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SOME CHARACTERISTICS OF THE RESPONSE OF THE ADRIATIC SEA COASTAL REGION TO THE ATMOSPHERIC FORCING

NEKE KARAKTERISTIKE ODGOVORA OBALNOG PODRUČJA JADRANSKOG MORA NA UTJECAJ ATMOSFERSKIH POREMEĆAJA

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In this paper the results of analysis of current data and sea-level data from the region of Virsko more are presented. The special attention was paid to the frequency domain below tidal and it was shown that the response to local wind prevails.

1. INTRODUCTION

Early field current measurements in the Adriatic sea were done by direct reading current meters usually during periods of relatively calm weather therefore the response to strong atmospheric forcing could not be obtained. Results of current measurements obtained by moored current meters in last couple of years showed however that the Adriatic sea and, specially, its coastal regions are characterized by a strong response to the atmospheric forcing on the time scale of several days. The character of the response should be mostly dictated by the density stratification. During a summer when there is a seasonal thermocline at about 20 m, the response has to be mostly baroclinic and probably concentrated in a very narow region near the coast (internal radius of deformation is about 4 km). On the other hand during a winter time the Adriatic sea is practically homogeneous vertically and response is expected to be barotropic.

In order to get some characteristics of the coastal region response to the atmospheric forcing in frequency range below. 25 cpd. we have analysed several current data time series together with simultaneous temperature, sea level, atmospheric pressure and wind records. All of the current data, sea surface temperature (SST) and wind data are collected during summer 1975 and 1976 in the region of Virsko more. Current data are obtained with Alexeev current meters at three levels (3,20 and 45 m) on the mooring at about 1,5 nM from the coast (Vir). In the analysis are included also current data from four moorings in the same region for March 1979. These data are obtained by Aanderaa RCM4 current meters. Spectral analysis of both cross shelf and alongshore velocity component was done as well as rotary spectral analysis (G o n e l l a, 1972). As most of the spectra are already presented in the previous article (Z o r e - A r m a n d a et al., 1977), only some of them will be shown here.

For the one-year long interval, from May 1 1975 through April, 31 1976 spectral analysis of sea level data for four locations along the Eastern Adriatic coast was also done. Using atmospheric pressure data of adjacent meteorological stations it was possible to obtain the adjusted sea level spectra. Winter and summer were separately analysed so that winter was defined as an interval from November 1 through March 31 and summer was taken from May 1 through September 30. Sea level data and atmospheric pressure data were filtered by a Doodson filter in order to remove tidal constituents. Doodson filters was centered at 0100 and 1300 hours to yield semidaily mean values. Locations of moorings, tidal stations and meteorological stations are shown on Fig. 1.

2. CHARACTERISTICS OF CURRENT FIELD

By inspection of all the available current spectra couple of interesting features could be seen (Figs. 2a, b, c, d). First is that most of the energy is contained in low frequency part of the spectrum and that tidal oscillations are less important in this coastal region. The other interesting feature is the increase of energy in low frequency part of the spectrum with depth. This characteristic could be seen mostly during a summer. It could be also noticed that the inertial oscillations are in average less important than tidal ones.

If, during a summer time, low frequency oscillations are mostly of a baroclinic character, good correlation between current and temperature changes should exist. At Fig 3 the time series of current velocity (daily means) for summer 1975 are presented, as data for summer 1976 show the same characteristics. At the same figures wind data and SST data are also plotted. We could see that there is a strong correlation between the velocity at 45 m and temperature changes. Strong current in negative y-direction (right handed coordinate system; x-axis parallel to the coast and y-axis normal to it) at the depth of 45 m appeared simultaneously with an SST minimum. Also it could be seen that the velocity component normal to the coast is very small on these time scales. This is also evident from the results of rotary spectral analysis, ellipses of rotation being strongly polarized to the general orientation of the coast (about 35° counter-clockwise from true north). This characteristic of coastal flow was found elsewhere (e. g. K u n d u & A l l e n, 1976). Sudden temperature decrease is obviously the upwelling connected with a wind action in the coastal region on the time scale of several days. It could be seen that in almost all the situations the upwelling is connected with a NE wind action drifting the surface water offshore, which is then replaced by a colder and denser deep water. There were, however, situations when the NE wind action is not followed by only one SST drop but by an temperature oscillation with a period of several days like in the interval from 18 to 30 of August 1975. These oscilations could be explained in terms of internal Kelvin waves.

Simultaneous appearance of the strong NW current and SST minimum could suggest the geostrophic balance of the alongshore velocity component.

