Seasonal thermohaline fluctuations in the middle Adriatic Sea (*)

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Summary. — Salinity and temperature time series were analysed for the open sea stations at the transect Split-Gargano, in the middle Adriatic, for the period 1961-1980. Thermohaline fluctuations were described in terms of the principal component scores and, in addition, were compared to heat and water flux at the atmosphere-sea interface. Temperature and salinity vertical gradients in the surface layer are well related to surface fluxes during the whole year. In deeper layers this influence is visible only under the vertically homogenous conditions. Vertical fluxes of heat and salt, compared to the rate of change of the heat and salt content, point to the season with important advection effects. Vertical exchange prevails in the cold season, while horizontal exchange is considerable in the warm period.

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1. – Introduction

The Adriatic Sea is a small, semi-enclosed sea of the Mediterranean connected to the Eastern Mediterranean via the Otranto Strait. According to its topography, it is divided into the northern, middle and southern Adriatic. The northernmost part is very shallow overlaying the continental shelf. This area is under the strong influence of the north Italian rivers, especially the Po River. The middle Adriatic is deeper, reaching 280 m in the Jabuka Pit. It is separated from the southern Adriatic by the Palagruža Sill (180 m depth). The southern Adriatic is much deeper, with the deepest part in the south Adriatic Pit, reaching 1233 m.

The earliest oceanographic research of the Adriatic Sea started already in the past century. However, systematic oceanographic measurements began in the 1950's (Zore-Armanda, 1991).

The transect Split-Gargano in the middle Adriatic is a region with a strong temporal variability of thermohaline structure caused by seasonally dependent circulation in the surface and intermediary layer. This area is exposed to the influences both from the northern and southern Adriatic. The dynamics on the investigated transect is controlled also by the topographic effect on the Palagruža Sill. A

(*) The authors of this paper have agreed to not receive the proofs for correction.

comprehensive review paper on the dynamics of the Adriatic Sea is given in the work by Orlić *et al.* (1992).

Generally, the current flows from the Adriatic into the Mediterranean in the surface and bottom layer, while the Mediterranean water enters the Adriatic in the intermediate layer. Surface circulation in the Adriatic is cyclonic and mainly follows the isobaths. The topographic barrier of the Palagruža Sill causes disturbances in the flow pattern and is also reflected in the thermohaline structure (Zore-Armanda and Bone, 1987). In winter, in the northern Adriatic, very cold dense water is formed, which sinks to the deep layers of the Jabuka Pit, and from time to time is advected across the Palagruža Sill. The transect area is also under the influence of advection of saltier water from the southern Adriatic which reflects the Mediterranean influence.

Advection of the Mediterranean waters, called "ingression" (Buljan, 1957), carries Mediterranean saltier water into the Adriatic (Buljan, 1953; 1965). Buljan and Zore-Armanda (1976) have observed temperature and salinity increase in "ingressional" years. In these works, although from sparse data, almost periodical salinity fluctuations have been observed.

The region of the Split-Gargano transect in the middle Adriatic, which is under a number of different influences, is suitable for the analysis of thermohaline fluctuations. Due to its intensive seasonal and long-term dynamics, and large spatial and temporal differences in a variety of different parameters, the Adriatic has become a test basin for modelling different phenomena like circulation, deep water formation, remote sensing, etc.

The main scope of this work was to describe heat and salt exchange processes at the seasonal scale in some characteristic layers at the Palagruža Sill and to calculate vertical coefficients of heat and salt exchange.

Conditions of heat and salt changes are described in detail in the section concerning methods, as well as essentials of the principal component and harmonic analysis. The results brought up the vertical coefficient of heat and salt exchange for the surface layer of the middle Adriatic.

2. – Materials and methods

2˙1. *Data.* – Data used in this work span the time interval from January 1961 to December 1980 and were collected on the regular monthly or seasonal cruises at oceanographic stations of the transect Split-Gargano (fig. 1). Measurements were done mostly once a month (only exceptionally few times) but on different dates. Data were analysed on an annual time scale, so that the data set extended from $t = 1$ to $t = 365$ days. Decadal frequency of data for every station is presented in fig. 2. Only the data with the same number of measurements for standard oceanographic depths (0, 10, 20, 30, 50, 75 and 100 m) at stations 8, 9, 10, 11, 12 and 13 (fig. 1) were used, while the data from the depths below 100 m were rare, and were not considered.

Taking into account that measurements were done only once per month at the Stončica station (station 9), it is obvious that there is an error due to undersampling. In order to determine the error, monthly mean data from the permanent coastal station Split, Marjan cape were compared to the daily values. The seasonal course for the station Marjan Cape was calculated from daily measurements as well as from monthly samplings for the same dates as the sea-truth measurements at the station Stončica. The difference between the two is the error due to undersampling. The error ranges between $\pm$ (0.1-0.3) °C which has small effect on further results.

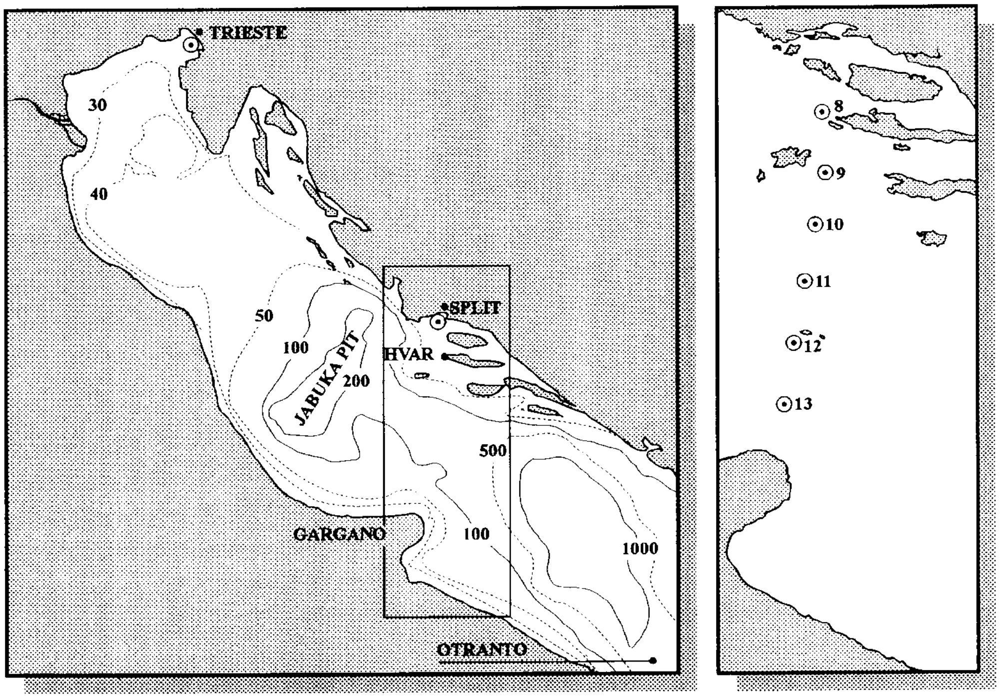

Fig. 1. – The transect Split-Gargano in the middle Adriatic Sea.

