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Predicting the currents in the Northern Adriatic and the problem of ill-defined wind forcing*

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The wind-induced currents in the Northern Adriatic have been studied by present authors using a hydrodynamical numerical model and empirical data collected in the area. In the model, based on linearized equations of motion and continuity, the wind momentum transferred at the sea surface is the only forcing mechanism. The usual quadratic law of the form:

$$(\tau_{xs}, \tau_{ys}) = C_D \rho_a (u_a, v_a) \sqrt{u_a^2 + v_a^2}$$

is used to parameterize the stress (τ_{xs}, τ_{ys}). The parameters in the equation, the drag coefficient (C_D), the air density (ρ_a), and the wind velocity (u_a, v_a) are often taken as constants. In this paper the constant parameters are used to define the starting, reference case; the influence of variability in the parameters, heterogeneous wind field and variable C_D in particular, is then examined. Four output fields, the sea-level displacement, vertically averaged current, surface current, and bottom current have been calculated for each simulated case. The predictions of the four fields differ considerably when the heterogeneous stress field, due to wind curl or drag coefficient, is introduced. Modelling results indicate that inadequate knowledge of the stress field combined with local topographic and coastal influences can produce a factor of two difference in current magnitude and tens of degree difference in current direction.

Predviđanje struja u sjevernom Jadranu i problem neadekvatno definiranog forsiranja vjetrom

U ranijim radovima autori su istraživali vjetrom uzrokovane struje u sjevernom Jadranu pomoću hidrodinamičkog, numeričkog modela i empirijskih podataka sakupljenih u području istraživanja. Korišteni model osniva se na lineariziranim jednadžbama gibanja i kontinuiteta, te djelovanju vjetra na po-

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vršinu mora kao jedinom mehanizmu forsiranja. Trenje (τ_{xs}, τ_{ys}) je parametrizirano pomoću uobičajenog kvadratnog zakona:

$$(\tau_{xs}, \tau_{ys}) = C_D \rho_a (u_a, v_a) \sqrt{u_a^2 + v_a^2}$$

Parametri u jednadžbi, koeficijent trenja (C_D), gustoća zraka (ρ_a) i brzina vjetra (u_a, v_a) često se uzimaju konstantnima. U ovom se radu konstantne vrijednosti ovih parametara koriste samo u početnom, referentnom eksperimentu, a zatim se istražuje utjecaj heterogenog vjetra i varijabilnog koeficijenta trenja. U svakom eksperimentu izračunata su izlazna polja razine, te površinskih, vertikalno usrednjenih i pridnenih struja. Ova se polja znatno mijenjaju uvođenjem heterogenog polja napetosti vjetra preko rotora vjetra i varijabilnog koeficijenta trenja. Rezultati modeliranja ukazuju da nepotpuno poznavanje polja napetosti vjetra, kombinirano s lokalnim topografskim i obalnim utjecajima, može izazvati dvostruko veće ili manje iznose stuja te desetine stupnjeva razlike u smjeru, u istoj točki istraživanog područja.

1. Introduction

Wind-induced motions in the Northern Adriatic have been the subject of several empirical and modelling studies (Mosetti, 1972; Stravisi, 1977; Malanotte-Rizzoli and Bergamasco, 1983; Kuzmić et al., 1985; Orlić et al., 1986). In our modelling studies of the area we have used a three-dimensional, linear, barotropic model applicable to winter, homogeneous conditions outside the coastal boundary layer. The only forcing mechanism in the model is momentum transfer at the air-sea interface. Therefore, the way and accuracy with which this transfer is modelled is of utmost importance for overall performance of the model, and validity of its predictions.

Confronted with present incomplete understanding of the momentum transfer at the interface and the need to predict wind-induced motions, we have modelled wind stress at the sea surface using the bulk coefficient approach in the usual form of quadratic law. Such a formulation of the wind stress allows for variability in the wind velocity, air density and drag coefficient. Throughout this paper the word variability will be used to designate spatial change only. The temporal change, although acknowledged, is not considered. When assessing the stress variability it is appropriate to distinguish between known, natural variability of parameters influencing the stress, and artificial variability, the differences in value of those parameters, due to our incomplete understanding. The dependence of air density on temperature and pressure is an example of the former, since that relation is understood well, while velocity and drag coefficient, entering the stress formula, could vary for both reasons.

The purpose of this paper is an assessment of the wind stress representation in our previous modelling studies of wind-induced currents in the Northern Adriatic. Particular attention is paid to the variability of the drag coefficient and heterogeneity of the wind field, and their influence on the model-generated current fields. To that end the mathematical model and the modelled area are briefly presented first. Three numerical, computer experiments, designed to assess the effects of the mentioned variabilities, are then presented and results of the simulations discussed.

