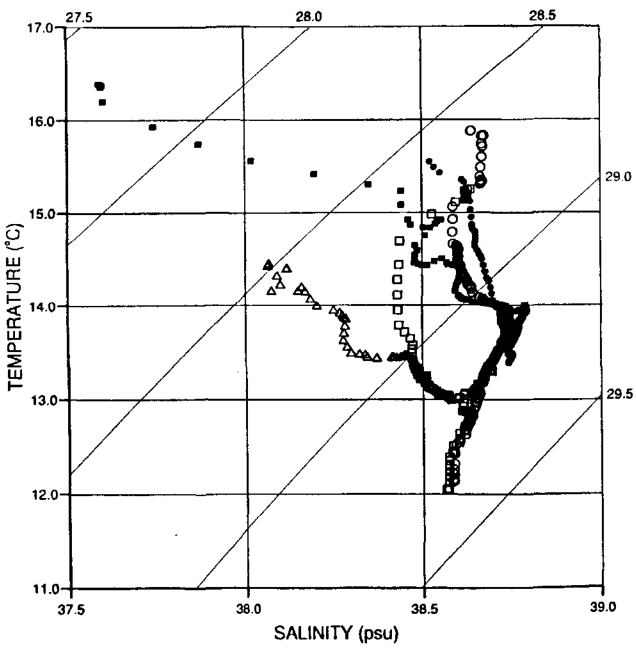

Figure 5

Temperature-salinity diagram for the E transect data (E1: open triangle; E2: open square; E3: open circle; E4: full circle; E5: full square). Isopycnals are also reported.

The coastal stations of the E transect reveal a different pattern as regards the surficial layer (0-20 m), with lower mean salinity and $\delta^{18}O$ values (E1: 38.16 psu, 1.19 ‰; E5: 38.15 psu, 1.24 ‰), which seems to be related to a dilution effect. Indeed, the E1 station is affected by the southward flow of less salty and isotopically lighter water, while E5 is affected by the inflow of continental water from the Albanian rivers. On the contrary, the F transect, being located on the deepest section of the Adriatic basin, is directly affected by the inflow of salty and isotopically heavy Ionian seawater.

The Mesoadriatic Pit

The water samples collected along the D transect during the ASCOP-20 Cruise (October-November 1991 - Tab. 5) exhibit lower $\delta^{18}O$ values both in the western and eastern sections of the transect, with a more significant ^{18}O depletion exhibited by surface waters at station D1, affected by dilution with continental waters. This hypothesis is confirmed by values of about 37.5 psu found in the surficial layer of the D1 station. The T/S diagram for this transect is reported in Figure 6.

The deepest stations, D2 and D3, show a 3-layer stratification: a) 0-20 m with a mean $\delta^{18}O$ value of 1.37 ‰ and a salinity of 38.25 psu; b) 30-100 m with higher $\delta^{18}O$ and salinity values (mean values: 1.51 ‰ and 38.56 psu) and c) 150-bottom with $\delta^{18}O$ values which are similar to those of the first layer, salinity of 38.40 and temperature values of about 10.4 °C. The heavier values of the intermediate

Table 5

$\delta^{18}O$ sea-water values (vs. V-SMOW) of the B, C and D transects.

Depth (m)	B1	B2	B3	B4		
0	0.71	0.54	0.62	0.62		
5	0.82	0.29	0.66	0.64		
10	0.92	0.90	0.80	0.92		
20	1.30	1.22	0.99	1.29		
Bottom	1.24	1.29	1.29	1.29		
	C1	**C2**	**C3**	**C4**	**C5**	**C6**
0	0.50	1.16	1.17	1.29	1.31	1.21
5	1.11	1.34	1.25	1.32	1.17	1.15
10	0.69	1.16	1.23	1.40	1.20	no
20	1.18	1.26	1.20	1.32	1.22	1.22
30		1.28	1.22	1.36	1.27	1.15
Bottom	1.19	1.26	1.23	1.39	1.28	1.17
	D1	**D2**	**D3**	**D4**		
0	0.95	1.41	1.36	1.30		
10	0.92	1.39	1.38	1.25		
20	1.29	1.32	1.40	1.27		
30	1.25	1.50	1.54	1.28		
50	1.39	1.57	1.54	1.38		
75	1.40	1.46	1.46	1.42		
100		1.53	1.52	1.42		
150		1.38	no	1.41		
200		1.48	1.37			
Bottom	1.72	1.42	1.36	1.37		