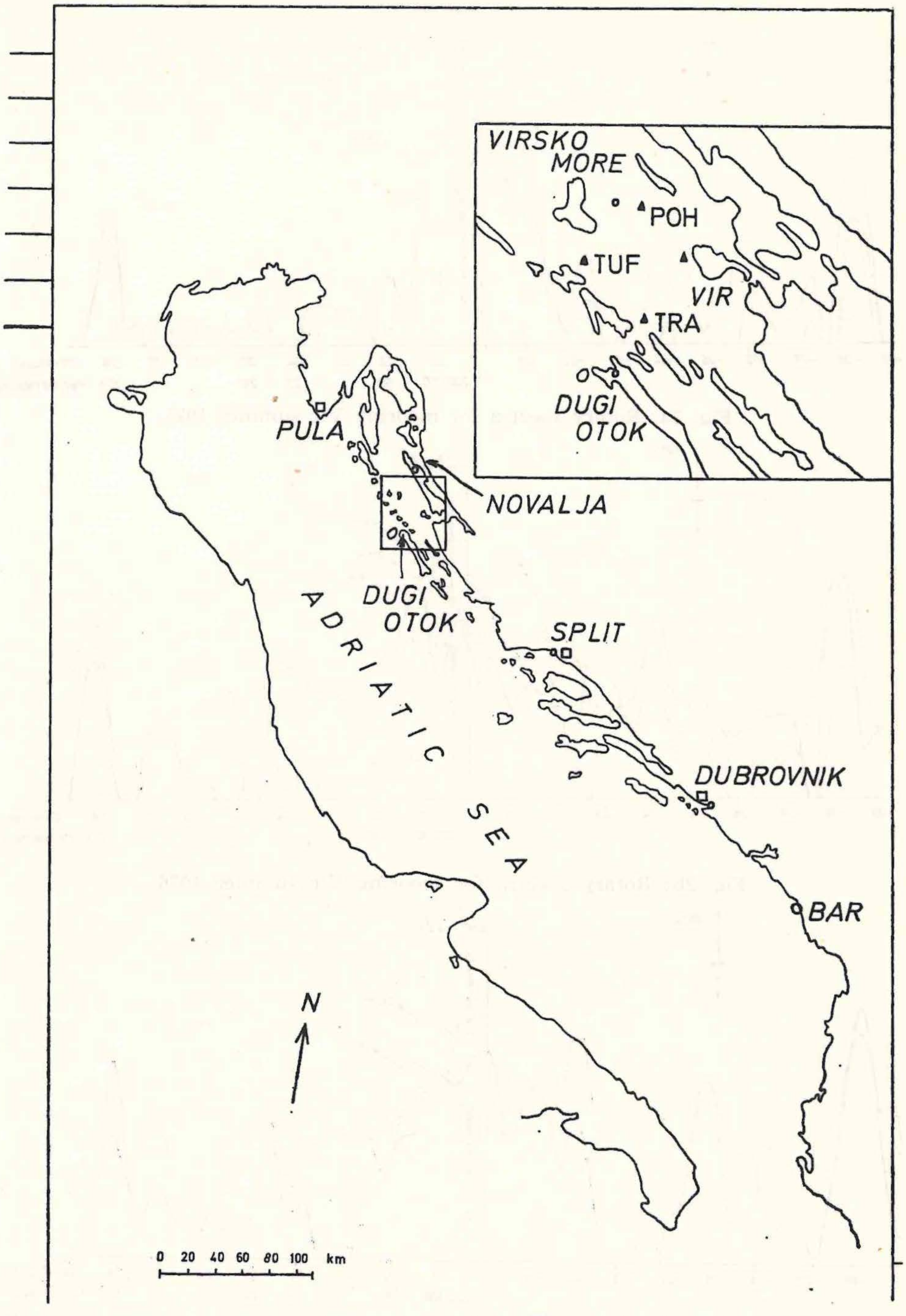

Fig. 1: Location of moorings (▲), meteorogical (□) and tidal stations (○).

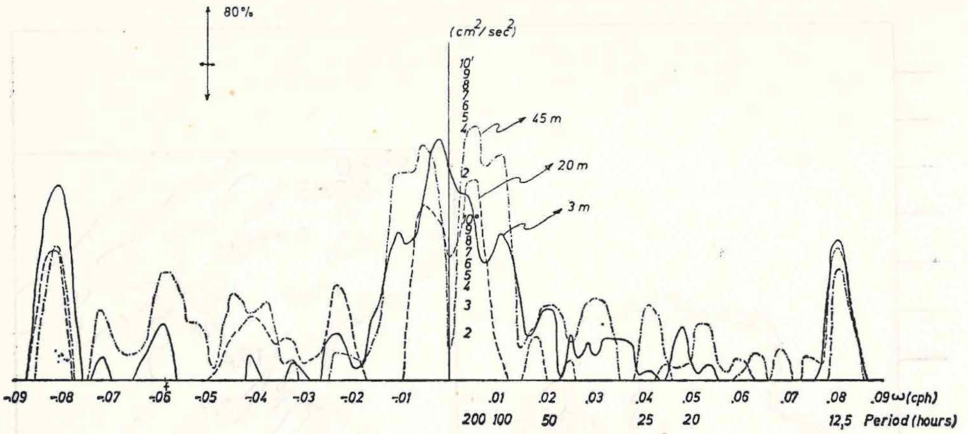

Fig. 2a: Rotary spectra for mooring Vir summer 1975.

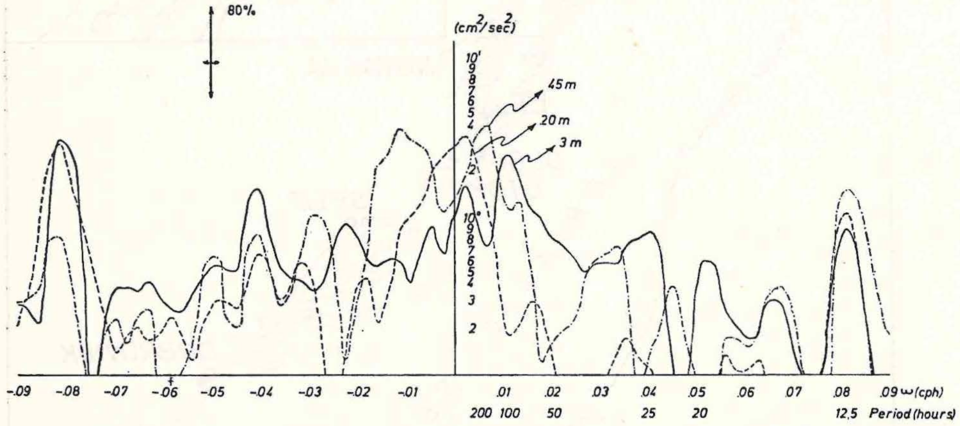

Fig. 2b: Rotary spectra for mooring Vir summer 1976.

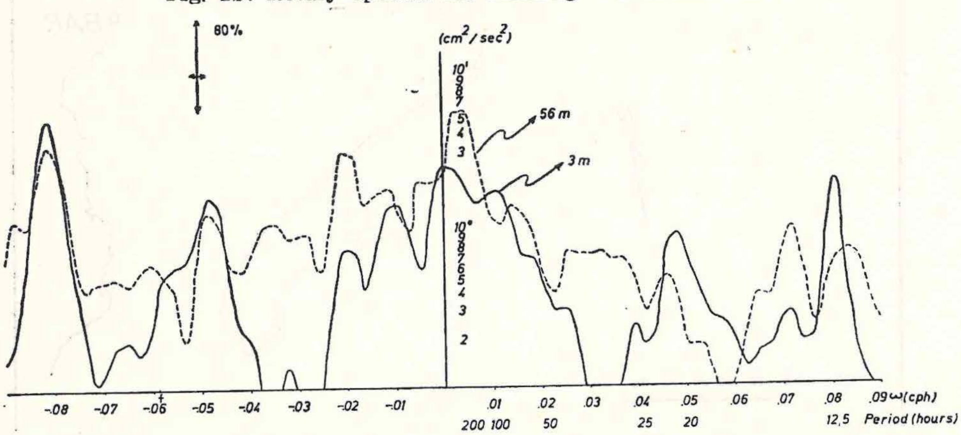

Fig. 2c: Rotary spectra for mooring Tuf March 1979.

