Cluster analysis as a statistical method for identification of the water bodies present in the Gulf of Trieste (Northern Adriatic Sea)

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Abstract. In the framework of Project ''Alpe Adria'', between 1991 and 1993, vertical CTD profiles were taken in the Gulf of Trieste. Temperature, salinity and density are averaged over metre intervals and analyzed with a cosine least squares fit procedure using two waves of annual and semiannual period. Data are organized into monthly matrices, on which cluster analysis, with a complete linkage method, based on the similarity ratio matrix is done. Four different water bodies are identified in the Gulf during the year using this method. However, only three water bodies are noted in November, mainly due to the break in thermal stratification and to mixing. The vertical distribution of the density excess varies seasonally, and shows the dominance of dense and homogeneous water during the winter, and strong stratification during the summer. Furthermore, an estimation of the volume of the water masses present and their temporal evolution is computed.

1. Introduction

In the framework of the Alpe Adria Project ''Campagna scientifica di ricerca e di monitoraggio sullo stato chimico, fisico e biologico delle acque dell'Alto Adriatico in relazione al fenomeno di formazione degli ammassi gelatinosi'', sponsored by the Friuli-Venezia Giulia and Veneto Regions, and the Republics of Slovenia and Croatia, 25 Italian stations, located on four transects running transversally to the Gulf of Trieste, were monitored during the period 1991-1993 (Fig. 1).

The Gulf of Trieste, situated in the northern part of the Adriatic, plays an important role in the general stream flow in the Adriatic. Although limited in size, the Gulf has an extremely dynamic oceanography. Morphologically it has a less steep sea-bottom near the western coast, than that which forms the eastern coast; it has an average depth of 17 m and a maximum of 26 m. Off Rt Savudrija, there is a steep slope which limits and affects water exchange with the Adriatic.

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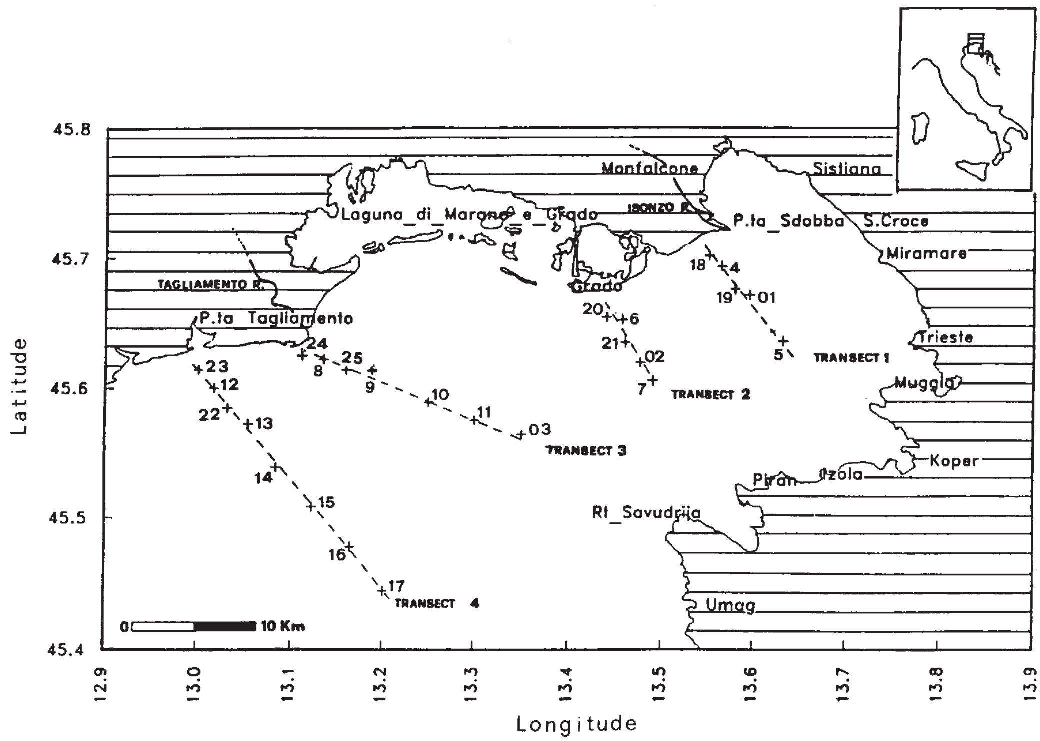

Fig. 1 - Gulf of Trieste (Northern Adriatic Sea).

The Gulf comes under the influence of several factors, the most important of which are: the strong thermal range between winter and summer, the fresh water inputs from the rivers of the Friuli plain and the Carso, the influence of the stream flowing along the Istro-Dalmatian coast, the tidal amplitude, and the action of the winds. Among these the ”Bora” wind causes an outward flow of the water and a vertical mixing of the water bodies, while south-east winds cause the opposite flow (Mosetti, 1972).

Three layers can be identified in the Gulf: a superficial one, whose generally clockwise flow is ruled by the wind; one near the sea-bed tied to the north-bound Adriatic stream and slowly flowing anticlockwise, and a third one in between (Stravisi, 1983).

In the Northern Adriatic, during spring and summer, the water column is strongly stratified thermally and the fresh water inputs mainly affect the superficial layer; in autumn and winter the water column tends to become homogeneous, and, in this situation the fresh water inputs remain in the coastal zone, and are separated from the off-shore waters by a frontal system which runs parallel to the coast (Franco, 1989).

The aim of this study is to follow, over a whole year, the possible evolution - both in space and time - of the water body in the Gulf of Triest by using a particular statistical procedure.

To achieve this aim it is necessary to identify the stratification and homogenization periods of the water column, the interaction between the fresh waters, coming mainly from the Isonzo