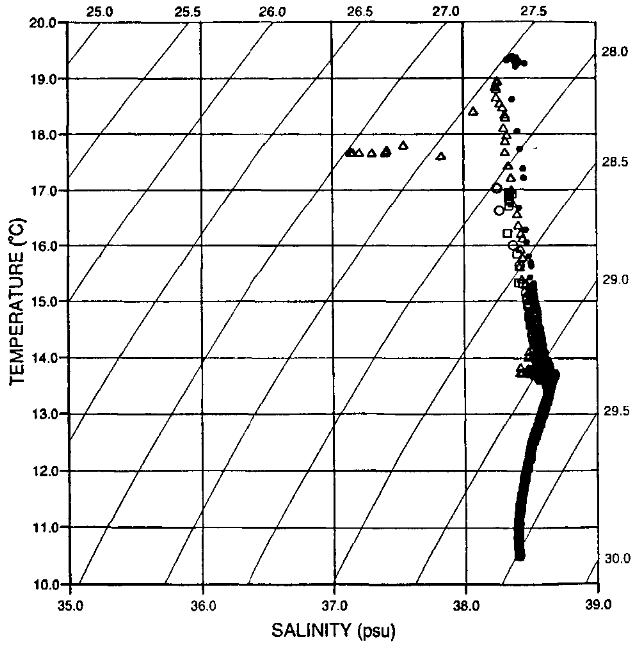

Figure 6

Temperature-salinity diagram for the D transect data (D1: open triangle; D2: open square; D3: open circle; D4: full circle). Isopycnals are also reported.

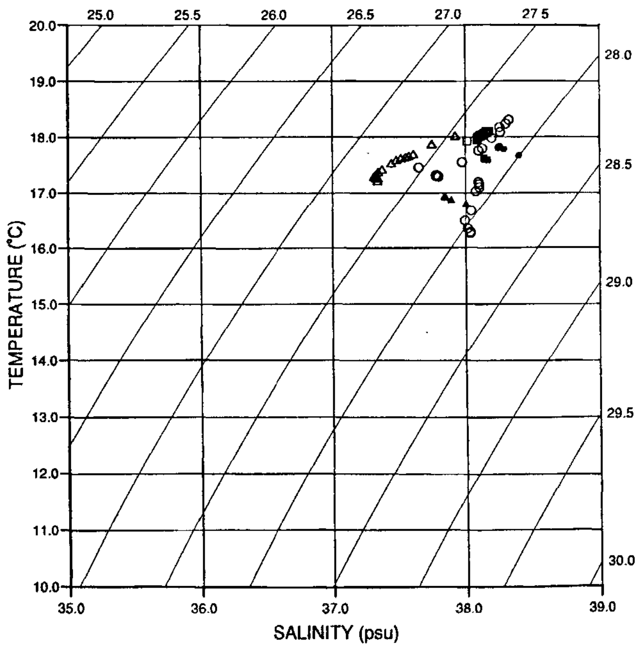

Figure 7

Temperature-salinity diagram for the C transect data (C1: open triangle; C2: open square; C3: open circle; C4: full circle; C5: full square; C6: full triangle). Isopycnals are also reported.

layer can be ascribed to the inflow of salty (38.60 psu) and ^{18}O enriched water which could be referred to intermediate water (MLIW) progressively modified by dilution moving northwards.

