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Air-sea interactions in the Adriatic basin: simulations of Bora and Sirocco wind events

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Two simulations of the response of Adriatic Sea to severe wind performed by an atmosphere-ocean coupled model and the comparisons with observed data and modelled fields published in literature are presented.

The model RAMS-DieCAST was applied to simulate the variations of sea currents and temperature profiles, from surface to bottom, induced by two episodes of intense wind over the Adriatic sea: a Bora wind event that occurred in January 1995 and a Sirocco wind event in November 2002.

The results of the simulations are compared with observed data at the sea surface. In the Bora episode, the computed surface temperatures are compared with satellite SSTs and *in situ* observed temperatures; in the Sirocco event the simulated surface currents and temperatures are compared with experimental data collected by surface drifters released in different regions of the Adriatic Sea during the same Sirocco event.

In both episodes the simulated temperature trends agree with the observed values and during the Sirocco episode the current fields are in quite good agreement with the drifter data.

The modelled sea temperature and velocity fields show also a good concordance with other simulation results in literature.

Keywords: Adriatic Sea, Bora, Sirocco, ocean-atmosphere interaction, ocean-atmosphere coupled model, surface currents, surface temperature, temperature profiles.

1. Introduction

The Adriatic Sea is located in the northernmost part of the Mediterranean Sea: its shape can be approximated with a tilted rectangle, about 800 km long and 200 km wide. The bathymetry is characterized by strong latitudinal and longitudinal asymmetries. The knowledge of the bathymetric configuration allows to split the Adriatic area in three sub-areas (Orlić et al., 1992). The Northern Adriatic is very shallow (the sea depth is lower than 100 m), the

Middle Adriatic is occupied by a depression (the Mid Adriatic Pit, that reaches its maximum depth of 270 m) and the South Adriatic is characterized by the deepest pit of Adriatic basin (the South Adriatic Pit – 1200m). The longitudinal asymmetry of Adriatic Sea is mainly due to the presence of a great number of islands along the eastern coast and their complete absence along the western coast; an additional element contributing to the longitudinal asymmetry is the difference in the orographic features between the opposite coastal lands: the Dinaric Alps close to the eastern sea coastal line and the Apennines more distant from the western coast (Gačić et al., 2001).

The climatological three-dimensional current patterns, the three-dimensional temperature and salinity fields and their seasonal modulations were derived respectively by Brasseur et al. (1996) and Wu and Haines (1998). The data sets (MODB-MED5 and MODB-MED4) are considered as reference data and are commonly used to inizialize ocean models.

The Adriatic Sea circulation and temperature patterns can change abruptly when the sea basin experiences the onset and growth of strong winds (Bora and Sirocco, in particular).

The Bora wind is a dry, cold and strong wind blowing unsteadly over the Adriatic Sea from NNE, NE or ENE; it has been studied since the second part of XIX century. The onset of Bora is closely related to atmospheric subsynoptic features, while its speed and direction depend on local orography. The Bora wind affects the Adriatic Sea circulation and its surface temperature, producing intense upwelling events along the eastern Adriatic coasts (Rachev and Purini, 2001), and causes heat loss and evaporation leading to dense water formation (Vilibić et al., 2004).

The Sirocco, on the contrary, is a warm, humid and steady wind blowing over the Adriatic basin from SSE. The Sirocco wind is the cause of a piling up of Adriatic water near the northernmost coasts, that occasionally floods the city of Venice (Orlić et al., 1994).

Many numerical experiments were carried out to study the Adriatic Sea response to wind forcing. Ocean models were developed and applied (Bergamasco et al, 1999; Rachev and Purini, 2001; Russo et al., 2003; Cushman--Roisin and Korotenko, 2007), and, more recently, atmosphere-ocean coupled models have been employed (Pullen et al., 2006; Pullen et al., 2007; Loglisci et al., 2004; Ferrarese et al., 2008). The current knowledge of Adriatic atmosphere and ocean was repeatedly summarized: in 2001 in the book "Physical Oceanography of the Adriatic Sea" edited by B. Cushman-Roisin; in 2007 in the special issue "Adriatic Sea" on Journal of Geophysical Research, and finally Grisogono and Belušić (2009) reported in a review article the meso- and microscale properties of the severe Bora wind. Model results can be compared with data taken by *in situ* sensors, like drifters (Poulain, 1999; Poulain and Chusman-Roisin, 2001; Poulain, 2001, Ursella et al., 2006) and/or "remote sensing" sensors, like satellite radiometers (Bignami et al., 2007).

