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The Adriatic response to the bora forcing: A numerical study(*)

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Summary. — This paper deals with the bora wind effect on the Adriatic Sea circulation as simulated by a 3-D numerical code (the DieCAST model). The main result of this forcing is the formation of intense upwellings along the eastern coast in agreement with previous theoretical studies and observations. Different numerical experiments are discussed for various boundary and initial conditions to evaluate their influence on both circulation and upwelling patterns.

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PACS 02.60.Cb – Numerical simulation; solution of equations.

1. – Introduction

The Adriatic Sea (fig. 1a) is a semi-enclosed basin connected with the Mediterranean through the Otranto Channel. Its northern part is characterized by a slowly decreasing shelf reaching its maximum depth in correspondence of the Pomo depression (about 300 m). After the bottom increase at the Pelagosa Sill (130 m), the depth reaches its maximum at the South Adriatic Pit (1200 m). Finally, the bathimetric profile rises again in the Otranto Channel to the depth of 800 m. The Adriatic Sea is strongly affected by several processes related to: 1) the river run-off (mainly, the Po river); 2) topographic variations; 3) strong air-sea interactions and 4) flow exchanges through the Otranto Channel. In this paper we will pay attention on point 3, having in mind that the Adriatic is affected mainly by two meteorological situations: the bora and the sirocco. While the second one —blowing from the south— induces large fluctuations of the residual sea level that can cause harmful events such as storm surges in the northern areas [1, 2], the bora —a cold, katabatic wind blowing from the northeast— does affect the entire basin by inducing both particular circulation patterns and the formation of dense and bottom waters in its northern areas. It is necessary to underline that

(*) The authors of this paper have agreed to not receive the proofs for correction.

