| | | |
|---|---|---|
| **ISSN: 0001-5113**<br>**AADRAY** | **ACTA ADRIAT,**<br>**38 (2): 31-43, 1997** | **UDC: 551.468 (262.3)**<br>**Original scientific paper** |

# The wind effect on the Kaštela Bay current field

Gordana BEG PAKLAR and Miroslav GAČIĆ*

*Institute of Oceanography and Fisheries, Split, Croatia*
**Osservatorio Geofisico Sperimentale, Trieste, Italy*

*The effect of winds on current field of Kaštela Bay at the synoptic scale was analyzed. The analyses were based on the data of four current measurement experiments carried out between 1982 and 1990 and respective wind data at the nearby meteorological station Split-Marjan.*

*In order to explain the characteristics of the Kaštela Bay, current field on the synoptic scale in terms of linear dynamics, two simple dynamic balances (viscous and EKMAN) were tested. The results of testing of dynamic balances were positive only for the stations in the bay interior. The testing of EKMAN balance for two stations in the bay interior gave appropriate signs and orders of magnitude for respective terms of the equation of motion. The results of the coefficients of bottom friction were satisfactory for one central bay station, assuming the viscous balance and linear parametrization of bottom friction.The value obtained for the bottom friction coefficients was* $1.98x10^{-3}$ $ms^{-1}$. *The negative correlations between winds and currents obtained in the bottom layer at most stations in the bay inlet, suggesting two-layer circulation, indicating the importance of the pressure gradient force.*

*The calculations of the exchange rate through the bay inlet give the values of 2500 to 3000* $m^3s^{-1}$ *at a wind speed of 10* $ms^{-1}$ *and respective flushing periods of 6 and 5 days.*

## INTRODUCTION

Kaštela Bay is small semienclosed bay on the eastern Adriatic coast with total area of 61 $km^2$ and mean depth of about 23 m (Fig. 1). The bay communicates with the adjacent sea through a relatively wide (1.8 km) and deep mouth (mean depth about 40 m). The basin depths increase from the coast to the opening, reaching about 50 m.

The great importance of wind forcing on the Kaštela Bay current field has been observed from the results of several empirical analyses (ZORE-ARMANDA, 1980; GAČIĆ, 1982). The EOF analysis showed that up to 70 % of the current field variance in the inlet can be explained as consequence of local wind forcing. The response of the current field in the bay inlet to the wind forcing can be described by a two-layer model during homogenious conditions (GAČIĆ *et al.*, 1987). Beside time series current analysis, wind induced currents in the Kaštela Bay have also been examined by numerical models. A three-dimensional numerical model showed considerable influence of complex topography on the currents induced by two most frequent wind systems, bora (NE) and scirocco (SE) (ORLIĆ *et al.*, 1989; BONE *et al.*, 1992). During four field experiments, of approximately two month duration, undertaken between 1982 and 1990, currents were measured at three and two stations in the bay inlet and in the bay interior respectively. It was attempted in this paper to obtain spatial distribution of wind induced current vectors in the bay and to explain it on terms of linear dynamics. Low-pass filtered current meter data and appropriate wind data collected at the nearby metereological station Split - Marjan (Fig. 1) were analysed only for the episodes with filtered wind speed over 5 ms$^{-1}$. Spectral analyses of the Kaštela Bay current field show that the energy maximum occurs in the periods of several days which are connected with local wind forcing (GAČIĆ, 1982). So, it is realistically to expect that in the periods with filtered wind speed over 5 ms$^{-1}$ wind induced currents prevail over all other components of the Kaštela Bay current field. Two simple dynamic balances were tested: EKMAN balance, between surface wind stress and CORIOLIS force, and viscous balance, between surface wind stress and bottom friction (ALLEN and KUNDU, 1978; ALLEN and SMITH, 1981). In addition to the testing of simple dynamic balances, water exchange through the bay inlet was examined.

## METHODS OF DATA PROCESSING

Currents in four field experiments carried out between 1982 and 1990 were measured at five stations in Kaštela Bay using 'AANDERAA' RCM4 current meters (Table 1, Fig. 1). Sampling intervals were 10 minutes. Hourly means were calculated from measured values and later used in analysis. Respective hourly means of wind data were available from the meteorological station in the close vicinity (Fig. 1).

The right-handed coordinate system used is oriented with the positive x axis toward east (E), and the positive y axis toward north (N). The bay inlet axis is oriented east-west, so eastward current components represent out- flowing current. East ($\tau_u$) and north ($\tau_v$) wind stress components were obtained from:

$$\tau_u = c_w \rho_a u_w (u_w^2 + v_w^2)^{1/2}, \qquad (1)$$

$$\tau_v = c_w \rho_a v_w (u_w^2 + v_w^2)^{1/2}, \qquad (2)$$

where $u_w$ and $v_w$ are east and north wind speed components, $c_w$ is drag coefficient and $\rho_a$ is air density. Drag coefficient is obtained from the following relation (PUGH, 1987):

$$c_w = 10^{-3}(0.63 + lw), \quad 2.5\ ms^{-1} \le w \le 21\ ms^{-1} \qquad (3)$$

with

$$l = 0.066\ sm^{-1} \qquad (4)$$

where $w$ is assumed to be wind speed from the meteorological station Split-Marjan (GAČIĆ *et al.*, 1991).