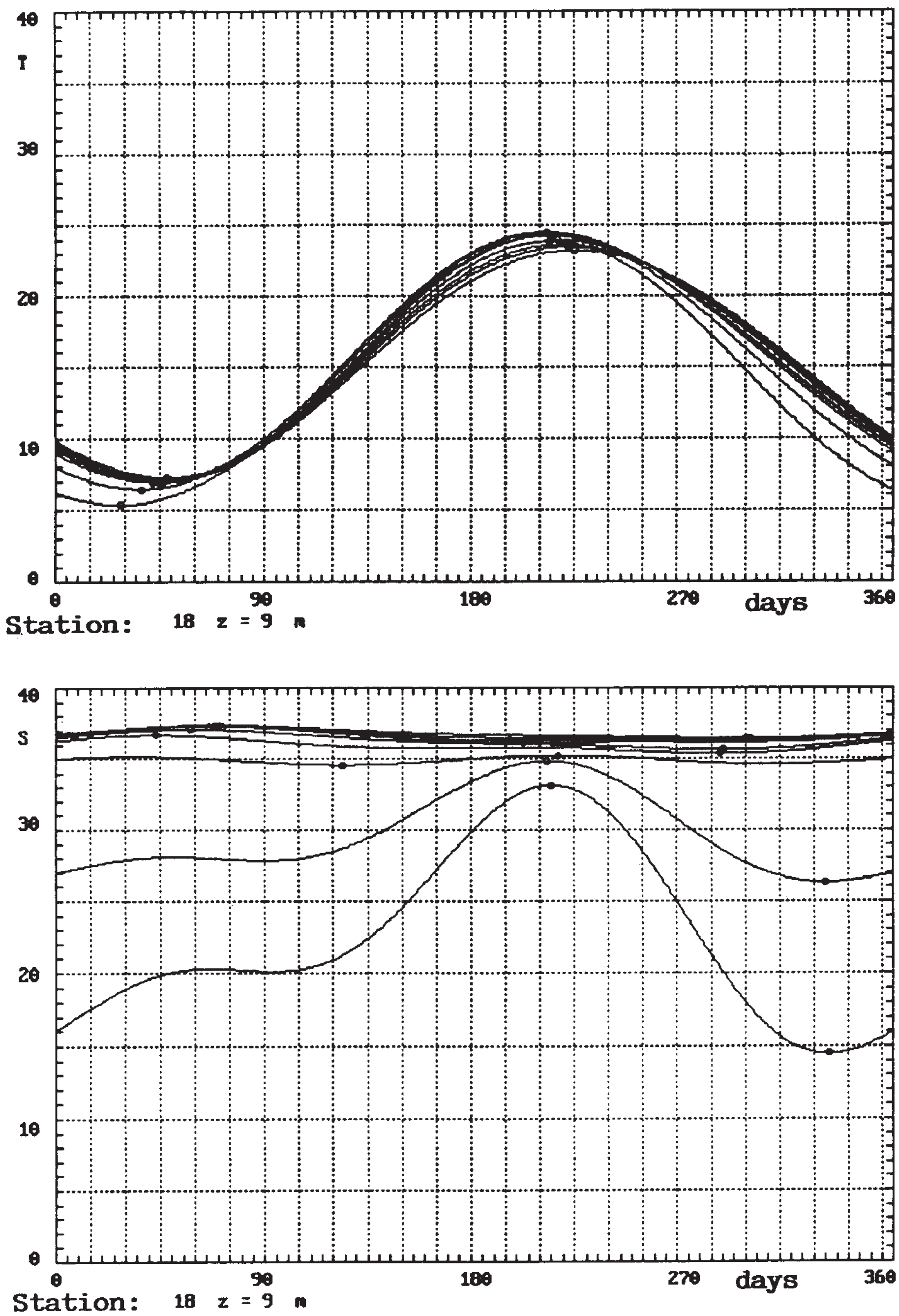

Fig. 2 - Station 18 (inner part of the Gulf) temperature and salinity data interpolated with the cosine best-fit procedure.

River, and the more saline ones, the formation and position of dense winter waters, and the exchange between waters of the Gulf and of the Northern Adriatic.

2. Materials and methods

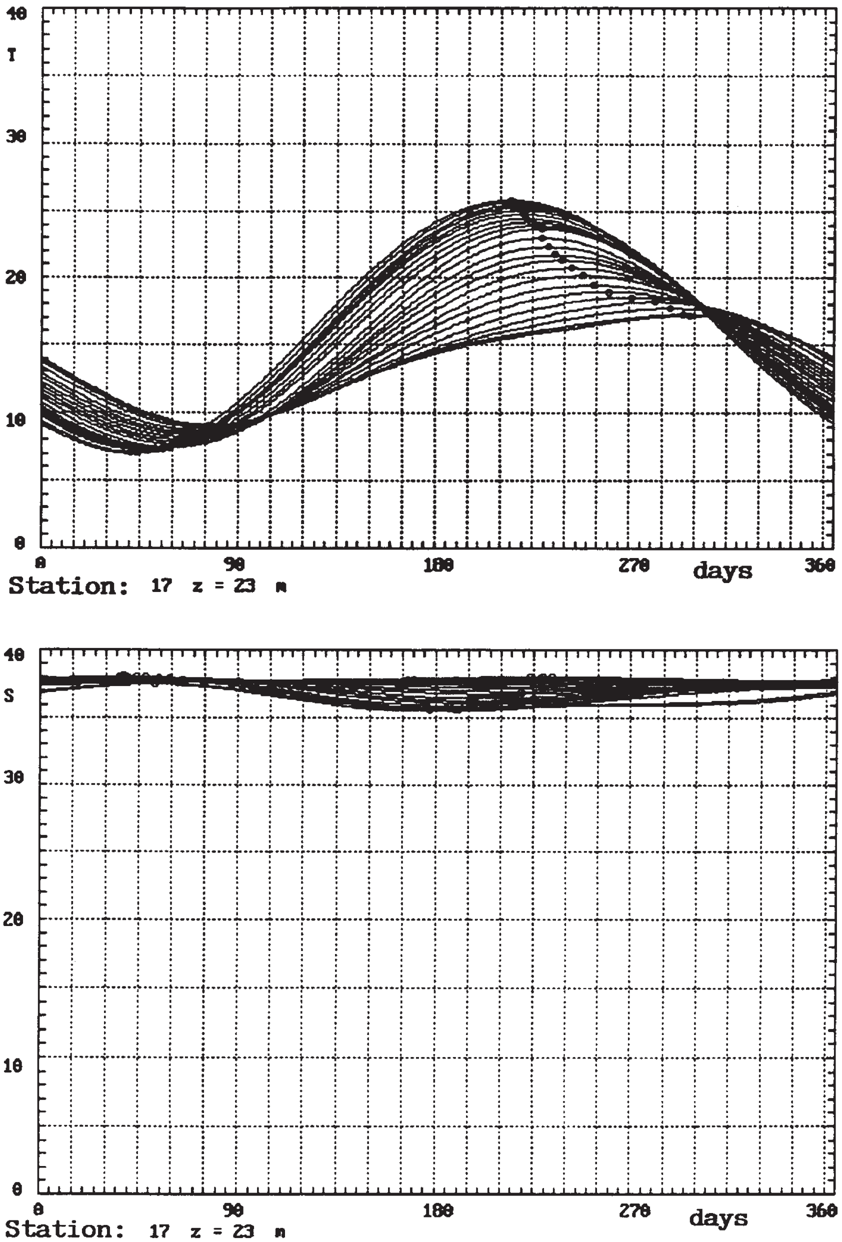

Fig. 3 - Station 17 (outer part of the Gulf) temperature and salinity data interpolated with the cosine best-fit procedure.

The monthly cruises were carried out as follows:

- 1991: 6 cruises from June to November;
- 1992: 8 cruises from March to November (none in October);
- 1993: 6 cruises from June to November.

The physical data were measured on vertical profiles using a CTD Idronaut mod. 401 probe.