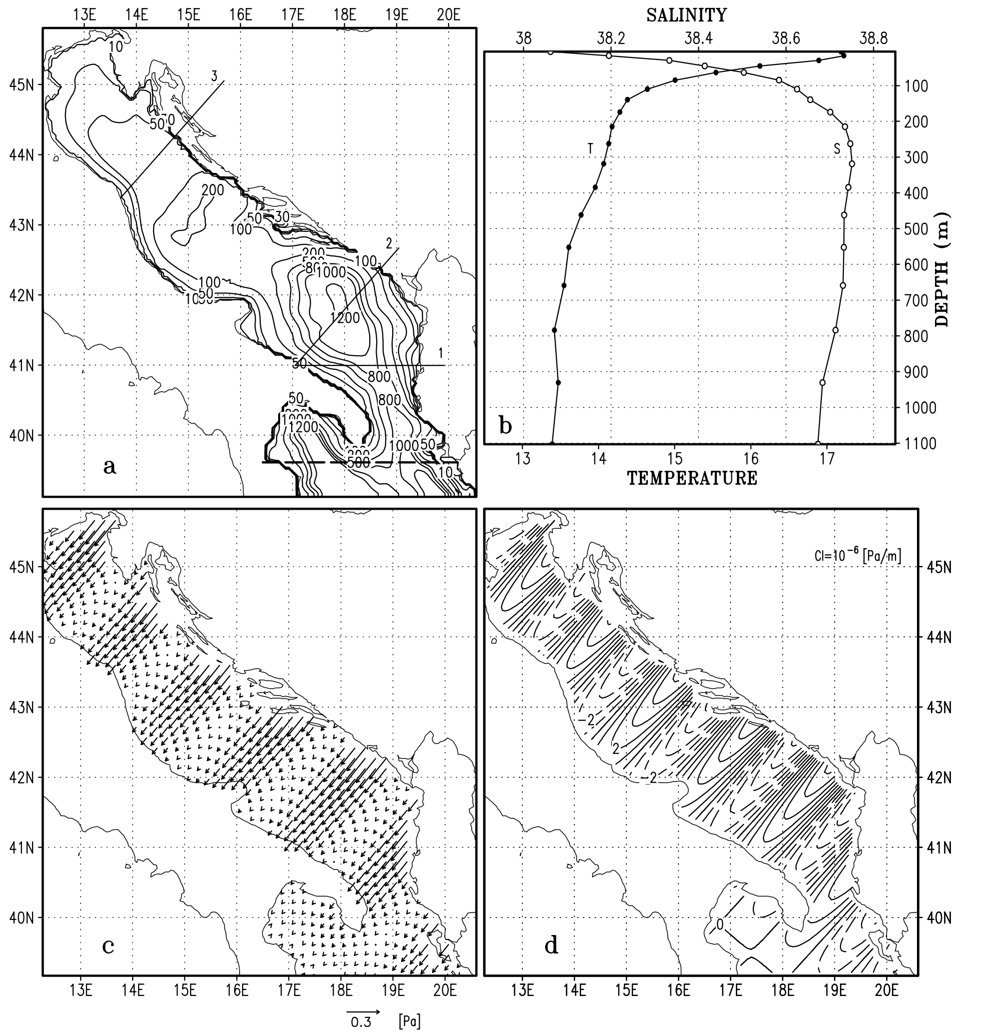

Fig. 1. – a) Adriatic sea bottom topography. Isobaths for 10, 30, 50, 100, 200, 500, 800, 1000 and 1200 m are plotted. Transects for which model results are analyzed are shown by straight lines. The dashed line indicates the northern end of the "sponge" region when the southern one coincides with the model boundary; b) vertical profiles of the initial temperature and salinity used in experiments 1 and 2; c) wind stress field; and d) wind stress curl ($\cdot 10^6$ Pa m^{-1}) used in numerical experiments.

such characteristic water masses contribute to the formation of the densest water in the eastern Mediterranean Sea [3].

A few numerical modeling studies on the response of the Adriatic Sea to the bora wind were carried out recently [4, 5, 1]. Different phenomena associated with bora were analyzed in these papers—the inertial oscillations and the Adriatic shelf seiches; the bora-induced currents and sea level variations; the upwellings along the eastern coast; the spreading of the Po river waters in an offshore direction, etc. Nevertheless, the relative importance of the bora forcing in driving the basin-wide circulation system and in the local circulation features is not yet well understood. The present study can be considered as an extention of the work of Bergamasco and Gačić [4], aiming to clarify some questions raised from the previous studies: i) What are the relative contributions of the bora-induced currents in modifying the residual Adriatic Sea circulation? ii) How does the bora forcing affect the exchange through Otranto Cannel? Within this framework, we chose a simple schematization of a bora event [4] and we used the numerical model DieCAST that, in further investigations, will be coupled with an atmospheric Limited Area Model in an operational oceanography context for the Adriatic Sea [6].

The brief description of the model used, initial and boundary conditions are described in sect. **2**. Section **3** presents the results of model simulations.

2. – The DieCAST Model

Referring to the bibliography for technical details [7-10], in the following we give a general outline of the DieCAST (Dietrich Center for Air Sea Technology) model. This model was derived from the modified Arakawa C grid SOMS (Sandia Ocean Modeling System) model [8, 9]. It is three-dimensional in a rotating frame, z-level, hydrostatic, Boussinesq, incompressible, rigid-lid. Instead of using the barotropic streamfunction, the DieCAST model uses top-level pressure adjustment. It uses conservative flux-based centered approximations in control volumes, and a weakly filtered "leapfrog" time integration scheme. A fourth-order approximation is used to communicate data between collocated A and staggered C Arakawa grids [10]. The Coriolis and vertical diffusion terms are coupled with an implicit treatment so that the Coriolis term conserves energy exactly. This finite differencing scheme results in a low dissipation model with a computationally efficient code [7].