Heat and water flux were calculated for Hvar station (close to the investigated transect), for the same period 1961-1980, on the basis of the monthly mean meteorological data.

2·2. *Principal component analysis.* – Temperature and salinity time series were subject to the principal component analysis (PCA) (Preisendorfer, 1982). The PCA was performed on the correlation matrix of standardised variables. Eigenvalues (PC_r) and eigenvectors were determined, applying the Varimax rotation. The significance of PC components was tested with rule N (Preisendorfer, 1982), using a Monte Carlo simulation of the random matrix of the same size as the original data matrix. Standardised salinity and temperature values are represented with a set of data $Y_i(z)$, where i denotes the individual day and z the depth. From the correlation matrix R_Y with Y_{ij} elements, ϕ and λ were determined as a solution of the matrix equation

(1) $$\Phi^{-1} R_Y \Phi = \lambda \,,$$

(2) $$R_Y \Phi - \lambda \Phi = 0 \,.$$

The columns of Φ are eigenvector and λ is a diagonal matrix of eigenvalues. The solution of the matrix equation is obtained as an infinite product of "rotations" of

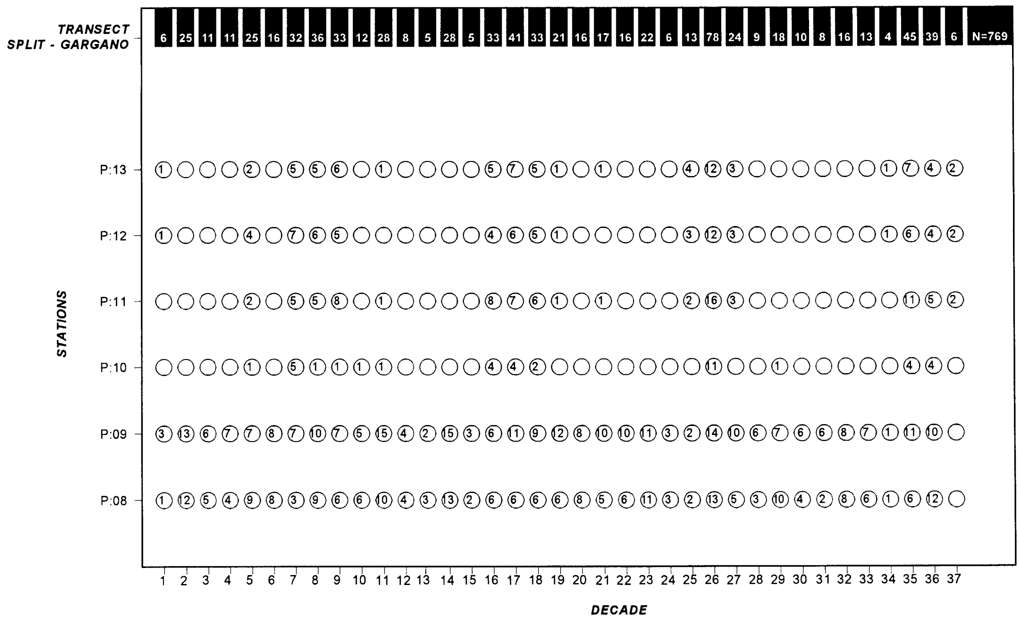

Fig. 2. – Number of measurements per decade at the Split-Gargano transect for the period 1961-1980.

matrices of the form (Jacobi's method)

$$\Phi_k = \begin{bmatrix} \cos \alpha_k & -\sin \alpha_k \\ \sin \alpha_k & \cos \alpha_k \end{bmatrix} . \tag{3}$$

After n such "rotations" R_{ij} will be transformed into

$$\Phi_n^{-1} \dots \Phi_1^{-1} R_Y \Phi_1 \dots \Phi_n . \tag{4}$$

With the proper selection of α_k this approaches a diagonal matrix form (eigenvalues on the diagonal). After the determination of Φ, the initial data set can be expressed with PC scores

$$Y_i(z) = a_{1i} \Phi_1(z) + \dots + a_n \Phi_n(z) . \tag{5}$$

For the symmetric matrix R_Y the accounted variance of the individual eigenvector is determined by the eigenvalue.

2·3. *Harmonic analysis.* – In order to smooth seasonal variability, introduced using data from different years and different stations, the function of the form

$$Y(t) = A_0 + A_1 \sin\left(\frac{2\Pi}{T} t + \varphi_1\right) + A_2 \sin\left(\frac{4\Pi}{T} t + \varphi_2\right) \tag{6}$$

was least-square fitted to temperature data. The same function was fitted to PC scores which resulted in the loss of orthogonality. It was not possible to approximate salinity data by a harmonic function, so that salinity means were determined by averaging inside months. Results are presented using the cubic spline function. Fluctuations in the field of temperature and salinity were compared to the fluctuations of the processes at the air-sea interface. The harmonic analysis was applied to most of the data in order to compare temperature fluctuations to the processes at the air-sea interface. When comparing atmospheric and salinity data, monthly mean values were taken.