*Table 1. Current measurement experiments in Kaštela Bay between 1982 to 1990*

| | |
|---|---|
| September 22 - November 4, 1982 | Station 1: 8, 20, 30, 40 m<br>Station 2: 8, 15, 22 m |
| April 28 - July 7, 1988 | Station 3: 5, 20, 30 m |
| August 11 - October 20, 1988 | Station 3: 5, 30 m |
| March 3 - May 12, 1989 | Station 3: 5, 30 m<br>Station 4: 5, 30 m<br>Station 5: 5, 30 m |
| October 16 - December 19, 1990 | Station 3: 5, 2o, 30 m |

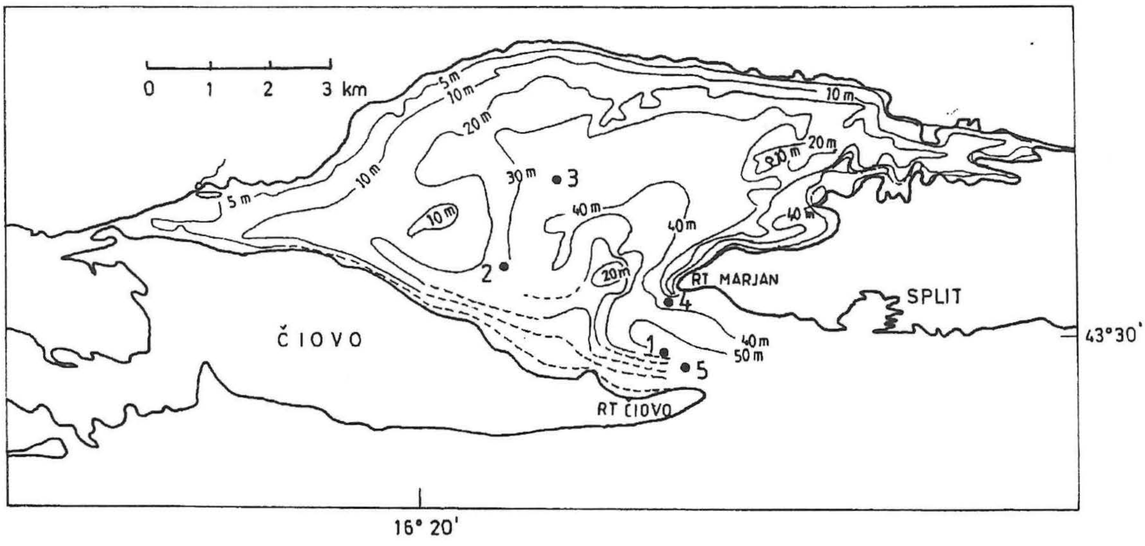



*Fig. 1. The map of Kaštela Bay with locations of current meter moorings (1-5). The meteorological station Split-Marjan is marked by a rectangle*

Tidal (diurnal and semi-diurnal) and other daily oscillations were removed from both current and wind time-series by means of a digital low-pass filter "24m214" (THOMPSON, 1983).

Current meter data and appropriate wind stress data were analyzed only for episodes with filtered wind speed exceeding 5 $ms^{-1}$ because it is realistically to expect that the wind induced currents then prevail over all other components of the Kaštela Bay current field (GAČIĆ, 1982). In order to explain current field response to the wind forcing in terms of linear dynamics, two simple dynamic balances were tested: viscous balance between surface wind stress and bottom friction, and EKMAN balance between surface wind stress and CORIOLIS force. The correlation matrix was calculated and appropriate terms from the equation of motion were compared:

$$-f\vec{c}\times\vec{k} = -g\Delta\zeta + \frac{\vec{\tau}}{\rho H} - \frac{\vec{\tau}_b}{\rho H}, \qquad (5)$$

where **f** is the CORIOLIS parameter, $\vec{c}$ is vertically averaged velocity, $\vec{k}$ is unit vector in z direction, **g** is the acceleration of gravity, $\zeta$ is the elevation of the water surface, $\vec{\tau}$ is the surface wind stress, $\vec{\tau}_b$ is the bottom friction, $\rho$ is the density of sea water and H is the depth. Testing of EKMAN balance was performed by comparing orders of magnitude of time averages of the appropriate terms in (5):

$$-f\vec{c}\times\vec{k} = \frac{\vec{\tau}}{\rho H}. \qquad (6)$$

Vertically averaged velocity was estimated by the trapezoidal rule for the experiments with good vertical resolution (minimum 3 measurements along a vertical). For example the vertically averaged E component of velocity for measurements in the four levels was estimated as:

$$U = \frac{1}{10}[u_0 + 2(u_1 + u_2 + u_3 + u_4) + u_{-H}] \qquad (7)$$

where $u_i$ $(i=1,...,4)$ are time averages of E velocity component in situations with filtered wind speed exceeding 5 $ms^{-1}$. Surface current $u_0$ is assumed to be equal to the current measured on the first level and bottom current $u_{-H}$ is assumed to be zero. For the situations with positive and significant correlation between E current and E wind stress components or between N current and N wind stress component in the whole water column, viscous balance was tested (WINANT and BEARDSLEY, 1979). Equation (5) with viscous balance gives:

$$\vec{\tau} - \vec{\tau}_b = 0, \tag{8}$$

Henceforth only the E direction will be considered, while in the N direction the equations are analogous. The dependence of bottom friction on bottom current can be assumed as linear:

$$\tau_{ub} = \rho\, r u \tag{9}$$

Following WINANT and BEARDSLEY (1979) the bottom stress is assumed to be a dependent variable and the wind stress an independent variable:

$$u = a\tau_u + b, \tag{10}$$

with

$$a = \frac{1}{\rho\, r} \tag{11}$$

Obtained results were compared with known results for the coefficient of bottom friction (WINANT and BEARDSLEY, 1979; ORLIĆ *et al.*, 1986).

