OCEANOLOGICA ACTA 1986 - VOL. 9 - N° 4

Wind-curl currents in the Northern Adriatic and formulation of bottom friction

Wind-induced currents
Bottom-slope effect
Wind-curl effect
Bottom friction
Northern Adriatic

Courants induits par le vent
Effet de la pente du fond
Effet du rotationnel des vents
Frottement sur le fond
Adriatique Nord

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Received 15/10/85, in revised form 20/1/86, accepted 27/1/86.

ABSTRACT

Wind and current data measured off the northwestern Adriatic coast in November and December 1978 have been analysed. The data have shown that bura—the characteristic winter wind in this area—induces downwind currents over the whole water column. A typical bura impulse of 10-12 m/s induces currents of about 50 cm/s at the surface and 30 cm/s at the bottom. The results of the numerical model of the Northern Adriatic have shown that it is possible to approximate the empirical results if the wind curl, besides the bottom slope, is taken into account. The numerical model has also shown that the alongshore dynamics in the station area can be reasonably well approximated by the balance of surface and bottom stresses. The empirical results and the mentioned balance suggest that, for this part of the Adriatic, the quadratic law for bottom friction is not superior to the linear one. Calculated values of the coefficient of linearized bottom friction ($1.13\text{-}1.24 \times 10^{-3}$ m/s) are in good agreement with values determined previously for the area by other methods.

Oceanol. Acta, 1986, **9**, 4, 425-431.

RÉSUMÉ

Courants du rotationnel des vents et frottement sur le fond dans le nord de l'Adriatique

Des données de vent et de courant ont été enregistrées au large de la côte nord-ouest de l'Adriatique en novembre et décembre 1978. Leur analyse indique que la boura, vent d'hiver caractéristique de cette région, induit des courants dans sa propre direction sur toute la colonne d'eau. Une impulsion de 10-12 m/s provoque des courants dont la vitesse est comprise entre 30 cm/s au fond et 50 cm/s en surface. Les résultats du modèle numérique de l'Adriatique Nord montrent qu'il est possible de retrouver les résultats empiriques en tenant compte d'une part de la pente du fond, et d'autre part du rotationnel de la tension tangentielle du vent. Le modèle numérique montre encore que la dynamique côtière de la zone étudiée peut être décrite en première approximation par l'équilibre entre la tension superficielle et celle du fond. Sur la base du même équilibre et des résultats empiriques, on voit que pour le frottement sur le fond dans l'Adriatique Nord, la loi quadratique n'est pas essentiellement meilleure que la loi linéaire. Les valeurs du coefficient de frottement sur le fond obtenues avec une loi linéaire ($1{,}13\text{-}1{,}24 \times 10^{-3}$ m/s) sont en bon accord avec certaines valeurs déjà obtenues pour la même région par d'autres méthodes.

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INTRODUCTION

It has been shown in a previous paper (Kuzmić *et al.*, 1985) that the wind induces the most pronounced, although transient, component of the Northern Adriatic current field during the colder part of the year. The developed numerical model of the Northern Adriatic has clearly indicated the controlling influence of the shallower zone along the Italian coast. Theoretical results have been compared to empirical data collec-

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ted during the MEDiterranean ALPine EXperiment (MEDALPEX) in spring 1982 at a station close to the Yugoslavian coast. It was found that only the vertical eddy viscosity coefficient of an order of magnitude smaller than the expected literature value could enhance the agreement between the model-generated and measured values. The comparison was performed assuming the homogeneous wind field and linear law of bottom friction. However, the introduction of wind curl as well as nonlinear bottom friction have been recognized as possible ways to improve the predictions.

Since 1978 a number of wind and current measurements have been performed in the Northern Adriatic from the oil-drilling platform Panon. The data taken in winter 1978/1979 at the station close to the northwestern Adriatic coast, which have recently been made available, allow further consideration of the questions posed in the previous work. Namely, the heterogeneity of the wind field over the northwestern Adriatic, which is comparatively better documented, justifies the consideration of the influence of the wind curl on currents in the sea. On the other hand, it seems that the water column in the northwestern coastal zone is characterized by the balance of alongshore surface and bottom stresses, which allows for simple, analytical assessment of the linearity/nonlinearity of bottom friction.