2·4. *Equations of the heat and salt changes.* – Temperature and salinity variations are governed by the heat and salt balance equation

$$\begin{cases} \varrho c_p \dfrac{\partial T}{\partial t} = \dfrac{\partial H_{\text{ver}}}{\partial z} + \dfrac{\partial H_{\text{hor}}}{\partial y}\,, \\[2ex] \varrho\beta \dfrac{\partial S}{\partial t} = \dfrac{\partial S_{\text{ver}}}{\partial z} + \dfrac{\partial S_{\text{hor}}}{\partial y}\,. \end{cases} \tag{7}$$

The horizontal parts (H_{hor}, S_{hor}) include both advective and diffusive effects and cannot be calculated with data from the Split-Gargano transect alone. Neglecting convection, the vertical part between surface ($z = 0$) and a bottom reference level ($z = -h$) is

$$\begin{cases} \displaystyle\int_{-h}^{0} \frac{\partial T}{\partial t}\,\mathrm{d}z = \int_{-h}^{0} \frac{\partial}{\partial z}\left(K_T \frac{\partial T}{\partial z}\right)\mathrm{d}z\,, \\[2ex] \displaystyle\int_{-h}^{0} \frac{\partial S}{\partial t}\,\mathrm{d}z = \int_{-h}^{0} \frac{\partial}{\partial z}\left(K_S \frac{\partial S}{\partial z}\right)\mathrm{d}z\,. \end{cases} \tag{8}$$

Using the parametrisation

$$\begin{cases} H_{\text{ver}} = \begin{cases} Q\,, & z = 0\,, \\ K_T \varrho c_p \dfrac{\partial T}{\partial z}\,, & z < 0\,, \end{cases} \\[3ex] S_{\text{ver}} = \begin{cases} \varrho\beta\langle S\rangle(E - P)\,, & z = 0\,, \\ K_S \varrho\beta \dfrac{\partial S}{\partial z}\,, & z < 0\,, \end{cases} \end{cases} \tag{9}$$

it was possible to determine the vertical heat and salt fluxes and their seasonal rate of change caused by vertical processes. From the heat and salt balance equations the difference between rate of change of heat and salt content and that caused by vertical processes is attributed to horizontal processes.

The terms in the previous equations have the following meaning, dimensions and/or values:

- Q: heat flux at the sea-atmosphere interface ($\mathrm{W\,m^{-2}}$),
- K_T: vertical coefficient of heat exchange ($\mathrm{m^2\,s^{-1}}$),
- ϱ: water density: 1024 ($\mathrm{kg\,m^{-3}}$),
- c_p: specific heat of the sea water: 3990 ($\mathrm{J\,kg^{-1}\,{}^\circ C^{-1}}$),

E-P: water flux at the air-sea interface (m s^{-1}),
K_S vertical coefficient of salt exchange (m^2 s^{-1}),
β: compressibility coefficient: $7.4 \cdot 10^{-4}$ (psu^{-1}),
h: depth (m).

In order to calculate the vertical change of heat and salt, it was necessary to determine K_T and K_S. The boundary conditions for the surface were applied, where Q and E-P were determined on the basis of climatological data.

3. – Results and discussion

3·1. *Principal component analysis of temperature and salinity field.* – The first three eigenvectors together describe 96.3% of the temperature variance and 94.8% of the salinity variance (table I). Using the three main components, the component loadings for temperature and salinity are determined and presented in fig. 3. The vertical distribution related to the temperature shows an expected thermocline structure at the depth of 30–40 m (fig. 3a)), while the one related to salinity shows halocline at almost the same depth (fig. 3b)). Standardised values of the PC scores are, because of the time scale, related to particular days. In order to present PC scores for each day of the year, the harmonic function (6) was fitted to the data, taking into account the fact that $A_0 = 0$. It is necessary to note that orthogonality of the main components is lost through this process. This analysis was possible only for the temperature. The harmonic functions, which were fitted to the component scores, explain 93% of the variance of PC_2 (significant at the 99% level), 38% of the PC_1 and 30% of PC_3, both significant at the 95% level.

In the surface layer, discrepancies of the component scores and the interpolated seasonal values, except for few values only, were not considerable. The largest discrepancies in the surface layer were in July and August. The largest positive discrepancies were found in the summer time and at the beginning of the cold season (fig. 4). In deeper layers considerable discrepancies were found in the autumn, in November (PC_1) and in October (PC_3) (not shown). The maximum discrepancies were delayed at deeper layers, relative to the surface.

It was not possible to obtain the statistically significant fit for the PCs in the salinity field. Interpolated seasonal course (6) describes less then 25% of the variance pointing to the large inter-annual salinity fluctuations (Zore-Armanda *et al.*, 1991). Large

TABLE I. – *Eigenvalues* (λ) *of the first three components, their contribution* (%) *and cumulative contribution* (cum) *in the salinity* (S) *and temperature field* (T) *and eigenvalue of the random process* (RP) *for the matrix of the same size.*

PC_r	S			T			RP	
	λ_r	%	cum	λ_r	%	cum	λ_r	%
1	5.25	75.1	75.1	4.96	70.8	70.8		
2	1.09	15.6	90.7	1.36	19.5	90.3		
3	0.29	4.1	94.8	0.40	6.0	96.3	0.85	12.2