In the present work the attention is focused on the surface variations of current and temperature and the vertical profiles of temperature in the sea caused by Bora and Sirocco. Two actual events, notable for their intensity, have been studied by using a coupled atmospheric-ocean model (RAMS-DieCAST): a Bora episode occurred on January 1995 and a Sirocco event occurred on November 2002.

The model has been inizialized by the outputs of the ocean model DieCAST running in stand-alone mode for ocean fields, and driven by the ECMWF analyses for atmospheric fields (initial and boundary conditions).

In the present paper, Section 2 briefly presents the model and the method, Section 3 describes the simulation results and Section 4 summaries the conclusions.

2. Model and method

The coupled model is composed by an atmospheric model, RAMS (Pielke et al., 1992, Walko et al., 1995), and an ocean model, DieCAST (Dietrich et al., 1975; Dietrich and Ko, 1994; Dietrich, 1997; Staneva et al., 2001). Its detailed description is available in Loglisci at al. (2004).

RAMS uses the full set of primitive dynamical equations integrated on the standard Arakawa C staggered grid and the terrain-following coordinate system. Turbulence, radiation fluxes, micro-physics, air interaction with the surface, sensible and latent heat fluxes, are parameterized. In particular, for the simulations described hereafter, the turbulent diffusion has been parameterized in horizontal by the deformation scheme and in vertical by Mellor-Yamada scheme; the radiation has been parameterized by the Chen-Cotton scheme and the lateral boundary conditions assume the Klemp-Wilhelmson condition.

The ocean model is DieCAST. It is a z-level, primitive, hydrostatic, Boussinesq, rigid-lid, finite difference model running with very low dissipation and fully fourth-order numerics. Fourth-order-accurate control volume approximations are used for all advection and horizontal pressure gradients terms, except for those adjacent to boundaries, where second-order accuracy is used. DieCAST model is described in detail in Staneva et al. (2001).

In the coupled model version, the two models RAMS and DieCAST have been set up with the same horizontal geometry in order to simulate the whole Adriatic Sea and they swap fluxes of dynamical and thermodynamical quantities (wind stress, latent and sensible heat, long and short wave radiation) at every time step. Conservation of fluxes has been achieved because both RAMS and DieCAST models are fully flux conservative and, in their coupling, their numerical structure has not been modified (Loglisci et al, 2004).

The simulation procedure is characterized by two phases. In the first one, DieCAST runs in stand alone mode (i.e. not coupled with RAMS) in order to prepare the initial conditions for the coupled model. In this phase it is driven by climatological conditions: MODB-MED5 for temperature and salinity fields (Brasseur et al., 1996), MODB-MED4 for sea currents (Wu and Haines, 1998) and May (1982) for wind stress. The time step is fixed to 10 minutes, and the total time of this run was typically about 90 days. The vertical resolution was set to 20 layers, of increasing thickness covering a maximum depth of 1100 m. The results were verified by comparison with satellite SST. The second phase is devoted to simulate the case study with the coupled model. The initial conditions are the oceanic fields, the outputs of DieCAST in stand alone mode, and the atmospheric fields, provided by the TL511 ECMWF global analyses with a resolution of 0.5×0.5 degrees. The coupled model boundary conditions are the 6–hours ECMWF analyses with a 30 seconds time step and a total simulation time of 10 days.

The numerical integration has been performed for both models over 101×101 horizontal grid cells (latitude from 40.3° N to 46.0° N, longitude from 12.0° E to 19.5° E) corresponding to 7 km resolution. The number of vertical level is 20 in the sea and 35 in the atmosphere.

3. Results

The simulation results of the two events are described in the following subsections, where the surface circulation, the temperature patterns and the vertical cross-sections of temperature predicted by the model are compared with the observations and the modelled fields in literature.