The structure of this paper is organized around the above mentioned considerations. The Panon data are described and analysed in the second section. The study of the wind-curl influence on currents in the Northern Adriatic, by means of a numerical model, is presented in the third section. The fourth section is devoted to analytical modelling and calculation of values of the coefficient of bottom friction for the Panon station area considering linear and quadratic parameterization. Finally, the results are discussed and conclusions drawn in the fifth section, where further research steps are also suggested.

DATA DESCRIPTION AND ANALYSIS

Currents at the Panon station ($\varphi = 45°24.8'N$, $\lambda = 13°01.6'E$, bottom depth 28 m) have been measured at three levels (3 m, 15 m, and 25 m) using Alexaev BPV-2 current meters. The location of the platform and topography of the Northern Adriatic are depicted in Figure 1. The observation period was from 18 November to 22 December 1978, and the sampling interval was 15 minutes. Hourly averages were calculated from the measured values and later used in the analysis. The wind has also been measured at the Panon platform (anemograph SIAP VT-1450 was located 35 m above the sea surface). The analog wind record was used to calculate hourly averages which were used in subsequent analysis.

The wind and current time series were decomposed into components in the Cartesian coordinate system with positive x axis running alongshore (east-northeastward), and positive y axis running onshore (north-northwestward). The series were digitally low-pass filtered in order to damp the oscillations of one day period and shorter. The prime target was, of course, the removal of the tidal signal from the current record. The time series thus obtained are shown in Figure 2. Since the data were collected from the fixed platform, no consideration was given to wave action. The error in the data was assumed to stay within the manufacturer's tolerances (*e.g.* ±1 cm/s for current speed and ±5° for its direction).

Three pulses in the wind record plotted in Figure 2*a* may be distinguished between 27 and 29 November, about 6 December and about 19 December 1978. In all three cases, the direction was west-southwestward, which is direction of the bura wind in the area (Polli, 1956). The daily wind speed averages were occasionally higher than 10 m/s. Analysis of the related synoptic situations (Deutscher Wetterdienst, 1978) revealed the connection between the bura episodes and cyclonic/anticyclonic disturbances over the Europe. In the first case the cyclone over the Gulf of Genova generated two further cyclones, one travelling southeastward over the Tyrrhenian Sea, the other moving over the Northern Adriatic towards the northeast. Simultaneously, the Asiatic anticyclone covered part of the Eastern Europe. The second bura episode coincided with a cyclone travelling over the Tyrrhenian Sea towards the Middle and Eastern Mediterranean; high pressure field dominated the Northern Europe at the time. The third impulse was related to a high pressure field over the Middle Europe and two cyclonic disturbances travelling over the Adriatic Sea.

The time series of currents in Figures 2*b*, 2*c* and 2*d* show the sea response to bura forcing. The maximum current speed at the 3 m level is about 50 cm/s while the 15 m and 25 m level values are near 30 cm/s. That confirms our previous finding that wind-induced currents represent a dominant albeit transient component of the Northern Adriatic current field, a finding which supports earlier empirical (Mazelle, 1915; Mosetti,