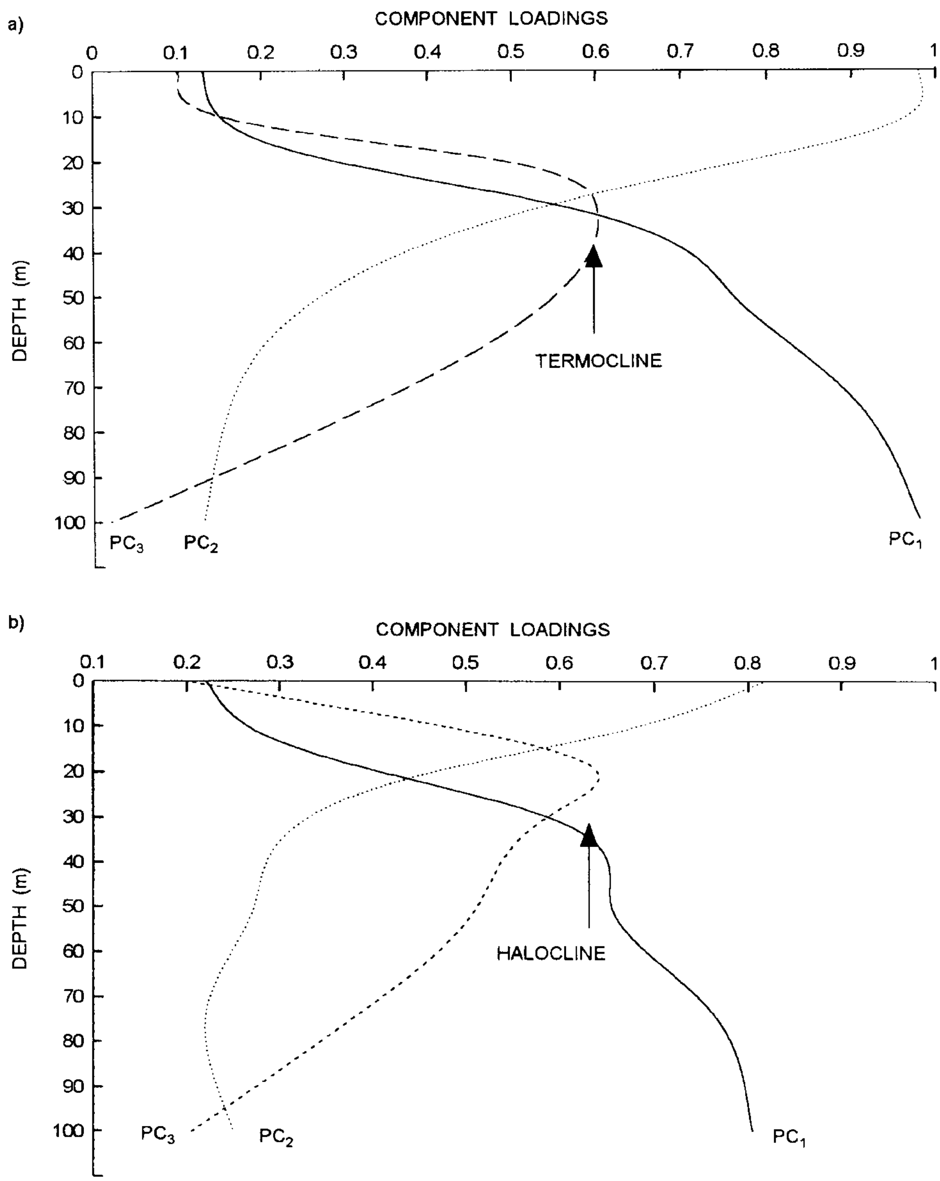

Fig. 3. – Vertical distribution of the first three principal components loadings in a) temperature and b) salinity field.

monthly salinity fluctuations are often reported in the literature, but still salinity is a conservative parameter at the monthly scale. Its large "monthly" fluctuations are due to large inter-annual fluctuations, in the Adriatic related to advection from the Mediterranean, while, for example, in the Gulf of California such fluctuations are caused by different long-term phenomena. The thermohaline fluctuations in the Gulf of California studied in a series of works (Bray, 1988; Ripa and Marinone, 1989; Castro

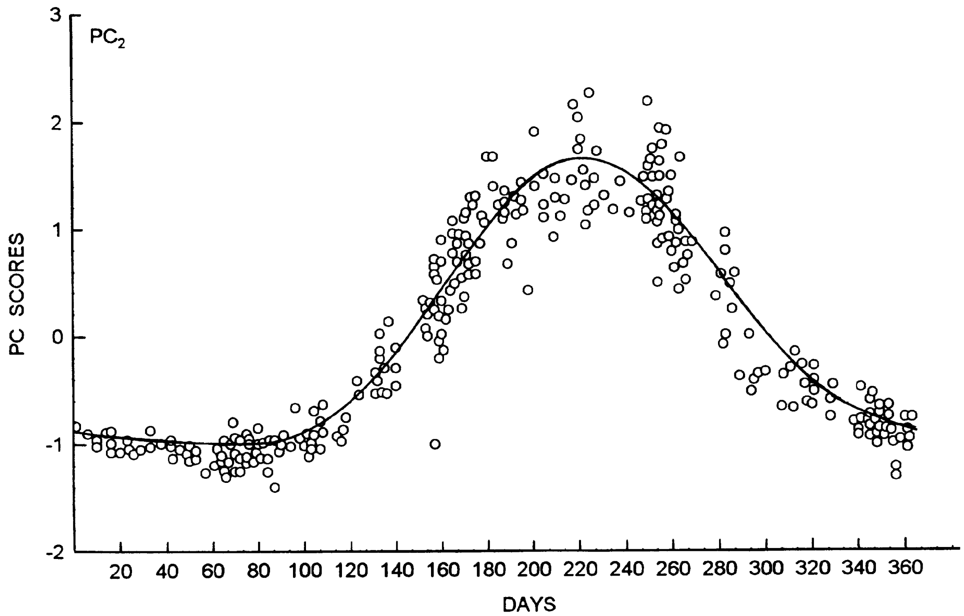

Fig. 4. – Individual PC_2 scores for temperature (circles) and interpolated seasonal curve (solid line) for the surface layer.

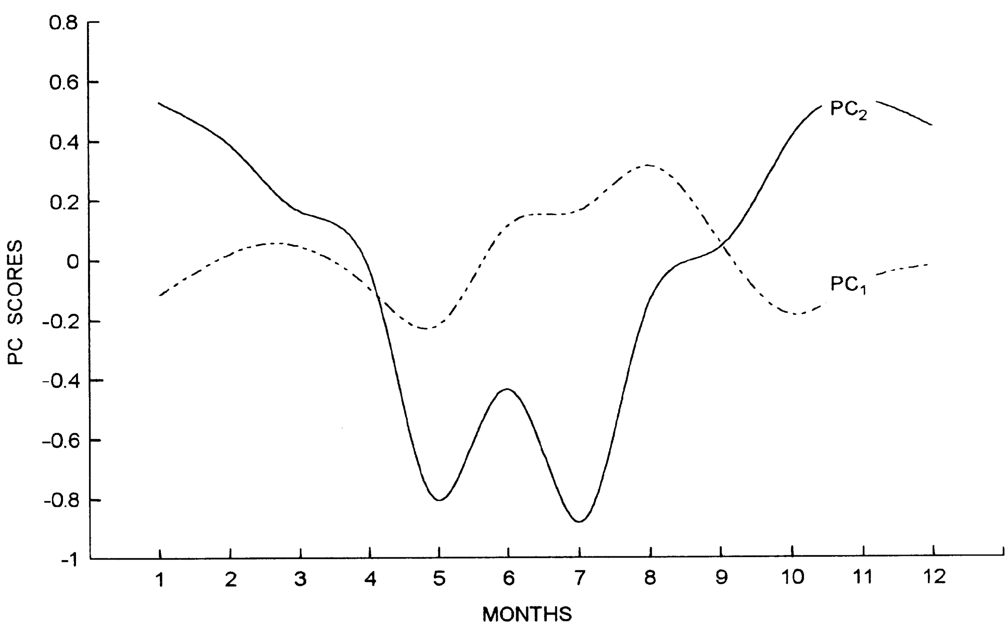

Fig. 5. – Seasonal course of the PC scores for the surface (PC_2) and intermediate (PC_1) layers in the salinity field obtained by cubic spline interpolation of monthly mean values.