3.1. Bora wind event

The Bora wind event has started on January 3rd and ended on January 6th, 1995.

The wind has reached the maximum intensity on January 4th, at midday (Qian at al., 2000, Loglisci et al., 2004). The simulation with the coupled model has started on January 1st and ended on January 9th.

Figure 1 shows the surface currents and the vorticity field on 2nd and 4th of January at midday, respectively before and during the Bora episode.

At 12 a.m. of January 2nd in the Middle and South Adriatic there are two cyclonic gyres following the bathymetry; in the North Adriatic a weak cyclonic gyre is also present (Figure 1a).

Due to the Bora, on January 4th, at 12 a.m. the surface current increases dramatically in the Middle and in the Northern Adriatic Sea, the cyclonic gyre in the North Adriatic (between 43.5° N and 45.0° N) becomes stronger and a cyclonic current in the extreme northern region also appears (Figure 1b) (Loglisci et al., 2004). The increase of cyclonic circulation is typical of the Bora events, as indicated by both observations and simulations (Orlić et al., 1992, Packlar et al. 2001, Rachev and Purini, 2001). Cushman-Roisin and Korotenko (2007), using ocean DieCAST model, simulated the surface currents during

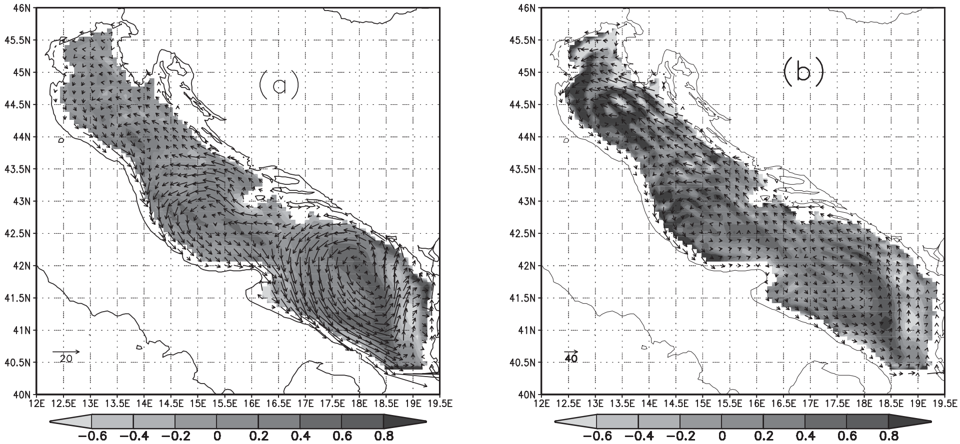

Figure 1. Surface currents computed by RAMS-DieCAST: vorticity map (10^{-5} s^{-1}) and water velocity (cm s^{-1}) (a) at 12 a.m. on 2 January 1995, (b) at 12 a.m. on 4 January 1995.

bora event on February 2003. Pullen et al. (2006) and Pullen at al. (2007) simulated the mean surface currents corresponding to Bora episodes of 29th September 2002 and from 31st January to 2nd February 2003, applying the two-way coupled model COAMPS-NCOM. These simulations show two well developed cyclonic circulations in the North Adriatic, the smallest of which is less evident in RAMS-DieCAST simulation.

On January 6th (not shown), the sea current strength decreases and the episode finishes up.

