Acta Adriat., 29 (1/2) : 5—20 (1988) YU ISSN: 0001—5113
AADRAY

UDK: 551.46 (262.3)
Original scientific paper

STORM SURGES ALONG THE EAST COAST OF THE ADRIATIC SEA

PRISILNE OSCILACIJE NIVOA MORA ZA VRIJEME OLUJNIH CIKLONALNIH PRODORA NA ISTOČNOJ OBALI JADRANA

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A statistical method for the forecasting of storm surges along the east coast of the Adriatic Sea was developed. On the basis of the theoretical results obtained by solving equations of motion and applying the multiple regression method the models for calculation of the residual sea levels were constructed. Models were tested for meteorological situations with strong cyclonic SE wind at Koper, Split and Dubrovnik stations. It was found that the multiple regression models present very good estimate of the residual elevations for the situations with permanent air pressure decrease and SE wind increase.

INTRODUCTION

In Anglo-American literature atmospherically forced sea level changes caused by passage of storms are usually called storm surges. Investigations of storm surge problem have very special and practical importance because the rise of the sea level can be significant in coastal regions and inundations sometimes can cause a lot of damage and losses of lives. For example, in Bay of Bengal, according to Welander (1961) two surges due to hurricanes in 1864 and 1878 killed 250 000 people.

In this paper storm surges along the east coast of the Adriatic Sea are studied. Although the surges in the Adriatic Sea are smaller than in ocean region, they are still of significant amplitude and cause inundations, specially in the northern Adriatic Sea.

The most important components of the forced sea level changes in the Adriatic Sea are tides and storm surges. Tides are caused by the permanent gravitational action the Moon and the Sun. Storm surges are consequence of the mechanical effect of the atmosphere on the sea (wind, air pressure) which is variable in space and time. Component of the sea level elevation due to storm surge is usually called residual elevation. Many theoretical studies as well as analysis of the experimental data suggest that in the Adriatic Sea these two components are linearly super imposed (Michelato *et al.*, 1983).

Nowdays, the methods mostly used among researchers to solve storm surge problem, especially for the purpose of the operative forecastings, are statistical methods and hydrodynamical numerical models. A review of statistical methods developed for the Adriatic Sea will be presented.

Storm surges were studided in the Adriatic Sea for periods characterized by the passage of different atmospheric formations: planetary waves, cyclones and anticyclones and mesoscale formations, as well as in functions of different meteorological parameters: air pressure, wind and geopotential.

The influence of air pressure on sea level changes was examined by Kasumović (1958), Polli (1960), Mosetti and Purga (1978/79), Karabeg and Orlić (1982) and Gačić (1983). Using different methods they have concluded that the sea level elevation is generally proportional to air pressure according to inverse barometer effect (—1 cm/hPa).

Literature dealing with the wind influence on sea level changes is smaller. This can be attributed to the difficulties when exact quantitative analysis is performed. Polli (1968) published a table with residual sea level elevations for different wind speeds. Sea level elevations vary from 20 to 100 cm for mean hourly wind speeds between 10 and 60 km/h. Considerable progress was obtained by Mosetti and Bartole (1974). They found empirical relation for residual elevation in function of instantaneous wind speed and wind speed time integral from the moment of wind appearance.

Wind and air pressure joint influence on the sea level changes is presented in several studies for the Adriatic Sea. Mosetti and Bajc (1972) associated the greatest sea level elevations in Venice with zonal air pressure gradient. Sguazzero *et al.* (1972) developed the model for Venice that residual elevations associate with earlier residual elevations in Venice and earlier air pressure gradients. Michelato *et al.* (1983) proposed the method, based on the multiple regression equation for 3 to 24 hours forecasts of residual elevations. Leder (1985) investigated partial effects of air pressure and wind velocity, as well as their joint effects on the residual elevations in Split. He concluded that residual elevations were function of air pressure, wind speed and wind speed square.

Kasumović (1958) and Squazzero *et al.* (1972) established that increase and decrease of sea level resulted from cyclonic and anticyclonic activity respectively.

It has been shown that long term oscillations of sea level are predominantly caused by planetary atmospheric waves (Penzar *et al.*, 1980 and Orlić, 1981).

THEORETICAL BASIS

Wind and air pressure time changes over the sea area are consequence of the passage of different atmospheric formations. In middle latitudes the most important wave disturbances are:

a) planetary waves; characteristic horizontal space scale is 10^3—10^4 km and time scale is about 10 days;

b) synoptic atmospheric formations; cyclones and anticyclones; characteristic horizontal space scale is about 10^3 km and time scale is 1—2 days;

c) meso-scale atmospheric formations; characteristic horizontal space scale is 10—10^2 km and time scale is about 1 hour.