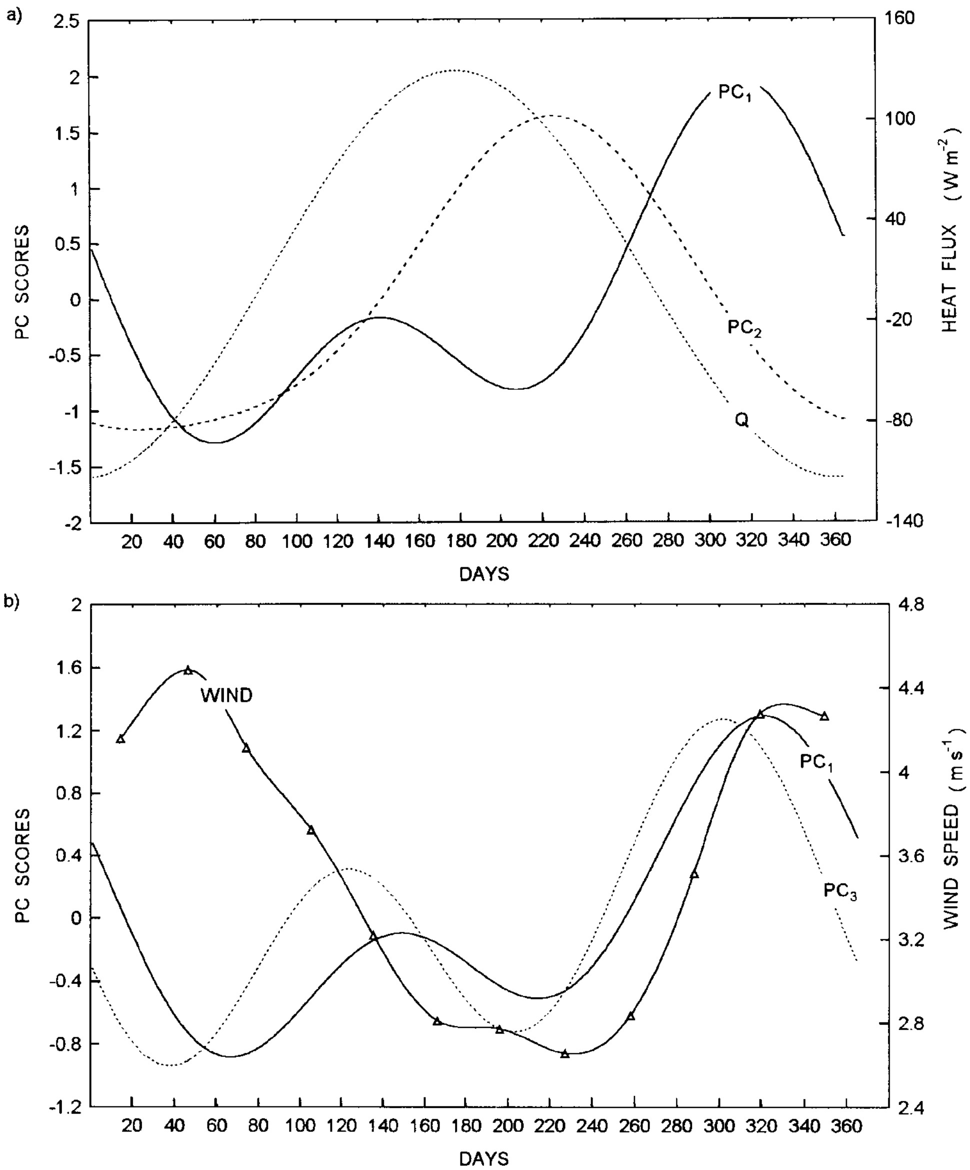

Fig. 6. – Seasonal course of the PC_1 and PC_2 scores in the temperature field compared to the heat flux at the air-sea interface (a)) and the seasonal course of the PC_1 and PC_3 scores in the temperature field compared to the wind speed at Hvar station (b)).

et al., 1994) depend on phenomena like El-Niño, while the Adriatic is influenced by "ingressions", which is a phenomenon of fluctuating intensity but of longer duration than El-Niño. So, monthly mean values obtained from data from the same month from all years had very large standard deviations. Corresponding PC scores, determined by averaging over the months, were presented using the cubic spline function (Fritsch, 1971) and are shown in fig. 5.

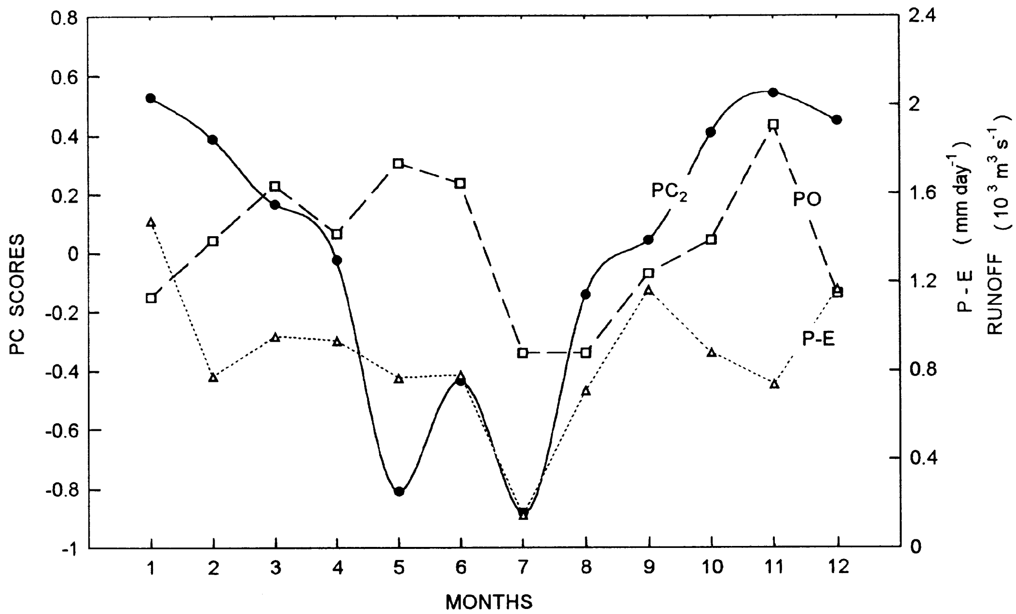

Fig. 7. – Seasonal course of the PC_2 scores for salinity (surface layer) compared to $P - E$ and Po River runoff (in 10^{-3} m^3 s^{-1}; mean values for the 1961-1970; Annali Idrologici).

