NUMERICAL SIMULATIONS OF THE ADRIATIC SEA AUTUMN CIRCULATION

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Abstract. This study presents the results of numerical simulations of the climatological Adriatic Sea circulation during the autumn. The simulations are carried out using the DieCAST ocean model. The sensitivity of the model circulation to the different mechanical forcing is studied. The main Adriatic Sea circulation features are simulated properly. It is shown that during the autumn the wind forcing is of crucial importance only for the formation of the northern Adriatic circulation, whereas the thermohaline circulation is found to be more important over the rest of the basin. Numerical experiments show that the model is able to simulate well the outflow current through Otranto channel.

Key words: Adriatic Sea, general circulation ocean model.

Introduction

The Adriatic Sea is a semi-enclosed basin connected with the Mediterranean Sea through Otranto channel. The Adriatic circulation is strongly affected by several processes related to the: river runoff; topographic control; strong air-sea interactions; exchange through the Otranto channel etc. The relative importance of these processes in driving the basinwide circulation system is not yet well understood. We carried out numerical simulations with autumn climatological forcing, because during that season a strong cooling occurs all over the Adriatic, the wind forcing is augmented, vertical mixing is inhibited, and the destruction of the well developed thermocline in spring and summer begins (Artegiani et al., 1997).

In autumn, the dominant winds blowing over the Adriatic Sea are the Bora (from northeast) and Sirocco (from southeast). The episodes of strong Bora and Sirocco winds affect the circulation of both the northern and the southern Adriatic (Rachev and Purini, 2001). One of the effects of the Bora wind is the reduction of the Levantine intermediate water inflow through Strait of Otranto. Due to the time averaging and to the coarse grids, the climatological wind data sets are unable to represent correctly the magnitude and the direction of these winds, and consequently their effects on the Adriatic Sea circulation. Therefore, it is of critical importance to have as precise forcing as possible, since small discrepancy could affect the simulations during long term integrations. That is why, we carried out numerical experiments with different climatological wind forcing (Hellerman and Rosenstein, 1983, May, 1982), trying to determinate more suitable mechanical forcing.

The DieCAST model

Referring to the bibliography for technical details (Beletsky et al., 1997, Dietrich et al., 1987, 1994, Dietrich, 1997) 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 (Dietrich et al., 1987, 1994). It is three-dimensional in a rotating frame, z-level, hydrostatic, Boussinesq, incompressible, rigid-lid model. 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 (Dietrich, 1997). 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 (Beletsky et al., 1997). The DieCAST model requires relatively less computation per time step and is able to resolve fine scale features using much lower resolution than analogous 3D ocean models.

The DieCAST model uses a very simple 'turbulence closure' scheme. In regions with strong vertical motion one might expect increased vertical mixing of momentum by sub-grid scale eddies. To determinate this, the increased vertical mixing is represented as an increased vertical viscosity which is added to the background vertical viscosity.

Model setup for the Adriatic Sea

Topography and domain

The model domain covers the entire Adriatic Sea, including the northernmost part of the Ionian Sea. The model basin extends from 12.2E to 20.5E and 39.1N to 45.8N. The horizontal resolution is 5.33 km and 20 vertical levels are used at depths (in meters): 0, 10, 22, 37, 54, 74, 97, 124, 156, 194, 238, 290, 350, 422, 505, 604, 719, 854, 1010, and 1200. The model grid is 126x137x20 points.

The bottom topography used in our numerical experiments is interpolated to the model grid from the 1 min (1.33x1.83 km) Adriatic Sea bathymetry.

Atmospheric forcing

The first experiment is forced by autumn (October - December) wind stresses (Fig. 1a) derived from the Hellerman and Rosenstein (1983) (hereafter HR83) monthly climatologies. It is well known that HR83 climatology is a relatively weak and smoothed wind stress field. The value of the area averaged over the model domain autumn wind stress magnitude is 0.011 Pa. Although we use HR83 wind stresses, because they are the best documented and widely used in numerical calculations.

