Wind-induced vertical shearing : ALPEX/MEDALPEX data and modelling exercise

M. KUZMIĆ (1), M. ORLIĆ (2)

(1) *Center for Marine Research Zagreb, Rudjer Bŏsković Institute,* 41000 *Zagreb, Yugoslavia*
(2) *Geophysical Institute, Faculty of Science, University of Zagreb,* 41000 *Zagreb, Yugoslavia*

ABSTRACT. The wind-induced vertical shearing in the Northern Adriatic, due to vorticity in the wind field, has been studied using hydrodynamical numerical model and empirical data collected during ALPEX/MEDALPEX. The influence of heterogeneous wind fields on the currents in the Northern Adriatic during winter has been modelled using climatological wind data for a ten-year period (1956-1965) and six stations along the Yugoslavian coast, as well as two-month time series of hourly wind magnitudes and directions for a coastal station in the area (Pula Airport). It is shown, through several gradually refined numerical experiments, that the heterogeneity in the wind field is a major factor in determining the wind-induced vertical shear. Model to data comparison shows that wind vorticity can produce current vectors of a magnitude, direction and relative position comparable to the ones obtained by measurements. The wind-vorticity interpretation presented here is an alternative to the one put forward in a previous paper in which improved prediction was sought by changing the magnitude of the depth-independent eddy viscosity coefficient. The ALPEX/MEDALPEX wind and current data have been analysed in both the time and frequency domains. Both analyses support the notion that dominant response of the Northern Adriatic to the wind is of the forced type. However, the analyses also indicate the presence of free oscillations and appear to provide, for the first time, evidence for the existence of basin-wide topographic waves in the Adriatic Sea.

Key words : numerical model, wind-curl effect, ALPEX, MEDALPEX, Northern Adriatic, vertical shearing.

Annales Geophysicae, 1987, **5B,** (1), 103-112.

INTRODUCTION

The central theme of this paper is the influence of an heterogeneous wind on the vertical shearing in the Northern Adriatic during winter. It has been already shown in a previous paper (Kuzmić *et al.*, 1975) that, in winter, the wind does induce the most pronounced, although transient component of the current field in the Northern Adriatic. The first discussion of the wind influence on the Northern Adriatic current field, however, was published as early as 1915 (Mazelle, 1915). The subject has been also considered more recently both empirically (Mosetti, 1972) and theoretically, using mathematical models (Stravisi, 1977 ; Malanotte-Rizzoli and Bergamasco, 1983). Stravisi used a two-dimensional model and sine-squared decaying bura forcing ; Malanotte-Rizzoli and Bergamasco modelled time-dependent stress using a two-layer baroclinic model.

In our previous study we were mainly concerned with the controlling influence of the real bottom topography and considered only the case of an homogeneous wind. Modelling predictions were also compared to the empirical data. It was found that, with a depth-independent vertical eddy viscosity coefficient, the magnitude of that coefficient had to be an order of magnitude smaller than the value expected from the literature in order to improve the agreement between model-generated and measured vectors.

In the present paper, the heterogeneity in the wind field over the Northern Adriatic, as suggested by available climatological data, is primarily considered. The paper is organized in five sections. After the introduction, the formulation of the numerical model and the modelled area are briefly presented in the second section together with the basic numerical experiments. The ALPine EXperiment (ALPEX)/ MEDiterranean ALPEX (MEDALPEX) data are described and analysed in both time and frequency domains in the third section. Comparison of the model predictions and empirical results is the subject of the fourth section. Results of the study are summarized in the final section.

MODEL FORMULATION AND NUMERICAL EXPERIMENTS

In our modelling study of the winter dynamics of the Northern Adriatic we have taken the approach pioneered by N. S. Heaps in which an integral transformation is used to describe the vertical distribution of velocity. The basic set of equations is derived

Annales Geophysicae, 87/01 B, 103 10 $ 3.00 © EGS-Gauthier-Villars

assuming that the water is homogeneous and incompressible, the motion hydrostatic, and the Coriolis parameter constant. Furthermore, neglecting the advective terms and lateral shear, the equations of continuity and motion may be written as :

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

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

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

where t denotes time ;
ζ is the elevation of the water surface ;
u, v are the horizontal components of currents 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 and the z axis is positive downwards. The state of rest is assumed initially ($\zeta = u = v = 0$).

Boundary conditions at the sea surface and at the bottom are of the form :

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

and

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

The stresses are defined as :

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

and

$$\tau_{xb} = k\rho u_h, \quad \tau_{yb} = k\rho v_h. \qquad (7)$$

In the above relations u_a and v_a denote the wind components, ρ_a is the density of the air, ρ is the density of sea water, C_D is a nondimensional drag coefficient and k is the coefficient of bottom friction. Along the solid boundary zero normal horizontal flow is assumed :

$$(u, v)_n = w_n = 0 \qquad (8)$$

while a radiation condition of the form

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

where the overbar denotes the vertical averaging, is postulated at the open boundary. An open boundary is artificial by definition and therefore each formulation has its unwanted features. This one is no exception — its appropriateness for the Northern Adriatic model has been considered by Kuzmić and Orlić (1985).

Before the numerical solution is attempted, (1) to (3) are transformed using the eigenfunction method, sometimes referred to as integral or spectral method. A detailed derivation and discussion of the method can be found in Heaps (1972, 1973) and will not be repeated here. We will state the transformed equations directly :

$$\frac{\partial \zeta}{\partial t} + \sum_{r=1}^{M}\left[\frac{\partial}{\partial x}\left(h a_r \varphi_r u_r\right) + \frac{\partial}{\partial y}\left(h a_r \varphi_r v_r\right)\right] = 0 \qquad (10)$$

$$\frac{\partial u_r}{\partial t} + \lambda_r u_r - f v_r = -g a_r \frac{\partial \zeta}{\partial x} + \frac{\tau_{xs}}{\rho h} \qquad r = 1, M \qquad (11)$$

$$\frac{\partial v_r}{\partial t} + \lambda_r v_r + f u_r = -g a_r \frac{\partial \zeta}{\partial y} + \frac{\tau_{ys}}{\rho h} \qquad r = 1, M \qquad (12)$$

where

u_r, v_r are the transformed velocity components ;

λ_r is the r-th eigenvalue of the vertical eddy viscosity operator ;

φ_r, a_r are coefficients depending on the r-th eigenvalue ;

M is the number of modes.