Some details of the application of the DieCAST model to the Adriatic Sea are as follows:
- region modeled: 12.2E to 20.5E, 39.1N to 45.8N;
- longitudinal resolution: $\frac{1}{15}$ deg (5.3 km);
- latitudinal resolution: variable such that $\Delta x = \Delta y$;
- vertical resolution: 20 layers, uniformly expanding vertical grid to a maximum depth of 1200 m;
- horizontal eddy viscosity and diffusivity: 65 m^2 s^{-1};
- vertical viscosity and diffusivity: 10 cm^2 s^{-1} plus contribution proportional to vertical velocity;
- bottom friction $\vec{\tau}_b = -C_d|\vec{V}|\vec{V}$, where the drag coefficient $C_d = 0.002$ and $\vec{V}$ is a bottom velocity.

Four numerical experiments were carried out (table I). The first two were integrated starting from motionless initial condition and horizontally uniform temperature and salinity vertical profiles (fig. 1b) corresponding to an autumn situation. The next two were initialized with model simulated fields (fig. 6a,c) using Hellerman and Rosenstein [11] autumn winds and MODB-MED4 (Mediterranean Oceanic Data Base) autumn climatology [12]. When open boundary conditions were used (experiments 2 and 4), the "sponge" region of 55 km width (fig. 1a) was specified adjacent to the southern boundary, where the temperature and salinity fields were restored to the climatology. The velocities on the southern boundary were specified by modifying the MODB-MED4 data set, to take into account that the net outflow through the boundary must be zero because of model requirements. The model simulated velocities adjacent to the open boundary were ad-

TABLE I. – *Model experiments.*

Experiment	Initial velocity, temperature and salinity	Southern boundary
(1)	motionless, horizontally uniform, autumn vertical profiles	closed
(2)	"	open
(3)	model simulated fields using MODB data set and Hellerman and Rosenstein (1983) winds	closed
(4)	"	open

justed to match the modified MODB velocities [10]. No heat and salt fluxes were applied directly to the model, but the so-called "relaxation" boundary condition for sea surface temperature and salinity was used with a restoring timescale of 10 days. Nevertheless, sensitivity experiments carried out showed that the simulated surface temperature and salinity are negligibly affected by "relaxation" procedure for a restoring timescale bigger than the total time of a model integration.

The model was forced by an idealized wind stress field pattern (fig. 1c,d), similar to that used by Bergamasco and Gačić [4]. The maximum wind stress magnitude was 3 dynes cm^{-2}, the wind stress curl varied in the range from $-5 \cdot 10^{-7}$ to $5 \cdot 10^{-7}$ dynes cm^{-3}, the wind field was assumed convergent (minimum value $-8 \cdot 10^{-8}$ dynes cm^{-3}). This wind pattern is close to what is known about the bora field from observational data [5, 1].

The numerical integration was carried out for five days, which is the duration of a bora event used also in the previous studies [4, 5].

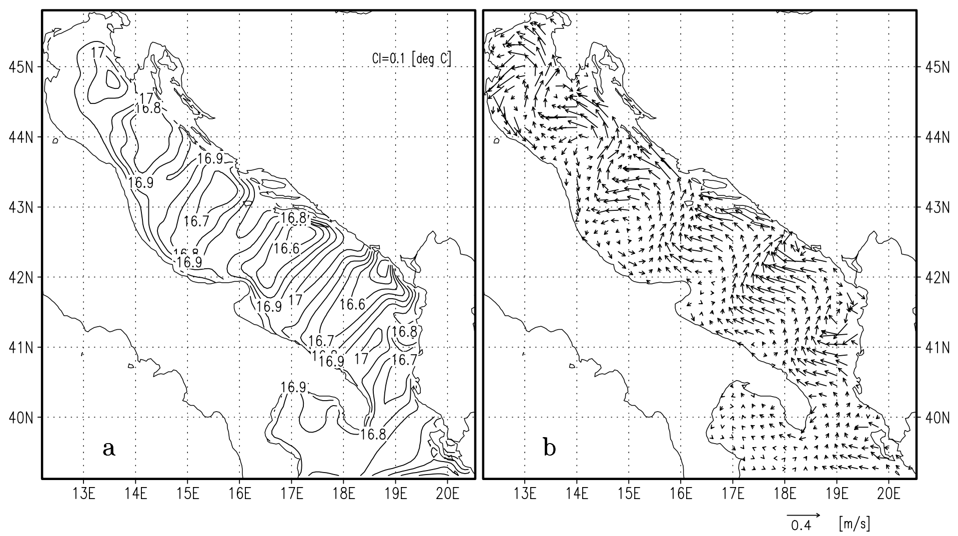

Fig. 2. – Sea surface fields simulated at the end of the experiment 1: a) temperature and b) horizontal velocities.