## RESULTS AND DISCUSSION

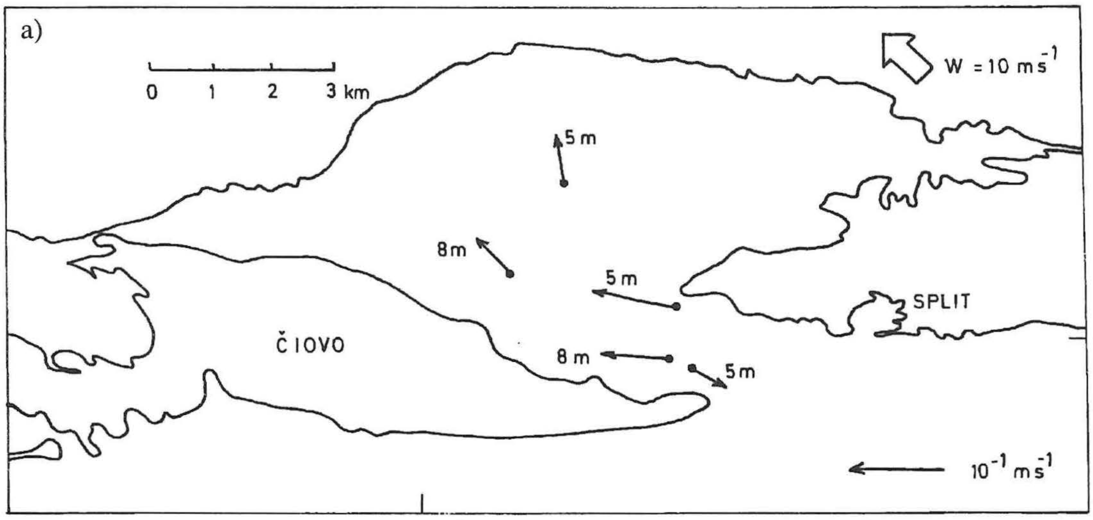
### Spatial distribution of the wind induced currents

Statistical analyses for the current measurement experiments were made for the periods with filtered wind speeds exceeding 5 $ms^{-1}$ (Table 2). High mean values were obtained for the surface and bottom layers at station 1 with strong polarization in the east-west direction. Small current means were obtained at interior bay stations 2 and 3 . Relatively higher standard deviations of N current component at the interior bay stations are related to high standard deviations of N wind stress component. The E current component in the surface layer at station 4 is much stronger than the N current component due to the orientation of the bay inlet (east-west). At 30 m depth the difference between E and N component is not significant, although the standard deviation is higher in the E direction. At station 5 the situation is quite opposite. In the surface layer, values of E and N components are similar, while in the bottom layer E current component is significantly higher.

Beside calculating averaged current vectors using all available data in periods with wind speed exceeding 5 $ms^{-1}$, averaged current vectors during two most frequent wind systems scirocco (SE) and bora (NE) were also calculated. Figs. 2a and 2b show averaged current vectors in surface and bottom layer obtained in the periods with scirocco wind speed exceeding 5 $ms^{-1}$. Empirical results gave an incoming flow of 10 $cms^{-1}$ in the whole surface layer of the bay inlet, except along south coast where current is upwind. Outgoing flow of approximately 10 $cms^{-1}$ is recorded in the whole bottom layer, except along the north coast of the bay inlet. The same current structure was obtained from detailed analyses of hydrographic properties during scirocco wind (ZORE-ARMANDA, 1980). Currents at the

*Table 2. Means and standard deviations of the wind and current meter data in the period with wind speed exceeding 5 $ms^{-1}$*

| | means | | standard deviations | | number of data |
|---|---|---|---|---|---|
| | E | N | E | N | |
| station (1) wind strees [$x10^{-3}$ $Nm^{-2}$] | -52.30 | 27.90 | 29.68 | 28.93 | 125 |
| current speed [$x1o^{-2}$ $ms^{-1}$] | | | | | |
| 8 m | -6.73 | 1.28 | 4.40 | 1.00 | 125 |
| 20 m | 0.13 | 0.09 | 2.00 | 1.30 | 125 |
| 30 m | 6.90 | -1.11 | 2.85 | 0.77 | 125 |
| 40 m | 10.01 | -2.64 | 8.19 | 2.64 | 125 |
| station (2) wind strees [$x10^{-3}$ $Nm^{-2}$] | -52.30 | 27.90 | 29.68 | 28.93 | 125 |
| current speed [$x1o^{-2}$ $ms^{-1}$] | | | | | |
| 8 m | -3.09 | 4.52 | 2.38 | 2.35 | 125 |
| 15 m | -0.58 | 3.43 | 1.23 | 2.57 | 125 |
| 22 m | 0.95 | 1.19 | 1.47 | 1.72 | 125 |
| station (3) wind strees [$x10^{-3}$ $Nm^{-2}$] | -52.90 | -4.54 | 37.01 | 56.65 | 1992 |
| 5 m | -0.85 | 2.26 | 3.48 | 4.88 | 1992 |
| 20 m | 3.06 | 1.96 | 2.56 | 3.18 | 1097 |
| 30 m | 2.05 | -0.08 | 2.50 | 3.04 | 1800 |
| station (4) wind strees [$x10^{-3}$ $Nm^{-2}$] | -54.00 | 6.18 | 43.74 | 44.75 | 695 |
| current speed [$x1o^{-2}$ ms-1] | | | | | |
| 5 m | -6.83 | 1.04 | 6.13 | 4.75 | 503 |
| 30 m | -4.78 | 4.78 | 2.32 | 1.56 | 225 |
| Station (5) wind strees [$x10^{-3}$ $Nm^{-2}$] | -54.00 | 6.18 | 43.74 | 44.75 | 695 |
| current speed [$x1o^{-2}$ $ms^{-1}$] | | | | | |
| 5 m | 3.00 | -1.77 | 4.76 | 2.87 | 694 |
| 30 m | 8.90 | 2.48 | 6.99 | 1.33 | 611 |