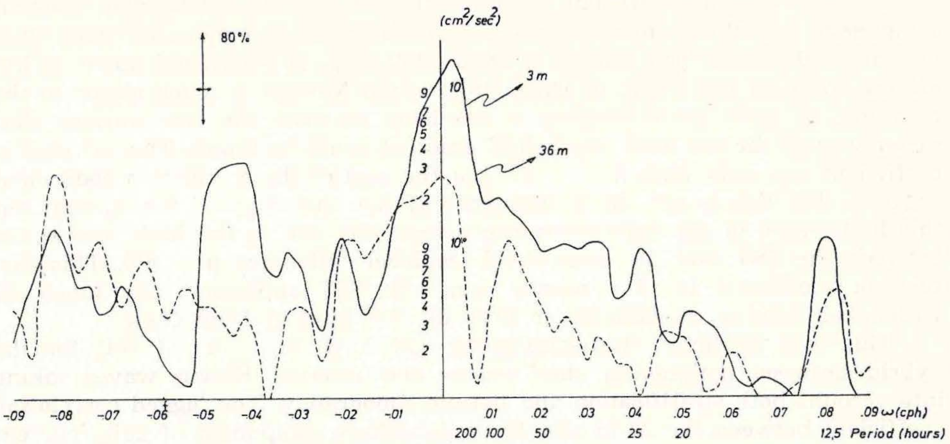

Fig. 2d: Rotary spectra for mooring Trata March 1979.

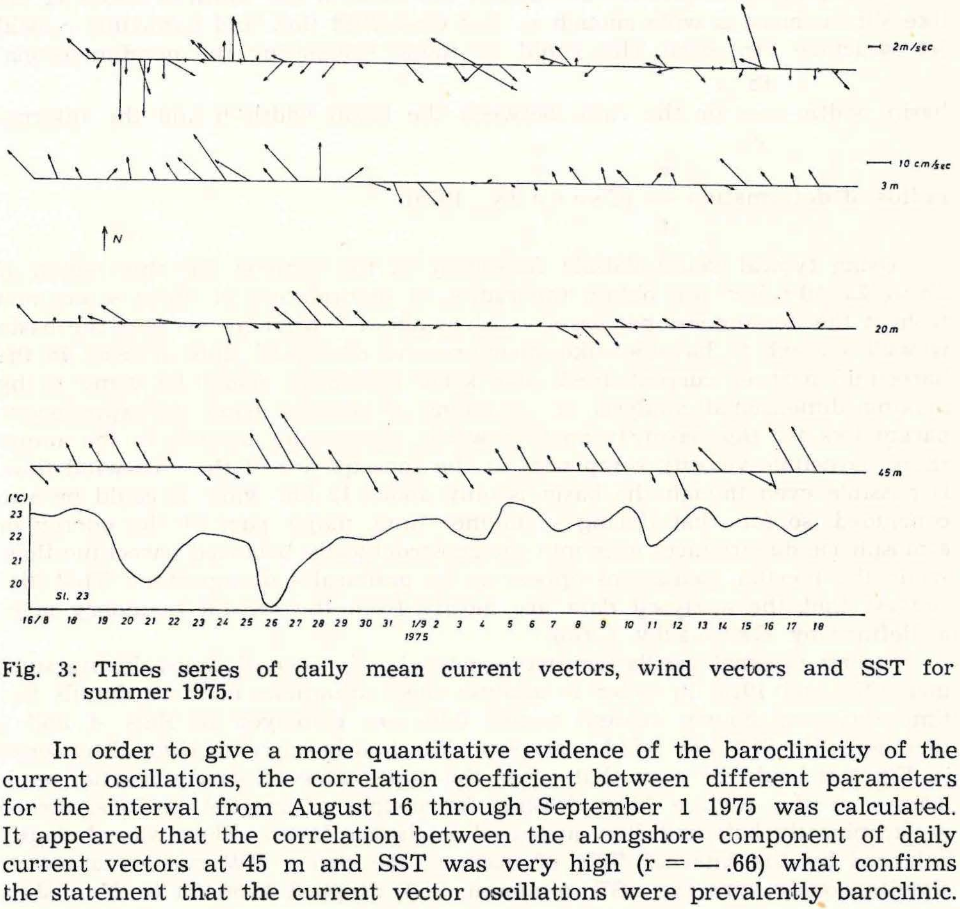

Fig. 3: Times series of daily mean current vectors, wind vectors and SST for summer 1975.

In order to give a more quantitative evidence of the baroclinicity of the current oscillations, the correlation coefficient between different parameters for the interval from August 16 through September 1 1975 was calculated. It appeared that the correlation between the alongshore component of daily current vectors at 45 m and SST was very high (r = — .66) what confirms the statement that the current vector oscillations were prevalently baroclinic.

The correlation coefficient between the 45 m daily alongshore current component and the difference in sea lavel between Novalja and Dugi Otok was also calculated. The station of Dugi Otok (Fig. 1) is situated about 30 km off the coast on the island of Dugi Otok, while Novalja is much closer to the coastline, so from the difference in sea level between the two stations characteristics of the sea level cross shelf gradient could be found. The correlation coefficient was very high (r = — .67) but the sign of the correlation coefficient suggests that this is not the consequence of the barotropy of the current but this high value of the correlation coefficient was due to the high correlation between the SST and the cross shelf sea level difference (r = .66). This correlation coefficient is of a proper sign, low SST appearing simultaneously with a sea level at Novalja lower than the sea level at Dugi Otok.