Transect D is located across the mesoadriatic pit (Jabuka Pit) where the presence of very dense water contributing to the formation of the Adriatic Bottom Water is reported by many authors (Zore-Armanda, 1963; Franco and Bregant, 1983; Artegiani *et al.*, 1993). Temperature and salinity seem to support this hypothesis, even though the $\delta^{18}O$ values of the bottom layer in the Jabuka Pit are, on average, slightly higher than those found in the northernmost part of the basin from which these waters are supposed to originate and slightly lower than those measured in Adriatic Bottom Water.

The Northern Adriatic

The data from transect C (Tab. 5 and Fig. 7), south of the Po delta, show a different situation as far as surface water is concerned. Close to the Italian coast the waters are considerably ^{18}O depleted with low salinity values (37.3 psu) due to mixing with fresh water from the Po river ($\delta^{18}O$ close to −10 ‰ according to Bortolami *et al.*, 1973). The highest $\delta^{18}O$ and salinity values are found in the central sections of the transect (stations C4 and C5) which are fairly homogeneous from surface to bottom: however, these values are slightly lower than those of transect D. The same situation is observed in the case of salinity and temperature values. The waters from station C6 are slightly ^{18}O depleted and have low salinity values (37.8 psu) which may perhaps be related to the inflow of river waters from the Dalmatian coast, as suggested by Mosetti (1984).

The values from transect B (Tab. 5 and Fig. 8) are quite different from those of the previous two transects. The inflow of river water with negative $\delta^{18}O$ values seems to be widespread in surface waters whose $\delta^{18}O$ values range from +0.29 to +0.92 ‰ in the top ten metres, while salinity ranges from 35.3 to 36.5 psu. By contrast, bottom water is still quite positive (+1.24 to +1.29 ‰) and salty (from 37.7 to 38.0 psu), reflecting the inflow of isotopically heavy and salty water from the Southern Adriatic.

In order to check the variability of the isotopic composition of bottom water and the vertical isotopic gradients where the depth is of only 20 to 30 metres, a number of measurements were carried out in the Gulf of Trieste and nearby areas. Samples were collected 5 times from May 1991 to February 1992 at eight different stations. The data obtained during the warm semester of 1991 (Fig. 9) indicate a marked vertical isotopic stratification throughout the water column in May, while the vertical gradients slowly but progressively decrease from May to July and August, apparently due to vertical mixing. A similar stratification in the salinity and temperature values during spring and summer was observed in the Gulf of Trieste by Aleffi *et al.* (1987-88). The $\delta^{18}O$ values of surface waters collected in May are quite negative, ranging from −4.49 to +0.05 ‰ and clearly suggesting a marked contribution of continental water. In the same way the salinity of the surface waters exhibits very low values ranging from 19.9 to 33.5 psu (Orel, pers. comm.). It must be pointed out that in May several rivers in this area are flooded by meltwater from the snow cover in the upper section of their mountain basin (Flora and Longinelli, 1989). The $\delta^{18}O$ values measured in May in the Isonzo river water are systematically