2. Mathematical model and the modelled area

Adequacy of the forcing function has been studied on a model in which the wind forcing is suddenly applied at the surface of a homogeneous, stagnant sea. If the nonlinear terms and lateral friction are neglected, and the hydrostatic approximation is made, the f-plane equations of motion and continuity read:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x} \int_0^h u \mathrm{d}z + \frac{\partial}{\partial y} \int_0^h v \mathrm{d}z = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} - fv = -g \frac{\partial \zeta}{\partial x} + \frac{\partial}{\partial z} (\mathrm{N} \frac{\partial u}{\partial z}) \tag{2}$$

$$\frac{\partial v}{\partial t} + fu = -g \frac{\partial \zeta}{\partial y} + \frac{\partial}{\partial z} (\mathrm{N} \frac{\partial v}{\partial z}) \tag{3}$$

where t denotes time,
ζ is the elevation of the water surface,
u,v are the horizontal components of current at depth z,
h is the 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 coordinate axes (x and y) are located at the undisturbed sea surface while the z axis is positive downwards. The state of rest is assumed initially ($\zeta = u = v = 0$).

Boundary conditions at the surface and bottom are, respectively:

$$-\rho \left(N \frac{\partial u}{\partial z}\right)_0 = \tau_{xs}, \qquad -\rho \left(N \frac{\partial v}{\partial z}\right)_0 = \tau_{ys} \tag{4}$$

and

$$-\rho \left(N \frac{\partial u}{\partial z}\right)_h = \tau_{xb}, \qquad -\rho \left(N \frac{\partial v}{\partial z}\right)_h = \tau_{yb} \tag{5}$$

The surface and bottom stresses used in the above formulas are further defined as:

$$\tau_{xs} = C_D \, \rho_a \, u_a \sqrt{u_a^2 + v_a^2} \,, \qquad \tau_{ys} = C_D \, \rho_a \, v_a \sqrt{u_a^2 + v_a^2} \tag{6}$$

and

$$\tau_{xb} = k \rho u_h, \qquad \tau_{yb} = k \rho v_h \tag{7}$$

Here, the u_a and v_a are the wind velocity components, u_h and v_h are the bottom current components, ρ_a is the air density, ρ is the sea water density, C_D is nondimensional drag coefficient, and k is the coefficient of bottom friction. Physically realistic requirement of no normal horizontal flow is enforced along the solid, coastal boundary:

$$(u,v)_n = w_n = 0 \tag{8}$$

while a radiation condition of the form:

$$\overline{w}_n + \sqrt{gh}\,\frac{\zeta}{h} = 0 \tag{9}$$

is postulated at the open boundary. In the latter equation overbar denotes vertical averaging.