Comparing (10)-(12) to (1)-(3), one can immediately see that the number of equations has increased from 3 to $1 + 2M$ — a price to be paid for the gain in vertical resolution. Ten modes have been used in all the runs presented in this paper. The set of (10)-(12) is then solved numerically, and at each time step one can recover the depth-dependent u and v components of velocity by a finite inverse transformation.

We have transformed the equations into numerical form using a forward-time staggered-space finite difference scheme which achieves computational economy and stability (Sielecki, 1968 ; Heaps, 1972). The part of the Adriatic considered in the model is shown in figure 1. Boundaries of the modelled area are schematized to fit a field of 31 × 24 rectangular boxes of 7.5 km in both the x (northeastward) and y (northwestward) directions. With this grid size and a maximum depth of 60 m the Courant-Friedrichs-Lewy stability criterion is satisfied with a time step of 2 min. The parameters f, ρ and g are set equal to $1.031 \times 10^{-4}\,\mathrm{s}^{-1}$, $1025\,\mathrm{kg\,m}^{-3}$ and $9.81\,\mathrm{m\,s}^{-2}$ respectively. The drag coefficient $C_D = 2.5 \times 10^{-3}$ (Simons, 1980) and $\rho_a = 1.247\,\mathrm{kg\,m}^{-3}$ are used in all calculations of the wind stress, giving a value of $\tau_{xs} = -0.15\,\mathrm{N\,m}^{-2}$ for a $7\,\mathrm{m\,s}^{-1}$ southwestward wind. The coefficient of linear bottom friction is taken as $2.5 \times 10^{-3}\,\mathrm{m\,s}^{-1}$ following Kaese and Tomczak (1974). The value of the vertical eddy viscosity coefficient is assumed depth independent, but is allowed to vary horizontally ($N = 0.01\,\mathrm{m}^2\,\mathrm{s}^{-1}$ for the average depth of 40 m). Further details on the numerical formulation of the Northern Adriatic model can be found in Kuzmić *et al.* (1985).

Yet another parameter is required to calculate the wind stress and run the model, the wind velocity, usually measured at 10 m above the water surface. The wind momentum, transferred by tangential shear at the surface, is the only forcing mechanism considered in the model. Therefore, more consideration has been given to the wind field over the area although the transfer is not modelled explicitly but by the usual bulk coefficient parameterization. Several sources of wind data were available for the analysis :

a) ten-year statistics (1949-1958) of wind direction and magnitude with resultant wind for the Pula station (see fig. 1), compiled by Penzar (1977),

b) ten-year statistics (1956-1965) of monthly mean wind frequency and force for 76 stations along the Yugoslavian coast (Yoshino, 1972), and

c) two-month time series (16 March-15 May, 1982) of hourly wind directions and magnitudes for the Pula Airport.

The climatological data for the Pula station point out the dominance of the southwestward wind (the so-called bura wind) in winter regarding both frequency and average speed. The data strongly support the notion of bura prominence in the wind-induced winter dynamics of the Northern Adriatic. The climatological statistics compiled by Yoshino were used to extract bura wind speed averages for the winter months (December, January, February) at 6 stations along the Northern Adriatic coast (Vedrian, Koper, Poreč, Rovinj, Fažana and Pula). Reduction to the standard 10 m height was applied. The empirical values from those stations were then interpolated using the method of local procedures (Akima, 1972), to obtain the wind values at the points required by the model.

The resulting spatial distribution was further calibrated to obtain the stress value at the Pula station implied by the time-series data and used in the previous, homogeneous-wind study. The information used to simulate the heterogeneity of the wind is summarized in table 1. The time-series data are analysed in more detail in the data section.

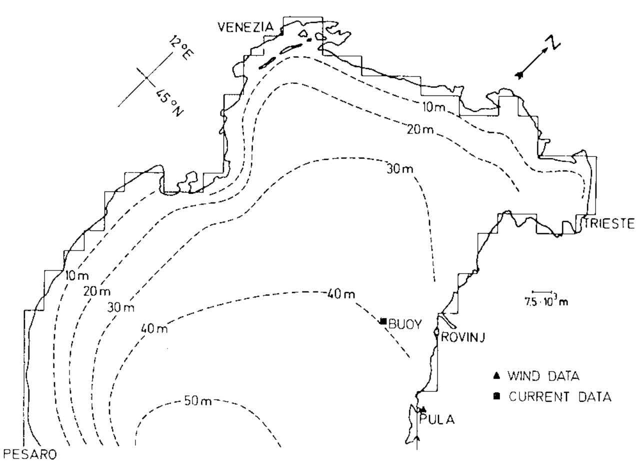

Figure 1

Geometry and bottom topography of the Northern Adriatic with locations of the data sampling points.

After all the necessary parameters have been set a number of runs has been performed to assess the influence of various factors. The model was run for up to 72 simulated hours but it was found that a reasonably steady situation can be attained after only 48 h. That turned out to be an important circumstance since all the simulations have been run on a PDP-11/34A without a floating point processor requiring more than 8 h of computer time per simulated day. Assuming that the transient behaviour is well characterized by a two-day period, 4 calculated fields were analysed for each run. These fields are sea-level displacement, vertically averaged current, surface current and bottom current. Out of all the runs carried out, 4 characteristic ones have been selected for presentation in this paper. The 4 above mentioned fields are presented for those 4 runs in figures 2 to 5. We will briefly consider each of them. Each figure has the same structure and is devoted to one of the output fields. The upper row presents the results for the case of an homogeneous wind, while the simulations in which the wind curl has been considered are displayed in the lower row. The left column, on the other hand, presents the runs in which the topography was kept uniformly flat, whereas the real bottom topography has been considered in the runs presented in the right column. The intensity and variability of the simulated

Table 1

Simulated heterogeneity in the wind field over the Northern Adriatic as abstracted from the climatological data. Southwestward stress, variable along the model y axis, is calculated using the relation : $\tau_{xs}(j) = -0.15 \times wf^2(j)$. In figure 1, point $j = 2$ corresponds to Pula, point $j = 6$ to Rovinj and point $j = 12$ to Trieste.