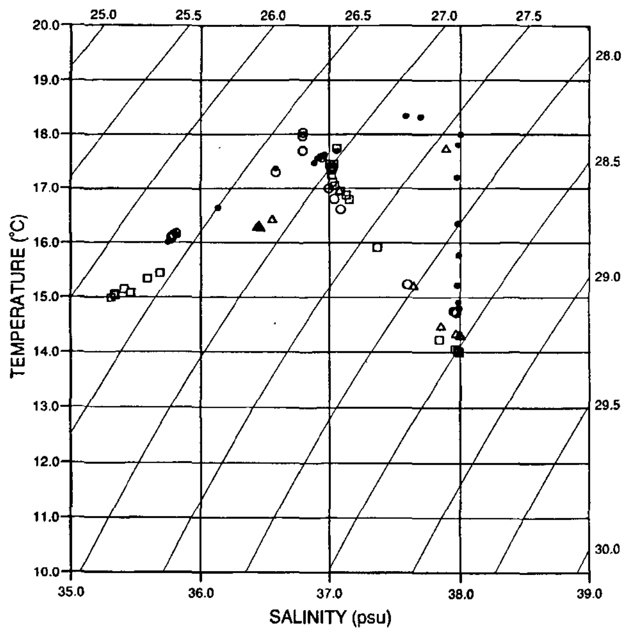

Figure 8

Temperature-salinity diagram for the B transect data (B1: open triangle; B2: open square; B3: open circle; B4: full circle). Isopycnals are also reported.

close to −10 ‰, the yearly range of values in this river being relatively narrow owing to several dams acting as homogenization reservoirs. The inflow of this water has no effect whatsoever on the Gulf of Trieste bottom water, where the marked vertical density gradients act as an effective barrier to vertical mixing. Bottom-water samples show quite positive and fairly homogeneous values throughout summertime, while salinity reaches values of 37.9 psu. The surface layer of isotopically light water is well defined in all the stations studied with a thickness of only a few metres (Fig. 9).

At the beginning of the cold semester (Fig. 10 - November) an increasing homogenization of the water column takes place in the stations within the Gulf of Trieste (A1, A2, A3, A4), while at stations A5, A6, A7 and A8 a small isotopic stratification is still found, probably related to the relatively large contribution of river water from the Tagliamento and Isonzo. In this period the mean $\delta^{18}O$ value of surface water in the Gulf of Trieste is about +0.9 ‰, while in the remaining section of the northern Adriatic basin this value is close to zero. October and November are normally rather rainy months in this area. As regards the surface layer, the salinity observed in the Gulf of Trieste (A1, A2 and A3) exhibits values around 36.7 psu while in the nearby areas (A4, A5, A6, A7 and A8) lower values (from 31.3 to 35.8 psu) are found (Orel, pers. comm.)