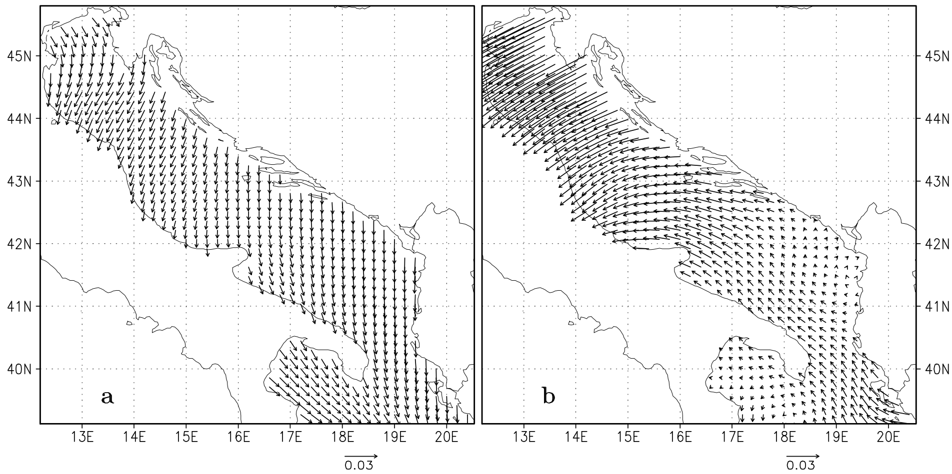

Fig. 1. Autumn wind stresses (Pa) fields over Adriatic Sea derived from: (a) Hellerman and Rosenstein (1983); (b) P. May (1982) data sets.

The second experiment is forced by autumn wind stresses of May (1982) (hereafter MAY82) which are stronger in the northern and middle Adriatic (Fig. 1b). Artegiani et al. (1997) showed that there are considerable differences in wind speed and direction between HR83 and MAY82 data sets. As we can see in Fig. 1 the dominant wind stress direction in the northern Adriatic during autumn is from the northeast, which corresponds to the Bora wind. At the same time in the southern Adriatic the directions of the wind stresses for HR83 and MAY82 data sets are opposite. It seems that the effects of the Sirocco and Bora winds are better represented in MAY82 data set.

No heat and salt fluxes are applied directly to the model, but the so called relaxation boundary condition for sea surface temperature and salinity is used.

Initial and boundary conditions

The model is initialized with autumn temperature and salinity fields obtained from MODB (Mediterranean Oceanic Data Base (Brasseur et al., 1996) climatology. Autumn data are interpolated to the model grid and then are checked for stability. Numerical experiments are integrated starting from motionless initial condition. One of the advantages of the MODB data set is that the geostrophically adjusted seasonal velocity fields are included. This allows us to specify the open boundary conditions on the southern boundary of the model basin (Fig. 2). We have assumed no barotropic inflow into our domain through the open boundary, since the 'rigid lid' DieCAST model in its present form does not allow mass addition. 'Sponge' region of 55 km width is specified adjacent to the open southern boundary, where the temperature and salinity fields are restored to the climatology.

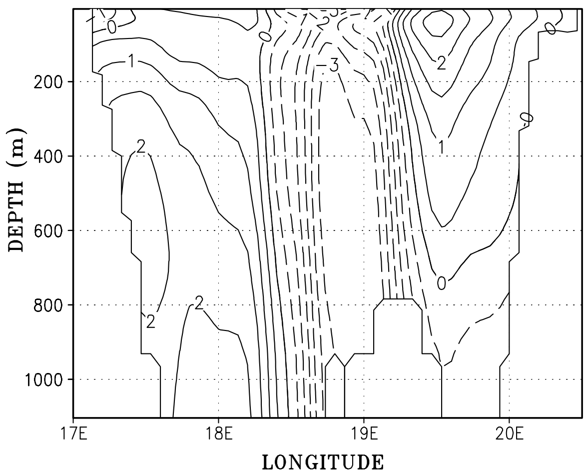

Fig. 2. Vertical distribution of meridional velocity (cm s^{-1}) at the southern open boundary of the model basin, obtained from MODB-MED4 data set.