j	$wf(j)$	j	$wf(j)$	j	$wf(j)$	j	$wf(j)$
1	1.19	7	0.56	13	1.43	19	1.08
2	1.00	8	0.61	14	1.47	20	0.90
3	0.85	9	0.69	15	1.47	21	0.69
4	0.73	10	0.88	16	1.42	22	0.42
5	0.65	11	1.15	17	1.34		
6	0.58	12	1.35	18	1.23		

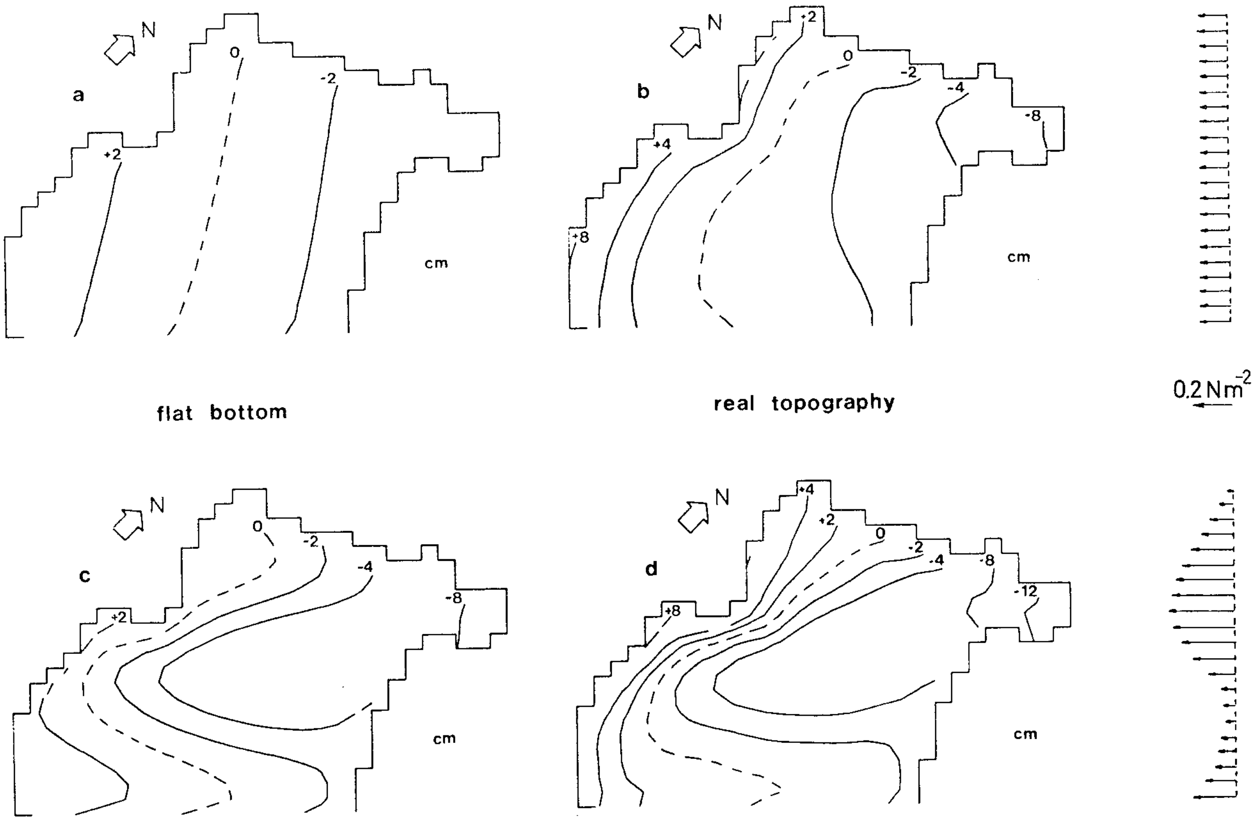

Figure 2
Sea-level distribution predicted by the model : (a) *flat bottom and homogeneous wind,* (b) *real topography and homogeneous wind,* (c) *flat bottom and heterogeneous wind,* (d) *real topography and heterogeneous wind.*