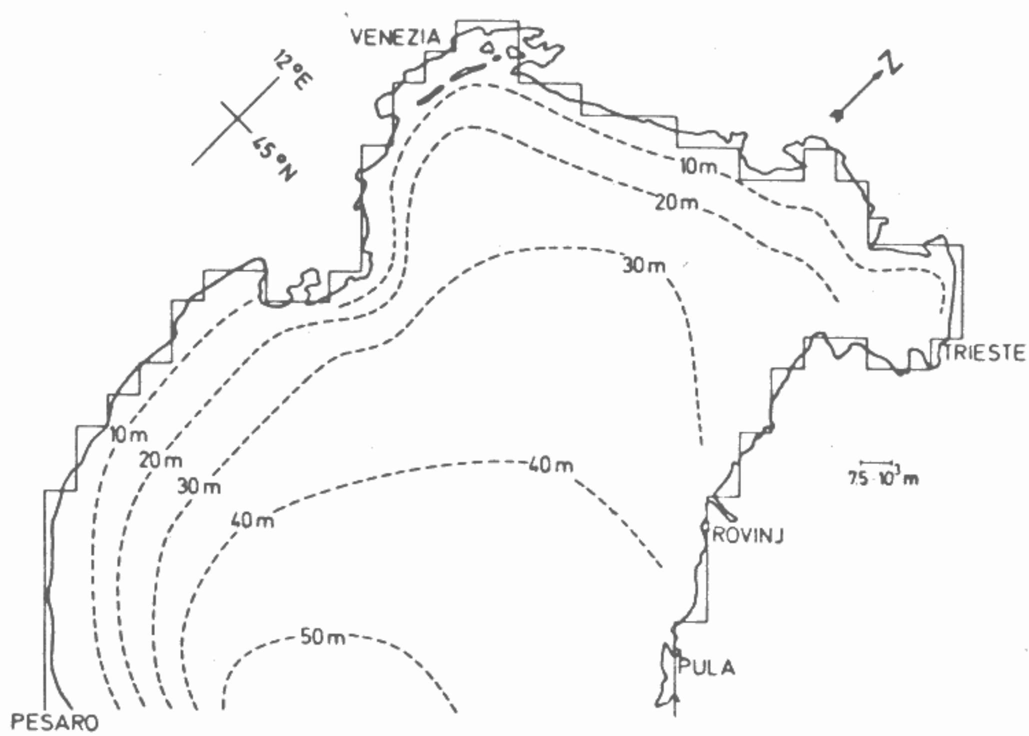

Figure 1. Geometry and bottom topography of the Northern Adriatic with model boundaries.

Before the numerical solution is attempted the equations (1) – (3) are transformed using the eigenfunction method developed by Heaps (1972). Its major advantage is the possibility to calculate quasi-continuous vertical distribution of currents by decomposition into vertical modes. Ten modes were used in all simulations presented later in this paper. The transformed equations are solved numerically using a forward-time, staggered-space finite difference scheme.

The model was then applied to the Northern Adriatic. To that end the part of the basin above the line connecting the cities of Pula and Pesaro (Figure 1) was covered by an ortogonal grid of points with spatial step of 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 2 minutes. Further details of the Northern Adriatic model formulation can be found in Kuzmić et al. (1985).

3. Modelling experiments and results

As pointed out in the introduction the momentum transfer at the air-sea interface is the only forcing function considered in our model. The surface stress produced by the wind is modelled using the quadratic law given by (6). The parameters used in (6) are often taken as constants although none of them actually is. Their natural or artificial variability, however, does not influence variability of the wind stress to the same degree. For example, variability of air density over expected temperature and pressure ranges is small enough to be safely ignored. Variability of the wind field, on the other hand, is a more difficult problem. It could be due to natural heterogeneity of the wind over particular area, but also due to inadequate knowledge and consequent error in evaluation of numerical values. Indeed, climatological data compiled by Yoshino (1972) suggest heterogeneity of the wind over the Northern Adriatic (wind-induced currents due to the wind--curl synthesized after Yoshino's data have been modelled by Kuzmić and Orlić, 1987). But, that as well as most other data sets available for the Northern Adriatic were collected at coastal stations. It has been established by several investigators (e.g. Schwing and Blanton, 1984) that the winds over land and marine surfaces differ in direction and magnitude, so that the use of one kind of measurements for the other could be erroneous.

The last of the three parameters, the drag coefficient, has attracted much more attention than the other two. Over the last fifty years huge amount of data has been collected and number of papers published discussing the coefficient and its variability. Older works (see e.g. Sverdrup et al., 1946) tend to suggest that this factor is constant for moderate to strong winds and equal to 2.6×10^{-3}. On the other hand there seems to be an agreement among contemporary researchers that its value increases with wind velocity, at least for moderate winds (see e.g. the reviews by Garratt, 1977, or Amorocho and DeVries, 1980). Although numerous authors agree on the increase with increasing wind speed, a variety of functional forms has been proposed to quantitatively describe the change. Dependence on parameters other than wind speed has also been suggested (e.g. Hsu, 1986). Some selected older and more recent data on drag coefficient variability with wind speed are presented in Figure 2.

Having briefly discussed variabilities related to wind forcing we will now consider in more detail three particular numerical experiments. They are selected to illustrate those variabilities using the example of the Northern Adriatic. The three experiments