This was predicted theoretically by Gill & Clarke (1974) for the hybrid between continental shelf waves and internal Kelvin waves taking into account both stratification and bottom topography. The lagged correlation coefficient between the 20 m and 45 m alongshore component of daily current vector was calculated and it was found that the correlation coefficient is maximum for the 1 day lag (r = .87); 45 m current leading that at 20 m.

Very important question is whether the basin of the width of about 12 km like Virsko more is wide enough so that crosswind flow and baroclinic coastal jet structure can exist. This could be found calculating the nondimensional basin width $\frac{fb}{c}$ or the ratio between the basin width b and the internal radius of deformation $\frac{c}{f}$ (Csanady, 1975).

Using typical Brunt-Vaisala frequency in the summer for this region of about $22 \cdot 10^{-1}$ sec^{-2} we obtain the radius of deformation of about 4 km and from it the nondimensional basin width is about 3 what means that the basin is wide enough to have jet-like structure and crosswind flow at least in the baroclinic part of current field. The same conclusion could be come to by making dimensional analysis of equations of motion using the appropriate parameters for this basin. In another words, geostrophic balance in the alongshore baroclinic velocity component as the consequence of the crosswind flow, is possible even though the basin is only about 12 km wide. It could be also concluded, so far, that during a summer time, major part of the energy of atmospheric disturbances goes into the geostrophically balanced baroclinic flow, while the inertial oscillations appear to be practically unimportant. That also suggest that the analysed data are mostly from the coastal boundary layer as defined by Csanady (1975).

Strong intertial oscillations were noticed only several times during summer 1975 and 1976. In order to analyse these situations in more details two time series of hourly current vector data are displayed in Figs. 4 and 5 together with SST and wind data. From the hourly current vector time series in Fig 4 it could be seen that, after the appearance of strong inertial oscillations in the surface layer lasting for couple of inertial periods, strong geostrophically balanced flow appeared in deeper layers. Flow was obviously balanced by the internal field of mass as the strong NW current appeared simultaneously with the SST minimum. SST dropped from 23 to 24 of July

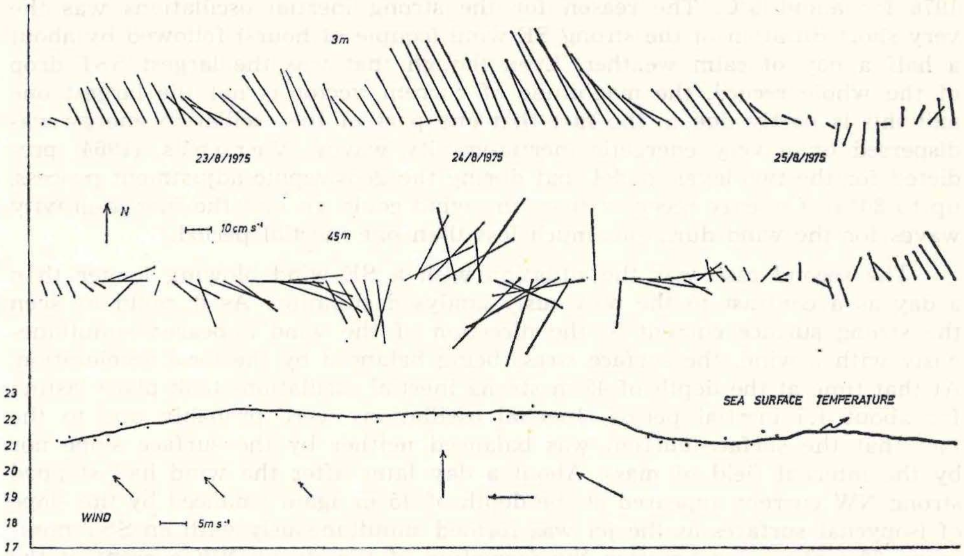

Fig. 4: Time series of hourly mean current vectors, SST and wind vectors for the interval from 23 through 25 August 1975.

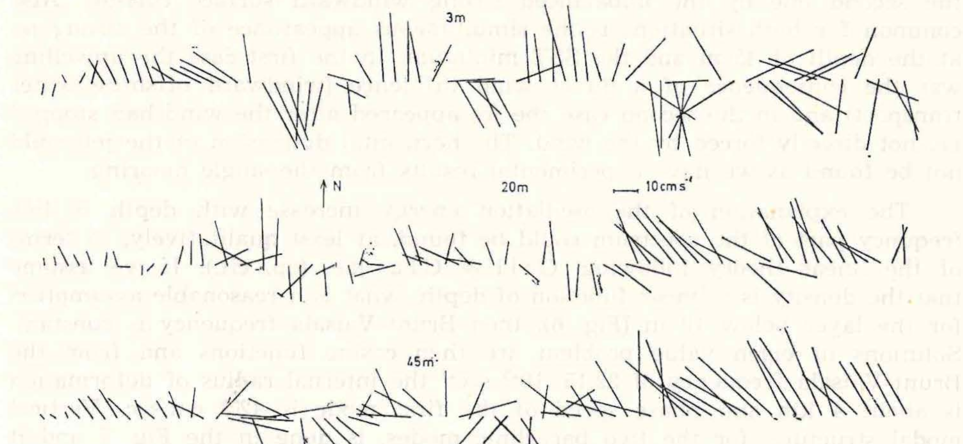

Fig. 5: Time series of hourly mean current vectors, SST and wind vectors for the interval from 22 through 24 July 1976.

1976 for about 6°C. The reason for the strong inertial oscillations was the very short duration of the strong SE wind (couple of hours) followed by about a half a day of calm weather. Even though that was the largest SST drop of the whole record, the magnitude of current vector is not the largest one and this is partly due to the fact that one part of the oscillation energy was dispersed by a very energetic inertia-gravity waves. Veronis (1964) predicted for the two layer model that during the geostrophic adjustment process, up to 80% of energy received from the wind could go into the inertia-gravity waves for the wind durations much less than one inertial period.