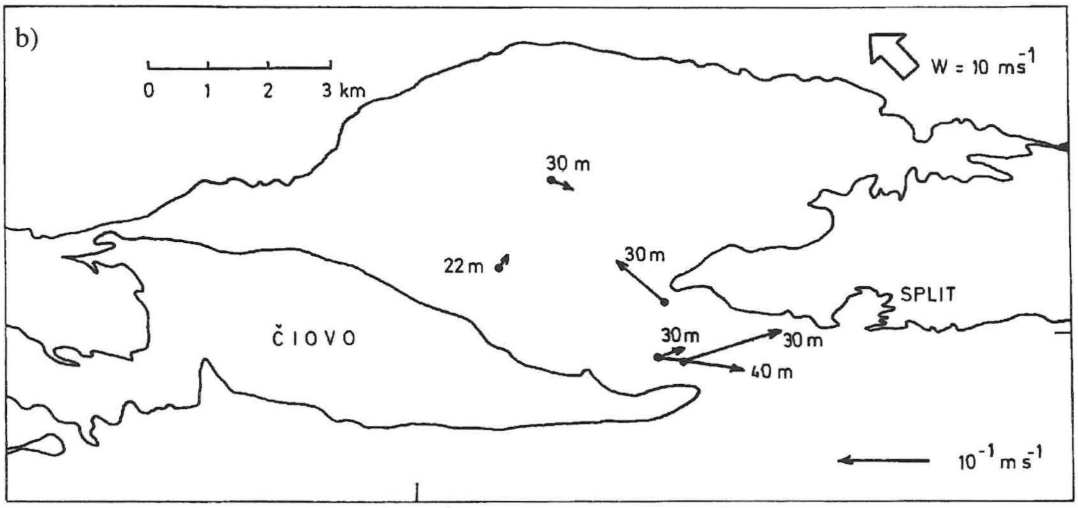




*Fig. 2. Spatial distribution of the averaged current vectors during scirocco wind episodes with filtered speeds exceeding 5 ms$^{-1}$ at the surface (a) and bottom (b) layer. The average wind speed during episodes with wind speed exceeding 5 ms$^{-1}$ was 10 cms$^{-1}$. Current meter level is denoted beside current vector*

bay interior station 2 are slightly deflected to the right of the wind, while at station 3 deflection due to the CORIOLIS force is more pronounced. Average current magnitude in the surface layer is about 5 cms$^{-1}$ and about 2 cms$^{-1}$ in the bottom layer.

From the empirical results it can be seen that bora induces week currents with randomly distributed directions in the surface and bottom layer (Figs. 3a,b). The currents induced by scirocco are significantly stronger than the bora induced currents. This is probably due to the different nature of these two wind systems. Scirocco blows along the Adriatic with long fetch length inducing great transports that probably affects the currents in the bay, especially in the inlet. On the contrary, the bora blows offshore with great spatial variability caused by orography (JURČEC *et al.*, 1986). Small magnitude currents probably results from the fact that the bora recorded at the meteorological station Split-Marjan is inappropriate for the whole area of the bay.

## Results of testing dynamic balances

High positive values of the coefficients of correlation between corresponding current and wind stress components, especially in E direction, at 8 and 20 m and negative at 30 and 40 m at station 1 confirms the assumption of two-layer model for the current system in the bay

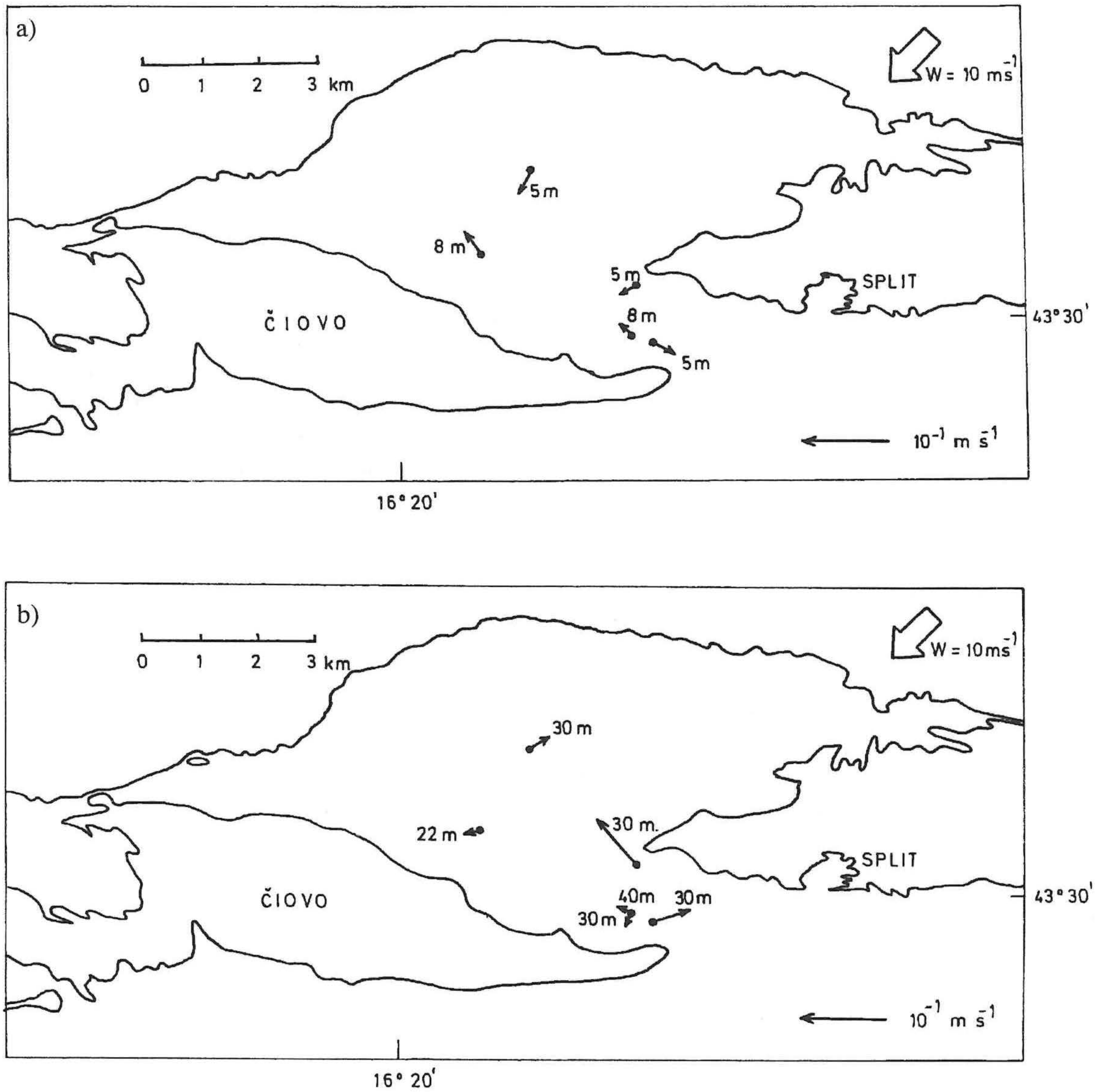



*Fig. 3. Spatial distribution of the averaged current vectors during bora wind episodes with filtered speeds exceeding 5 ms$^{-1}$ at the surface (a) and bottom (b) layer. The average wind speed during episodes with wind speed exceeding 5 ms$^{-1}$ was 10 cms$^{-1}$. Current meter level is denoted beside current vector*

inlet (Table 3). Drift currents prevail in the surface layer and upwind gradient currents predominate at the bottom. At the depth between 20 and 30 m drift currents change direction by $180^o$ and become compensatory currents (GAČIĆ *et al.*, 1987).