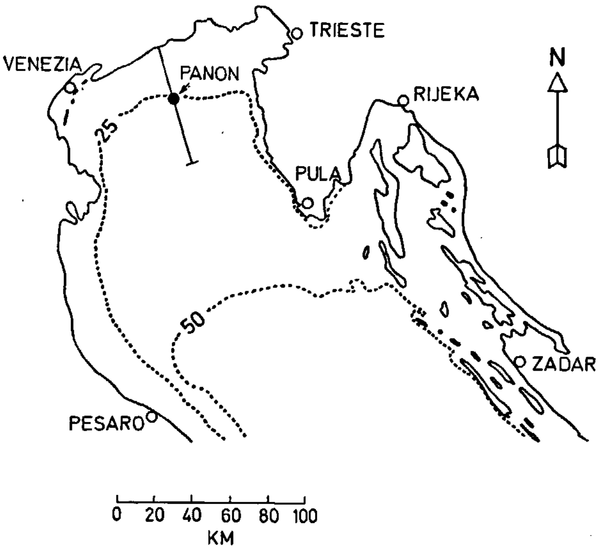

Figure 1

The Northern Adriatic with marked 25 and 50 m isobaths. Also shown is position of the Panon station and the transect for which the numerical model current predictions have been analysed.

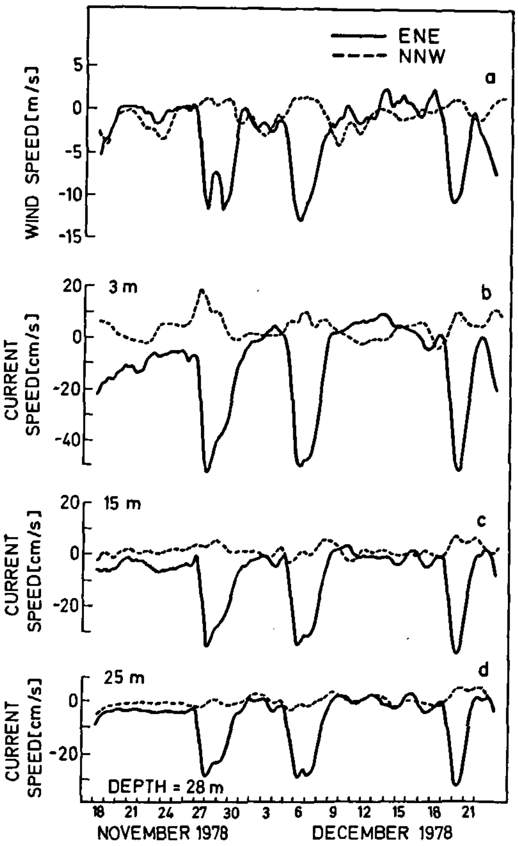

Figure 2

The low-pass filtered (cut-off frequency 0.04 *cph) time series of wind and currents at the Panon station for the period* 18 *November*-22 *December* 1978.

1972) and theoretical (Stravisi, 1977; Malanotte Rizzoli, Bergamasco, 1983) results for this area. The sea response to the wind action is direct: every major peak in the wind series has a counterpart in the current series. It must be concluded that the free oscillations were lacking in the area during the measurement period. The lack of time lag between wind and currents suggests the case of frictionally controlled flow. The fact that the action of bura in the Panon area induces downwind currents throughout the water column suggests that the wind influence is more important for the local dynamics than the alongshore sea-surface slope. This assumption will be tested first by running a numerical model and then by setting up an analytical model for the northwestern Adriatic area.

NUMERICAL MODEL

Our aim is to model the influence of suddenly applied wind on homogeneous, stagnant sea. By neglecting the nonlinear interactions and lateral friction and after introducing the hydrostatic approximation, the f-plane equations of motion and continuity read:

$$\frac{\partial u}{\partial t} - fv = -g\frac{\partial \zeta}{\partial x} + \frac{\partial}{\partial z}\left(N\frac{\partial u}{\partial z}\right) \tag{1.1}$$

$$\frac{\partial v}{\partial t} + fu = -g\frac{\partial \zeta}{\partial y} + \frac{\partial}{\partial z}\left(N\frac{\partial v}{\partial z}\right) \tag{1.2}$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}\int_0^h u\,dz + \frac{\partial}{\partial y}\int_0^h v\,dz = 0, \tag{1.3}$$

where

u, v denote the horizontal components of velocity,

ζ is elevation of the water surface,

h is undisturbed depth of water,

N is the coefficient of vertical eddy viscosity,

f is the Coriolis parameter, and

g is the acceleration of gravity.