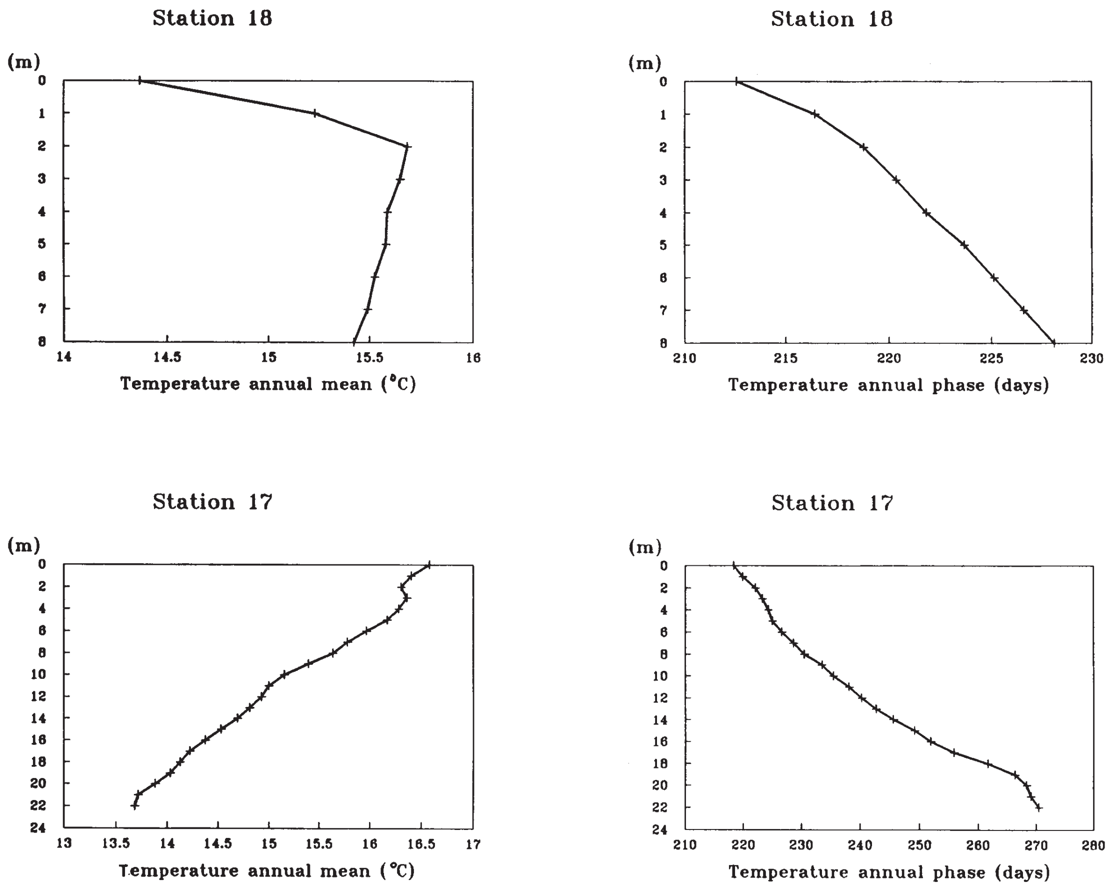

Fig. 4 - Temperature annual mean and annual phase.

The profiles of pressure, temperature and conductivity recorded with a 0.2 dbar pressure step were averaged over metre intervals from the surface to the bottom (maximum depth of 26 m). The parameters derived, such as salinity and density excess $\gamma(S,t,0)$ are obtained by application of algorithms for the computation of fundamental seawater properties (UNESCO, 1983).

In order to obtain a continuous time series, these values were interpolated with the cosine least squares fit procedure using two waves of annual (T = 365.25 days) and semi-annual ($T/2$) period (Stravisi, 1983). The interpolations function used was

$$\varphi\left(z,t\right) = A(z) + a(z)\,\cos\left[2\,\pi\left(t-\alpha\left(z\right)\right)/\,T\right] + b\left(z\right)\cos\left[\pi\left(t-\beta\left(z\right)\right)/\,T\right], \tag{1}$$

where

$A(z)$=average value,

$a\,(z)$=amplitude of the annual oscillation,

$\alpha\,(z)$=annual phase,

$b\,(z)$=amplitude of the semi-annual oscillation,

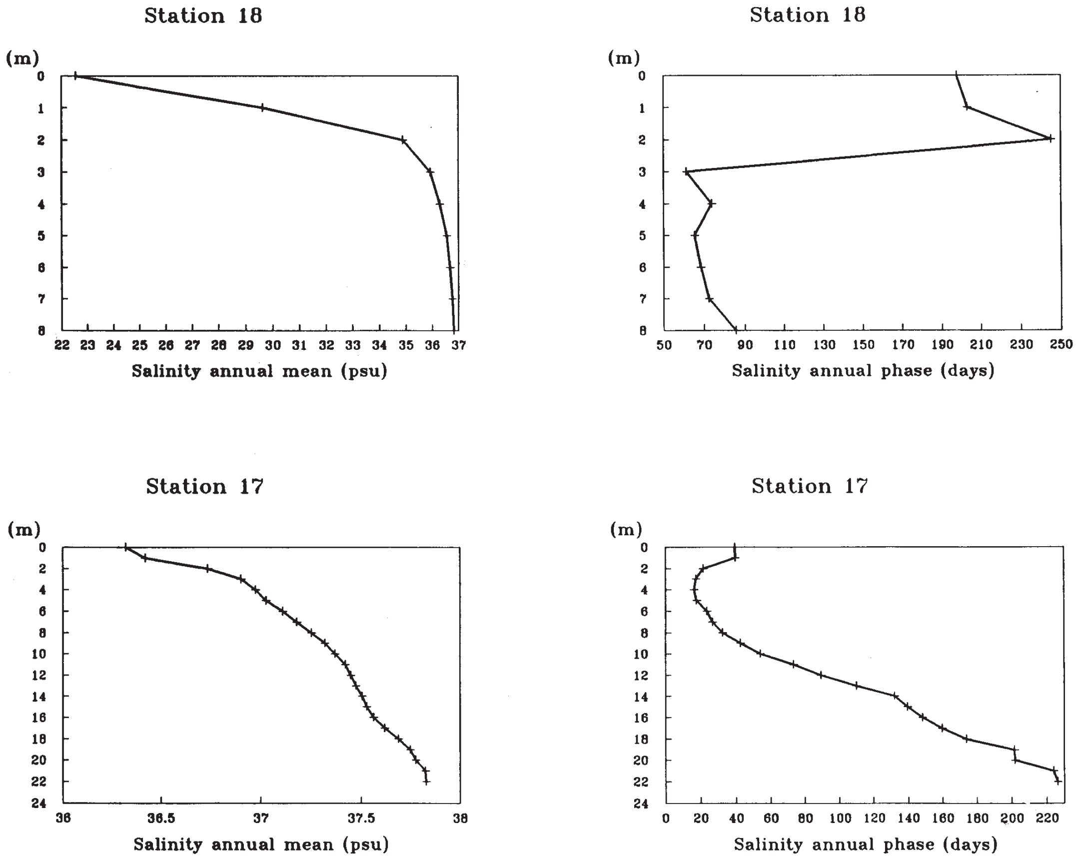

Fig. 5 - Salinity annual mean and annual phase.

$\beta(z)$=semi-annual phase.

The annual and semi-annual phase is given by the day of the year when the maximum occurred.

Temperature and salinity data were organized in a matrix and, after standardization of the data, cluster analysis (Burba et al., 1992) with a complete linkage method based on the similarity ratio matrix (Feoli et al., 1982) was computed for each month.

The similarity ratio formula used was

$$SIM_{i,j} = \frac{\sum_{r=1}^{R} X_{r,i} * X_{r,j}}{\sum_{r=1}^{R} \left(X_{r,i}\right)^2 + \sum_{r=1}^{R} \left(X_{r,j}\right)^2 - \sum_{r=1}^{R} X_{r,i} * X_{r,j}} \qquad (2)$$

which corresponds to the Jaccard index for quantitative data.