*Table 3. Correlation matrix for station 1 during periods with wind speed exceeding 5 $ms^{-1}$ in 1982*

| station 1 n=125 | | $u$ | $v$ | $\tau_u$ | $\tau_v$ |
|---|---|---|---|---|---|
| 8 m | $u$ | 1 | | | |
| | $v$ | -0.799** | 1 | | |
| | $\tau_u$ | 0.824** | -0.508** | 1 | |
| | $\tau_v$ | -0.714** | 0.309** | -0.702** | 1 |
| | | $u$ | $v$ | $\tau_u$ | $\tau_v$ |
| 20 m | $u$ | 1 | | | |
| | $v$ | -0.799** | 1 | | |
| | $\tau_u$ | 0.676** | -0.833** | 1 | |
| | $\tau_v$ | -0.586** | 0.535** | -0.702** | 1 |
| | | $u$ | $v$ | $\tau_u$ | $\tau_v$ |
| 30 m | $u$ | 1 | | | |
| | $v$ | -0.431** | 1 | | |
| | $\tau_u$ | -0.863** | 0.356** | 1 | |
| | $\tau_v$ | 0.615** | -0.748** | -0.702** | 1 |
| | | $u$ | $v$ | $\tau_u$ | $\tau_v$ |
| 40 m | $u$ | 1 | | | |
| | $v$ | -0.935** | 1 | | |
| | $\tau_u$ | -0.827** | 0.862** | 1 | |
| | $\tau_v$ | 0.685** | -0.865** | -0.702** | 1 |

**significant at level of 99.9%

Because of significant and high negative correlation between N current component and E wind stress component at station 2 EKMAN balance was tested (Table 4). The signs and order of magnitudes of the appropriate terms in the equation of motion are in agreement with EKMAN balance ($-fV=-2.85x10^{-6}$ $ms^{-2}$, $\tau_u/\rho H=-1.86x10^{-6}$ $ms^{-2}$). The positive correlation between N current component and N wind stress component in the whole water column suggests the possibility of viscous balance, so the regression analysis was performed. The magnitude of $1.98x10^{-3}$ $ms^{-1}$ obtained for coefficient of bottom friction with assumption of linear parametrization of bottom friction is acceptable.

*Table 4. Correlation matrix for station 2 during periods with wind speed exceeding 5 $ms^{-1}$ in 1982*

| station 2 n=125 | | $u$ | $v$ | $\tau_u$ | $\tau_v$ |
|---|---|---|---|---|---|
| 8 m | $u$ | 1 | | | |
| | $v$ | -0.598** | 1 | | |
| | $\tau_u$ | 0.684** | -0.637** | 1 | |
| | $\tau_v$ | -0.751** | 0.750** | -0.702** | 1 |
| | | $u$ | $v$ | $\tau_u$ | $\tau_v$ |
| 15 m | $u$ | 1 | | | |
| | $v$ | -0.564** | 1 | | |
| | $\tau_u$ | 0.712** | -0.680** | 1 | |
| | $\tau_v$ | -0.586** | 0.791** | -0.702** | 1 |
| | | $u$ | $v$ | $\tau_u$ | $\tau_v$ |
| 22 m | $u$ | 1 | | | |
| | $v$ | 0.762** | 1 | | |
| | $\tau_u$ | -0.583** | -0.776** | 1 | |
| | $\tau_v$ | 0.900** | 0.817** | -0.702** | 1 |

**significant at level of 99.9%

Correlation coefficients between N wind stress component and E current component in the surface layer at station 3 are statistically significant (Table 5), so the EKMAN balance in N direction was tested. Coriolis term is higher than wind stress term and signs are inappropriate ($fU=0.99x10^{-6}$ $ms^{-2}$, $T_v/\rho H=-0.13x10^{-6}$ $ms^{-2}$).

*Table 5. Correlation matrix for station 3 during period with wind speed exceeding 5 $ms^{-1}$ in 1988, 1989 and 1990*

| station 3 | | $u$ | $v$ | $\tau_u$ | $\tau_v$ |
|---|---|---|---|---|---|
| 5 m n=1992 | $u$ | 1 | | | |
| | $v$ | -0.254** | 1 | | |
| | $\tau_u$ | 0.048 | -0.184* | 1 | |
| | $\tau_v$ | 0.185** | 0.405** | -0.557** | 1 |
| | | $u$ | $v$ | $\tau_u$ | $\tau_v$ |
| 20 m n=1097 | $u$ | 1 | | | |
| | $v$ | 0.083** | 1 | | |
| | $\tau_u$ | -0.036 | -0.048 | 1 | |
| | $\tau_v$ | 0.341** | -0.258** | -0.514** | 1 |
| | | $u$ | $v$ | $\tau_u$ | $\tau_v$ |
| 30 m n=1800 | $u$ | 1 | | | |
| | $v$ | 0.307** | 1 | | |
| | $\tau_u$ | -0.076** | 0.271** | 1 | |
| | $\tau_v$ | 0.123** | -0.319** | -0.538** | 1 |

*significant at level of 99.5%
**significant at level of 99.9%

Testing of the EKMAN balance in E direction gave the correct signs and the same orders of magnitude of wind stress and CORIOLIS term ($-fV=-1.92\times10^{-6}$ ms$^{-2}$, $\tau_u/\rho H=-1.52\times10^{-6}$ ms$^{-2}$). N current component shows two-layer structure, with downwind current in surface layer and compensatory bottom layer.