The Cartesian coordinates (x and y) are laid at the undisturbed water surface and the z axis is positive downwards. The state of rest is assumed initially ($\zeta = u = v = 0$).

Boundary conditions of the sea surface and the bottom are:

$$-\rho\left(N\frac{\partial u}{\partial z}\right)_0 = \tau_{xs},$$

$$-\rho\left(N\frac{\partial v}{\partial z}\right)_0 = \tau_{ys}\,at\ z=0 \tag{2.1}$$

and

$$-\rho\left(N\frac{\partial u}{\partial z}\right)_h = \tau_{xb},$$

$$-\rho\left(N\frac{\partial v}{\partial z}\right)_h = \tau_{yb}\,at\ z=h \tag{2.2}$$

where the stresses are:

$$\tau_{xs} = K\,\rho_a u_a\sqrt{u_a^2+v_a^2},$$

$$\tau_{xs} = K\,\rho_a v_a\sqrt{u_a^2+v_a^2}\,at\ z=0 \tag{3.1}$$

$$\tau_{xb} = k\,\rho\,u_h, \qquad \tau_{yb} = k\,\rho\,v_h, \qquad at\ z=h \tag{3.2}$$

Here, u_a and v_a are the wind components, u_h and v_h are bottom current components, ρ_a is the density of air, ρ is the density of sea water, K is nondimensional drag coefficient, and k is coefficient of bottom friction. Along the solid boundary zero normal horizontal flow is assumed:

$$(u,\ v)_n = w_n = 0$$

while a radiation condition of the form:

$$\bar{w}_n \pm \sqrt{gh}\frac{\zeta}{h} = 0 \tag{5.1}$$

where overbar denotes the vertical averaging, is postulated at the open boundary. Application of the condition (5.1) does not influence the northmost part of the modelled area (Kuzmić, Orlić, 1985), where the Panon platform was located, although it does introduce unrealistic vectors near the open boundary. Therefore, more general form of the radiation condition, namely

$$\frac{\partial \varphi}{\partial t} \pm c\frac{\partial \varphi}{\partial x} = 0 \tag{5.2}$$

(with φ standing for either the vertically-averaged velocity normal to the open boundary or the sea level, and c being the appropriate phase velocity) has also been tried. More specifically, the first order approximation by Orlanski (1976) and its zeroth order reduction by Camerlengo and O'Brien (1980) have been tested using a difference scheme forward in time and upwind in space. Experiments with condition (5.2) have brought improvements but also some difficulties. Consequently, the condition (5.1) has been used in all runs presented in this paper.

The equations (1) are not solved directly, but using the integral, eigenfunction transformation instead. The eigenfunctions of the vertical boundary value problem are used to decompose the velocity components and the transformed equations of motion and continuity are used to find the appropriate weighting coefficients. The vertical problem is solved analytically for constant eddy viscosity coefficient N, while the horizontal problem is treated numerically. The approach was developed by Heaps (1972, 1973); its major advantage is the possibility to calculate quasi-continuous vertical distribution of velocity and thus obtain required three-dimensionality.

In order to apply the model to the Northern Adriatic, the part of the basin above the line connecting the cites of Pula and Pesaro (Fig. 1) was covered by ortogonal grid of points, as in McHugh (1974). Transformed differential equations of motion and continuity were translated into finite difference equations using the forward-time, staggered-space approximation. Details of the Northern Adriatic model formulation can be found in Kuzmić *et al.* (1985). The spatial step used in discretization was 7.5 km in both horizontal directions. With such a step and maximum depth of 60 m the CFL stability criterion was satisfied with the time step of 120 seconds.