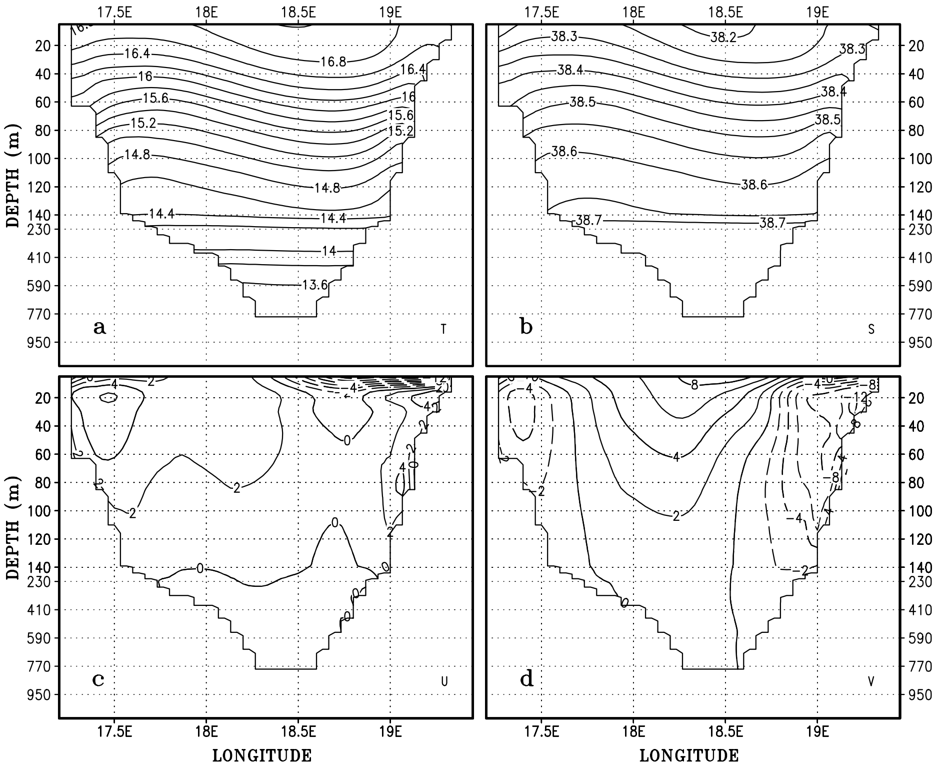

Fig. 3. – Vertical distributions of: a) temperature; b) salinity; c) zonal velocity; and d) meridional velocity (cm s^{-1}) for the transect 1 at the end of the experiment 1.

3. – Results and discussion

Horizontal distributions of the surface temperature and horizontal velocities in experiment 1 are shown in fig. 2. The surface field patterns are characterized by northeast-southwest oriented, offshore elongated zones of upwellings and downwellings. The strong shear in the bora wind field results in an intense Ekman pumping velocity, which is approximately two orders of magnitude larger than the typical one in the oceanic boundary layer. The strongest upwelling occurs along the Albanian coast. These model results are in good agreement to results of Bergamasco and Gačić [4]. Surface currents (fig. 2b) are stronger and have downwind component under the applied wind stress maxima and are weaker and directed upwind under the bora minima. The intense cyclonic gyre is formed in the northernmost Adriatic. Analogous results were obtained in [1], also.