The correlation matrix at both levels at station 4 shows that E wind stress component induces downwind current component and component deflected to the right of the wind (Table 6). EKMAN balance was not tested because of the small number of measurements along the vertical.

*Table 6. Correlation matrix for station 4 during periods with wind speed exceeding 5 ms$^{-1}$ in 1989*

| station 4 | | | | | |
|---|---|---|---|---|---|
| | | $u$ | $v$ | $\tau_u$ | $\tau_v$ |
| | $u$ | 1 | | | |
| | $v$ | -0.890** | 1 | | |
| 5 m | $\tau_u$ | 0.329** | -0.197** | 1 | |
| n=503 | $\tau_v$ | -0.361** | 0.087* | -0.653** | 1 |
| | | $u$ | $v$ | $\tau_u$ | $\tau_v$ |
| | $u$ | 1 | | | |
| 30 m | $v$ | -0.833** | 1 | | |
| n=225 | $\tau_u$ | 0.330** | -0.125* | 1 | |
| | $\tau_v$ | -0.036 | -0.123* | -0.659** | 1 |

*significant at level of 99.5%
**significant at level of 99.9%

Correlation coefficients between current and wind stress components at station 5 in the surface layer are not statistically significant (Table 7). In the bottom layer, N current component is directed downwind, while E component forms the compensatory layer. Results of regression analysis, with the assumption of viscous balance, gave unacceptably high values of coefficients of linear bottom friction (Table 8). This leads to the conclusion that apart from the friction forces, some other forces, acting in the opposite direction of the wind, should be taken into account. This particularly applies to the pressure gradient force.

Significant high negative correlations between E current components at 5 m and 30 m depth at stations 4 and 5 (Table 9) suggest that the bottom flow at station 5 is compensatory to the surface flow at station 4 (GAČIĆ *et al.*, 1991).

*Table 7. Correlation matrix for station 4 during periods with wind speed exceeding 5 ms$^{-1}$ in 1989*

| station 5 | | | | | |
|---|---|---|---|---|---|
| | | $u$ | $v$ | $\tau_u$ | $\tau_v$ |
| | $u$ | 1 | | | |
| 5 m | $v$ | -0.907** | 1 | | |
| n=654 | $\tau_u$ | -0.031 | 0.100 | 1 | |
| | $\tau_v$ | -0.020 | -0.069 | -0.742** | 1 |
| | | $u$ | $v$ | $\tau_u$ | $\tau_v$ |
| | $u$ | 1 | | | |
| 30 m | $v$ | 0.648** | 1 | | |
| n=611 | $\tau_u$ | -0.334** | -0.596** | 1 | |
| | $\tau_v$ | 0.412** | 0.541** | -0.717** | 1 |

*significant at level of 99.5%
**significant at level of 99.9%

*Table 8. Results of the regression analysis of the data obtained in experiment in 1989 during periods with wind speed exceeding 5 ms$^{-1}$*

| | a [kg$^{-1}$m$^2$s] | b [ms$^{-1}$] | r [ms$^{-1}$] | coef. corr. between currents and winds |
|---|---|---|---|---|
| station 3 30 m E dir. | 0.154 | 28.14x10$^{-3}$ | 6.49x10$^{-3}$ | 0.335** |
| station 4 30 m E dir | 0.291 | -35.85x10$^{-3}$ | 3.35x10$^{-3}$ | 0.330** |
| station 5 30 m N dir | 0.163 | 23.05x10$^{-3}$ | 6.09x10$^{-3}$ | 0.541** |

**significant at level of 99.9%

*Table 9. Correlation coefficients between current components at station 4 and 5 during periods with wind speed exceeding 5 ms$^{-1}$ in 1989*

| station 4-5 | | |
|---|---|---|
| | $u_5$(5 m) | $u_5$(30 m) |
| $u_4$(5 m) | -0.048 | -0.788** |
| $u_4$(30 m) | -0.503** | 0.016 |
| | $v_5$(5 m) | $v_5$(30 m) |
| $v_4$(5 m) | 0.189** | 0.273** |
| $v_4$(30 m) | -0.351** | -0.274** |

**significant at level of 99.9%

## Water exchange through the bay inlet

Small values of correlations between currents at the same levels of stations 4 and 5 point to the high lateral variability of the current field in the bay inlet (Table 9). Because of strong lateral variability of the currents in the bay inlet, calculations of exchange rates were performed only for the experiment from 1989 with two mooring in the bay inlet. The flushing period is defined as:

$$t_i = \frac{V_b}{T_u}, \tag{12}$$

where $V_b$ is basin volume and $T_u$ is the exchange rate. Incoming current components, necessary for exchange rates calculation, were obtained using linear interpolation in the whole inlet cross-section (LEGOVIĆ, 1982). The inlet cross-section was divided into a meter thick horizontal layers and vertical columns one hundred meters wide. The exchange rate was obtained by summing up the products of rectangle surfaces and appropriate incoming current components. Exchange rates during two scirocco wind events with speeds of approximately 10 $ms^{-1}$ are 2500 $m^3s^{-1}$ and during the bora wind of the same speed 3000 $m^3s^{-1}$ (Fig. 4). The corresponding flushing periods are 6 and 5 days respectively.