Since the central theme of this paper is the influence of heterogeneity in the wind field on the Northern Adriatic currents, we ran the model using the homogeneous (Fig. 3*a*) and heterogeneous (Fig. 3*b*) wind forcing. The homogeneous wind field was formulated in accord with the wind measured at the Panon station. The simulation of the wind curl over the area required an additional element of information. Climatological statistics (Yoshino, 1972) were used to extract the southwestward wind speed averages for the month of December at six stations along the Northern Adriatic coast (Vedrian, Koper, Poreč, Rovinj, Fažana, Pula). The empirical values from those stations were then interpolated using the method of local procedures (Akima, 1972). Finally, the spatial distribution thus obtained was calibrated so as to get the proper wind speed magnitude at the Panon station. It is quite possible that the direction of bura is closer to the ENE-WSW axis than the NE-SW axis assumed in the model. However, we had at our disposal only statistics for the eight major wind directions and opted for bura blowing southwestward.

Nondimensional coefficient K, in the wind stress equations, was selected equal to 2.5×10^{-3} (Simons, 1980). The vertical eddy viscosity coefficient was set equal to 0.01 m^2/s in accord with the value used in simulation of winter residual circulation in the Adriatic (Hendershott, Rizzoli, 1976). The coefficient of bottom friction k was assumed equal to 0.001 m/s, a value verified later in this paper. The usual values were assigned to other necessary parameters (Coriolis parameter, acceleration of gravity, air density, and sea density).

It should be mentioned here that the density field of the Northern Adriatic is vertically well mixed in winter. Therefore, the assumed sea homogeneity actually implies the neglect of the horizontal density gradients. Aforementioned disregard of the nonlinear terms and lateral friction also seems in order considering the offshore distance of the Panon station and an estimate of the coastal boundary layer width of less than 1 km (Lick, 1976).

Simulations were performed for 48 simulated hours, *i.e.* until viscous balance was attained as found in empirical data. The model-generated currents are presented for the plane crossing the Panon station perpendicularly to the northwestern coast, as indicated in Figure 1. Figure 4*a* contains results for the homogeneous wind, while the heterogeneous case is presented in Figure 4*b*. The Panon station and current meter locations are indicated on both figures. In the figures positive velocity magnitude is east-northeastward, and the negative magnitude is west-southwestward.

In the case of homogeneous wind (Fig. 4*a*) the bottom-slope current is formed over narrow coastal strip and is directed downwind, as would be expected from the well-known analytical results of Weenink (1958). However, at the position of Panon station and the depths of the two lower current meters the model predicts upwind currents—contrary to the empirical evidence. Introduction of curl in the wind field considerably improves the prediction (Fig. 4*b*). With the hete-

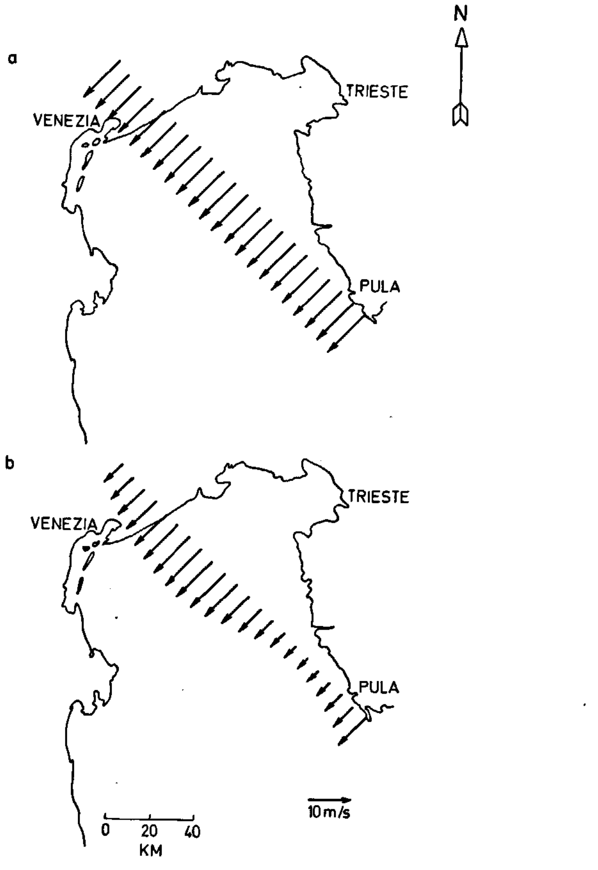

Figure 3

Schematization of the bura wind field over the Northern Adriatic: a) homogeneous field, b) heterogeneous field.