Figure 3 presents vertical structures of temperature, salinity, zonal and meridional velocities in the transect 1 in the southern Adriatic, close to the Otranto Channel (fig. 1a). The upwelling close to the eastern coast is evident. Open-sea upwelling is also evident at fig. 3a and b, located under the area of positive wind stress curl. The downwelling takes a place near the Italian coast. The vertical distribution of the horizontal current components (fig. 3c,d) shows typical features of the Ekman dynamics [4]. The surface zonal velocity is directed westward at the transect 2 (not shown) and at the right part of

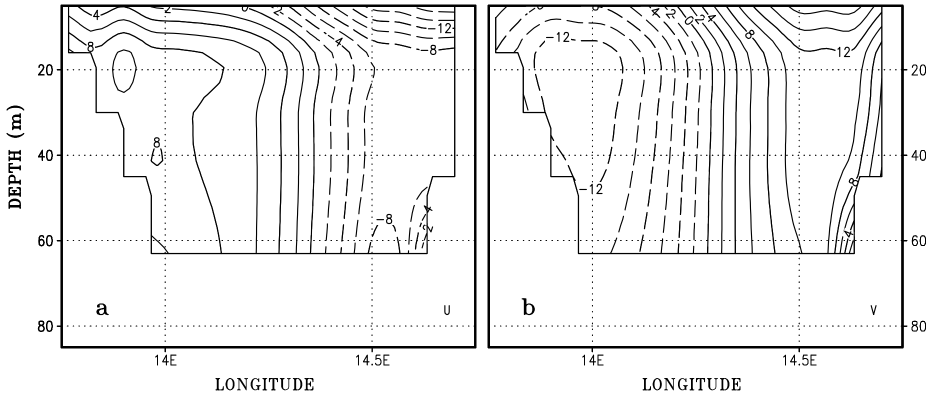

Fig. 4. – Vertical distributions of: a) eastward velocity; and b) northward velocity for the transect 3 at the end of the experiment 1.

the transect 1 (fig. 3c), while the countercurrent appears in deep layers. The formation of coastal countercurrent below the northward flowing current is evident in fig. 3d. There is not such overturning at transect 3 (fig. 4), located in the shallow northern Adriatic, where the strong current along the eastern coast penetrates over the whole of the water column. This current is compensated by south flowing current near western coast.

The comparison of the present results with the study of Bergamasco and Gačić [4] shows that the physical differences between the models used (rigid lid *vs.* free surface) are not significant for the simulation of the upwelling phenomenon [7].

The only difference between experiment 1 and experiment 2 (table I) is that in the latter the open boundary conditions are specified on the southern boundary. This influences significantly the model dynamics in southern Adriatic, increasing the exchange through the Otranto Channel. The surface inflow is intensified considerably (fig. 5). At

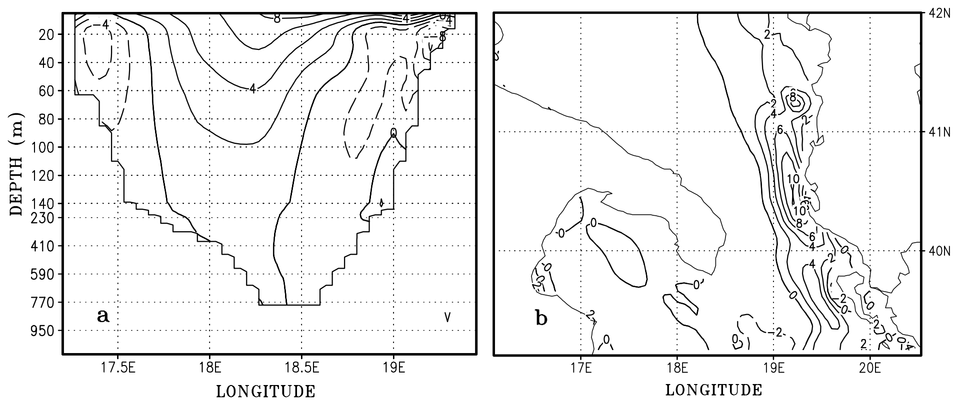

Fig. 5. – Experiment 2: a) vertical structure of the northward velocity for the transect 1; b) the difference between the model simulated northward velocity at the surface in experiments 2 and 1. The contour interval is 2 cm s^{-1}.