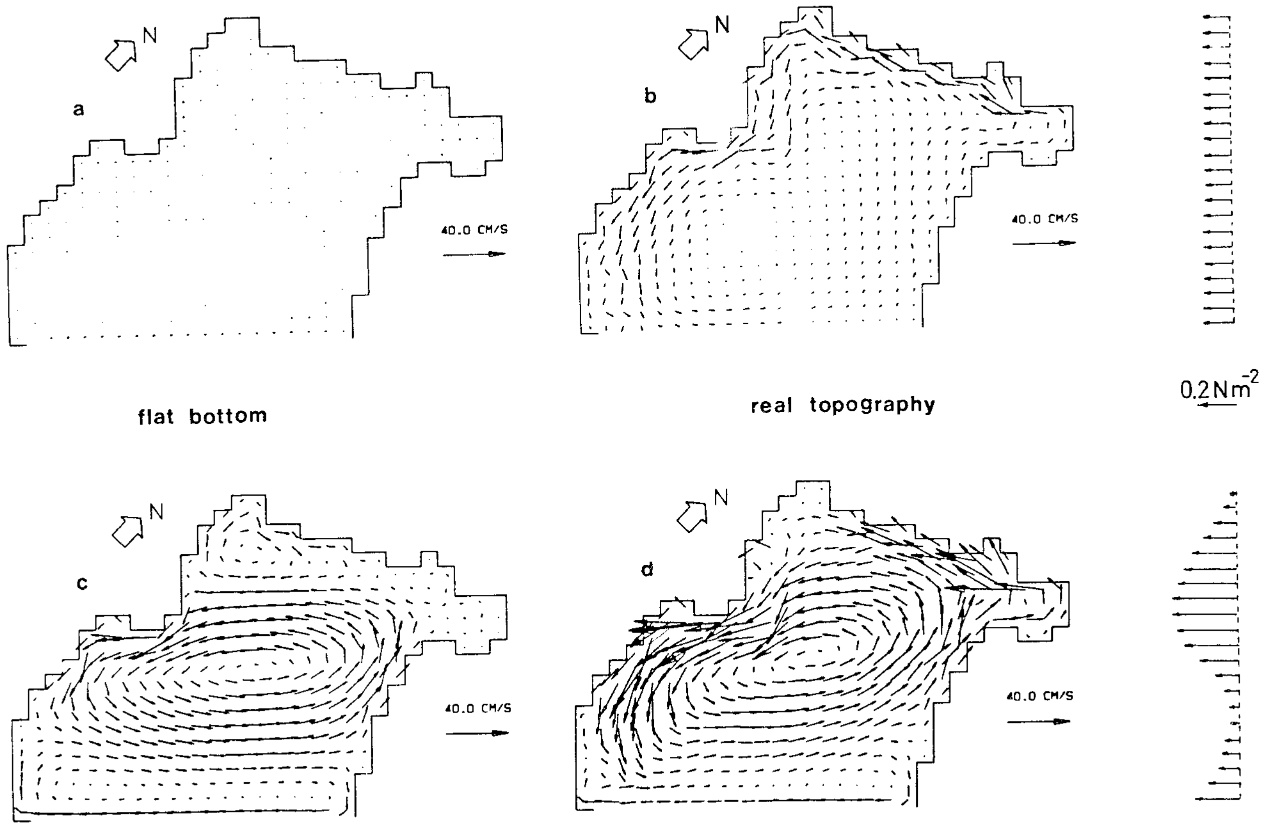

Figure 3
Vertically averaged currents predicted by the model : (a) *to* (d) *same as in figure* 2.

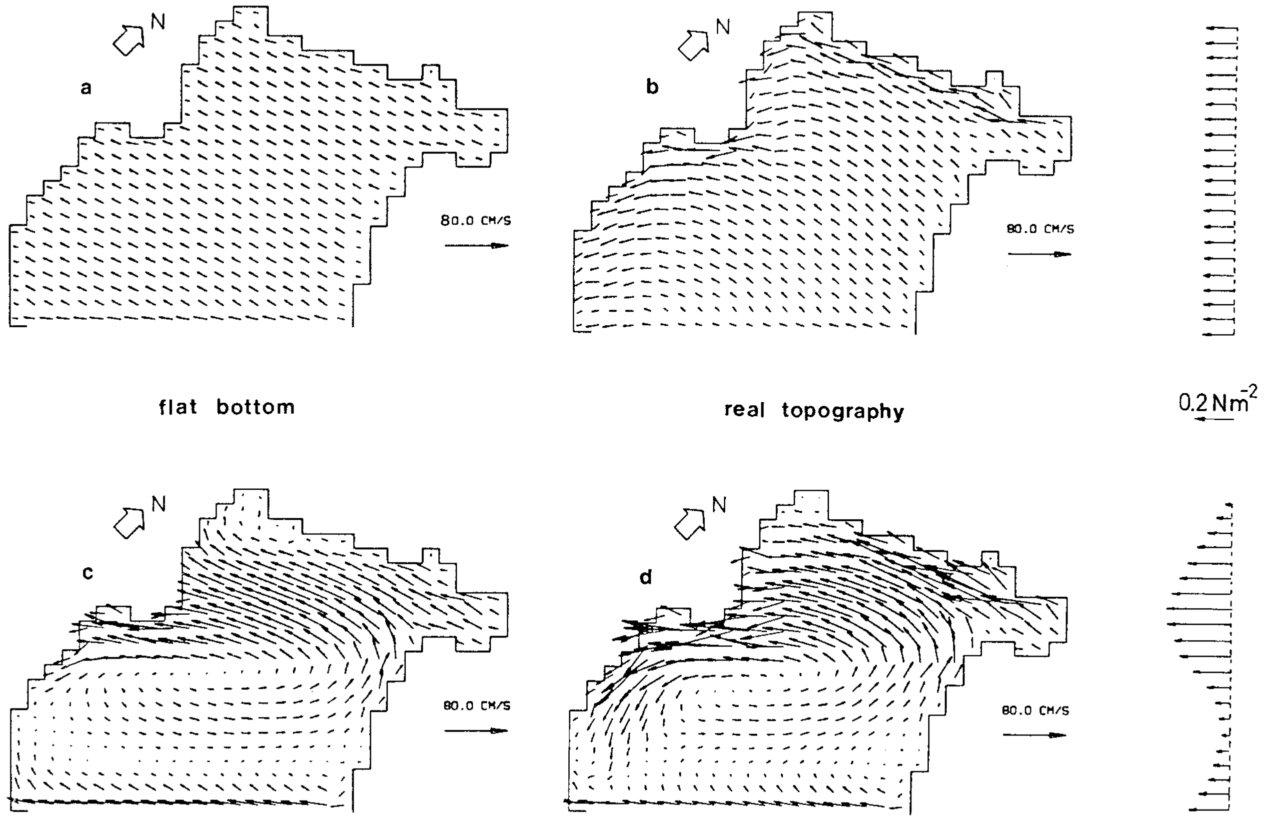

Figure 4
Surface currents predicted by the model: (a) *to* (d) *same as in figure* 2.