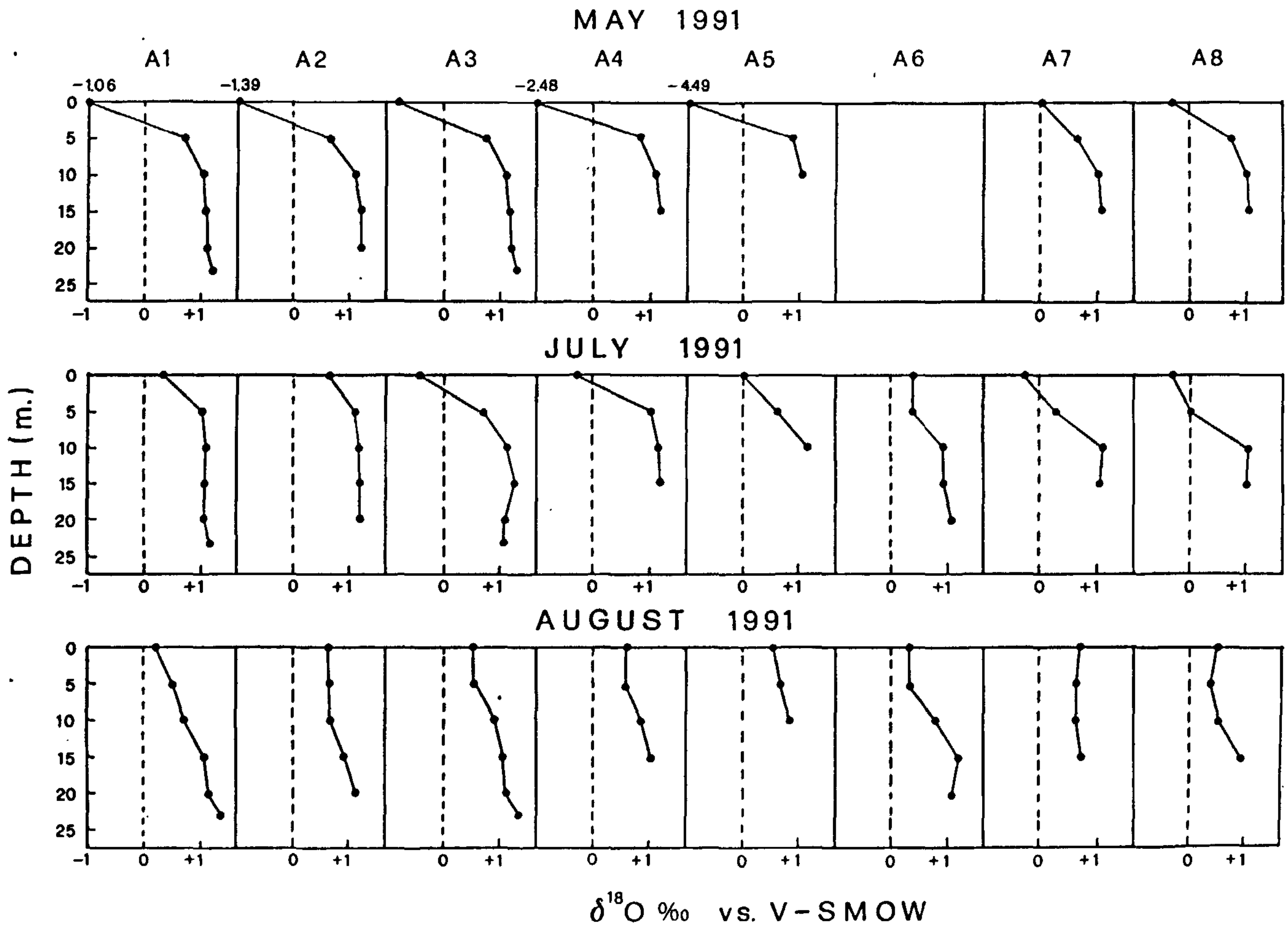

Figure 9

Vertical profiles of $\delta^{18}O$ during the warm semester in the Gulf of Trieste.