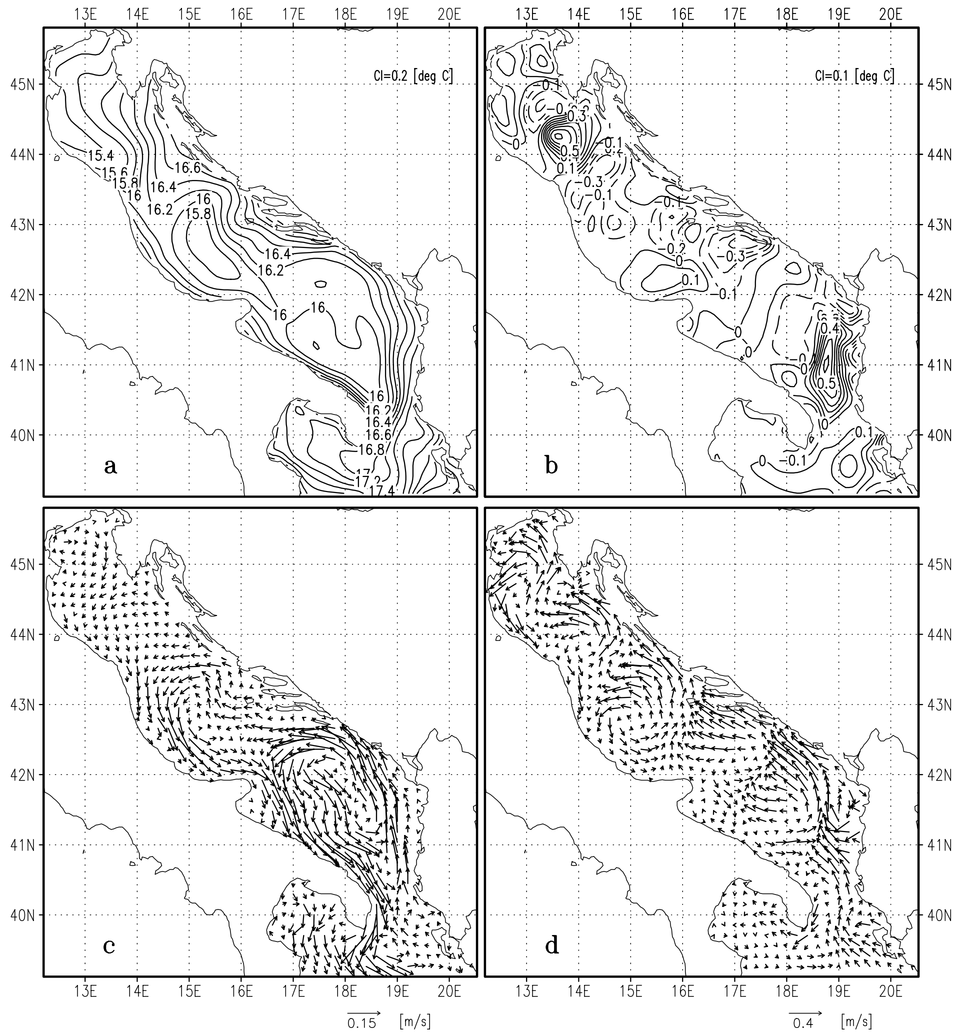

Fig. 6. – Sea surface temperature (a) and horizontal velocity (c) fields used for the initialization of experiments 3 and 4. b) and d) The same fields, but after 5 days of integration with bora wind forcing in the experiment 4.

the same time, the bora induced coastal countercurrent along the Albanian coast is reduced twice. Since the water exchange with the Ionian Sea is of crucial importance for the Adriatic Sea circulation [13], the question raised is: Can the bora-induced currents reverse or block the Levantine Intermediate Water inflow? The experiments 3 and 4 were carried out to answer this question.