Cyclones and anticyclones have the most important influence on sea level change. From tide gauge records it is known that the highest positive sea levels appear on the east coast of the Adriatic Sea during passage of an intensive cyclone, when horizontal air pressure gradients cause strong southern wind (Michelato, 1975).

The theoretical basis for the dynamical relations between atmospheric forcing and sea response are storm surge equations which are obtained from equations of motion after introducing some assumptions (Groen and Groves, 1962; Orlić, 1983).

Since storm surge equations are linear it is possible to examine the influence of wind air pressure independently. If one examines the influence of air pressure, the solution may be expressed as:

$$Y = -\frac{p_a - \overline{p_a}}{g^p} \qquad \ldots\ldots (1)$$

where Y is the residual sea level elevation, p_a is air pressure, $\overline{p_a}$ is mean value of air pressure taken over the basin area, g is gravity acceleration and p is density of sea water. With $g = 9.81\ ms^{-2}$ and $p = 1030\ kgm^{-3}$ decrease (increase) of air pressure for 1 hPa, with constant $\overline{p_a}$, will cause increase (decrease) of sea level for 1 cm. It is so called inverse barometer effect and equation (1) is called statical equation.

The influence of the wind on sea level changes may be expressed as:

$$Y = \frac{1}{g^{ph}} \vec{T} \cdot \vec{r} + C_1 \qquad \ldots\ldots (2)$$

where $\vec{T}$ is wind stress, $\vec{r}$ is wind fetch, C_1 is constant and h is depth. There are many empirical relations for wind stress. One of the most used is (Michelato, 1975):

$$\vec{T} = Kp_a\ (v^2_x + v^2_y)^{1/2}\ (\vec{i}v_x + \vec{j}v_y) \qquad \ldots\ldots (3)$$

where v_x and v_y are zonal and meridional wind speed components, P_a is air density and K is constant. It can be seen from equations (2) and (3) that residual elevation Y is proportional to wind speed square, air-sea density ratio and wind fetch, but in an inverse proportion with sea depth.

The multiple regression model of the surge

The general form of the model can be expressed in multiregression equation as (Draper and Smith, 1981):

$$\hat{Y}_i = A_o + A_1 X_{1i} + A_2 X_{2i} + \ldots + A_k X_{ki} \qquad \ldots\ldots (4)$$

where the predictand $\hat{Y}_i$ is described as a linear combination of k predictors X_{ki}. The numbers A_j ($j = 1, \ldots, k$) are the so called partial regression coefficients and term A_o is the intercept of the regression.

In equation (4) $\hat{Y}_i$ is estimated residual elevation and X_j ($j = 1, \ldots, k$) are meteorological parameters which will be chosen in such a way that $\hat{Y}_i$ will be the best approximate value for measured residual elevation Y_i. The most common method for calculation of coefficients A_j is the least-squares method. wich assumes that:

$$\sum_{i=1}^{N} (Y_i - \hat{Y}_i)^2 = \min. \qquad \ldots. (5)$$

where Y_i are the N measured values of the residual elevations. From minimization condition (5) one obtains the following system of linear equation (normal equations):

$$\begin{aligned} &A_o (1,1) + A_1 (1,X_1) + \ldots + A_k (1,X_k) = (1,Y) \\ &A_o (X_1,1) + A_1 (X_1,X_1) + \ldots + A_k (X_1,X_k) = (X_1,Y) \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad \ldots\ldots (6) \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ &A_o (X_k,1) + A_1 (X_k,X_1) + \ldots + A_k (X_k,X_k) = (X_k,Y) \end{aligned}$$

where the symbol ( ) indicates summation i. e.:

$$(u, v) = \sum_{i=1}^{N} u_i v_i$$

By solving the system (6) the coefficients of the multiple regression $A_o, A_1, \ldots, A_k$ are obtained. From all combinations of independent variables the best one is with the greatest value of the multiple correlation coefficient which is calculated from the following formula:

$$R = \frac{\sum_{i=1}^{N} (Y_i - \overline{Y}) \cdot (\hat{Y}_i - \overline{Y})}{\left(\sum_{i=1}^{N} (Y_i - \overline{Y})^2 \cdot \sum_{i=1}^{N} (\hat{Y}_i - \overline{Y})^2\right)^{1/2}} \qquad \ldots\ldots (7)$$

where $\overline{Y}$ is mean value of Y_i.
It is known that R is linear coefficient between dependent variable Y and its linear regression $\hat{Y}$ in relation to $X_1, X_2, \ldots, X_k$. Multiple correlation coefficient has values between 0 and 1, i. e. $0 \leqslant R \leqslant 1$. If the R value is near 1 it means that Y strongly depends on X_i. Value $R = 1$ means functional dependence and $R \leqslant 1$ stohastic dependence.