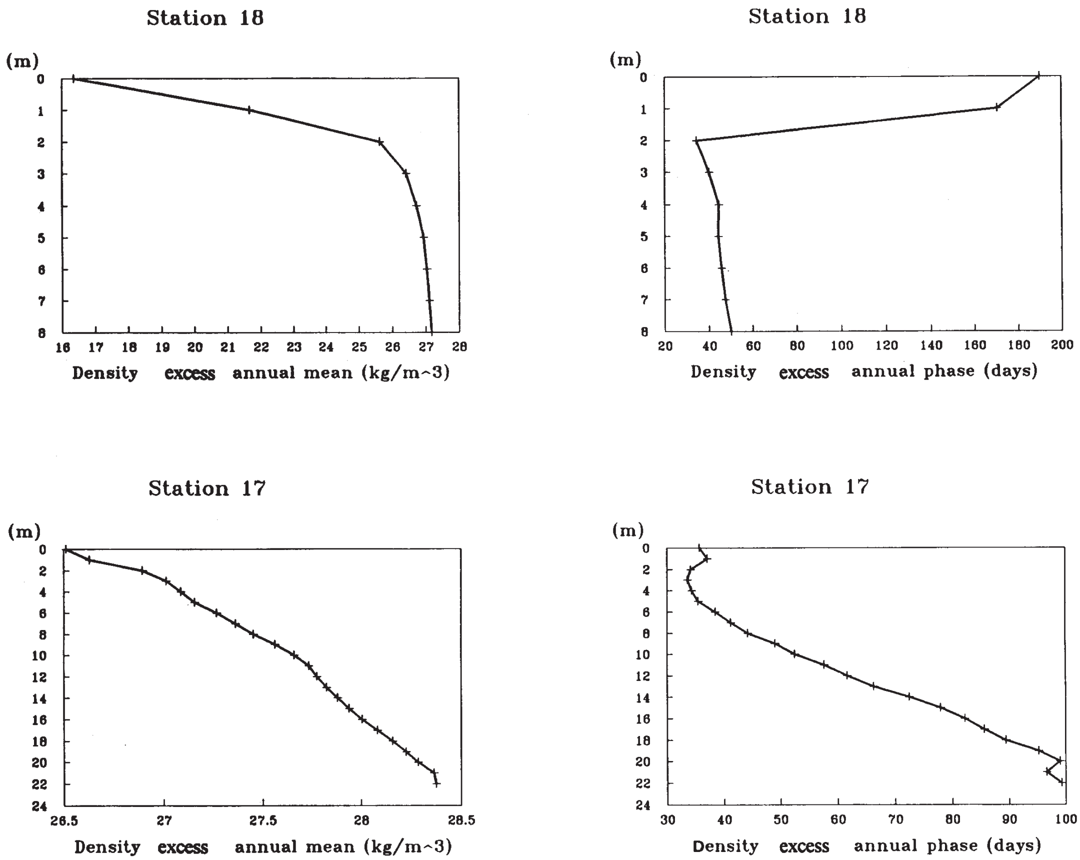

Fig. 6 - Density excess annual mean and annual phase.

Monthly volume of the related water masses was estimated using the following methods: Trapezoidal, Simpson, Simpson 3/8 rule; the net volume being expressed as the mean of these methods ± the relative error in percentage. For each month and each station, the upper and lower limits of the water masses were defined in order to create its horizontal distribution. Finally, the volumes of the different water bodies were derived from the differences between these horizontal distributions.

3. Data analysis

3.1. Cosine least squares fitting procedure

Interpolation of the observed data on temperature and salinity in the Gulf of Trieste gives the results represented in Figs. 2 and 3, which correspond to two limit situations in the Gulf: the former identifies the inner part affected by river inputs (St. 18); the latter, corresponding to the more external part, presents more saline features (St. 17).

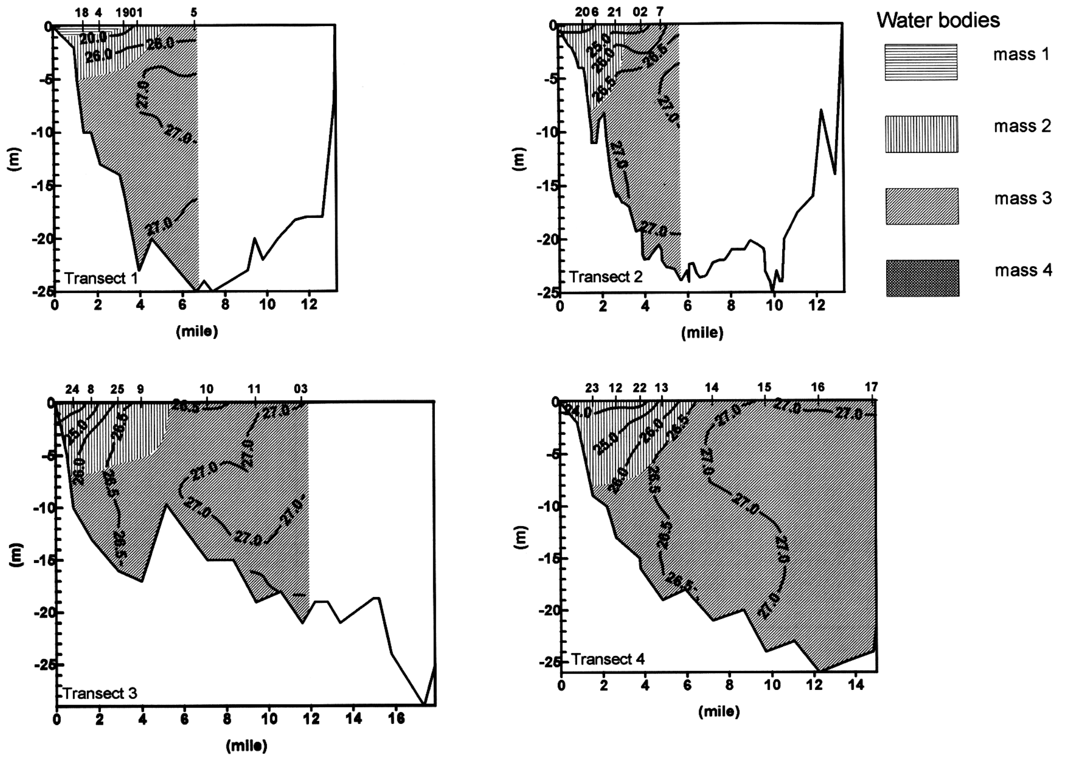

Fig. 7 - November density excess γ(S,t,0) distribution and water bodies identified with the cluster analysis of temperature and salinity data, organized into monthly matrices, using a similarity ratio with a complete linkage method.

The oscillation of the annual temperature shows a maximum amplitude around 19°C in the surface layer, decreasing linearly in the water column towards the seabed, with a minimum amplitude of 9°C in the outer part of the Gulf. This pattern is observed at each station by analyzing the mean annual temperature, as well as the temperature annual phase, which shows a high correlation of 0.98 (Fig. 4). The annual phase, moreover, increases from the coast (16 days) towards the center of the Gulf, where the highest value of 40 days is found. The annual minimum and maximum temperatures (5.63°C and 26.18°C) are observed at the surface, at the end of January and July, respectively, shifting towards the bottom in March and September, with values of 7.83°C and 22.19°C.

The time series analysis of the salinity shows that the periodicity of one year is affected by noise. For all the stations the mean annual salinity increases with depth, first exponentially then linearly, independently of their locations in the Gulf. The salinity for most of the stations presents a variation of phase in the upper layer (0-6m), with an initial increase followed immediately by a decrease. Below this layer the phase decreases almost linearly. This trend is found especially in the stations of the central part of the Gulf (Fig. 5). A minimum value of salinity of 14.80 is observed at the surface in December at the station beyond the mouth of the Isonzo River.