The surface temperature and salinity in all model experiments are relaxed to the seasonal climatological values (Fig. 3). Assuming such surface boundary condition we specify the buoyancy fluxes to be proportional to the deviation of the model simulated surface temperature and salinity from the climatological ones.

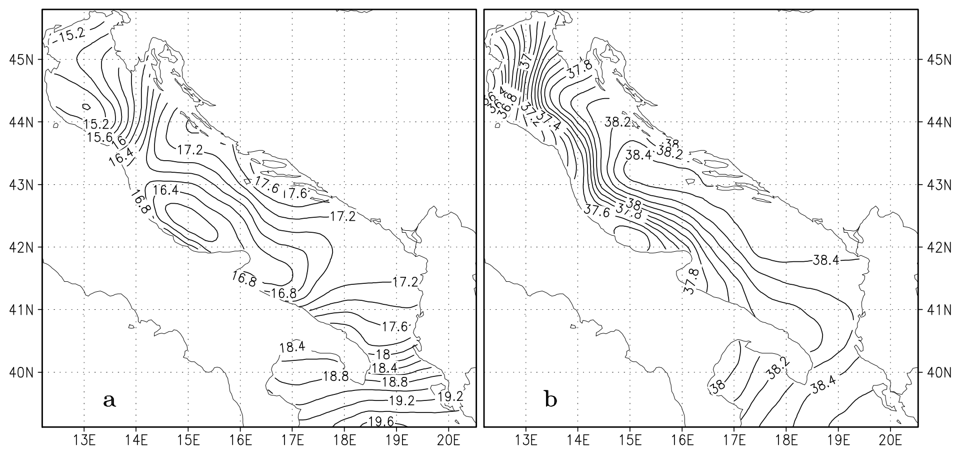

Fig. 3. Adriatic Sea surface (a) temperature; and (b) salinity fields for autumn, derived from MODB-MED4 (Brasseur et al., 1996) data sets.

In Fig. 3 we show the autumn Adriatic Sea surface temperature and salinity from MODB data sets. The temperature field exhibits well marked frontal areas in the northern Adriatic and close to the Otranto channel (Fig. 3a). Artegiani et al. (1997) showed that the strong salinity frontal areas exist, particularly close to the italian coast, related to the river runoff. This frontal area is well represented in MODB data (Fig. 3b).

Model experiments and parameters

Three main numerical experiments are carried out with different choices of the wind forcing used. The first experiment is forced by HR83 autumn wind stresses, the second - by MAY82 autumn wind stresses, and the third one is without wind forcing. Some sensitivity experiments are performed also. The time step used in all experiments is 10 min, the value of the bottom drag coefficient is 0.002. The relaxation time is 10 days. The background vertical viscosity we used is 10^{-3} m^2 s^{-1} and the horizontal eddy viscosity and diffusivity is 65 m^2 s^{-1}. The numerical integration was carried out for one month, for which period the circulation reached a quasi-steady state.

Using the autumn wind and thermohaline forcing allows us to compare the simulated circulation with autumn Adriatic circulation obtained in other climatological studies and with some satellite images available.

Results of numerical experiments

Artegiani et al. (1997) showed that the forcing of the general Adriatic Sea circulation had three major components: 1) river runoff; 2) wind and heat forcing at the surface; and 3) Otranto Chanel forcing. They suggested that these forcing components are equally important. The river runoff was not included explicitly in present simulations and we focused our study to the rest two forcing components. The simulated resulting autumn Adriatic Sea circulation (Fig. 4a, 5a, 6a) is in a good agreement with that described in Artegiani et al. (1997) and Orlic et al. (1992). The current speed reaches 15 cm s^{-1} in the southern Adriatic near the Italian and Croatian coasts. 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.