RESULTS

From hourly values of wind vector, air pressure and sea level data for Koper, Split and Dubrovnik (Fig. 1) and the year 1982, the situations with highest positive residual elevations are chosen. These situations are characterised by intensive cyclonic activity and strong SE wind over the Adriatic area.

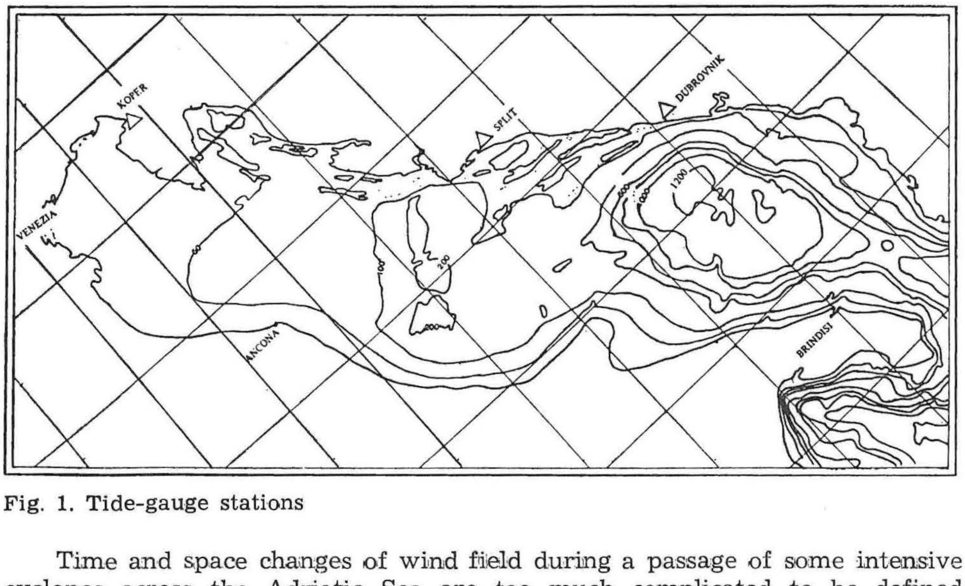

Fig. 1. Tide-gauge stations

Time and space changes of wind field during a passage of some intensive cyclones across the Adriatic Sea are too much complicated to be defined exactly. But, it can be seen that storm surges with highest residual elevations appeared in meteorological situations when wind from south quadrant blew at least 30 hours in two days with mean hourly speed greater than 7 m/s. An area of such a wind field must be North, Middle and South Adriatic or larger area for Koper, Split and Dubrovnik respectively.

A number of such meteorological situations was investigated but here only one typical will be presented. In period from December 17 to 21, 1982, a strong SE wind was blowing along the entire Adraitic Sea. Synoptic situation for December 18, 1982, is shown in Fig. 2.

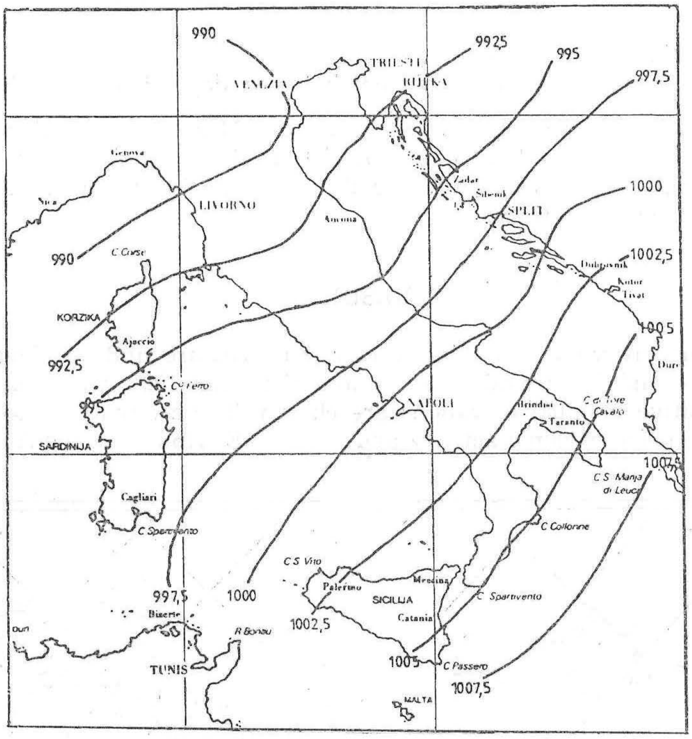

Fig. 2. Air pressure distribution at sea level, December 18, 1982, 04 GMT

Using the multiregression equation (4) and storm surge equations (1) and (2) three models were tested for calculation of sea level residuals at Koper, Split and Dubrovnik. The equations for models may be written:

$$\hat{Y}(t) = A_o + A_1\,P(t) + A_2\,V(t) \qquad \ldots\ldots (8)$$

$$\hat{Y}(t) = A_o + A_1\,P(t) + A_2\,V^2(t) \qquad \ldots\ldots (9)$$

$$\hat{Y}(t) = A_o + A_1\,P(t) + A_2\,V(t) + A_3\,V^2(t) \qquad \ldots\ldots (10)$$

where t is time, $\hat{Y}(t)$ is estimated residual elevation in cm, P(t) is air pressure in hPa, V(t) is wind speed in ms^{-1} and A_i are constants calculated from hourly values of data shown in Figs. 3,4 and 5.

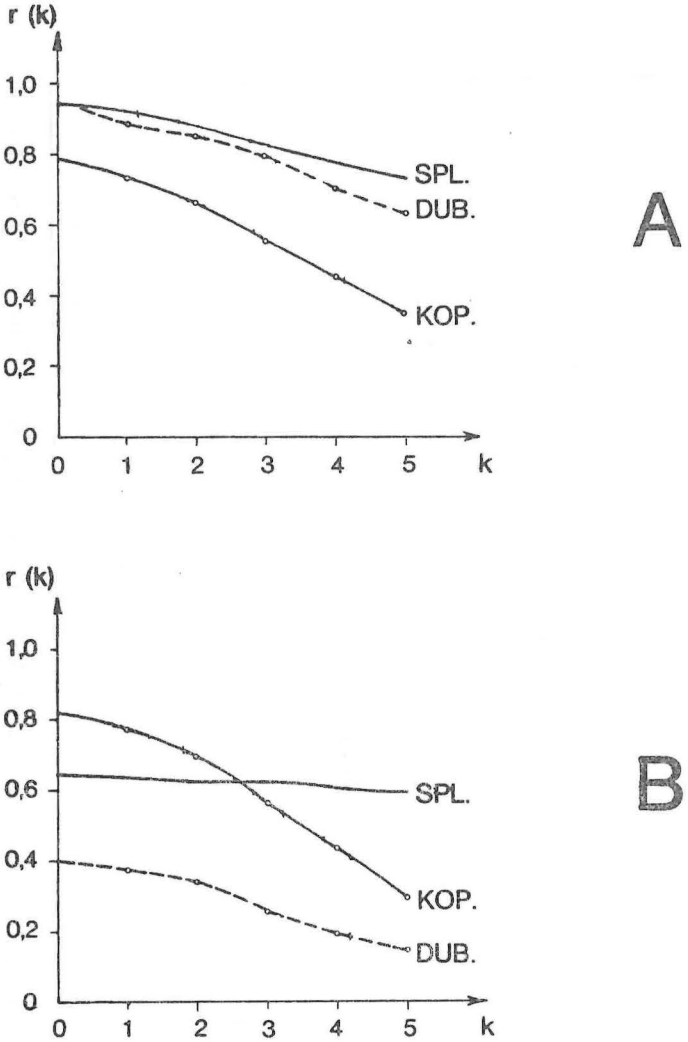

Fig. 2a. Cross correlation coefficients r(k) between air pressure and residual elevation (A) and wind speed and residual elevation (B) at Koper, Split and Dubrovnik stations

All variables are function of time t. This means that sea responds to atmospheric forcing instantaneously. This assumption was examined previously by