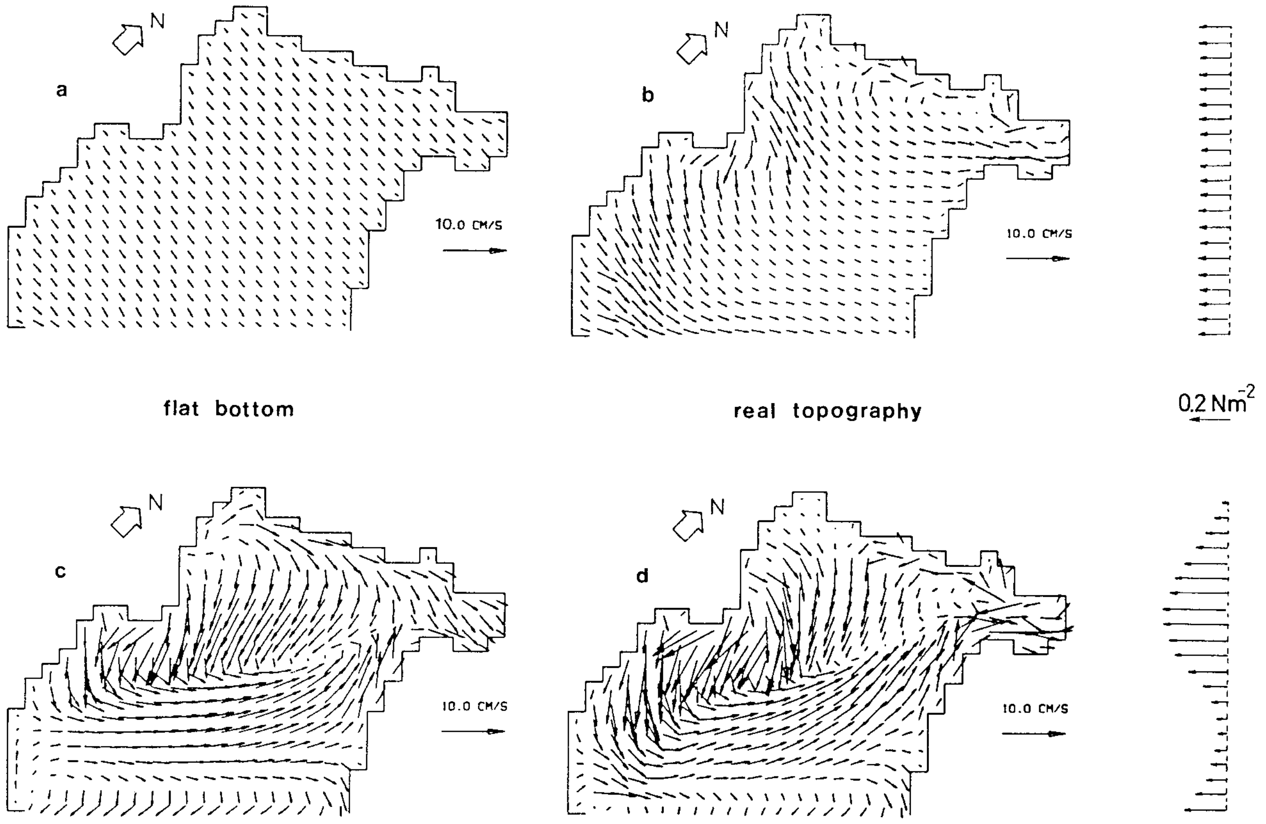

Figure 5
Bottom currents predicted by the model: (a) *to* (d) *same as in figure* 2.

wind stress is indicated on the right side of each figure. As pointed out before, only the soutwestward wind has been considered.

The combination of homogeneous wind field and flat bottom results in a rather regular distribution of the sea level heights (fig. 2*a*). The properly deflected surface exhibits a windward slope and small elevations. This regularity is lost when the real topography is introduced while keeping the stress uniform (fig. 2*b*). The effect of an heterogeneous wind is clearly visible on figure 2*c*. It is, perhaps, instructive to view the variable stress as a variation around the constant one. Then, the surface lines in figure 2*c*, when compared to the ones in figure 2*a*, follow predictably the variation in the stress. As a consequence of the particular coastal geometry and wind stress intensity, the sea level change due to the wind curl only is rather asymmetrical (+ 2 cm along the southwestern coast, – 8 cm in the Gulf of Trieste). Finally, the topographic effect is superimposed on the wind-curl contribution in the run presented in figure 2*d*. The elevation range is further extended, but the extremes are less asymmetrical due to the effect of the shallower zone along the Italian coast.

Let us consider next the vertically averaged currents. In the first case, the lack of vorticity and the regularity of the bottom topography, combined with the « neutral » boundary condition, induce insignificant vertically averaged currents (fig. 3*a*). When the real topography is taken into account (fig. 3*b*) the so-called bottom-slope current is clearly revealed, in agreement with the early theoretical results of Weenink (1958).

The effect of the wind curl is depicted in figure 3*c*. Three gyres are formed due to this particular distribution of stress : a large, cyclonic gyre in the middle of the area, a smaller, anticyclonic one above it, and another anticyclonic gyre below it, the latter one probably influenced by the open boundary condition. Decomposing again the variable stress around the constant value, one can relate the excess stress to southwestward transport and deficit stress to northeastward transport. The joint effect of bottom slope and wind vorticity is displayed in figure 3*d*. It is interesting to note that the upper anticyclonic gyre is overshadowed by the topographic effect.

The effect of the shallower zone along the Italian coast can be observed in the surface current field as well (fig. 4*b*). The influence of the wind vorticity is strongly felt at the surface — strongly enough, the simulation suggests, that in part of the modelled area (lower portion of the central, cyclonic gyre) the water is flowing in the upwind direction (figs. 4*c* and 4*d*). The compensating, return currents can be observed in all the 4 bottom current fields. The topographic modification of the reference uniform pattern (fig. 5*a*) is clearly visible in figure 5*b*. The bottom field for the case of flat bottom and heterogeneous wind apparently suggests the combination of horizontal and vertical compensation. Modifications of this field by the topographic effect are shown in figure 5*d*.

The simulations just described constitute the basic numerical experiments performed with the model. The experiments suggest that there are two major components of the wind-induced current field in the Northern Adriatic : the bottom-slope current and the wind-curl contribution. In order to assess the validity of the presented predictions, and of the model in general, the model-predicted currents have been compared to the current measurements collected during MEDALPEX. Before describing that comparison, however, we will take a closer look at the empirical data set.

DATA DESCRIPTION AND ANALYSIS

ALPEX and MEDALPEX were designed to study meteorological processes in the Alps region and oceanographic phenomena in the Mediterranean Sea, respectively. The Yugoslavian contribution to ALPEX took place during the special observing period (March-April, 1982) whereas MEDALPEX was carried out in the Northern Adriatic in spring 1982 (16 March-15 May). We shall analyse here only a part of the ALPEX/MEDALPEX data base : the wind data from the Pula Airport (44° 54′ N, 13° 55′ E) and the current data from the station 20 km offshore from Rovinj (45° 03′ N, 13° 19′ E). The positions of the measurement points are indicated in figure 1. The wind was registered at the 73 m height, the height of the station being 63 m. The currents were measured by Aanderaa RCM 4 current meters at 2 depths (8 and 35 m), in water of 40 m deep, with a 10 min sampling interval. Hourly mean values of wind and currents were computed and used in subsequent analysis.