In the temperature field, component scores which correspond to the surface layer (PC_2) were correlated with the heat flux (the correlation coefficient was $r = 0.82$ for the time lag of 31 days). The heat flux was determined applying the Gill (1982) equation set to the Hvar station. The monthly mean data were used for calculations. Function (6) was fitted to the data. The obtained value of the heat flux was compared to the component scores of the PCA.

The component scores of the PC_1, which correspond to the deeper layers lag four months behind heat flux. Component scores had two maxima: in May and in November (fig. 6a)). Maximal values in May are the consequence of the fast transport of heat in deep layers as the thermocline layer is not yet formed to prevent the vertical mixing process. In the summer, when the thermocline is formed, deeper layers do not receive heat, and lower temperatures were present. The temperature drop, below the thermocline, when the thermocline is fully developed, is attributed to upwelling. Lower temperatures are observed below the thermocline layer throughout the summer (Zore-Armanda, 1969a). Besides the heat flux, the influence of wind on the temperature of the water column is also considerable (fig. 6b)). The increase of the wind speed in autumn corresponds to an increase in the temperature of deeper layers. The heat from the warm surface layers is transported to deeper layers by wind-induced mixing.

In the salinity field, component scores corresponding to the surface layer (PC_2) during the heating season are proportional to the differences $P - E$, while in autumn and winter PC_2 scores and $P - E$ differences are opposed in phase (fig. 7). Earlier investigations (Pucher-Petković and Zore-Armanda, 1973) proved that the north Italian rivers, especially the Po River, influenced the waters of the Jabuka Pit. When the thermocline is well developed, lighter north Italian waters reside in the surface

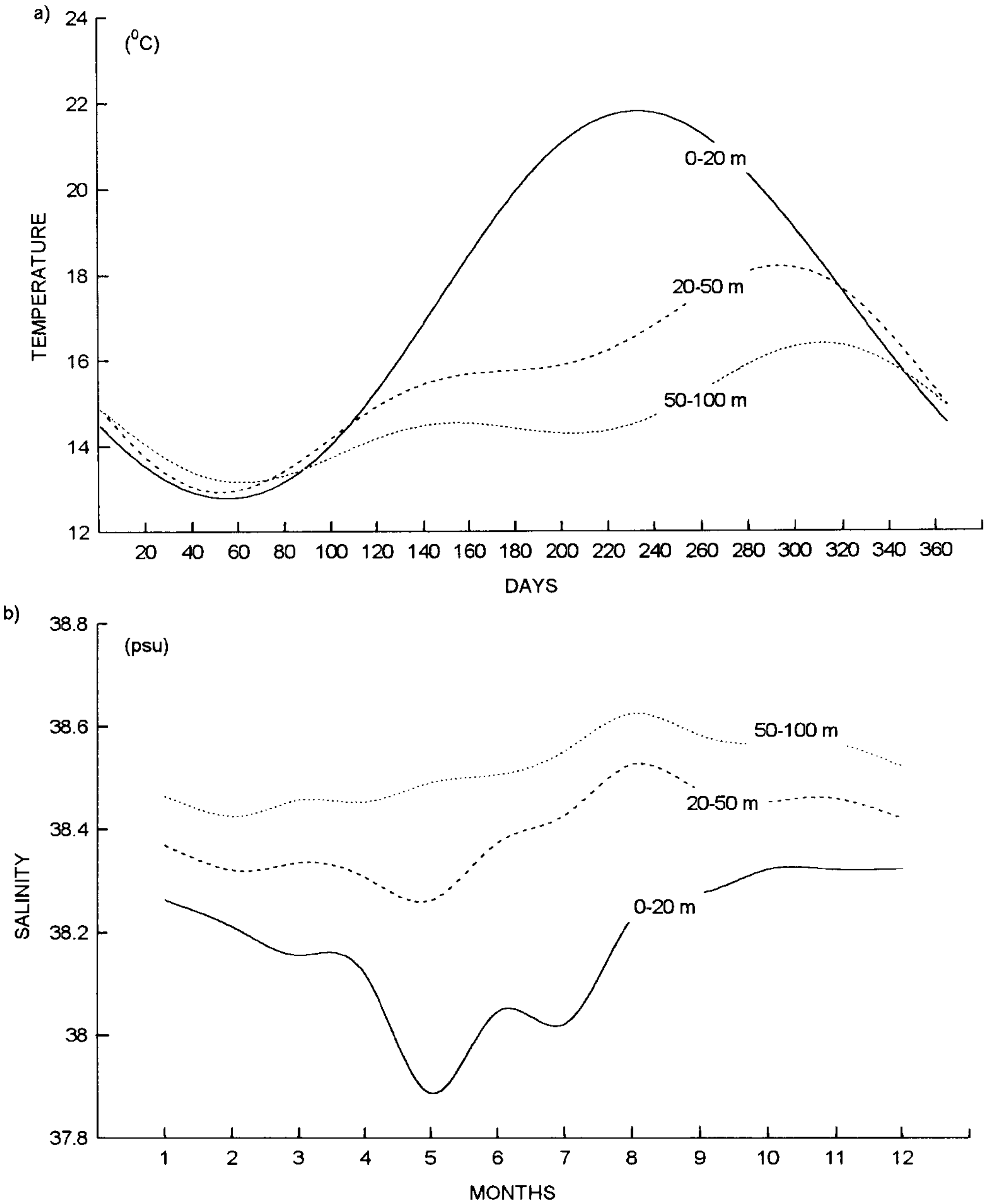

Fig. 8. – Seasonal course of a) the mean sea temperature and b) salinity at the Split-Gargano transect for selected layers.