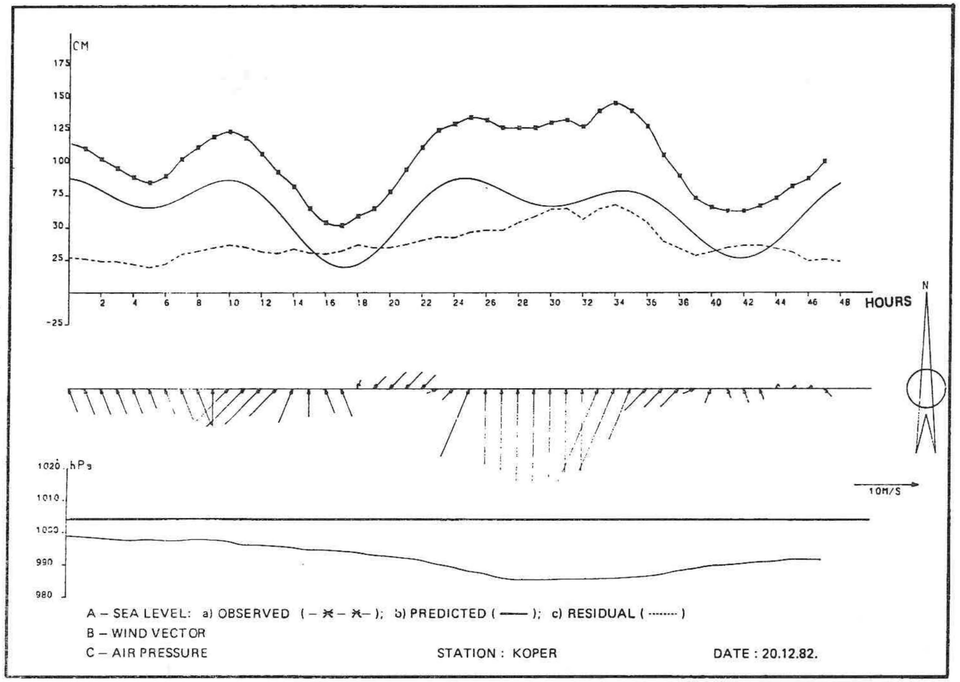

Fig. 3. Residual elevation, wind vector and air pressure time series in Koper on December 20, 1982, 00 GMT

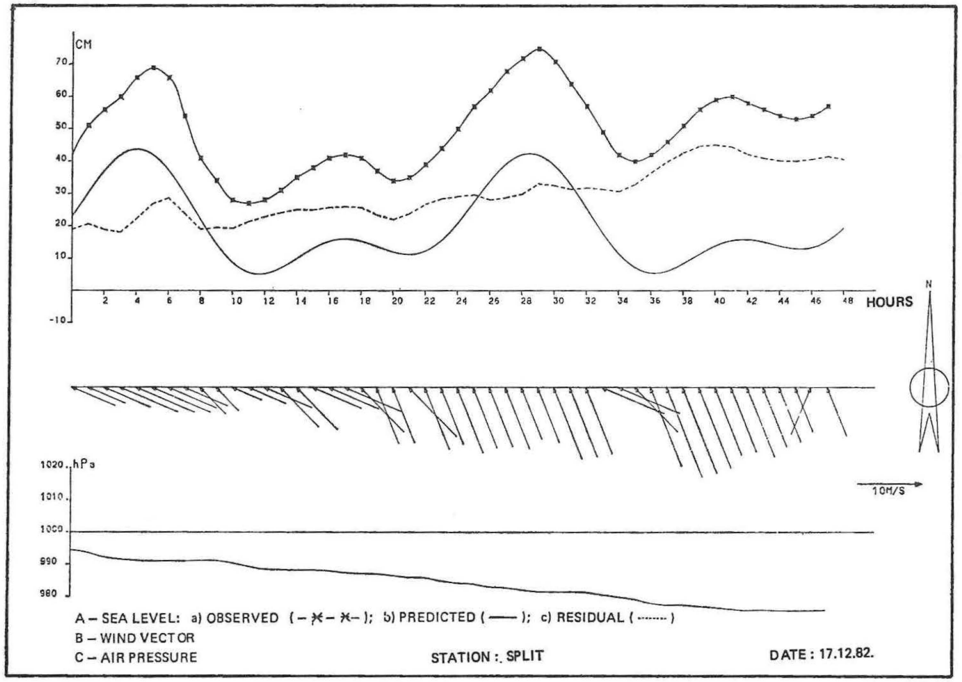

Fig. 4. Residual elevation, wind vector and air pressure time series in Split on December 17, 1982, 00 GMT