The data were low-pass filtered, in order to eliminate tidal and higher-frequency oscillations, and were then decimated to 24 h values, which are presented in figure 6. Moreover, the original time series were decomposed into Cartesian components (NE and NW), the linear trend was eliminated, and the Tukey window was applied. Energy spectra were thereafter computed *via* the FFT method, with 10° of freedom. The subtidal parts of the spectra are shown in figure 7. Finally, cross-spectral analysis was performed, between the Cartesian components of wind and upper level currents, as well as between the upper and lower level current components. The number of degrees of freedom was equal to 22, and the limiting value of the coherence squared was computed at the 95 % confidence level (fig. 8). The wind was used rather than the wind stress in all the analyses, because the coherence squared with current is significantly higher for wind than for wind stress — an independent finding in accordance with results obtained, e.g., by Hickey (1981).

The time series of wind (fig. 6) shows three pronounced wind pulses, between 21 and 22 March, 23 and 24 March and 13 and 15 April, 1982. In all three cases the wind was from the NE quadrant. Such a wind is frequent above the Northern Adriatic during winter, and is called bura. In March and April 1982 the bura pulses were strong, with the magnitudes of low-pass filtered winds exceeding $10\ \mathrm{m\,s^{-1}}$. They were connected, as is usually the case, with the cyclonic disturbances propagating above the Adriatic Sea.

Simultaneously with the wind pulses, strong currents occurred in the Northern Adriatic (fig. 6). Their direction at both depths was almost opposite to the bura direction. The magnitudes were considerable, up to 50 cm s^{-1}. Such currents surpass all the other components of the Northern Adriatic current field, and we may therefore conclude that the wind forcing is of primary importance for the dynamics of the basin. The difference between currents at the 2 depths was small in both speed and direction. An explanation of the observed characteristics of the wind-driven currents, and, particularly, of the measured vertical shear, will be offered later in this paper.

Figure 6 shows that, besides the forced motions, free oscillations also occurred in the Northern Adriatic. Particularly illustrative is the situation after 25 March : at that time, the wind dropped to rather low values, while the currents persisted with magnitudes of up to 10 cm s^{-1}. These currents were obviously barotropic, although suppressed towards the bottom, and they turned clockwise with a few day period. These free oscillations should be interpreted in terms of the second-class (topographic) modes of enclosed basins, the first-class oscillations being of smaller periods and, therefore, removed by the filtering process. The modelling of topographic waves goes back to Lamb (1932) and to his study of free oscillations in a rotating circular basin with a parabolic depth profile. Recent interest in such waves stems from a series of observations implying their existence, one of the most striking being the demonstration of basin-wide vorticity waves in Southern Lake Michigan (Saylor *et al.*, 1980). The data presented here appear to provide the first indication on the existence of these waves in the Adriatic Sea. However, the associated magnitudes are relatively small (the waves were ignored in our previous analysis). A careful spectral analysis of the data will be needed in future investigations of this phenomenon.

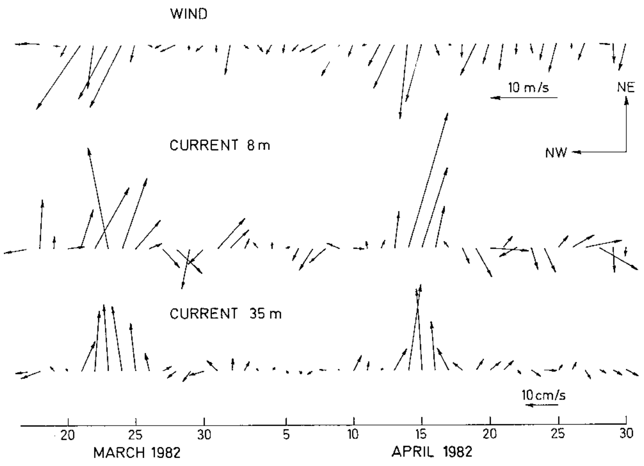

Figure 6
Low-pass filtered vector time series, decimated to 24 h *values of* (a) *wind measured at the Pula station,* (b) *upper level current* (8 m) *and* (c) *lower level current* (35 m) *measured at the station off Rovinj.*

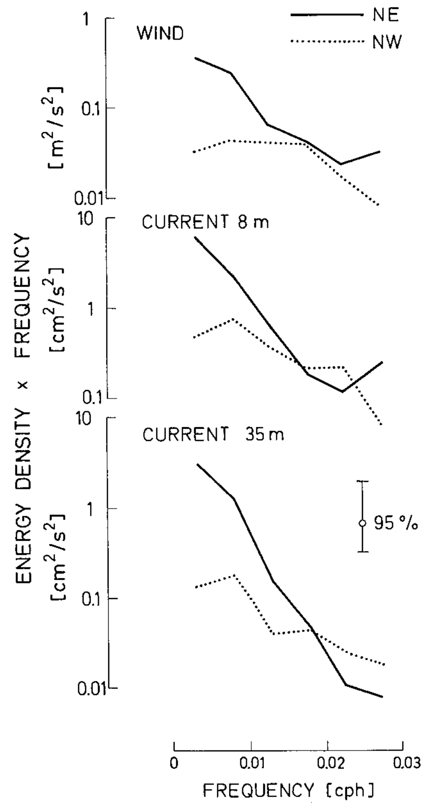

Figure 7
Spectra of the wind and current data time series presented in figure 6.

The spectra (fig. 7) show subtidal wind and current oscillations to be aligned with the NE/SW axis : the NE components are characterized by significantly higher energies than the NW components. Free oscillations manifest themselves by (insignificant) peaks in the NW components of the current spectra at a period close to 5 d, but are completely lost in the large energy maxima of the NE components of the spectra. These maxima are broad, reflecting the continuous distribution of energy in the NE wind spectrum, and they support our conclusion that the directly wind-forced currents dominate over all other contributions to the Northern Adriatic current field.