layer and are transported by the SE current to the Split-Gargano transect (Zore-Armanda, 1956). They bring about decrease of salinity in the surface layer. As a consequence of ice melting, the largest Po runoff is observed in May which coincides with salinity spring minimum at the transect (fig. 7). In summer, due to the current system in the intermediate layer (Zore-Armanda, 1969b), advection of saltier water

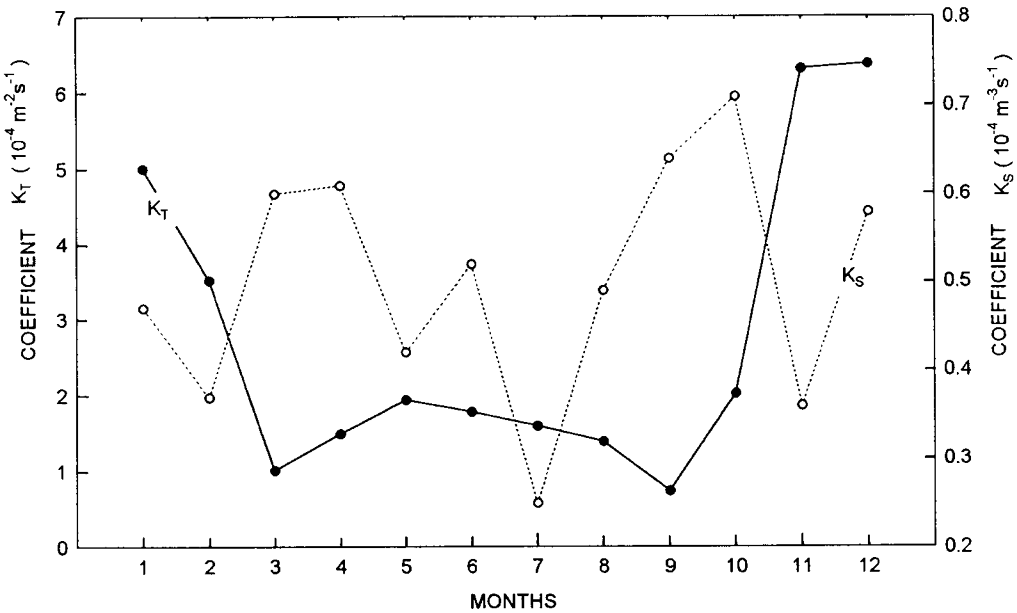

Fig. 9. – Seasonal course of the mean heat and salt exchange coefficient for the surface layer.

from the southern Adriatic (Mediterranean) is observed. Less saline water resides at the surface, since the mixing is prevented by the fully developed thermocline, and in the summer period in the middle Adriatic the influence of the Po River inflow could have been observed. Component scores, which correspond to salinity, are besides the seasonal forcing, controlled by specific dynamic conditions at the Palagruža Sill.

It is evident that vertical mixing processes have an essential role on thermohaline properties of the whole water column. These vertical processes are under direct atmospheric influence. In addition, thermohaline properties are also under the considerable influence of the horizontal advection process, which depends both on oceanographic and meteorological conditions.

3˙2. *Heat and salt exchange.* – The results of the PCA helped resolve three characteristic layers: 0–20, 20–50 and 50–100 m. For these layers, temperature and salinity mean values were determined (fig. 8) by a vertical integration between the top and the bottom of each layer. The integral was approximated by using the trapezoidal rule. Coefficients of vertical turbulent exchange in the surface layer were first determined for both heat and salt. Surface boundary conditions were applied and climatological means were taken for heat and water flux (Hvar station).

Vertical heat and salt gradients were determined from the difference between the surface and 10 m depth. The correlation coefficient between the vertical heat gradient and the heat flux is 0.91 (significant at the 99% level). It allowed us to determine the vertical exchange coefficient for heat using the least-square method. The seasonal course of the vertical heat exchange coefficient is shown in fig. 9. The value obtained by