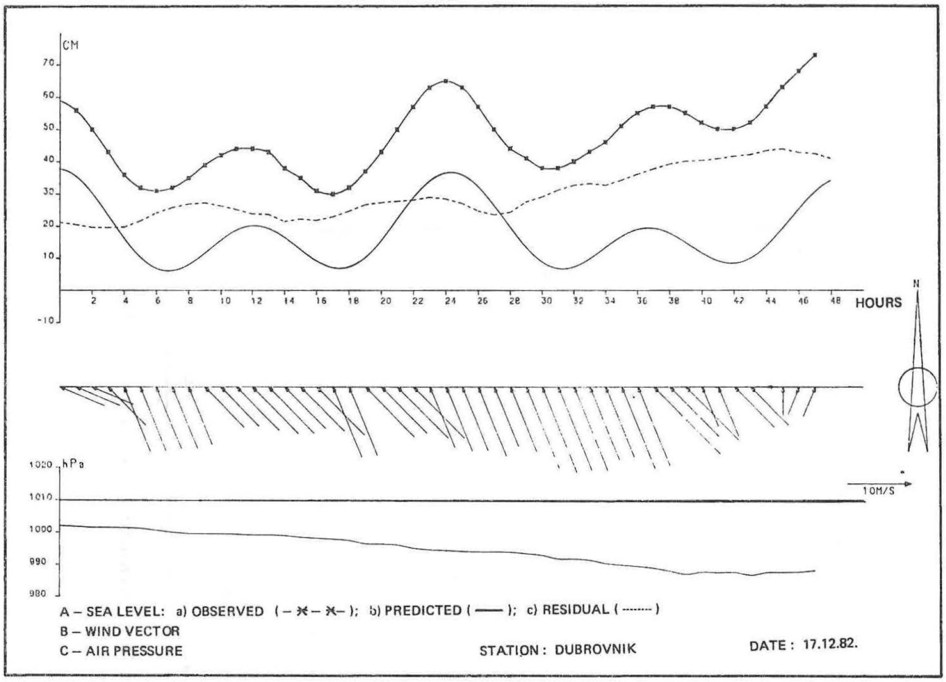

Fig. 5. Residual elevation, wind vector and air pressure time series in Dubrovnik on December 17, 1982, 04 GMT.

calculating cross correlation coefficients between air pressure and residual elevation and wind speed and residual elevation to time lag of 5 hours (Fig. 2a.). At all stations zero-lag cross correlation coefficient was highest. Hence the assumption of instantaneous response is correct.

From storm surge equations it was expected that the model (9) would be the most appropriate for the description of sea level dependence on the air pressure and speed. However, for all stations the model defined with equation (10) is the best one, its multiple correlation coefficient being always higher than that for models (8) and (9). This means that model (10) is the best approximation for measured residuals.

It can be explained by the fact that drag coefficient K in equation (3) for wind stress is not constant. Wu (1982) determined that drag coefficient is complex function of wind speed V.

All statistical parameters included in multiple regression calculation are presented in Table 1. Regression equations for residuals may be written for Koper, Split and Dubrovnik respectively:

$$\hat{Y}(t) = 1292{,}0 - 1{,}27\ P(t) + 0{,}81\ V(t) + 0{,}06\ V^2(t) \qquad \ldots\ldots 11)$$

$$\hat{Y}(t) = 1194{,}8 - 1{,}17\ P(t) - 1{,}43\ V(t) + 0{,}10\ V^2(t) \qquad \ldots\ldots (12)$$

$$\hat{Y}t) = 1391,3 — 1,36\ P(t) — 0,86\ V(t) = 0,03\ V^2(t) \qquad ..... (13)$$

It must be taken in consideration that P(t) and V(t) are measured at different heights: 92, 122 60 m for Koper, Split and Dubrovnik respectively, depending on the locations of meteorological stations.

Testing of equations (11), (12) and (13) was done for similar meteorological situations by comparing observed and calculated values. Comparisons between observed and calculated values by model of residual elevations are shown in Figs. 6, 7 and 8 for Koper, Split and Dubrovnik. Some statistical parameters for those situations are presented in Table 2.

Table 1. Mean values of residual elevations $\overline{Y}$, air pressure $\overline{P}$, wind speed $\overline{V}$, coefficients of regression A_0, A_1, A_2 and A_3 and multiple correlation coefficient R for situations shown on Figs 3, 4 and 5.

DATE	KOPER December, 20—22	SPLIT December, 17—19	DUBROVNIK December, 17—19
$\overline{Y}$ (cm)	38.3	30.0	29.9
$\overline{P}$ (hPa)	991.9	984.3	994.6
$\overline{V}$ (ms^{-1})	5.9	9.6	9.9
A_0 (cm)	1292.0	1194.8	1391.3
A_1 (cm/hPa)	—1.27	—1.17	—1.36
A_2 ($cm/(ms^{-1})$)	+0.81	—1.43	—0.86
A_3 ($cm/(m^2s^{-2})$)	+0.06	+0.10	+0.03
R	0.92	0.96	0.95

Table 2. Mean values of residual elevations $\overline{Y}$, air pressure $\overline{P}$, wind speed $\overline{V}$ and multiple correlation coefficients R for situations shown on Figs. 6,7 and 8.

DATE	KOPER October, 13—15	SPLIT October, 04—06	DUBROVNIK December, 09—11
Y (cm)	40.8	18.5	11.9
P (hPa)	989.9	990.8	1005.2
V (m/s)	8.2	8.4	6.9
R	0.87	0.87	0.97

It is easy to realize a good agreement between observed and calculated values in Koper and Dubrovnik. The agreement is not so good in Split because strong NE wind decreased sea level previously, but it can be seen that the agreement is the best at the end of the situation when air pressure quickly decreases and wind speed increases.

Comparison between model (11) for Koper and result obtained by Michelato (1975) for Venice, was also done. It was noticed that this two-dimensional numerical model for 48 hours SE wind duration and 30 knots final wind velocity gives a similar result like model (11) for Koper.