Initial conditions for experiments 3 and 4 were obtained after one month model integration using autumn MODB-MED4 data set [12] and Hellerman and Rosenstein [11] autumn winds. The initial surface temperature and velocity fields are presented on fig. 6a and 6c, correspondingly.

After one month of integration the resulting autumn Adriatic Sea circulation (fig. 6c)

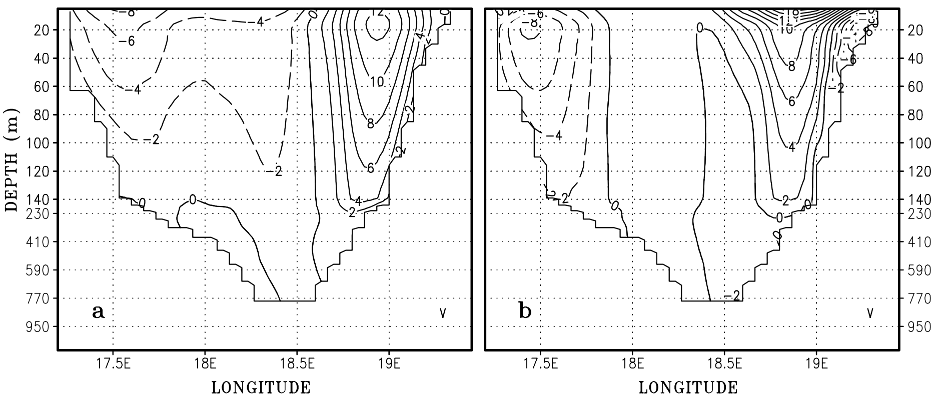

Fig. 7. – Vertical profiles of the northward velocity for transect 1: a) at the beginning; and b) at the end of integrations of the experiment 4.

reached a quasi-steady state and is in a good agreement with that described in [14, 13]. The current speed reaches $15\,\mathrm{cm\,s^{-1}}$ in the southern Adriatic near the Italian coast. The vertical distribution of the temperature in the central part of the southern Adriatic shows a doming pattern, due to strong cyclonic circulation. The water exchange through the Otranto Strait is simulated properly (fig. 7a). The recent estimate of [15] based on direct Eulerian current measurements gives stronger exchange with Ionian Sea by approximately 30%.

Figures 6b, 6d and 7b represent the results of the experiment 4. The comparison between fig. 6c and d shows that the bora-induced surface currents intensify the eastern branch of the South Adriatic residual cyclonic circulation and weakens the western branch. The situation is reversed at depths below 15–20 m. The surface circulation in the northern Adriatic is strongly affected by the bora forcing and it is reversed in the northernmost part of the sea from initially anticyclonic to cyclonic. The upwelling and downwelling regions (fig. 6b) are significantly modified (compare with fig. 2a) due to a superposition of the bora-induced vertical motions and these, connected with the Adriatic Sea residual circulation.

The vertical distribution of the northward velocity at transect 1 (fig. 7b) can be considered (in the first approximation) as a superposition of the velocity simulated in experiment 2 (fig. 5a) and the velocity shown on fig. 7a. As the simulated autumn inflow current along the eastern coast (fig. 7a) is stronger (down to depth of 300 m), then the bora-induced reverse one can only reduce, but not invert completely the Levantine Intermediate Water inflow. The current reversal takes place below 300 m where the weak southward current is simulated close to the eastward coast (fig. 7b). This southward current is stronger in the experiment 3 (not shown) which was carried out with closed southern boundary. We note that the difference between simulated velocity fields in experiments 3 and 4 is the same as in experiments 1 and 2 (see fig. 3d and fig. 5). Recent observations [15, 16] show that the current fluctuations in the Strait of Otranto are significant over a broad spectrum of scales, from synoptic to a seasonal time scales, and even interannual time scales [13]. Thus the complete current reversals can occur in the case of extremely strong bora event or relatively weak inflow, as was suggested by Bergamasco and Gačić [4].

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