Thermohaline forcing

It is well known that Adriatic Sea, as a whole, is dilution basin. The analysis of Raicich (1996) reveals noticeable spatial and time variability of the fresh water balance, whose horizontal distribution is largely affected by river runoff. The model results of Bergamasco et al. (1999) show that adding the fresh water discharge to the other forcings, modifies the circulation of the northern and central Adriatic substantially, forming well pronounced southward flowing current along the Italian coastline. Since in our simulations the river runoff is not added explicitly, the salt flux is not correctly represented, due to the smoothness of the climatological surface salinity fields. Thus, the southward flowing current along the western coast in the northern Adriatic (Poulain, 1999) is not properly simulated (Fig. 4a, 6a). That is why we will focus our analysis mainly to the southern Adriatic circulation.

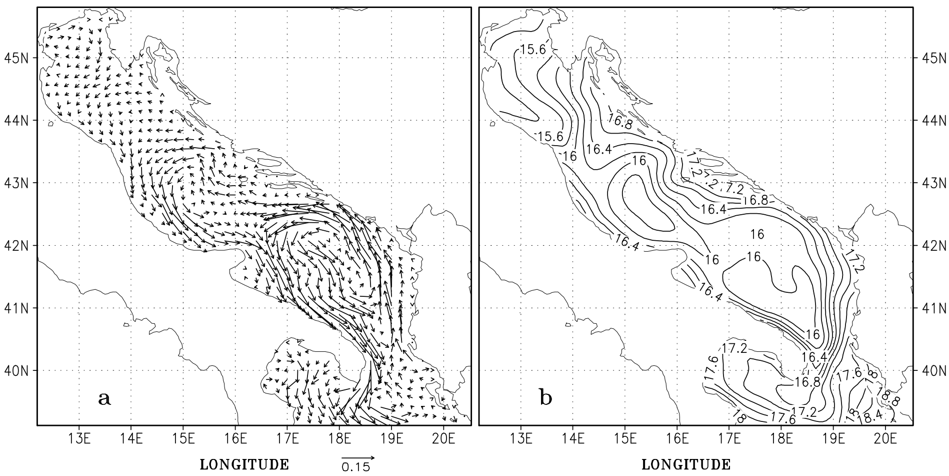

Fig. 4. Simulated surface fields in experiment 1 (HR83 autumn wind stress): (a) velocity (m s^{-1}); (b) temperature.

The situation is somewhat changed in the second experiment where the MAY82 wind stresses was used. The surface circulation of the northern Adriatic in this experiment (Fig. 5a) is close to this, described by Orlic et al. (1992). The modeled surface velocities are about 10 cm s^{-1}, which is in good agreement with the estimations of Orlic et al. (1992).

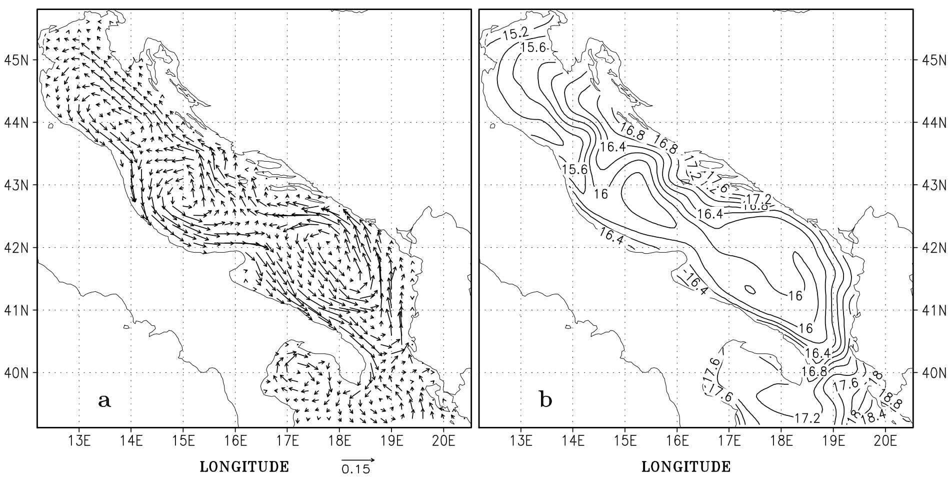

Fig. 5. Simulated surface fields in experiment 2 (MAY82 autumn wind stress): (a) velocity (m s^{-1}); (b) temperature.