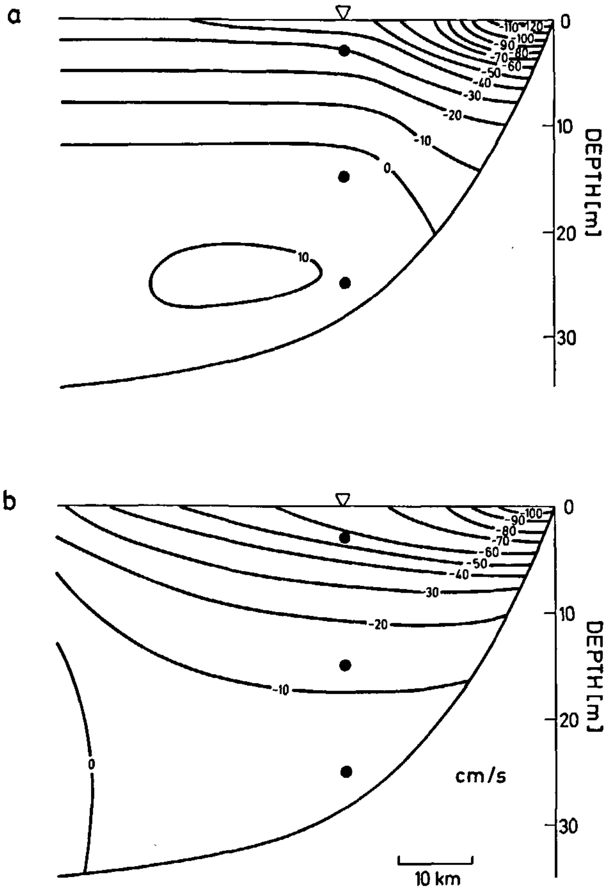

Figure 4

Distribution of simulated velocities in cross-section indicated in Figure 1, for the homogeneous (a) and heterogeneous (b) wind fields. Positive values indicate east-northeastward currents, negative values west-southwestward ones. Also indicated is position of the Panon platform (∇) and locations of current meters (●).

rogeneous wind, at all three current meter depths, more precisely throughout the water column at the Panon location, currents have downwind direction. Furthermore, the magnitude of the surface current is rather realistic. For the middle and bottom current meters the model predicts current magnitudes somewhat lower than the empirical values—a result that will receive further attention in the paper.

It is illuminating to consider also the distribution of the sea-surface elevations as predicted by the model. The results for the case of homogeneous wind are given in Figure 5 *a*. One can readily observe the surface slope directed from the Yugoslavian towards the Italian coast with significant difference between the extremes (cca 40 cm). This difference is reduced in case of heterogeneous wind (Fig. 5 *b*). Formation of internal (offshore) minimum in the middle of the modelled area makes further difference. Similar results have been obtained by Stravisi (1977) who applied a two-dimensional model to the upper northwestern part of the Adriatic Sea. The appearance of this internal sea-surface minimum is particularly interesting since it signifies a diminishing of the alongshore sea-surface gradient at the Panon station—a fact that will be used in formulation of an analytical model for this area.

ANALYTICAL MODEL

Let us set a Cartesian coordinate system, such that the x axis is directed east-northeastward and passing through the Panon station. Next, let us consider the equation (1.1) and see if there are terms that could be locally neglected. It has been shown that the wind-induced currents in the Northern Adriatic are characterized by viscous balance which suggests smaller importance of the term due to local acceleration. Due to the closeness of the northwestern coast one can expect, and empirical data confirm the expectation (*see* Fig. 2), the *v*-component of current to have a small magnitude, which allows elimination of the Coriolis term from the equation. Finally, numerical simulations have shown the alongshore sea surface gradient to be of small magnitude, in the Panon station area, which warrants the disregard of the corresponding term in the equation (1.1). After integration of the remaining term along the vertical, taking into account (2), one gets:

$$\tau_{xb} - \tau_{xs} = 0 \qquad (6)$$

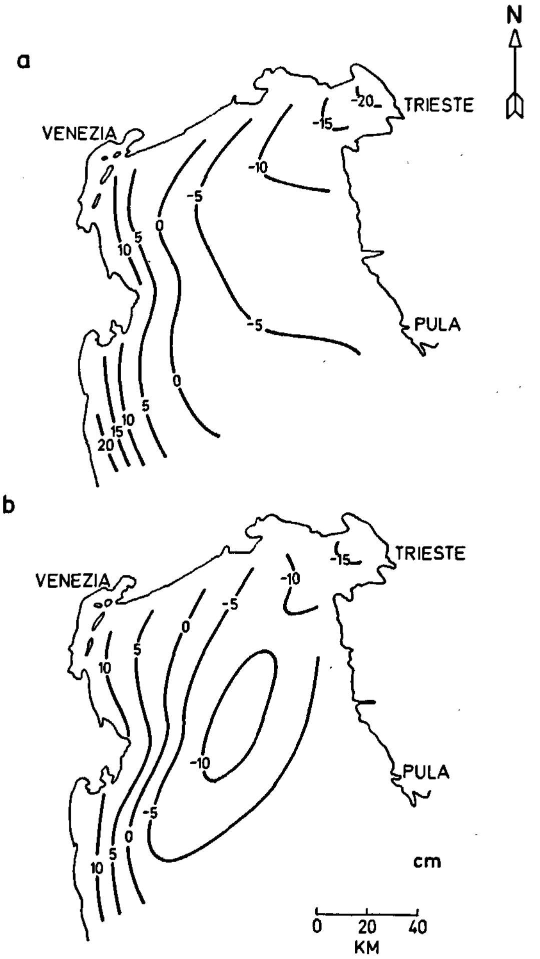

Figure 5

Distribution of the sea levels in the Northern Adriatic for the homogeneous (a) and heterogeneous (b) wind fields.

In other words, alongshore dynamics in the Panon area could be reasonably well approximated by the balance between the surface and bottom stresses. In the balance, friction can be described by either quadratic ($\tau_{xb}=C_D\rho|u_h|u_n|$) or linear ($\tau_{xb}=k\rho u_h$) law; here, C_D denotes the coefficient of nonlinear bottom friction.

The fact that wind speed and direction have been measured at the Panon platform allowed determination of the wind stress at the sea surface. At the other end of the water column, the currents were measured 3 m above the bottom, *i.e.* in the bottom logarithmic layer (Bowden, 1978), permitting the evaluation of the bottom stress.

Following Winant and Beardsley (1979) one can assess the applicability of the linear and quadratic laws of bottom friction to the Northern Adriatic, and also try to calculate magnitudes of the coefficients C_D and k. The model (6) with nonlinear bottom friction suggests the following relation:

$$\rho |u_3| u_3 = a + b\tau_{xs} \qquad (7.1)$$

while the same model with linear bottom friction gives:

$$\rho u_3 = c + d\tau_{xs}. \qquad (7.2)$$

The symbol u_3 denotes *u*-component of current at 3 m above the bottom while *a, b, c* and *d* are coefficients to be determined.

The wind stress is defined using the wind data reduced to standard height (10 m above the water surface) by applying the potential law for neutral atmosphere (Hess, 1959). The left-hand sides in the equations (7) are calculated directly from the data. The correlation coefficients can be used to judge the suitability of the linear relationships (7) and the least square analysis enables one to calculate the coefficients *a, b, c* and *d*. It is readily seen that *b* equals $1/C_{D3}$ and *d* equals $1/k_3$. The 3-metre values can be further used to calculate the values C_{D1} and k_1.

Table

Results of correlation and regression analysis of wind and bottom current data measured at the Panon station. The analysis of days with wind stress higher than 0.01 *N/m*^{2} *is given in the first row; the second row presents results of the analysis of the whole period* (18 *November-*22 *December,* 1978).