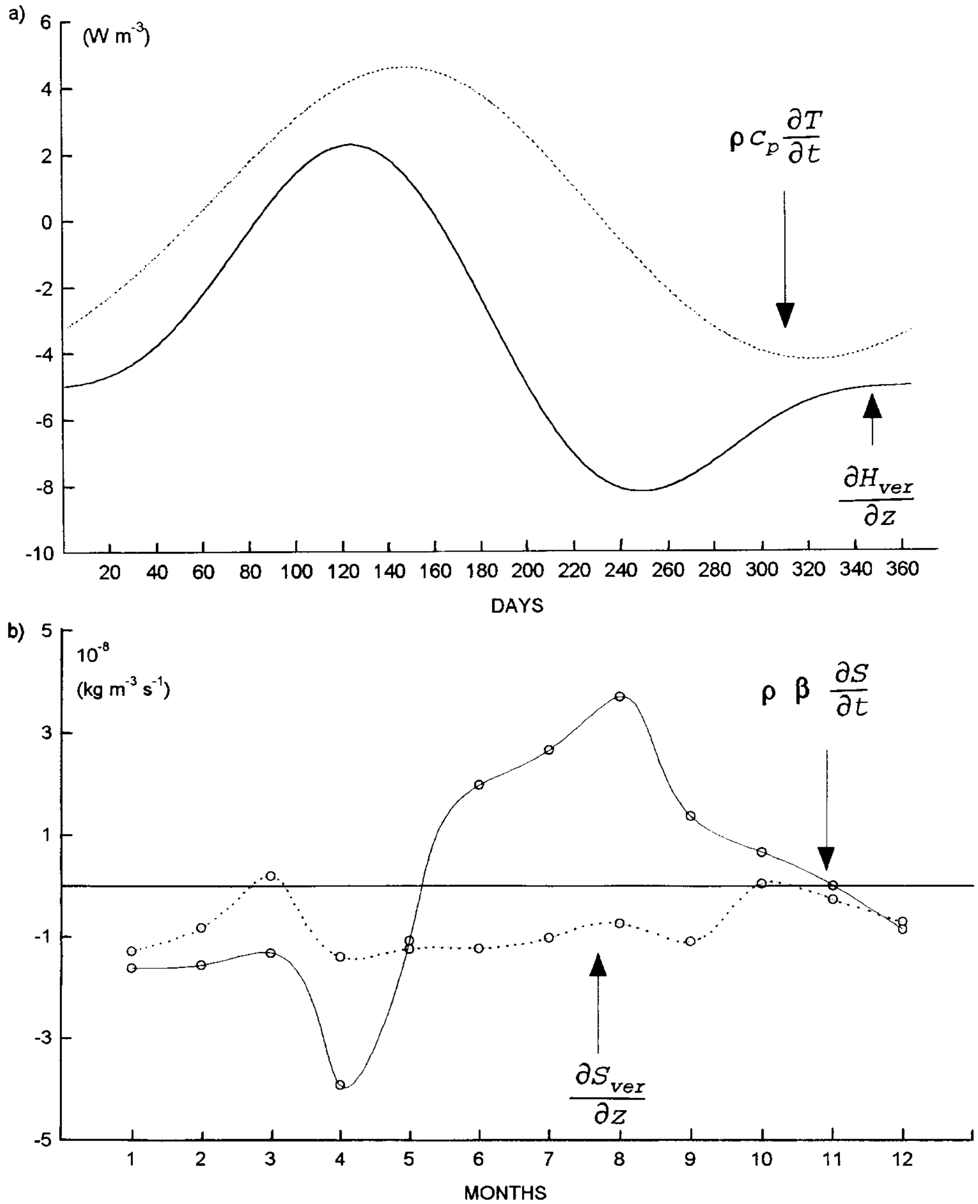

Fig. 10. – Rate of change of a) heat and b) salt content in the upper 20 m (dotted line) and difference in the vertical fluxes at the top and bottom of the layer (solid line).

the least squares method is

$$K_T = (3.05 \pm 0.09) \cdot 10^{-4}\,\mathrm{m^2\,s^{-1}}.$$

The relationship between the water flux and the surface salinity was already discussed, and the vertical coefficient of the salt exchange for the surface layer is determined using different relations through the year for the water flux, as indicated in the schema:

$$E - P = \begin{cases} (E - P) & \text{September-April} \\ E - (P + R) & \text{May-August} \end{cases}$$

were R denotes the quotient between the Po River inflow and the area of the Adriatic shelf. Taking the Po runoff into account, the correlation coefficient between the water flux and the vertical coefficient of salt exchange in the surface layer was 0.83, (significant at the 99% level), enabling determination of the salt exchange coefficient. The seasonal course of the vertical salt exchange coefficient is shown in fig. 9. The value obtained by the least-squares method is

$$K_S = (0.406 \pm 0.09) \cdot 10^{-4}\, \mathrm{m}^2\, \mathrm{s}^{-1}.$$

This value is an order of magnitude lower than the vertical heat exchange coefficient.

Finally, it was possible to determine the vertical contribution to the heat and salt in particular layers of the water column and to compare it with the rate of change of the heat and salt content which was determined using Stirling's formula of the centred finite differences (Scheid, 1968).

Results for the upper layer are presented in fig. 10. Thermohaline changes in that layer are the consequence of the vertical processes, being under the atmospheric influence throughout the whole year. However, in the summer season thermohaline changes are also under the horizontal advective control. From March to May heat content changes follow changes that originate from vertical processes. In this period there is no heat transport from the southern or northern Adriatic, according to well-known circulation patterns (Zore-Armanda, 1956). After the development of the thermocline the two curves separate. The cooling of the surface layer is weaker than that due to vertical heat content change. The difference is attributed to the horizontal advection of water from the northern Adriatic. This water is warmer in the summer season than the water of the middle Adriatic. This horizontal contribution to the heat content change in the upper 20 m in the summer is observed in salt content change as well, since the water from the northern Adriatic is less saline. It causes large salinity changes and minimal salinity values in the surface layer in the summer time.

In the middle layer, between 20 and 50 m, it is more difficult to explain the relationship between vertical and horizontal contribution to the heat and salt rate change, especially in the season of the fully developed thermocline. The differences are partly due to the value of the coefficient of the vertical heat exchange. In this layer, a significant difference is observed between salt content change due to vertical processes and the total salt content change. This difference accounts for the salinity increase due to advection of saltier southern Adriatic or Mediterranean waters.

The coefficient of the vertical heat exchange calculated in this paper is comparable to the one calculated for the northern Adriatic by Malačić (1991) and Supić (1993) and for the Gulf of California (Ripa and Marinone, 1989). In earlier investigations in the middle Adriatic, the coefficient of the vertical heat exchange was not calculated for the whole year on the basis of the long-term data set. For the summer season Zore-Armanda (1964) has obtained a somewhat larger value while Gačić (1971) has obtained a considerably larger value.

Until now the coefficient of the vertical salt exchange was not calculated for the middle Adriatic. Values from Apel (1987) are in concordance with those from this paper. For the Gulf of California, Ripa and Marinone (1989) have found an order of magnitude larger value.

4. – Conclusions

The PCA was proved useful in distinguishing different layers in the middle Adriatic at the seasonal scale. Thermocline and halocline, which develop between 30 and 40 m, determine the conditions of vertical heat and salt exchange. Surface conditions in the winter season influence the deeper layer, especially in the presence of wind.

The influence of the Po River runoff can be observed in the middle Adriatic only because the periods of developed thermocline and secondary maximum Po runoff coincide. A similar annual salinity course is observed in the northern Adriatic close to the sea surface (Orlić, 1989).

Fluctuations of thermohaline properties of the surface layer in the middle Adriatic are under the considerable influence of the vertical mixing processes, as a consequence of the direct atmospheric influence. Fluctuations in deeper layers are influenced more by horizontal advection and diffusion.

The intensity of the heating process is different in different years. In the years of stronger heating, heat from the surface influences the temperature of the deeper layers few months later, which is reflected in highest positive discrepancies of PCs.

Negative discrepancies, seen from individual PC scores found at the stations of the transect close to the Italian coast, are larger than at station 9 in the vicinity of the Croatian coast. The difference is attributed to the advection of deeper northern Adriatic water.

The unusual increase in PC_2 for the surface layer for salinity may be attributed to the advection from the southern Adriatic which follows the sill topography and carries saltier water towards the Italian coast.

The coefficient of heat exchange is an order of magnitude larger than the coefficient of salt exchange in the Adriatic Sea. This is probably due to the very large seasonal temperature variations of the Adriatic waters, in addition to the different processes that are responsible for the exchange of heat and salt.

In this work heat and salt exchange processes are described in details for the two characteristic layers at the Palagruža Sill. Vertical exchange coefficients for heat and salt are calculated at the seasonal scale. These coefficients, together with surface heat and water fluxes at the air-sea interface, will enable our future work on quantification of each contribution to the annual cycle in the rate of change of the heat and salt content.

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