There are three stable features of the modeled circulation, which are simulated (with some differences) in all of model experiments: 1) middle Adriatic cyclonic gyre; 2) southern Adriatic gyre; and 3) outflow through Otranto channel. Obviously, these circulation features are controlled by lateral thermohaline variations of the water properties and by bathymetry. The wind forcing has a minor role in a formation of these features. For example, the outflow current through Otranto channel (close to the Italian coast) is simulated in the third experiment, which is carried out without wind forcing (Fig. 6a) and even in the second experiment (Fig. 5a) in which directions of the outflow current and applied MAY82 wind stresses are opposite.

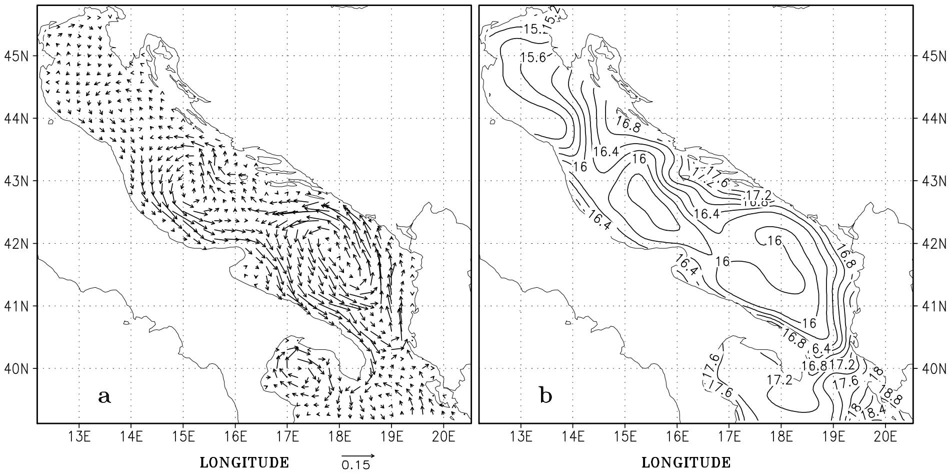

Fig. 6. Simulated surface fields in the third experiment (without wind forcing): (a) velocity (m s^{-1}); (b) temperature.

The outflow current brings out relatively cold and less salty waters which are spread as a tongue southwest when they enter the Ionian Sea (Fig. 4b, 5b, 6b). The inflow through the southern boundary of the model basin brings waters with higher salinity and temperature and as a result the well pronounced hydrographic front is formed.

The water exchange with Ionian Sea through Otranto Strait is of crucial importance for the Adriatic Sea circulation (Orlic et al., 1992). The estimates of Raicich (1994) give for entire Adriatic an annual fresh water gain between 0.65 and 1.1 m $year^{-1}$, which should result in a net outflow of about 0.006 Sv. Thus, the water transport through the Strait of Otranto can be considered in balance, i.e. the net transport is zero in the first approximation. The resent observations (Poulain, 1999) 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 (Orlic et al., 1992). The estimated mean water flux through the Otranto Strait based on direct Eulerian current measurements gives value of 0.9 Sv (Civitarese et al., 1998) that is unrealistically large, compared with those found in literature.

The open boundary conditions on the southern boundary in our model experiments are specified qualitatively according to the MODB-MED4 data set (Brasseur et al., 1996). The actual MED4 data are modified, so the net outflow through the southern boundary is kept to be zero during the integration (because of model requirements) (Fig. 2). This approach allows only a part of the spatial variability to be included in our model studies. More suitable approach is: to specify the river runoff, which to be balanced by the outflow through the open boundary. Nevertheless, the model results show that including the open boundary forcing (even qualitatively) permits the thermohaline structure in the southern Adriatic to be kept close to the climatology for longer periods of model integration.