The second case was the situation with a SE wind blowing longer than a day as a contrast to the previously analysed situation. As it could be seen the strong surface current in the direction of the wind appeared simultaneously with a wind, the surface stress being balanced by the local acceleration. At that time at the depth of 45 m strong inertial oscillations took place lasting for about 1.5 inertial period. Inertial oscillations were probably due to the fact that the surface current was balanced neither by the surface slope nor by the internal field of mass. About a day later after the wind had stopped strong NW current appeared at the depth of 45 m again balanced by the slope cf isopycnal surfaces as the jet was formed simultaneously with an SST minimum. The phase lag between the formation of the strong NW current at the depth of 3 and 45 m was about half a day.

Common for both situations is the appearance of strong inertial oscillations; in the first case they were caused by the short wind duration and in the second one by the unbalanced strong windward surface current. Also common for both situations is the simultaneous appearance of the strong jet at the depth of 45 m and the SST minimum. In the first case the upwelling was the consequence of a direct wind influence (windward offshore water transport) and in the second case the jet appeared after the wind had stopped i.e. not directly forced by the wind. The horizontal dimension of the jet could not be found as we have experimental results from the single mooring.

The explanation of the oscillation energy increase with depth in low frequncy part of the spectrum could be found, at least qualitatively, in terms of the linear theory following Gill & Clarke (op. cit.). If we assume that the density is a linear function of depth, what is a reasonable assumption for the layer below 10 m (Fig. 6), then Brunt-Vaisala frequency is constant. Solutions of eigen value problem are then cosine functions and from the Brunt-Vaïsala frequency of $22.15 \cdot 10^{-3}$ sec^{-1} the internal radius of deformation is about 4 km and phase speed of the first mode is 42.3 cm/sec. Vertical modal structure, for the two baroclinic modes, is done in the Fig. 7 and it could be seen that the currentmeter at the depth of 45 m was exactly on the zero-crossing of the second mode and on that level we isolate only a first mode. On the other hand 20 m current meter was on the level where first and second mode are in antiphase, so it is »feeling« the difference between the two modes and consequently the energy level is lower there. It could be also seen from daily current vector time series that there is a phase lag of about a day between the oscillations at the depth of 45 and 20 m what suggests the prevalence of the first mode. This is to be expected as the distance of the mooring from the coast is very close to the radius of deformation of the second mode. Barotropic mode was not taken into account as the mooring was only 2 km from the coast so that baroclinic modes are prevalent, and specially the first one.

Even though the linear theory has given satisfactory but qualitative explanation of the oscillation energy increase with depth it is not clear why friction and complicated shape of coastline doesn't distort more the current

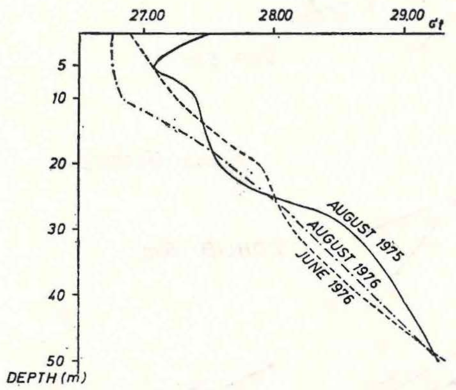

Fig. 6: Typical vertical distribution of σ_t.

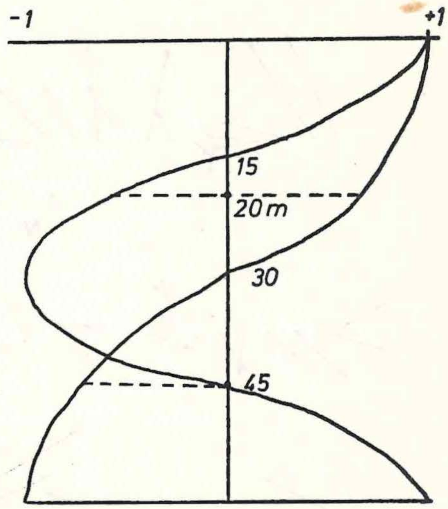

Fig. 7: Vertical distribution of the first two baroclinic modes.

field. These are preliminary conclusions and they have to be checked by more experimental results. So far it could be concluded, that the complex modal structure gives the apparent increase of oscillation energy with depth in low frequrency part of the spectrum.

During a winter time the oscillation energy increase with depth is not so evident as it could be seen from the two spectra at 5 and 36 m at the mooring Trata and from the spectra at 5 and 56 m at the mooring Tuf for March 1979 (Figs 2a and 2b). This suggests that during a winter the response is prevalently barotropic as it could be expected.

Daily mean current vector time series for four moorings for March 1979 (Fig. 8) shows that as soon as the wind starts blowing windward current appears at the depth of 5 m and, in lesser extent, in deeper layers. Mean current vector for the whole interval of measurements shows another interesting feature; at the surface there is a strong shoreward current, while in deeper layers the current is seaward (Fig. 9). This could be explained in terms of Ekman dynamics as the mean wind vector for the same interval was northwestward of appreciable magnitude (about 3 m/sec) so the shoreward surface current shows the Ekman-type balance except for the mooring Pohlib where the mean current vector is downwind due probably to the position of the mooring. As the Ekman-type balance probably doesn't hold in the basin itself in this barotropic case, the shoreward surface transport is the