The general tendency of the density excess follows the salinity trend in the stations close to the coast, while in the central and outer parts of the Gulf, the trend is also influenced by the tem-

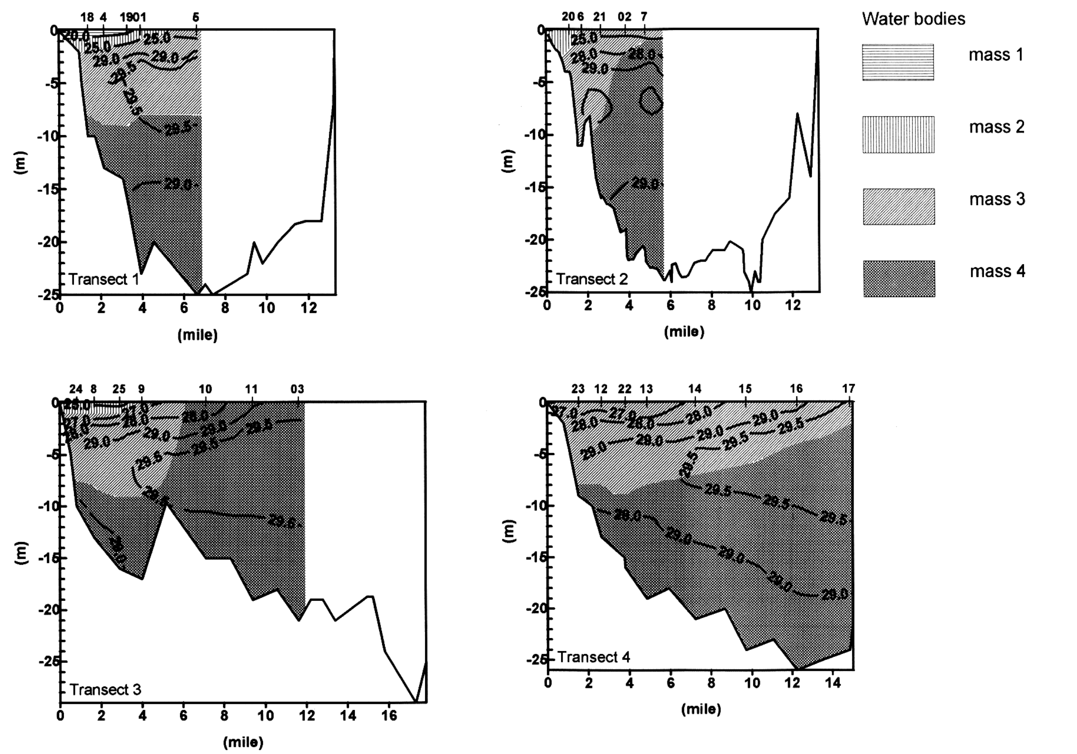

Fig. 8 - February density excess γ(S,t,0) distribution and water bodies identified with the cluster analysis of temperature and salinity data, organized into monthly matrices, using a similarity ratio with a complete linkage method.

perature (Fig. 6). The difference of amplitude between the surface layer and the bottom layer is minimum during the winter period (0.09 kg/m^3) in the stations less influenced by fresh inputs. The maximum amplitude occurs during the summer, with the presence of thermal stratification (4.55 kg/m^3). From October to March, the vertical distribution of the density excess shows a stratification in the surface layer (0-4 m), with values oscillating from less than 20 to 29 kg/m^3, while the subsurface layer remains mainly homogeneous, with a highest value of 29.40 kg/m^3. The surface heating starting in March onwards leads to a stratification over the whole water column. This trend is maintained until the end of September, when the minimum value of density excess of the subsurface layer is 26.50 kg/m^3.

3.2. Cluster analysis

All the dendrograms obtained by cluster analysis on the monthly temperature and salinity data define four principal groups. Each group corresponds to a specific water body for the relevant month. The temporal evolution of each water body, described in the next section, begins in October, when the cooling period starts. However, in November only three water bodies are noted (Table 1 and Figs. 7, 8, 9 and 10).

From October onwards, the first water body shows a decrease in temperature and salinity,

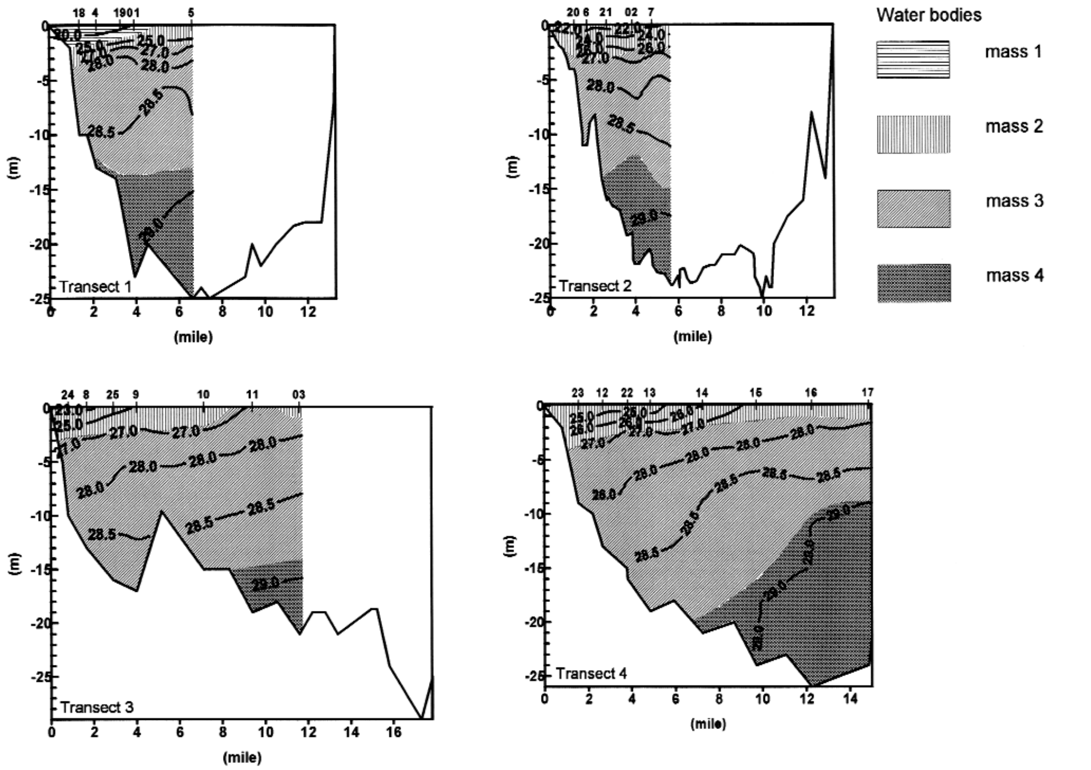

Fig. 9 - April density excess γ(S,t,0) distribution and water bodies identified with the cluster analysis of temperature and salinity data, organized into monthly matrices, using a similarity ratio with a complete linkage method.

reaching in February the minimum mean values of 6.24 ±0.29 °C and 21.03 ±1.03, respectively. From March until August the temperature mean increases, oscillating from 8.35 ±0.22 °C to 25.07 ±0.86 °C, while the salinity increases from 21.27 ±1.34 to 32.98 ±0.34. This water body is generally located near the west coast, but in June this water body is detected only in Station 18 at the surface.