Figure 8*a* shows the results of cross-spectral analysis for the NE components of wind and current at 8 m. The coherence squared is significantly high for « synoptic » periods (≥ 3 d), confirming the predominantly forced nature of the sea motions. The current at 8 m amounts to about 3 % of the wind speed, and it opposes the wind with a slight lag (10-20°, i.e., 5-6 h). Figure 8*b* shows that the NE components of currents at the 2 depths of observations are highly coherent for the whole subtidal frequency interval. Moreover, the 35 m value is shown to be about 30 % smaller than the 8 m value, and the lower level current lags behind the upper level one for 10-15° (i.e., 3-8 h).

To summarize, we have shown that the dominant response of the Northern Adriatic to wind action is in the forced motions, the free oscillations being of considerably smaller magnitudes. The sea follows the wind promptly : frictional adjustment times are much smaller than the typical periods of atmospheric disturbances. Consequently, wind-driven flow in the Northern Adriatic may be well approximated by a frictionally controlled model, which neglects the acceleration. Csanady (1982) illustrates the effects of acceleration *versus* the influence of bottom friction on the basis of a very instructive analytical model.

MODEL TO DATA COMPARISON

After the basic numerical experiments had been performed and the importance of bura-induced motions established by examination of field data, a logical next step was to simultaneously assess the results of these two separate lines of investigation. Before attempting such a comparison of modelling results and field-data measurements it is important to recall the major assumptions of the model, the conditions under which data were taken as well as the processing procedures to which the data were submitted. A mismatch at this level can render the results of the comparison meaningless. The consequences of the major model assumptions (linearity, disregard of lateral shear, homogeneity of the sea, steady state and selective forcing) as well as the major characteristics of the area around the MEDALPEX station have been considered and reported in a previous paper (Kuzmić *et al.*, 1985). Let us only repeat here that the conclusions of the discussion support the idea of comparing the model results to MEDALPEX data. The comparison is currently limited to only one point, and its result is summarized in figure 9. A pair of measured vectors is shown in the upper part of the figure. The vectors are obtained by averaging the 3 bura episodes, presented and discussed in the data section, in a manner suggested by Scott and Csanady (1976). Again, one can see that bura induces upwind currents at both depths. The 2 vectors show rather small differences in direction as well as in magnitude. Both vectors represent significant percentage of the forcing wind vector (3.1 % at the 8 m, 2.2 % at the 35 m depth). The lower part of the figure shows the modelling results. Both predictions are for the real bottom topography case and the only difference is, as indicated, in the treatment of wind. The model prediction on the left corresponds to the case b of the figures 2 to 5, while the prediction on the right corresponds to the case d. As can be seen from figure 9, the homogeneous wind vectors are rather poorly related to the measured ones, in terms of direction and magnitude, as well as in their relative position. Introduction of the wind curl improves the prediction in all 3 aspects. The magnitude of the upper level vector attains 81 % of the measured value (compared to 36 % in the homogeneous case), while the lower level vector shows even greater improvement (61 % in the heterogeneous case, only 14 % in the homogeneous case). These percentages testify that the lower-to-upper level ratio has been markedly improved (it almost doubled). Although the current vectors calculated with the inhomogeneous wind are in a proper relative position, their direction is still considerably different from the observations. The improvements obtained by modifying the wind field still leave the following inadequacies :

a) the magnitude of the current vectors at both levels is smaller than suggested by the data ;

b) the direction at both levels is incorrect ;

c) the ratio of lower-to-upper level vector is lower than required.

When analysing these discrepancies one should distinguish two possible sources : insufficient data on which the calculation of model parameters has been based, and possibly inadequate model formulation. Concerning the data, the major component of empirical information is the spatially variable wind field over the area. Both the time series data, used to calculate the reference stress, and the climatological data, used to define spatial variability, have been measured at coastal stations. As Schwing and Blanton (1984) pointed out, the use of land base wind data in coastal oceanographic studies is common but could be erroneous. Since the wind velocity, over land or sea, is a complicated function of conditions at the air-sea interface and in the air, discrepancies can occur leading to the underestimation of the magnitude of marine winds (by as much as a factor of 2) and significant differences in direction. Therefore wind

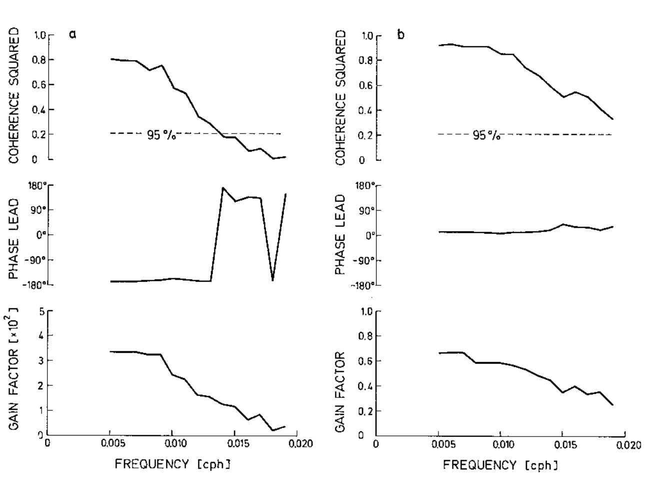

Figure 8

Results of cross-spectral analysis of (a) *the* NE *components of wind and current at* 8 m, *and* (b) *the* NE *components of upper level* (8 m) *and lower level* (35 m) *current.*

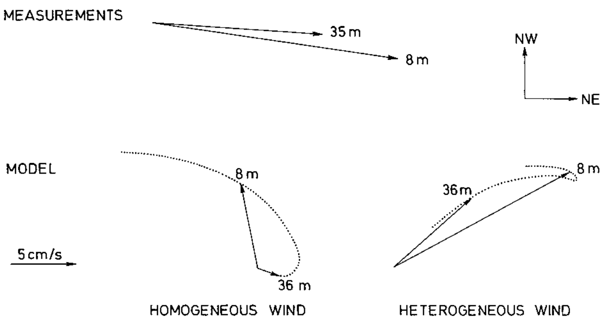

Figure 9

Model to data comparison of current vectors at two levels for homogeneous and heterogeneous wind model predictions.

measurements over the water surface, preferably at more than one station, are needed in order to correctly represent the wind stress in the model. But, denser array of coastal stations (we used 6), with more detailed measurements (we had data for 8 major directions) would also certainly improve the assessment of the spatial variability. A better assessment of the wind field characteristics would affect, although not necessarily eliminate, all the discrepancies mentioned above. One should also take into account inconclusive knowledge of the vertical eddy viscosity and bottom stress coefficients. The prediction using homogeneous wind forcing was based on the values for those coefficients estimated by other researchers of the Adriatic Sea. The same values were used in the heterogeneous case in order to identify the influence of wind vorticity. Some of our numerical experiments, not presented in this paper, suggest that somewhat different values for the coefficients would further improve the prediction.