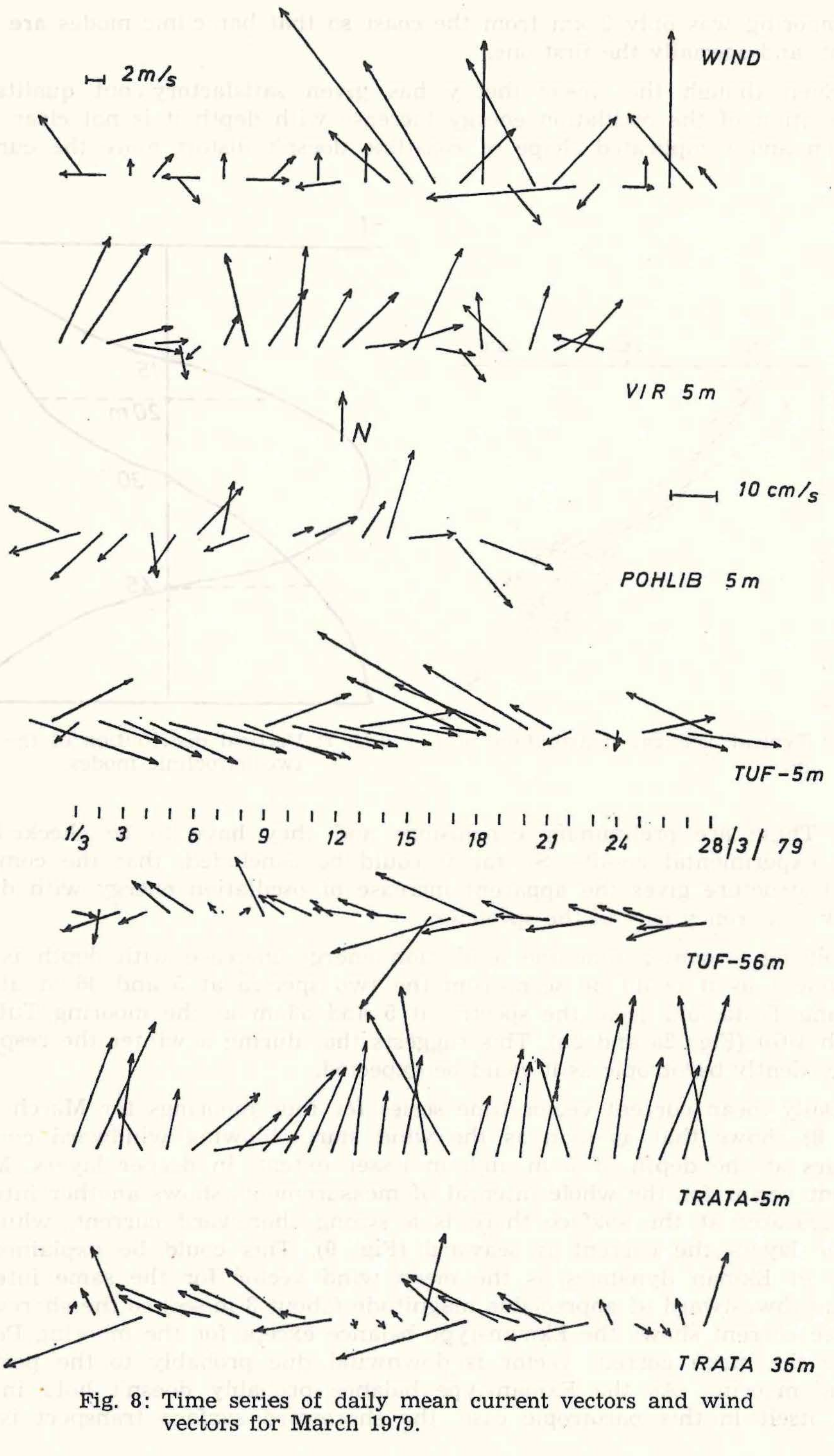

Fig. 8: Time series of daily mean current vectors and wind vectors for March 1979.

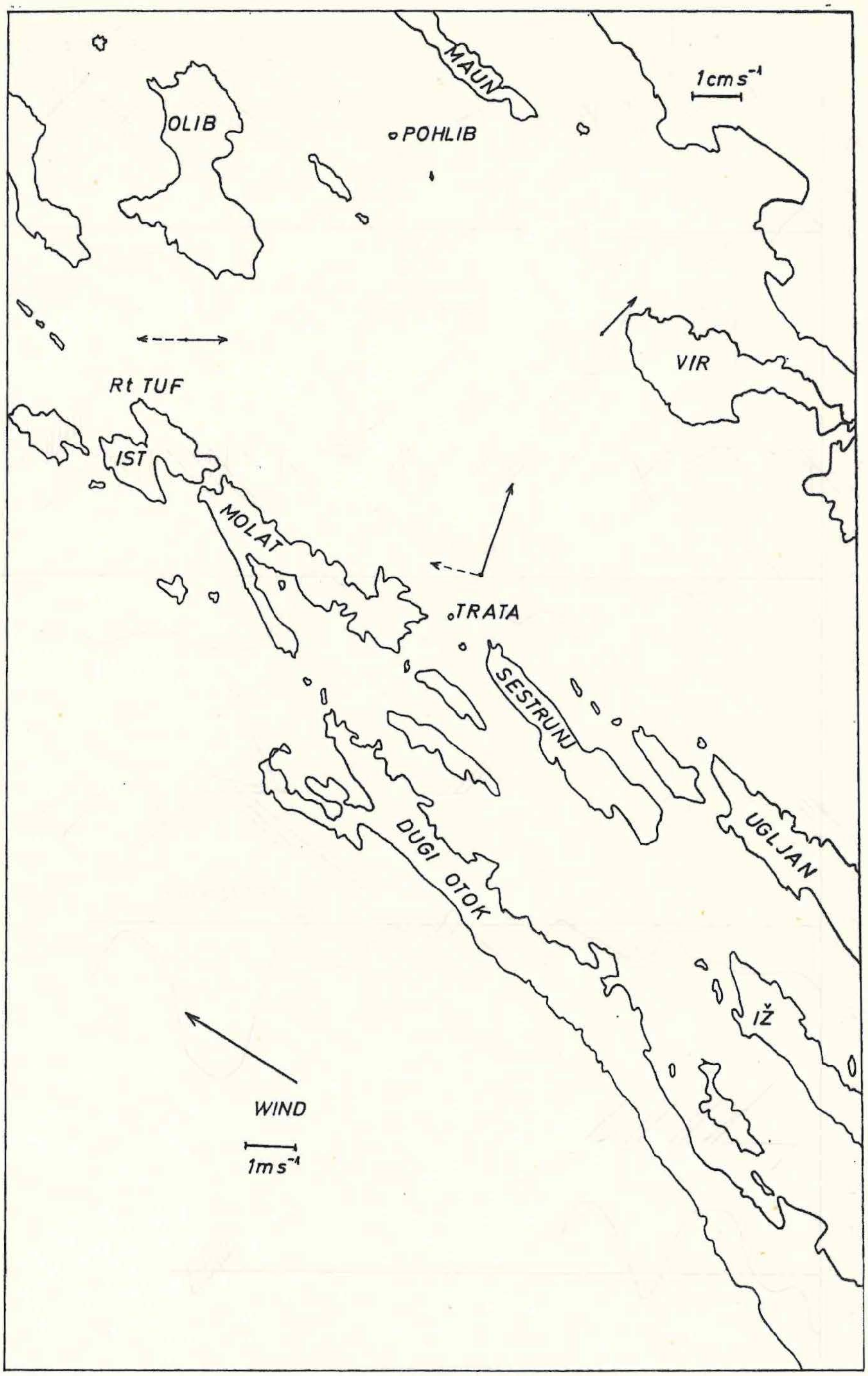

Fig. 9: Mean current vectors for the whole interval of current measurements during March · (——— surface — — — deeper layer).