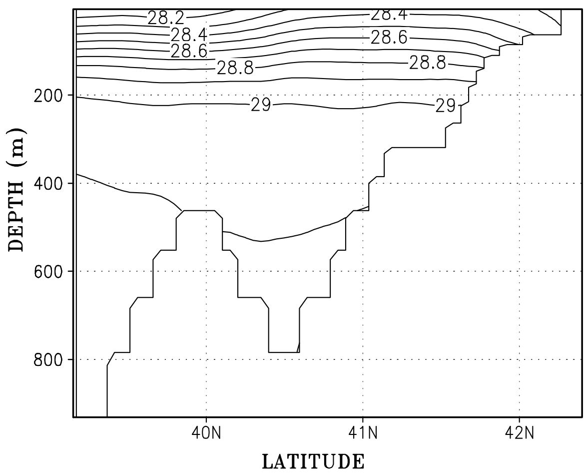

Fig. 7. Vertical transect along the longitude 18.8°E of the density (σ_t units) in experiment 3 (without wind forcing).

Figure 7 represents a vertical transect of the density along the Otranto channel and southernmost part of the Adriatic Sea at longitude 18.7°E. (following approximately stations 103-203-302-403 of POEM01 cruise in autumn 1985, Salusti and Serravall, 2002) for the third experiment (without wind forcing). The pattern of the isopicnals on Fig. 7 is qualitatively the same as in POEM01 results (Salusti and Serravall, 2002). It seems that the water exchange through Otranto Strait is not related to some long lasting atmospheric forcing, but probably is due to the vertical thermohaline structure in the vicinity of the Otranto channel, formed in the process of mixing of water masses with different characteristics.

Wind forcing

The analysis of Artegiani et al. (1997) shows that the density-driven circulation is week in the northern and middle Adriatic during winter, and that baroclinic dynamics is significantly enhanced during spring and summer. From other side, the magnitude of the wind stress reaches its minimum in spring and its maximum in winter. This suggests that the wind-driven and density-driven currents will have different importance in formation of the seasonal Adriatic Sea circulation. The present model results show that during autumn the wind-driven circulation predominates only in the northern Adriatic. The thermohaline circulation is found to be more important over the rest of the basin.

As mentioned earlier, the HR83 wind data is relatively weak and smoothed. The analysis of both datasets and model results show that MAY82 data represents better the characteristical features of the wind field over Adriatic Sea known from observations. In general, the simulated circulation in numerical experiments using MAY82 winds is more realistic (Fig. 5a) and some specific features of the circulation can be simulated properly.

For example, in the northern Adriatic, the cyclonic circulation is simulated with a wide northward wind-driven current near the eastern coast. As the wind magnitude decreases to the south, the contribution of the wind forcing is less in the middle and southern Adriatic, than in the northern Adriatic where it is compatible with the thermohaline forcing. The topographic control is important for the generation of the middle and southern Adriatic gyres, also (Orlic et al., 1992).

Conclusions

We have examined the Adriatic Sea circulation in autumn using climatological forcing. Model results show that the May (1982) wind data set better represents the main features of the wind field over Adriatic Sea (known from observations), then the Hellerman and Rosenstein (1983) data set. It is showed that during autumn, the wind-driven circulation predominates only in the northern Adriatic, while the thermohaline circulation is more important over the rest of the basin. The bottom topography is important factor in controlling the Adriatic Sea circulation. Further studies are needed to improve the thermohaline forcing, mainly by including the river runoff and reliable surface heat fluxes.

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Числено моделиране на есенната циркулация на Адриатическо море

Н. Рачев, Р. Пурини

Резюме: Представени са резултати от числено изследване на циркулацията на Адриатическо море през есента. Изчисленията са извършени с помощта на океанския модел DieCAST. Изследвана е моделната циркулация при прилагането на различни ветрови напрежения. Моделните резултати добре възпроизвеждат основните характеристики на циркулацията на Адриатическо море. Показано е, че през есента ветровото форсиране има съществена роля при формиране на циркулацията в северната част на морето, а термохалинното форсиране е определящо за формиране на теченията в централните и южни райони на морето. Резултатите от числените експерименти показват възможностите на използвания модел да възпроизведе добре процесите на обмен на водни маси през пролива Отранто.