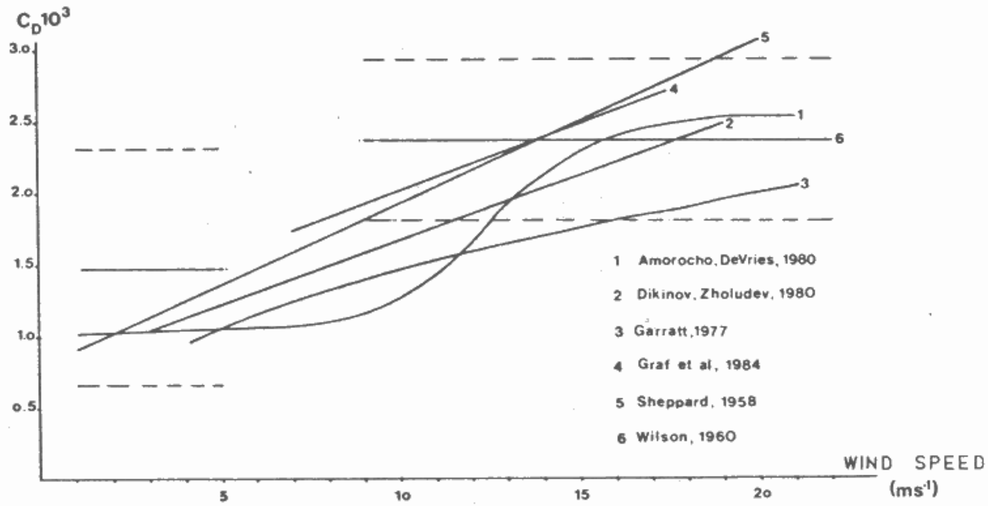

Figure 2. Dependence of the drag coefficient on wind speed.

differ only in the applied wind-stress field – all other parameters have been kept unchanged. In all three cases an offshore, NE wind, locally known as bura, is simulated, but:

A) In the first experiment uniform, homogeneous wind of 12 m/s is assumed; that speed, air density of 1.247 kg/m^3 and drag coefficient equal to 2.5 x 10^{-3} (selected after Simons, 1980) yield a constant wind stress of 0.46 N/m^2.

B) In the second experiment heterogeneous wind is simulated using the climatological data compiled by Yoshino (1972) and the same values for ρ_a and C_D as in the first experiment. Details about the procedure employed to obtain the stress information needed in the model may be found in Orlić et al. (1986).

C) In the third experiment the same heterogeneous wind field is combined with a wind-speed dependent drag coefficient – particular formula proposed by Amorocho and DeVries (1980) is used:

$$C_D = (1.04 + 1.5\,(1 + \exp(-(|u_a| - 12.5)/1.56))^{-1}) \times 10^{-3} \qquad (10)$$

This equation is also presented graphically in Figure 2.

In all experiments the wind stress was suddenly applied and then kept unchanged. After 48 hours of simulated time four output fields, namely the sea-level displacement, surface, vertically averaged and bottom currents are typically plotted and used in the analysis. Detailed vertical distribution of currents at twenty selected points is also calculated. However, only composite plot of the surface and bottom currents for the three cases and three selected points is presented in this paper (Figure 3). The three points, out of more than 350 used in calculation, are: one off the northwestern Italian coast, another in the middle of the basin, and the third one off the Istrian coast. The shape of the stress function for each case is plotted in the right margin of the figure. The plot summarizes well the difference between homogeneous and heterogeneous wind (A vs B) and between the constant and variable drag coefficient (B vs C). Let us look at the surface first. All three points are outside shallow coastal strip, where topographic gradients are significant, so A vectors are very much alike. The heterogeneous wind, however, results in a considerable change of magnitude and direction (B vectors). Variable drag coefficient affects primarily magnitude, but at the central point one can observe a significant directional change as well (C vectors). Near the bottom the situation is similar although the currents are of smaller magnitude (in the figure bottom currents are magnified five times compared to the surface ones). Current vectors induced by homogeneous wind

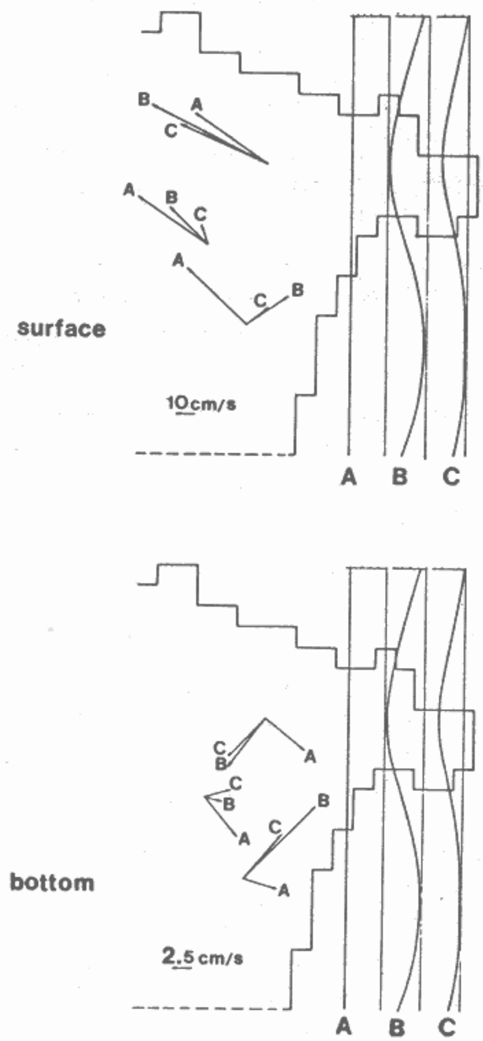

Figure 3. Model-generated currents at the three selected points for the three investigated wind-stress functions.