The second water body shows a small increase in temperature but a high increase in salinity, compared to the first water body. From October to February, the mean values of temperature and salinity of 19.13 ±0.22 °C and 34.18 ±1.45 decrease to 6.78 ±0.33 °C and 29.92 ±1.48. The mean thermohaline value increases, from March to August, from 9.10 ±0.35 °C to 25.11 ±0.45 °C for the temperature, and from 32.15 ±2.80 to 34.47 ±0.50 for the salinity. In September a decrease in temperature (~2.2 °C) is observed, while the salinity does not present any considerable variation.

The third water body is governed especially by variations in temperature during the year, while the salinity shows a small oscillation. In October it has a mean temperature of 19.62 ±0.35°C and a mean salinity of 36.48 ±0.62; in February its mean temperature decreases to 7.02 ±0.27 °C, while the mean salinity increases to 36.18 ±1.87. Later, these values increase until August, reaching a mean temperature of 22.88 ±1.36 °C. During this month the mean salinity is of 36.90 ±0.51.

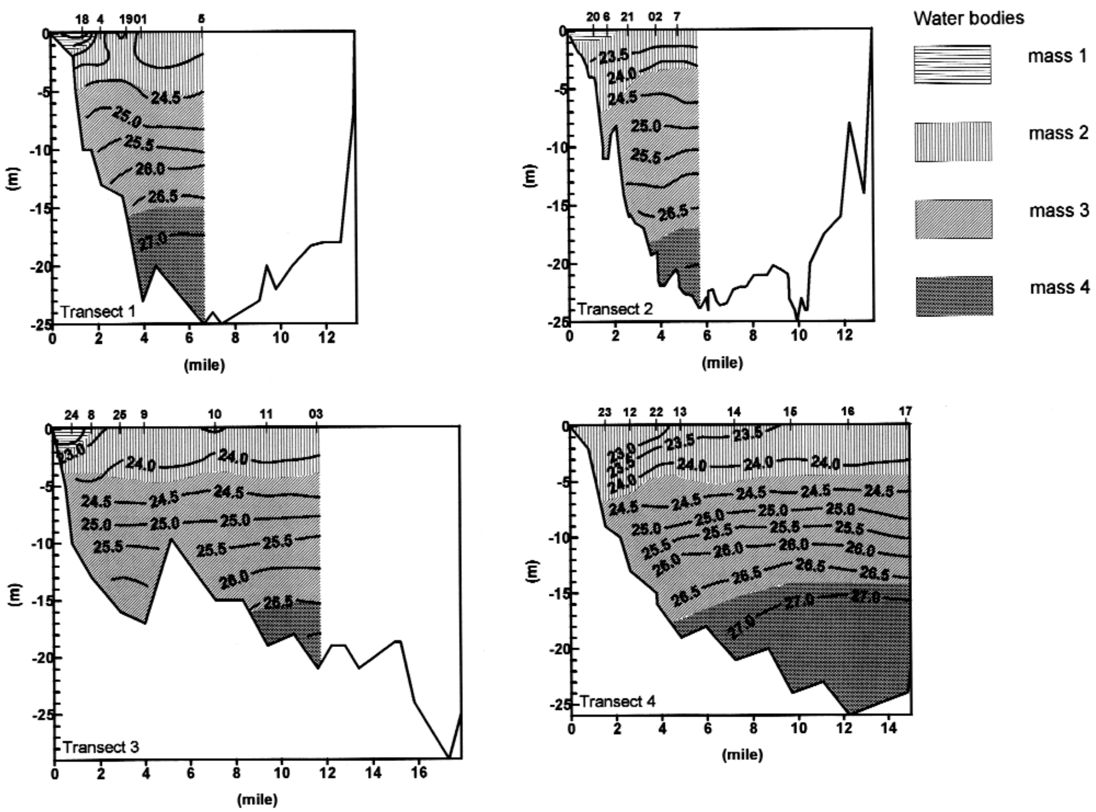

Fig. 10 - August density excess γ(S,t,0) distribution and water bodies identified with the cluster analysis of temperature and salinity data, organized into monthly matrices, using a similarity ratio with a complete linkage method.

Below this water body, a fourth water body is found. The cluster analysis shows the absence of this water body in November; it appears in December with a mean temperature of 14.18 ±0.63 °C and a mean salinity of 37.02 ±0.30. During this month it shows the highest temperature (15.57 °C) of the whole water column. Its density is governed mainly by the salinity, which has the highest value (37.74) of all the four water bodies. The temperature decreases until March, when a minimum of 8.76 °C is observed. From April until September this water body shows lower values of temperature than the others, varying from 9.83 ±0.28 °C to 17.23 ±0.98 °C, while the salinity remains almost steady (37.54 ±0.13 -37.93 ±0.05). In October this water body shows characteristics quite similar to those observed for the third water body.

3.3. Volume calculation

The studied area extends in a parallel direction to the western coast; it is delimited to the east by Italian territorial waters, to the NE by the Isonzo River Mouth and to the SW by the western offshoot of the River Tagliamento delta. The volume of this part of the Gulf is approximately $1.05*10^{10}$ m^3, which represents almost 3/5 of its total volume. Monthly volume and relative error

Table 1 - Water body statistical values of temperature, salinity and density excess obtained from cluster analysis.

	OCTOBER			NOVEMBER			DECEMBER			JANUARY		
	T(°C)	S	γ(S,T,0)	T(°C)	S	γ(S,T,0)	T(°C)	S	γ(S,T,0)	T(°C)	S	γ(S,T,0)
MASS1												
MIN	17.11	21.17	14.91	12.27	15.86	11.73	8.17	14.83	11.46	5.63	17.58	13.85
MAX	18.36	31.13	22.24	12.92	20.16	14.96	8.95	19.07	14.68	6.39	20.56	16.13
AVG	17.91	26.72	18.96	12.67	18.58	13.77	8.62	17.48	13.48	6.11	19.52	15.33
STD	0.43	3.13	2.29	0.28	1.93	1.45	0.33	1.89	1.44	0.34	1.37	1.05
MASS2												
MIN	18.64	31.38	22.25	12.54	23.02	17.21	8.29	23.69	18.37	5.63	26.62	20.95
MAX	19.52	36.52	26.08	15.46	36.12	26.80	10.74	34.63	26.72	7.80	35.62	27.96
AVG	19.13	34.18	24.36	14.74	33.91	25.18	9.91	32.14	24.73	6.93	32.81	25.70
STD	0.22	1.45	1.08	0.59	2.41	1.76	0.55	2.66	2.03	0.44	2.34	1.83
MASS3												
MIN	18.71	33.57	23.67	15.36	33.79	24.82	10.52	33.19	25.33	7.25	30.96	24.05
MAX	20.40	37.55	27.05	17.42	37.81	27.69	13.35	37.67	28.63	10.25	37.99	29.53
AVG	19.62	36.48	25.99	16.28	36.55	26.87	12.10	36.39	27.65	8.73	36.82	28.59
STD	0.35	0.62	0.51	0.46	0.56	0.38	0.70	0.70	0.48	0.74	0.82	0.61
MASS4												
MIN	17.09	37.28	26.87				13.33	36.41	27.31	10.22	36.72	28.24
MAX	18.65	37.92	27.74				15.57	37.74	28.10	12.62	37.70	28.86
AVG	18.13	37.60	27.23				14.18	37.02	27.72	11.02	37.21	28.49
STD	0.52	0.20	0.28				0.63	0.30	0.15	0.66	0.24	0.14