The maximum values of observed residuals in 1982 are two times higher than mean tidal ranges at all studied stations. Those values are 125, 60 and

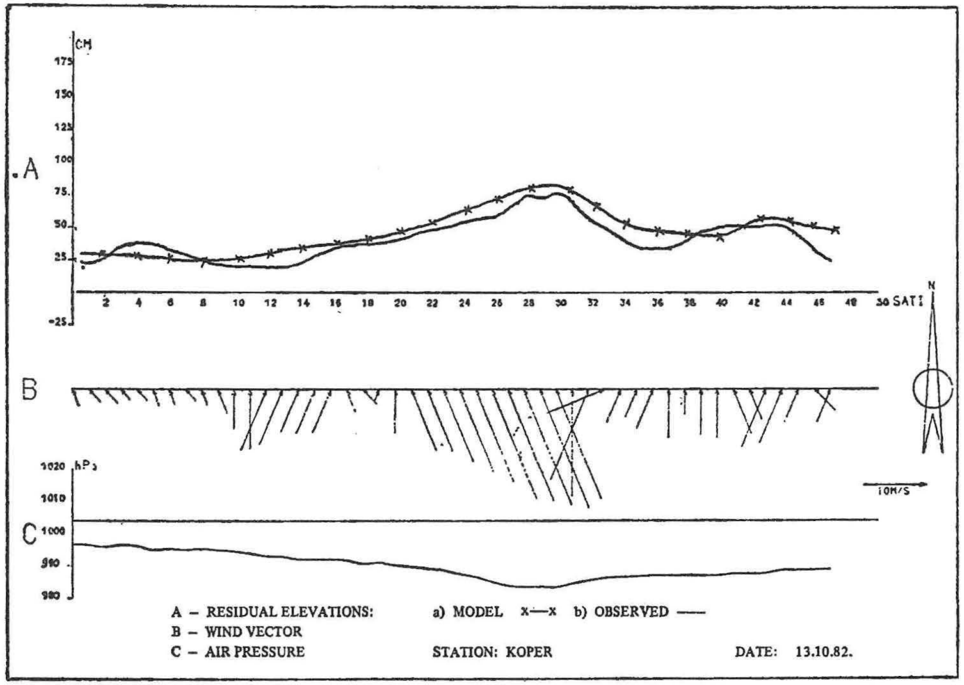

Fig. 6. Comparison between observed and by model calculated residual elevations in Koper, October 13, 1982, 00 GMT

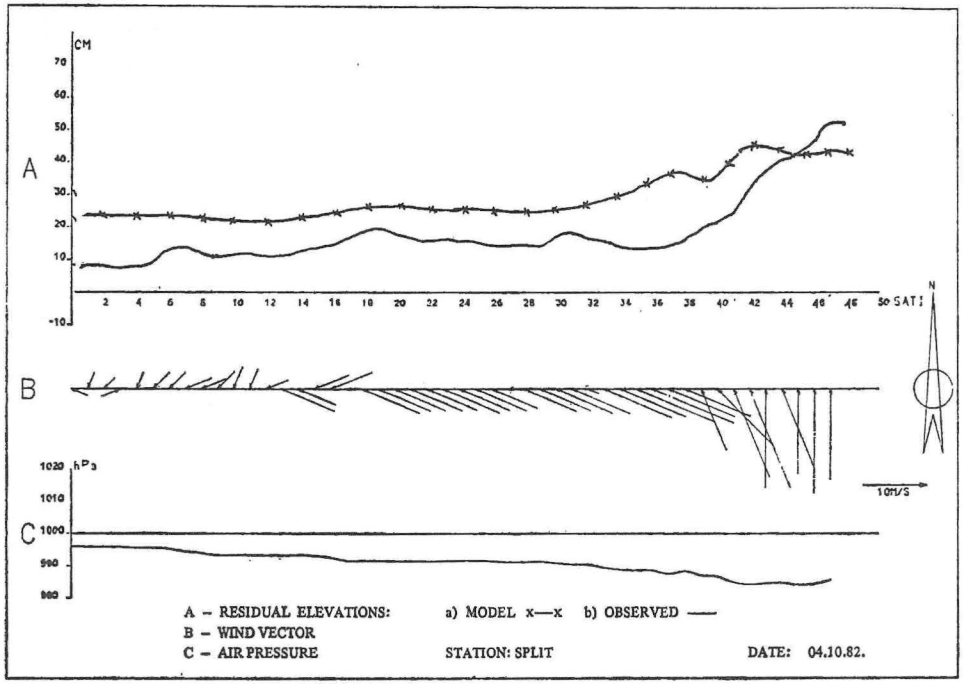

Fig. 7. Comparison between observed and by model calculated residual elevations in Split, October 04, 1982, 18 GMT

55 cm for Koper, Split and Dubrovnik respectively. Residuals increase going towards the North Adriatic Sea because wind fetch increases and depth decreases.