(A vectors) are most similar to each other, although the difference is more pronounced than at the surface. Heterogeneous wind (the wind curl) reverses direction of the bottom current completely when one goes from the upper to the lower point, with considerable magnitude variation as well (B vectors). Response to variable drag coefficient visibly affects both the magnitude and direction of bottom currents (C vectors). This figure clearly demonstrates that the same variability in the stress field (either natural or artificial) can induce different current changes in different parts of the basin, which presents a warning against one-point verification procedures.

In conclusion of this preliminary study several points should be underlined:

a) the wind stress is an important parameter in numerical, oceanographic models, which critically depends on our knowledge of particular wind field and the drag coefficient used in parameterization;

b) the true wind field over the Adriatic Sea, to the best of our knowledge, is presently not known in enough detail and with the accuracy required by numerical models;

c) the drag coefficient seems to be a complex function of various parameters which makes its determination difficult in general, as well as in the particular case of the Northern Adriatic;

d) modelling results from the Northern Adriatic study indicate that inadequate knowledge of the stress field combined with local topographic and coastal influences can produce a factor of two difference in curent magnitude and tens of degress difference in direction.

However, despite the lack of empirical data and consequent uncertainity in model predictions, computer modelling combined with careful analytical studies and field data verification is still the most powerful way to tackle problems. In this regard presented problems should be taken as an invitation for better and more numerous measurements.

References

Amorocho J. and DeVries J.J. (1980). A new evaluation of the wind stress coefficient over water surfaces, Journal of Geophysical Research, **85**, 433–442.

Dikinov Kh. Zh. and Zholudev V.D. (1980). On calculations of the drag coefficient and wind stress at the sea surface (in Russian). Okeanologija, **20**, 837-843.

Garratt J. R. (1977). Review of drag coefficients over oceans and continents, Monthly Weather Review, **105**, 915–929.

Graf W. H., Merzi N. and Perrinjaquet C. (1984). Aerodynamic drag measured at a nearshore platform on lake of Geneva, Archives for Meteorology, Geophysics and Bioclimatology, **33A**, 151–173.

Heaps N. S. (1972). On the numerical solution of the three-dimensional hydrodynamical equations for tides and storm surges, Mémoires Société Royale des Sciences de Liège, **6/1**, 143–180.

Hsu S. A. (1986). A mechanism for the increase of wind stress (drag) coefficient with wind speed over water surfaces: a parametric model, Journal of Physical Oceanography, **16**, 144–150.

Kuzmić M., Orlić M., Karabeg M., and Jeftić Lj. (1985). An investigation of wind-driven topographically controlled motions in the Northern Adriatic, Estuarine Coastal and Shelf Science, **21**, 481–499.

Kuzmić M. and Orlić M. (1987). Wind-induced vertical shearing: ALPEX/MEDALPEX data and modelling exercise, Annales Geophysicae, **B5**, 103–112.

Malonotte-Rizzoli P. and Bergamasco A. (1983). The dynamics of the coastal region of the northern Adriatic Sea, Journal of Physical Oceanography, **13**, 1105–1130.

Mosetti F. (1972). Alcune ricerche sulle correnti nel golfo di Trieste, Rivista Italiana di Geofisica, **21**, 33–38.

Orlić M., Kuzmić M., and Vučak Z. (1986). Wind-curl currents in the Northern Adriatic and formulation of bottom friction, Oceanologica Acta, **9**, 425–431.

Schwing F. B. and Blanton J. O. (1984). The use of the land and sea base wind data in a simple circulation model, Journal of Physical Oceanography, **14**, 193–197.

Sheppard P. A. (1958). Transfer across the earth's surface and through the air above, Quarterly Journal of the Royal Meteorological Society, **84**, 205–224.

Simons T. J. (1980). Circulation models of lakes and inland seas, Canadian Bulletin of Fischeries and Aquatic Sciences, **203**, 1–146.

Stravisi F. (1977). Bora driven circulation in Northern Adriatic, Bolletino di Geofisica Teorica ed Applicata, **19**, 95–102.

Sverdrup H. U., Johnson M. W. and Fleming R. H. (1946). The Oceans, Prentice Hall, New York, 489–511.

Wilson B. W. (1960). Note on surface wind stress over water at low and high wind speeds, Journal of Geophysical Research, **65**, 3377–3382.

Yoshino M. M. (1972). Monthly mean wind frequency and force by directions at the selected climatological stations in Yugoslavia, Climatological Notes, **10**, 23–44.