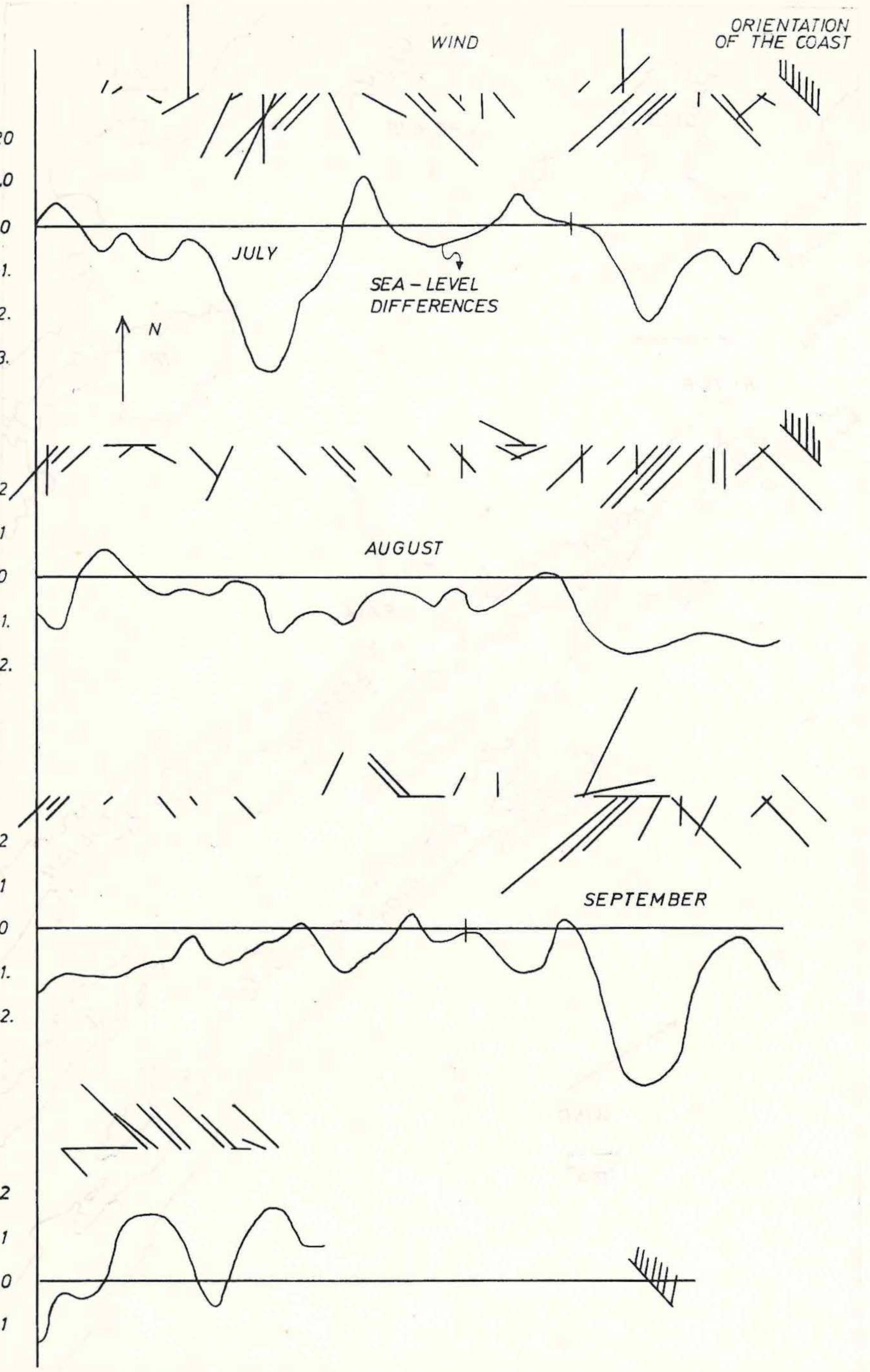

Fig. 10: Sea level differences between Novalja and Dugi Otok and wind data for summer 1976.

reflection of the situation at the open sea. In favour of this conclusion is shoreward surface transport at the mooring Trata and Tuf which are close to the openings of the basin of Virsko more.

3. ANALYSIS OF SEA LEVEL DATA

Characteristics of the sea level response to the atmospheric forcing were found by calculating sea level spectra for four sea level data time series.

In order to find out the influence of the wind to a sea level, time series of sea level data, with a mean removed, for stations Novalja and Dugi Otok were compared with a wind data for station Vir (Fig. 10).

In all the situations with a NE wind (wind normal to the coastline in an offshore direction) the sea level difference is of a proper sign i.e. always in these situations the station Dugi Otok has higher sea level than Novalja for couple of centimeters. This is due to the windward sea water transport. Simultaneously with a higher sea level at Dugi Otok than at Novalja, the upwelling takes place near the island of Vir and coastal jet develops at the depth of 45 m as it was shown previously. In the situation with a SE wind (parallel to the coastline) the sea level at Novalja is higher than sea level at Dugi Otok due to the Ekman transport toward the coast. It was shown earlier in this paper that the shoreward water transport develops as the consequence of the Ekman type balance at the open sea. SE wind has weaker influence on the sea level slope than the NE wind partly because the crosswind water transport is smaller than the windward water transport. The reason for the stronger influence of the NE wind could be also the fact that the downwind water transport develops almost simultaneously with a start of the wind while the Ekman transport appears after about a day after the wind starts blowing and the wind duration is in average only two or three days. From adjusted sea level spectra for winter and summer (Fig. 11 and 12) it could be seen that sea level changes at the frequencies greater than .05 cpd are of the order of centimeter which is too small to isolate it from background noise. From Figs 11 & 12 it follows also that there is no any prominent peak in the frequency range in question. Toward zero-frequency there is a strong energy increase, specially for the winter time what could be attributed to the steric effect. Very low energy level for frequencies above .05 cpd shows that current field changes on these time scales are mostly mondivergent and therefore sea level doesn't appear as a very suitable parameter in the study of coastal barotropic currents, as stated already by Caldwell et. al. 1971. It was shown previously that cross shelf sea level differences are much more adequate for this kind of study.