Regarding the adequacy of the model formulations, there are two immediate suspects : one is linear bottom friction and the other is depth independent vertical eddy viscosity. Judging by the result of the correlation and regression analysis of the wind and current data from the PANON platform (Orlić *et al.*, 1986) the linear law of bottom friction, used in the model, is not inferior to the quadratic formulation, at least in part of the Adriatic Sea. The vertical variability of the eddy viscosity coefficient, however, seems an important and desirable feature that would help minimize and possibly eliminate the remaining inadequacies.

CONCLUSIONS

The wind induced vertical shearing in the Northern Adriatic during winter has been studied in this paper using an hydrodynamical numerical model and empirical data collected during ALPEX/MEDALPEX.

The influence of the heterogeneous wind field on the currents in the Northern Adriatic has been investigated for the first time using a three-dimensional numerical model. The only other author, to our knowledge, who modelled heterogeneous wind stress, Stravisi (1977), employed a two-dimensional storm surge model and considered the upper part of our modelling area (above the line connecting the Po river delta and midpoint between Rovinj and Trieste). Malanotte-Rizzoli and Bergamasco (1983) simulated time-dependent, but homogeneous wind stress. In the present study, we have employed climatological data to synthesize the wind curl field and through the use of several gradually refined numerical experiments, we have identified the heterogeneity of the wind field as a major factor in determining the wind-induced motions. Horizontal effects of the wind vorticity are summarized in figure 10. The circulation induced at the surface is presented in the upper part of the figure. A large cyclonic gyre is formed covering most of the modelled area. Another anticyclonic gyre is apparently formed below it but the proximity of the open boundary, as presently defined, casts some doubt on the prediction of circulation at the interface of the two gyres. A similar cyclonic circulation can be observed at the bottom, protruding more into the Gulf of Trieste. A part of another anticyclonic gyre is again visible near the open boundary. As for the vertical distribution of currents it has been shown and confirmed through comparison to data that the vorticity in the wind field can produce current vectors at different depths of magnitude, direction and relative position comparable to the ones obtained by measurements. This wind vorticity interpretation should be viewed as an alternative to the one put forward in a previous paper (Kuzmić *et al.*, 1985) in which the improvement in prediction was sought through the variation of the magnitude of the depth-independent eddy viscosity coefficient. Present empirical data on both wind and vertical eddy viscosity are insufficient to rule out either interpretation. We expect both to play a part in the solution together with the vertical variability of the eddy viscosity coefficient, and we plan to present some modelling results along those lines in the near future.

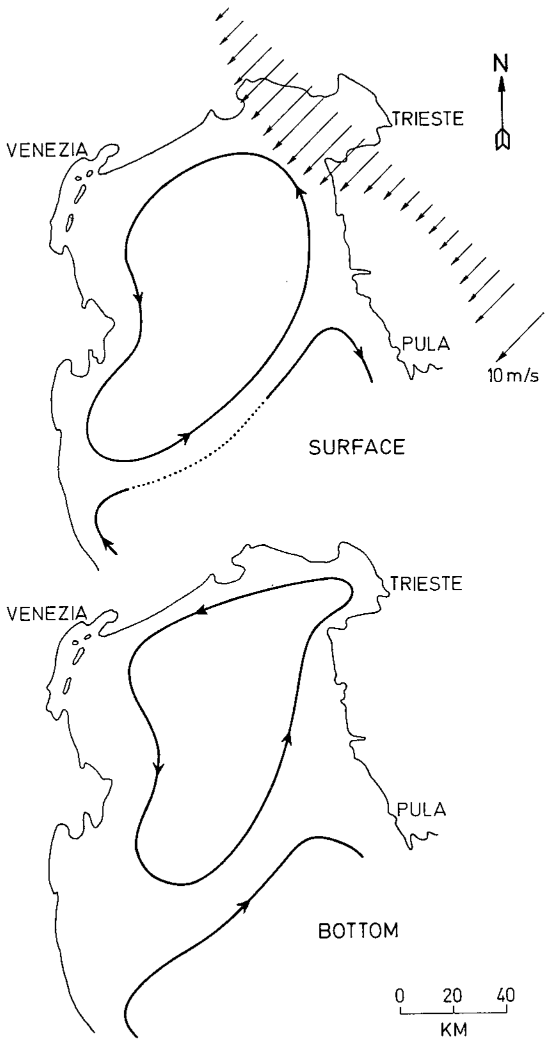

Figure 10
Wind curl induced circulation at the surface and bottom of the Northern Adriatic schematized from the model predictions.

On the empirical side, the wind and current data collected during ALPEX/MEDALPEX have been thoroughly analysed in the time and frequency domains. Both analyses support the notion that the dominant response of the Northern Adriatic to wind is of the forced type with bura inducing the strongest albeit transient current. However, both analyses also indicate the presence of free oscillations and appear to provide, for the first time, evidence for the existence of basin-wide topographic waves in the Adriatic Sea.

Acknowledgements

The authors would like to thank the Hydrometeorological Office of the SR Croatia, Zagreb, for supplying the wind data. The current data were collected in cooperation with the Center for Marine Research, Rovinj.

This work was supported by the Selfmanagement Community of Interest for Scientific Research of the SR Croatia through a grant to the Center for Marine Research, Zagreb.

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