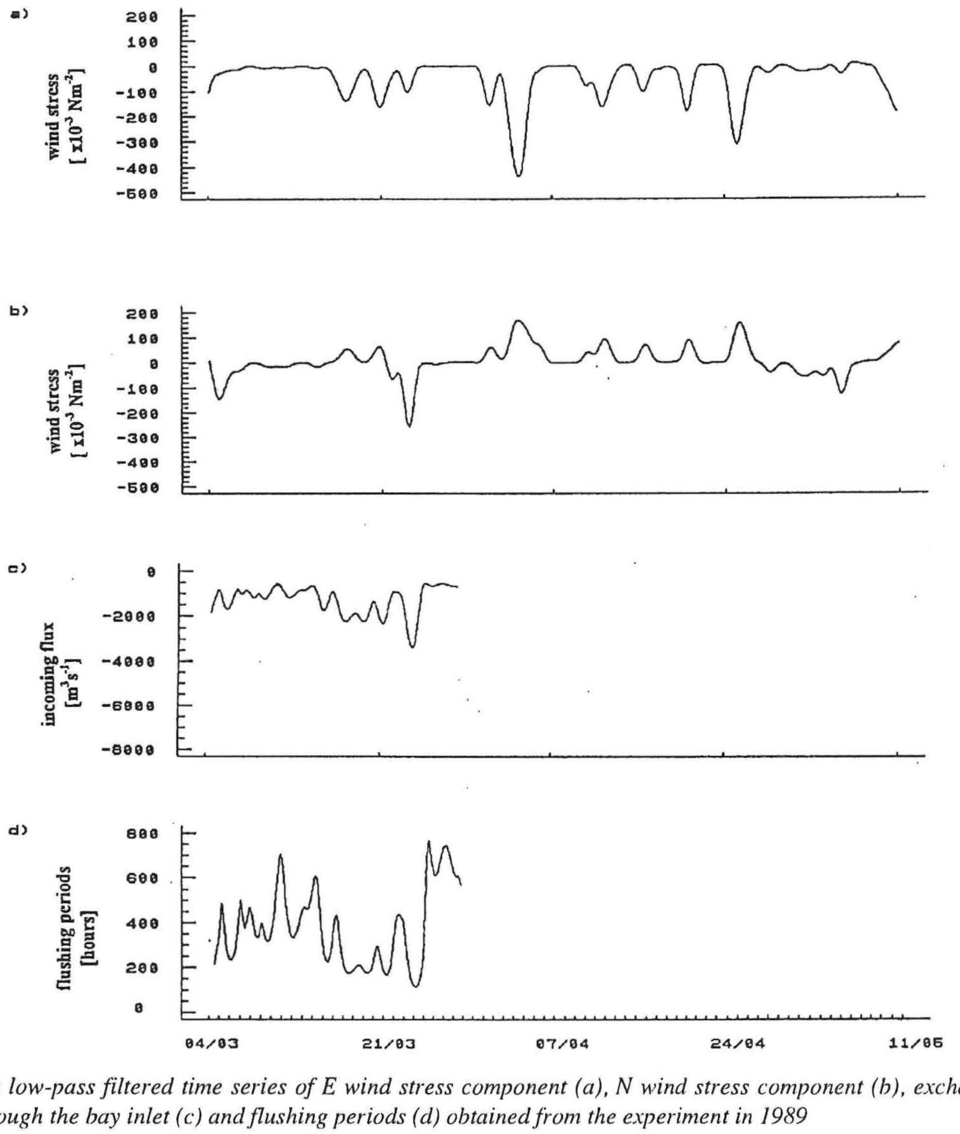



*Fig. 4. The low-pass filtered time series of E wind stress component (a), N wind stress component (b), exchange rate through the bay inlet (c) and flushing periods (d) obtained from the experiment in 1989*

## CONCLUSIONS

The results of the present study in the Kaštela Bay indicate that wind currents in the bay inlet are polarized in east-west direction with downwind current in the surface layer and upwind current in the bottom layer, with considerable horizontal variations across the inlet. Negative results in testing EKMAN balance and unacceptably high coefficients of bottom friction in the bay inlet, point to the fact that some other terms of the equation of motion should be taken into consideration. This particularly applies to the horizontal pressure gradient force, also suggested by the results of numerical models (ORLIĆ *et al.*, 1989; BONE *et al.*, 1992). Negative correlations between currents and wind stress components in the bottom layer obtained in the bay inlet as a result of compensatory currents also confirm the importance of the pressure gradient force. It was shown (RATTRAY and HANSEN, 1965; WANG, 1979) that two-layer vertical structure can be obtained taking into account horizontal pressure gradient force and vertical turbulent momentum exchange. The effect of acceleration term on the wind induced currents in the bay inlet was studied by GAČIĆ *et al.*, 1991. Coefficients of bottom friction obtained by regression analysis for stationary and unstationary state differ only by 10 %.

At the stations placed in the bay interior, surface currents turn to the right of the wind direction. This deflection is better pronounced in deeper layers. Testing of two simple dynamic balances, EKMAN and viscous, were positive only for the stations in the bay interior. EKMAN balance in the E direction was satisfied at both stations in the bay interior. Assuming viscous balance in the N direction and linear parametrization of bottom friction at the southernmost station in the interior of the bay (2), the value for the obtained coefficient of linear bottom friction (*r*) was $1.98 \times 10^{-3}$ $ms^{-1}$. A similar value was obtained as a result of regression analysis along Long Island coast (WINANT and BEARDSLEY, 1979).

Magnitudes of mean currents in the bay inlet are considerable higher than the corresponding values in the bay interior, showing the importance of the wind induced transports from the adjacent sea.

Spatial distribution of the averaged current vectors during scirocco and bora winds shows higher magnitudes of wind vectors during scirocco. These differences result from different nature of two wind systems. Scirocco blows homogeneously along the whole Adriatic Sea and induces great transport of water, while the bora blows offshore with great spatial variability caused by orography. Results of analyzed current meter data suggest that effect of orography during bora can be observed even in such a small area as Kaštela Bay. This is in agreement with the results of single level atmospheric model integration (JURČEC *et al.*, 1986).

Correlation coefficients between current components were also estimated. In calculating the current components dependence the numerator of the correlation coefficient term represents the REYNOLDS stress in the horizontal plane. The REYNOLDS stress describes turbulent momentum exchange (PEDLOSKY, 1979; MONIN and YAGLOM, 1977). Because of higher standard deviations and higher correlation coefficients of current components, the bay inlet stations have higher REYNOLDS stress than the bay interior ones.