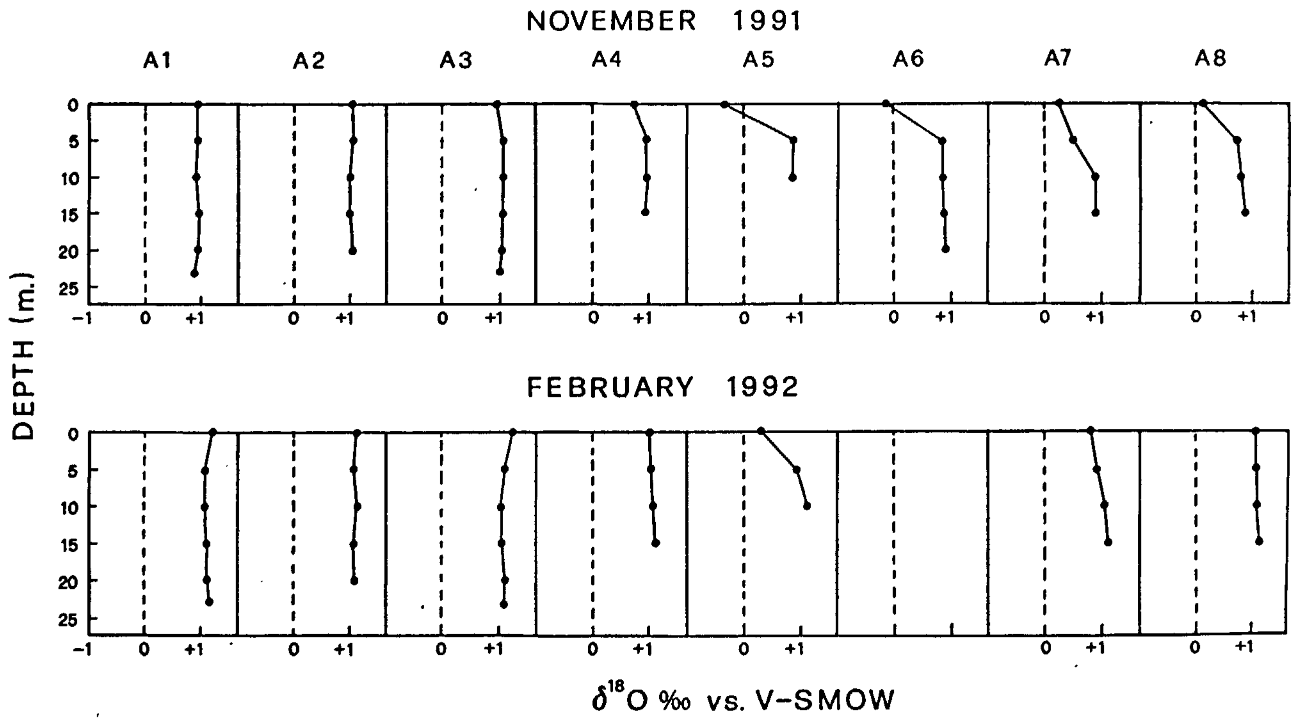

Figure 10

Vertical profiles of $\delta^{18}O$ during the cold semester in the Gulf of Trieste.

In February the vertical homogenization of the water column is almost complete in all the stations, the $\delta^{18}O$ values being close to +1.0 ‰ and the salinity values (in the Gulf of Trieste) ranging from 37.4 at the surface to 37.6 at the bottom (Orel, pers. comm.). This may be defined as a typical winter situation with surface water temperatures as low as 8 °C related to strong north-easterly winds and the density gradients of the water column gradually disappearing. Two stations in the Gulf of Trieste (A1 and A3) show $\delta^{18}O$ values slightly heavier at the surface than at the bottom. This may perhaps be related to evaporation effects taking place, despite the low temperature, because of the high winds prevailing in the cold semester.

The presence of bottom water with heavy $\delta^{18}O$ values during summer and the moderate decrease of $\delta^{18}O$ values during winter at all depths in the northernmost Adriatic prove that the northward flow of water from the Southern Adriatic to the Gulf of Trieste is active throughout most of the year. Aleffi *et al.* (1987-88) reported relatively high salinity values (around 38 with a maximum of 38.7 psu) occurring repeatedly throughout the year in the bottom layer.

CONCLUSIONS

According to the reported data the following conclusions can be drawn:

1) quite positive and rather homogenous oxygen isotope values are found in the Southern Adriatic, related to the inflow at intermediate depth of ^{18}O enriched and saltier water from the Central-Eastern Mediterranean. Moving northward these positive values are quite well preserved over long distances, even though slightly lower values are found in the northern section due to increasing addition of continental water;

2) a strong stratification of the water column may be detected in spring and summer up to the northeasternmost section of the Adriatic Sea (Gulf of Trieste), low $\delta^{18}O$ values of surface layers being related to a marked contribution of isotopically light river water. The origin of isotopically heavy bottom water in the Northern Adriatic must be essentially related to the advection of water from the South;

3) a homogenization of the water column takes place in this area beginning in autumn and continuing throughout winter. This process is essentially related to the marked and progressive cooling of surface waters: some minor effect of evaporation related to wind action may also take place.

Since the results of this study agree with previous considerations by Mosetti (1966, 1984) and Franco (1970) about the presence of southern sea-water up to the Gulf of Trieste, one can conclude that the isotopic study may definitely be considered a useful tool, alongside other classical methods, to detect mixing processes between continental and marine water, to characterize different water masses and to trace their origin and evolution.

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