4. CONCLUSIONS

Presented analysis shows that the investigated area of Virsko more responds stronly to wind forcing on the time scale of several days. During a summer the response is prevalently baroclinic and due to small dimensions of the investigated region the response to local forcing prevails, the upwelling and coastal jet being caused by an offshore wind.

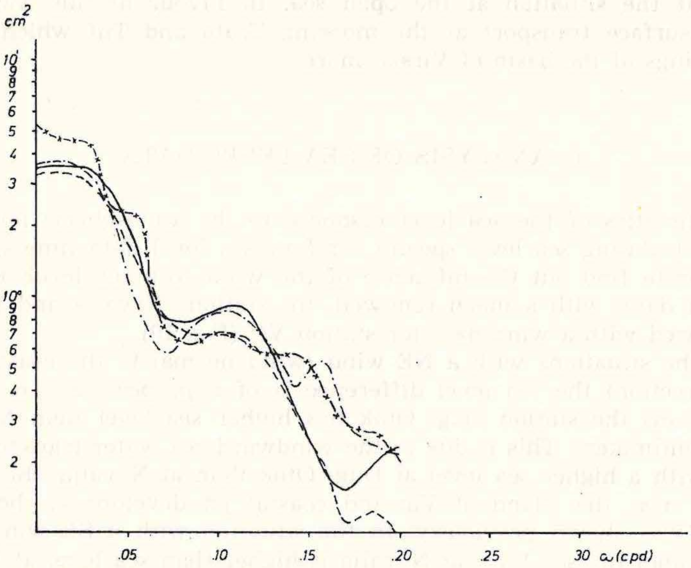

Fig. 11: Adjusted sea level spectra for Dubrovnik (———), Split (———), Bar (— — —) and Novalja (—x—x) for summer 1975.

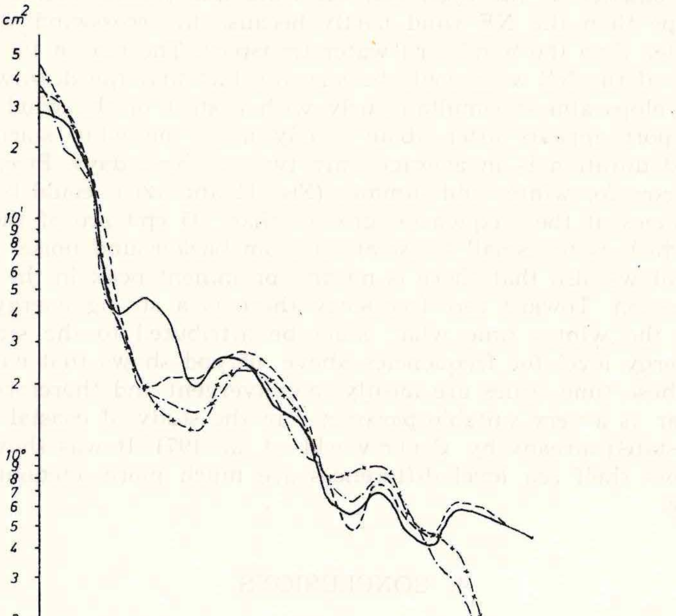

Fig. 12: Adjusted sea level spectra for Dubrovnik (———), Split (— . —), Bar (— — —) and Novalja (—x—x) for winter 1975/76.

Current oscillations are polarized parallel to the local orientation of coastline.

Inertial oscillations are found to exist very rarely and their energy is, in average, smaller than tidal ones due probably to the position of mooring being inside the coastal boundary layer. During a winter barotropic motions are more important and in the region of Virsko more crosswind flow due to local forcing doesn't appear. Shoreward sea water transport is the consequence of the SE wind action over the whole Adriatic.

The analysis of cross shelf sea level slope shows the significant influence of the wind, while the energy level in adjusted sea level spectrum in the frequency range in question, is very low, therefore the oscillations in current field are prevalently nondivergent.

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NEKE KARAKTERISTIKE ODGOVORA OBALNOG PODRUČJA JADRANSKOG MORA NA UTJECAJ ATMOSFERSKIH POREMEĆAJA

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KRATKI SADRŽAJ

Analiza podataka o strujama kao i meteoroloških podataka iz Virskog mora pokazuje da postoje jake oscilacije u strujnom polju na periodu od nekoliko dana koje su vezane uz utjecaj sinoptičkih poremećaja. U stratificiranom moru (ljeto) odgovor je uglavnom baroklini i zbog relativno malih dimenzija bazena prevladava odgovor vezan uz lokalni utjecaj vjetra. Uzdizanje vode (upwelling) i jako strujanje uz obalu uzrokovano je burom tj. vjetrom okomitim na obalu. Inercijalne oscilacije su znatno slabije energije nego plimne oscilacije vjerojatno zbog činjenice da je strujomjerna stanica bila veoma blizu obali tj. unutar obalnog rubnog pojasa.

U zimskoj situaciji prevladava barotropsko strujanje, a strujanje prema obali je rezultat Ekmanove ravnoteže na otvorenom moru. Analiza podataka o nagibu nivoa mora okomito na obalu pokazala je znatan utjecaj vjetra na taj nagib.

Spektri korigiranog nivoa mora pokazali su da je energija oscilacija na periodima od nekoliko dana veoma mala i zimi i ljeti (amplituda oscilacija je reda veličine 1 cm). To ukazuje da su oscilacije u strujnom polju uglavnom bezdivergentne u ispitivanom području frekvencija.