Because of the strong horizontal variability of the current field in the bay inlet, exchange rates and flushing periods were calculated only for the experiment with two moorings. In the case of one mooring the assumptions of the lateral homogeneity should be taken into account and the calculations would be strongly dependent on mooring position. The value of exchange rate calculated from measurements from 1989 during bora wind with speed of 10 $ms^{-1}$ is 3000 $m^3s^{-1}$ and during scirocco wind with the same speed is 2500 $m^3s^{-1}$. The respective flushing periods are 5 and 6 days.

## REFERENCES

ALLEN, J. S. and P. K. KUNDU. 1978. On the momentum, vorticity and mass balance on the Oregon Shelf. J. Phys. Ocean., 8(1): 13-27.

ALLEN, J. S. and R. L. SMITH. 1981. On the dynamics of wind-driven shelf currents. Circulation and fronts in continental shelf seas. Phil. Trans. R. Soc. Lond., A 302: 617-634.

BONE, M., G. BEG, A. SMIRČIĆ and M. UVODIĆ. 1992. Modelling study of drift currents in the area of Brač and Split Channel and the Kaštela Bay (in Croatian). Studije i elaborati, 122. Institute of Oceanography and Fisheries, Split, 209 pp.

GAČIĆ, M. 1982. Notes on characteristics of the response of near-shore current field to the onshore wind. Bilješke-Notes, Institute of Oceanography and Fisheries, Split, 47, 6 pp.

GAČIĆ, M., V. DADIĆ, N. KRSTULOVIĆ, I. MARASOVIĆ, M. MOROVIĆ, T. PUCHER-PETKOVIĆ and N. SVILIČIĆ. 1987. Near-shore transport processes induced by the wind. Estuar. Coast. Shelf Sci., 24(1): 35-46.

GAČIĆ, M.,B. GRBEC and V. DADIĆ. 1991. Wind-induced currents in an inlet of a semi-enclosed bay (Kaštela Bay, Adriatic Sea). Acta Adriat., 32(2): 607-620.

JURČEC, V., A. BAJIĆ and K. PANDŽIĆ. 1986. The simulation of bora and scirocco in the Middle Adriatic. Hidrogr. godišn. 1984-1985: 59-71.

LEGOVIĆ, T. 1982. Water exchange between a coastal basin and adjacent sea, with an application to Rijeka Bay. Deep-Sea Res., 29: 999-1012.

MONIN, A. S. and A. M. YAGLOM. 1977. Statistical fluid mechanics: mechanics of turbulence, Vol. 1, The Mit Press, Cambridge, 756 pp.

ORLIĆ, M., M. KUZMIĆ, and Z. VUČAK. 1986. Wind-curl currents in the Northern Adriatic and formulation of bottom friction. Oceanol. Acta, 9: 425-431.

ORLIĆ, M., M. KUZMIĆ and Z. PASARIĆ. 1989. Modelling wind-driven transports in the Kaštela Bay. UNEP Mediterranean action plan, Priority action programme, Regional activity centre Split. CPP/ 1988-1989/YU/DOC. 3A, 43 pp.

PEDLOSKY, J. 1979. Geophysical Fluid Dynamics. Springer-Verlang, New York, 624 pp.

PUGH, D. T. 1987. Tides, surges and mean sea-level. Wiley, New York, 472 pp.

RATTRAY, M. and D. V. HANSEN. 1965. Gravitational circulation in straits and estuaries. J. Mar. Res., 23(2): 104-121.

THOMPSON, R. O. R. Y. 1983. Low-pass filters to suppress inertial and tidal frequencies. J. Phys. Ocean., 13(6): 1077-1083.

WANG, D. P. 1979. Wind-driven circulation in the Chesapeak Bay, Winter 1975. J. Phys. Ocean., 9(3): 564-572.

WINANT, C. D. and R. C. BEARDSLEY. 1979. A comparison of shallow currents induced by wind stress. J. Phys. Ocean., 9(1): 218-220.

ZORE-ARMANDA, M. 1980. Some dynamic and hydrographic properties of the Kaštela Bay. Acta Adriat., 21(2): 55-74.

Accepted: 1 February 1997

# Utjecaj vjetra na strujno polje Kaštelanskog zaljeva

Gordana BEG PAKLAR i Miroslav GAČIĆ*

*Institut za oceanografiju i ribarstvo, Split, Hrvatska*
*Observatorij za eksperimentalnu geofiziku, Trst, Italija*

## SAŽETAK

Analiziran je utjecaj vjetra na strujno polje Kaštelanskog zaljeva na sinoptičkoj skali pomoću podataka iz četiri strujomjerna eksperimenta, provedena u razdoblju od 1982. do 1990. godine, i odgovarajućih podataka o vjetru s obližnje metereološke stanice Split-Marjan.

Da bi se karakteristike strujnog polja Kaštelanskog zaljeva na sinoptičkoj skali objasnile linearnom dinamikom testirane su dvije jednostavne dinamičke ravnoteže: EKMANOVA i viskozna ravnoteža. Testiranje EKMANOVE ravnoteže dalo je dobre rezultate za dvije postaje u središtu zaljeva. Zadovoljavajući rezultati za koeficijente pridnenog trenja, uz pretpostavku o viskoznoj ravnoteži i linearnu parametrizaciju pridnenog trenja, dobiveni su za jednu postaju u središtu zaljeva. Dobiveni koeficijent pridnenog trenja iznosi $1.98 \times 10^{-3}$ $ms^{-1}$. Negativne korelacije između vjetra i struja dobivene u pridnenom sloju na postajama u vratima zaljeva, ukazuju na primjenjivost dvoslojnog modela strujanja i na važnost sile gradijenta tlaka.

Proračuni ulaznog toka kroz vrata zaljeva daju vrijednost od 2500 do 3000 $m^3s^{-1}$ za puhanja vjetrova brzinom od 10 $ms^{-1}$, a odgovarajuća vremena izmjene su 6 i 5 dana.