	FEBRUARY			MARCH			APRIL			MAY		
	T(°C)	S	γ(S,T,0)	T(°C)	S	γ(S,T,0)	T(°C)	S	γ(S,T,0)	T(°C)	S	γ(S,T,0)
MASS1												
MIN	5.83	19.80	15.58	8.05	20.25	5.71	11.80	20.35	15.27	16.30	22.56	16.14
MAX	6.44	22.32	17.51	8.54	23.17	17.94	12.50	28.07	21.19	16.90	27.10	19.51
AVG	6.24	21.03	16.51	8.35	21.27	16.47	12.19	24.78	18.64	16.67	24.80	17.78
STD	0.29	1.03	0.79	0.22	1.34	1.04	0.21	3.17	2.43	0.26	1.85	1.37
MASS2												
MIN	6.10	28.07	22.01	8.43	27.00	20.88	12.19	27.30	20.26	16.78	28.23	19.97
MAX	7.26	32.50	25.42	10.02	37.31	28.96	14.22	36.64	27.64	19.28	36.25	265.36
AVG	6.78	29.92	23.45	9.10	32.15	24.87	13.14	32.64	24.54	17.90	33.53	24.18
STD	0.33	1.48	1.16	0.35	2.80	2.20	0.47	2.40	1.91	0.55	2.17	1.70
MASS3												
MIN	6.31	28.35	22.13	7.83	34.34	26.69	10.37	34.65	26.28	14.71	34.63	25.22
MAX	8.15	37.87	29.05	9.14	37.89	29.55	12.76	37.57	28.87	17.41	36.52	26.76
AVG	7.02	36.18	28.34	8.44	37.21	28.94	11.49	36.86	28.14	16.13	35.74	26.12
STD	0.27	1.87	1.48	0.22	0.52	0.42	0.57	0.52	0.50	0.75	0.53	0.45
MASS4												
MIN	7.30	34.02	26.57	8.76	37.04	28.70	9.20	36.631	28.70	11.04	36.76	27.45
MAX	10.22	38.05	29.75	9.22	37.72	29.25	10.30	37.77	29.14	14.60	37.83	28.84
AVG	8.24	37.33	29.07	8.99	37.38	28.99	9.83	37.54	28.97	12.97	37.44	28.28
STD	0.72	0.45	0.37	0.14	0.20	0.16	0.28	0.13	0.11	1.07	0.23	0.37

Table 1 - continued.

	JUNE			JULY			AUGUST			SEPTEMBER		
	T(°C)	S	γ(S,T,0)	T(°C)	S	γ(S,T,0)	T(°C)	S	γ(S,T,0)	T(°C)	S	γ(S,T,0)
MASS1												
MIN				23.23	31.84	20.88	23.57	32.49	21.18	21.31	28.18	19.23
MAX				26.18	32.43	21.49	25.87	33.45	22.18	22.94	30.53	20.89
AVG	20.50*	27.28*	18.76*	24.71	32.16	21.28	25.07	32.98	21.79	21.98	29.74	20.23
STD				1.20	0.24	0.28	0.86	0.34	0.32	0.60	0.93	0.61
MASS2												
MIN	20.65	30.39	20.23	23.10	33.26	21.85	23.98	33.82	22.20	21.96	32.23	21.79
MAX	23.76	36.18	25.28	25.90	36.42	24.74	25.91	36.11	24.35	23.90	36.93	25.56
AVG	21.85	34.98	24.24	24.48	35.54	23.91	25.11	34.47	23.67	22.93	35.84	24.59
STD	0.61	1.23	1.01	0.61	0.64	0.60	0.45	0.50	0.48	0.44	1.00	0.79
MASS3												
MIN	16.28	35.69	25.20	19.52	36.06	24.70	20.15	36.01	24.16	18.36	36.66	25.50
MAX	21.22	37.70	27.74	23.71	37.72	26.86	25.10	37.79	26.85	22.19	37.77	27.30
AVG	18.92	36.80	26.41	21.66	36.90	25.78	22.88	36.90	25.41	20.87	37.25	26.24
STD	1.40	0.53	0.75	1.17	0.45	0.66	1.36	0.51	0.77	0.99	0.26	0.46
MASS4												
MIN	13.36	37.36	26.86	14.96	37.52	26.86	15.81	37.57	26.74	16.52	37.84	27.48
MAX	16.15	37.89	28.27	19.54	37.97	28.27	19.98	38.02	28.12	17.89	38.00	27.94
AVG	14.76	37.70	27.50	17.60	37.78	27.50	18.58	37.81	27.27	17.23	37.93	27.71
STD	0.85	0.13	0.36	1.23	0.12	0.36	1.05	0.10	0.33	0.98	0.05	0.15

* only one surface data

for each water body obtained by cluster analysis are presented in Table 2.

The first water body located near the western coast has a maximum annual volume of $1.45*10^8$ m^3 in October, associated with the fresh water inputs from the whole Gulf; in winter it has a constant volume of $3.29*10^7$ m^3, which increases in April to $6.69*10^7$ m^3, mainly due to the inputs from the Isonzo River. From May to July a reduction in the volume is seen, reaching the annual minimum of $2.50*10^7$ m^3. In August and September this volume increases, being greater in August than in September. In fact, the volume of the latter is $7.49*10^7$ m^3, while in August it is $1.14*10^8$ m^3.

The second water body is distributed throughout the studied area and has an even more regular temporal evolution than that observed for the first water body. Generally it shows a decrease in volume from October onwards until February, when it reaches its annual minimum of $2.01*10^8$ m^3. From March to September, except for a slight decrease in August, this water body increases progressively in volume, reaching its annual maximum of $5.70*10^9$ m^3 in September.

The third water body is particularly extended in October and in November, with a maximum annual for October of $9.26*10^9$ m^3. From December to April, the volume remains almost constant, varying from $7.16*10^9$ m^3 to $7.96*10^9$ m^3, except during February when a remarkable reduction in volume (annual minimum of $2.53*10^9$ m^3) is observed, which is mainly due to an increase in volume of the underlying water body. Finally, the third water body shows, from May to September, a slight volume oscillation, varying from $4.19*10^9$ m^3 to $5.80*10^9$ m^3.

Table 2 - Monthly volume and relative error for each water body obtained from cluster analysis.

	OCTOBER		NOVEMBER		DECEMBER		JANUARY	
	m^3	%	m^3	%	m^3	%	m^3	%
MASS1	1.45E+08	± 0.96	3.29E+07	± 1.58	3.29E+07	± 1.58	3.29E+07	± 1.58
MASS2	6.95E+08	± 1.86	1.31E+09	± 0.64	6.64E+08	± 1.19	6.69E+08	± 0.82
MASS3	9.26E+09	± 0.15	9.12E+09	± 0.17	7.55E+09	± 0.61	7.96E+09	± 0.16
MASS4	3.59E+08	± 0.59			2.23E+09	± 0.36	1.80E+09	± 0.31
	FEBRUARY		MARCH		APRIL		MAY	
	m^3	%	m^3	%	m^3	%	m^3	%
MASS1	3.29E+07	± 1.58	3.29E+07	± 1.58	6.69E+07	± 1.70	3.29E+07	± 1.58
MASS2	2.01E+08	± 0.65	9.71E+08	± 0.33	1.01E+09	± 0.47	1.25E+09	± 0.29
MASS3	2.53E+09	± 0.36	7.60E+09	± 0.27	7.16E+09	± 0.07	5.12E+09	± 0.19
MASS4	7.70E+09	± 0.16	1.85E+09	± 0.26	2.22E+09	± 1.25	4.06E+09	± 0.19
	JUNE		JULY		AUGUST		SEPTEMBER	
	m^3	%	m^3	%	m^3	%	m^3	%
MASS1	2.50E+07	± 4.87	3.13E+07	± 6.10	1.14E+08	± 3.05	7.49E+07	± 1.59
MASS2	2.98E+09	± 0.17	4.01E+09	± 0.19	2.74E+09	± 0.14	5.70E+09	± 0.18
MASS3	5.56E+09	± 0.14	4.19E+09	± 0.15	5.80E+09	± 0.15	4.56E+09	± 0.16
MASS4	1.89E+09	± 0.37	2.23E+09	± 0.29	1.81E+09	± 0.35	1.22E+08	± 0.69