Degrees of freedom	Comparison of τ_{xs} with $\rho\|u_3\|u_3$				Comparison of τ_{xs} with ρu_3			
	correlation coefficient	a [Nm^{-2}]	b	C_{D3}	correlation coefficient	c [$kg\ m^{-2}\ s^{-1}$]	d [$m^{-1}s$]	k_3 [ms^{-1}]
10	0.75	2.38	257.35	3.89×10^{-3}	0.76	—18.99	972.07	1.03×10^{-3}
33	0.85	—0.12	243.14	4.11×10^{-3}	0.85	—19.63	967.58	1.03×10^{-3}

The results of correlation and regression analysis are given in the Table. The calculations were performed for days with the stress larger than 0.01 N/m^2 (first row in the Table) and also for all days in the measurements interval (second row in the Table). The correlation coefficients obtained are significantly high, at the confidence level of 95%, and moreover $|a| \ll \rho(u_3)^2_{max}$ and $|c| \ll \rho |u_3|_{max}$. This confirms applicability of the model (6) for the Panon area. It can be seen from the Table that the correlation coefficients for nonlinear formulation of bottom friction are not higher than the ones for the linear case. This leads to the conclusion that in the Northern Adriatic the quadratic law for bottom friction is not superior to the linear one. When the C_D and k values from the table are recalculated for the 1 m depth, assuming the logarithmic law and roughness length of 0.00001-0.01 m, one obtains $C_{D1} = 4.67 - 6.12 \times 10^{-3}$ and $k_1 = 1.13 - 1.24 \times 10^{-3}$ m/s. The described calculation of C_D seems to be the first empirical study of the coefficient for the Northern Adriatic. The obtained values for the coefficient k are in good agreement with the ones calculated from damping of seiches in the Adriatic Sea (Godin, Trotti, 1975), but are lower than those obtained by Caloi (1938) from seiches decay in the Gulf of Trieste.

CONCLUSION

Analysis of wind and current data measured at the Panon station near the northwestern Adriatic coast has shown that the dominant component in the current field is produced by bura—the characteristic winter wind in the area. The sea response is prompt and direct with the current flowing downwind throughout the water column. The numerical model, based on the assumption of viscous balance, has shown the importance of the heterogeneity in the wind field, besides the bottom slope effect, in the development of current field. The model has also shown that the sea-surface alongshore gradient decreases considerably in the northwestern coastal strip enabling the use of simpler analytical model based on alongshore balance of the surface and bottom stresses. Application of the analytical model has shown that the linear and quadratic formulations of bottom friction are of comparable validity for the Northern Adriatic. The analytical model was also used to calculate numerical values of the coefficients in both formulations.

A recurrent discrepancy between the numerical model predictions and empirical results has been observed: the two lower current meters have shown consistently higher velocities than predicted by the model for the same depths. In order to explain this disparity we have performed several numerical experiments varying the value of the vertical eddy viscosity coefficient, N. Lowering the value improves the prediction of near bottom currents but simultaneously spoils the results for the surface layer. This leads to a conclusion that vertically variable eddy viscosity coefficient would improve the prediction.

On the empirical side, of crucial importance are wind measurements over the sea surface. Our modelling studies have shown the importance of the wind-stress curl in the development of the Northern Adriatic currents.

However, the wind data used in those studies came exclusively from terrestrial stations. An array of offshore meteorological buoys is needed to assess the true heterogeneity of the bura over the sea. Another important piece of empirical evidence concerns the benthic boundary layer. Our determination of the nondimensional drag coefficient C_D, as well as the linear coefficient k, has been limited by the lack of knowledge of the true value of roughness length for the Northern Adriatic. Velocity profiles measured in the logarithmic layer would resolve this problem.

Acknowledgements

We thank Mr. Ivo Lukšić for suggesting use of climatological data in determination of heterogeneity of the wind field over the Northern Adriatic. This research has been supported by the Selfmanagement Community of Interest for Scientific Research of SR Croatia.

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