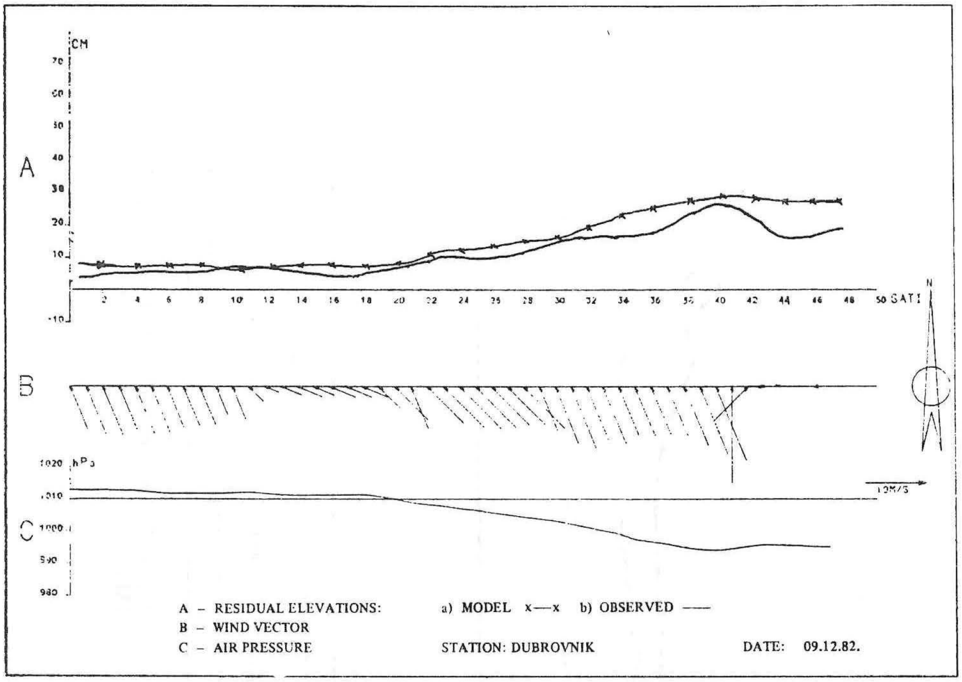

Fig. 8. Comparison between observed and by model calculated residual elevations in Dubrovnik, December 09, 1982, 14 GMT

CONCLUSIONS

Storm surges are a significant part of sea level changes along the eastern coast of the Adriatic Sea, especially during the intensive cyclonic activity, when their values are two times higher than mean tidal ranges.

The most important conclusion of the study here presented is the possibility of the storm surge forecasting at Koper, Split and Dubrovnik by means of very simple stohastic models.

Residuals increase going towards the northern Adriatic Sea because wind fetch increases and depth decreases.

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Accepted: October 26, 1988

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Acta Adriat., 29 (1/2) : 5—20 (1988)

PRISILNE OSCILACIJE NIVOA MORA ZA VRIJEME OLUJNIH CIKLONALNIH PRODORA NA ISTOČNOJ OBALI JADRANA

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KRATKI SADRŽAJ

U ovom radu se istražuju prisilne oscilacije nivoa mora nastale djelovanjem atmosferskih faktora (storm surges) koje se javljaju na istočnoj obali Jadranskog mora za vrijeme olujnih ciklonalnih prodora. Ova istraživanja nemaju samo znanstveni značaj, već i praktičnu vrijednost, jer veći porast nivoa mora dovodi do poplavljivanja obalnog područja, što uzrokuje materijalne štete a ponekad i gubitke ljudskih života.

Za prognozu prisilnih oscilacija nivoa mora na istočnoj obali Jadranskog mora primjenjena je statistička metoda. Na osnovu teorijskih rezultata koji se dobiju rješavanjem jednadžbi gibanja i primjenom metode višestruke regresije razvijeni su modeli za računanje rezidualnog nivoa mora. Bazu podataka su činile satne vrijednosti vektora vjetra, tlaka zraka i nivoa mora za 1982. godinu u Kopru, Splitu i Dubrovniku.

Modeli su testirani za meteorološke situacije sa jakim ciklonalnim jugom. Nađeno je da modeli višestruke regresije predstavljaju vrlo dobru procjenu rezidualnih nivoa mora u meteorološkim situacijama koje se karakteriziraju trajnim padom tlaka zraka i povećanjem brzine juga.

Maksimalne izmjerene vrijednosti rezidualnih nivoa mora u 1982. godini su dva puta veće od srednjih amplituda morskih doba i iznose 125, 60 i 55 cm za Kopar, Split i Dubrovnik.