Generally, the volume of the fourth water body has a very variable behaviour; its maximum extension is in February, when it occupies almost all the water column, while it is extremely reduced in September and October, and disappears in November from the studied area. Its temporal evolution can be divided into two periods: from December to March and from April to October. The former has a volume varying from $1.80*10^9$ m^3 to $7.70*10^9$ m^3, the latter from $1.81*10^9$ m^3 to $4.06*10^9$ m^3, observed in August and May, respectively.

4. Discussion

The stations located near the coast are clearly influenced by external parameters, like fresh water inputs from the Isonzo and Tagliamento Rivers and the Lagoons of Marano and Grado. This is especially seen by analyzing the water coming from the Isonzo River, which flows over the salty marine water below, creating a sharp halocline between the surface and the layer at a depth of 3 m. Analysis of the annual salinity phase shows that the subsurface layer observed at the coastal stations has a similar trend to that observed at the stations of the central part of the Gulf, which are less influenced by these freshwater inputs. During the winter, the freshwater inputs are confined to the zone running along the western coast of the Gulf, with a varying width depending on the volume of the river flow, and separated by a frontal system from water of higher salinity and temperature.

From the temperature pattern, it can be established that the large thermal range between winter and summer affects the whole water column. The cooling process influences the entire water column almost simultaneously from October to February, but the seawater heating, on the contrary, starts from the surface towards the bottom, with surface-bottom differences of 9°C in July in the outer part of the Gulf. The maximum surface heating occurs in July and shifts towards the bottom in September. The difference between cooling and heating can be imputed to the different seasonal mixing conditions: the mean wind velocity is governed by the Bora annual cycle, and is greater during the winter and minimum in summer (Stravisi, 1977). The annual temperature phase shows a timelag between the surface and the bottom, that increases from the coast towards the centre of the Gulf, due to the greater depth of the seabed.

The water bodies determined by cluster analysis show well-defined characteristics. Due to the break in the stratification and to the mixing process, only three water bodies are observed in November. The first is identified as brackish water, coming mainly from the Isonzo River, which spreads into the Gulf to a greater or lesser extent depending on the river flow, with a thickness of 1-2 m and an influence zone of about 2.7 miles. During summer the flow of this water body decreases in intensity, allowing mixing in the water. Therefore, the cluster analysis groups it with the waters coming from the lagoons and the Tagliamento River, increasing the volume of this water body.

In October, the second water body initially forms a frontal system located in the inner part of the Gulf (transect 1) and close to the western coast, maintaining its position until November. From December, a reduction in its dimensions is observed, especially in the inner part, the water body being confined to the superficial layer (0-2 m) and reaching its minimum annual volume in February. Due to the surface heating, this front disappears in March, and a well-defined stratification with an initial thickness of 2-3 m is observed. The maximum deepening and enlargement of this water body occurs in September, reaching a depth of 13 m and a maximum volume of $5.70*10^9$ m^3, as a result of the commencement of the mixing, due to the cooling of the surface.

During the period of vertical instability in the water column, the third water body is located below and externally to the previous frontal system. In November an almost homogeneous water column is identified, with a maximum volume of $9.12*10^9$ m^3, and in December, initiation of the temperature inversion occurs in the layer near the seabed. At the same time the formation of a core of dense water (fourth water body) with a higher temperature and salinity is observed. This inversion of temperature from the surface towards the bottom increases until February, allowing this dense water body (average density excess of 29.07 ± 0.37) to achieve its maximum development (Stravisi, 1983), reaching the surface and forcing the third water body to decrease sharply in volume. During this period the third and fourth water bodies form the entire column in the outer part of the Gulf.

The $5.85*10^9$ m^3 reduction in volume of the fourth water body from February to March can be explained either as a consequence of mixing with the upper layer or of its movement out of the Gulf; during this month in fact, the fourth water body is detected only in the outer part of the Gulf. With the start of thermal stratification in March, the subsurface layer decreases in density, probably allowing the ascendent eastern current to come into the Gulf along the Istro-Dalmatian coast, involving in this case, the deep layer throughout the studied area. The flow of saline water from the south and located near the bottom is hindered by the bottom morphology which rises sharply near Rt Savudrija and allows exchange between the deep water of the Gulf and this water body to take place only by turbulent diffusion (Mosetti, 1966, 1967). This diffused water probably constitutes the fourth water body located close to the bottom and identified in April.

From May to August the third and fourth water bodies maintain their horizontal structure with a well-defined stratification throughout the water column. Due to the maximum enlargement of the second water body, and deepening of the third in September, the fourth water body sink closer and closer to the seabed and decreases in volume. From October, a new frontal system develops, while in November, the fourth water body disappears as a consequence of the mixing process and the regression of the ascendent eastern current.

5. Conclusions

An analysis of the results obtained by the statistical procedures made it possible to define the thermohaline features of the waters in the Gulf of Trieste. These features vary seasonally, showing high density homogeneous waters in winter, and low density waters in summer; the latter is characterized by a strong thermal stratification of the water column. Furthermore it is possible to define formation, distribution, volume and evolution of the water bodies present in the Gulf throughout the year. In general four main water bodies are identified.

The first water body is formed mainly by the input from the Isonzo river, but also by water coming from the lagoons and Tagliamento river. These inputs spread into the superficial layers of the area along the western coast, varying the dimension and distribution of this zone of influence in relation with the volume of these freshwater inputs.

The second water body appears to be extremely dynamic, both in position and volume, throughout the year. In autumn and winter, it mainly forms a thermohaline gradient zone with vertical structure, located parallel to the western coast and with a relatively small volume. In general this water body tends to exit the Gulf along the coast. In summer it forms the low density surface layer, increasing in volume, and its movement in the Gulf is governed mainly by the wind.

The third water body occupies, in autumn and winter, almost the whole water column, and is affected in the outer part of the Gulf by the waters of the Northem Adriatic. During this period its oscillation in volume depends on its interaction with the other water bodies. In summertime it forms the thermal stratification in the intermediate layer, and shows little oscillation in volume.

The fourth water body is the densest, and has two different temporal evolutions. During the winter months it develops near the seabed, forming in February a dense core in the Gulf, while during the thermal stratification period, it tends to be replaced by water with similar thermohaline features, the latter being related to the ascendent Istro-Dalmatian stream and being spread in the Gulf through turbulent diffusion.

The statistical analyses used proved suitable for identification of the water bodies present in the Gulf of Trieste. Moreover, it was possible to study the evolution, both in space and time, of each water body, using the groups obtained from cluster analysis.

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