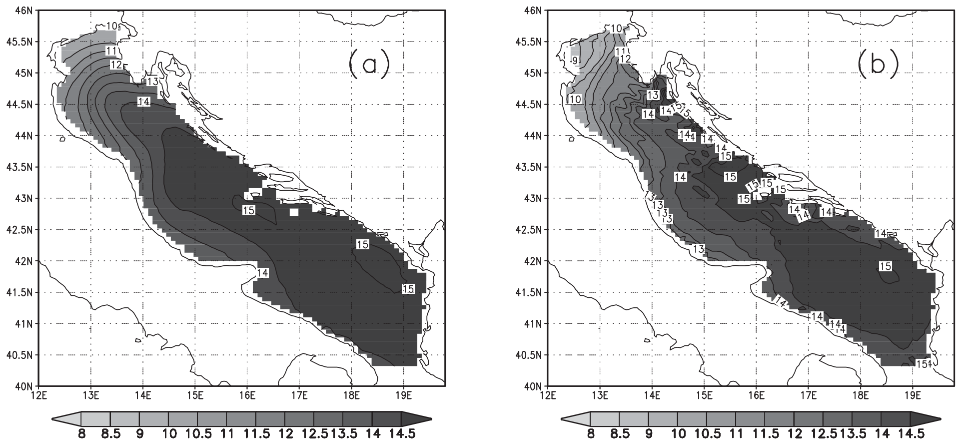

Figure 2. Surface temperature computed by RAMS-DieCAST: (a) at 12 a.m. on 2 January 1995, (b) at 12 a.m. on 4 January 1995.

At the beginning of the episode, the modelled surface temperature field has its minimum value at 10 °C in the North, and its maximum value at 15 °C in the South (Figure 2a). The Eastern coast is warmer than the western cost at the same latitude. During the Bora episode, the patterns of surface temperature change and on the 4th of January the isotherms become very irregular and the sea surface is subject to a general cooling. The effects of Bora are very evident at midday (Figure 2b).

On January 6th the surface temperature shows a decrease, by almost 2 °C since the Bora onset in the extreme Northern Adriatic, and of about 1 °C in the North Adriatic (South of the Po river).

Figure 3 shows the temperature sections in the Northern and Middle Adriatic before and after the Bora event. The comparison between Figures 3a and 3b shows that, in the Northern Adriatic, the whole water column cools its temperature of about 2 °C.

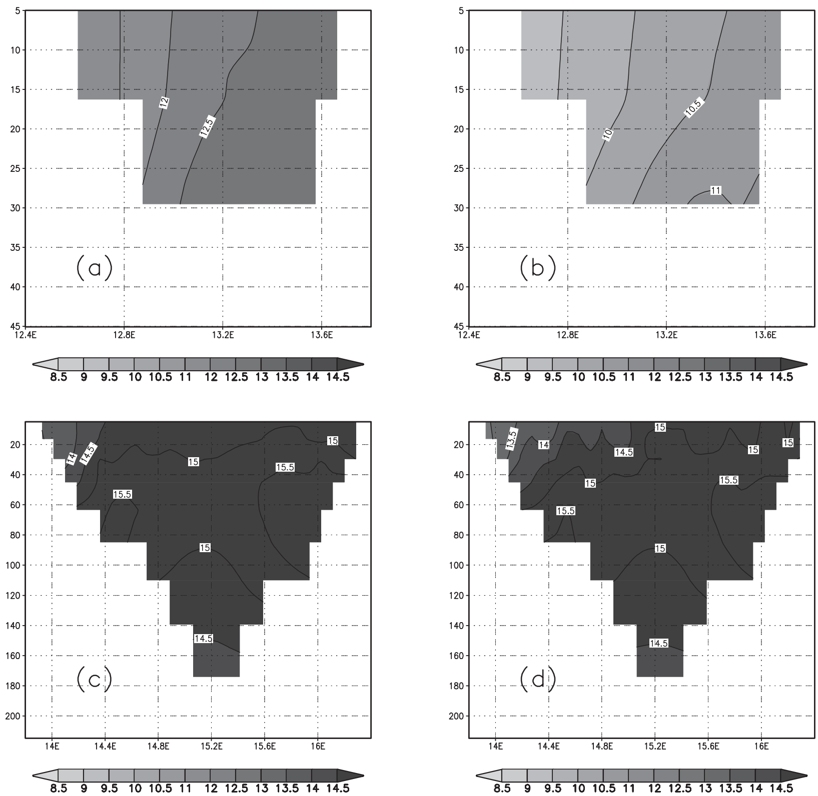

Figure 3. Vertical section of temperature (°C) computed by RAMS-DieCAST at 45° N (a) on 2 January 1995 at 12 a.m., (b) on 8 January 1995 at 12 a.m. and at 43.25° N (b) on 2 January 1995 at 12 a.m., (d) on 4 January 1995 at 12 a.m., (vertical scale in meters).

In the Middle Adriatic and in the Southern Adriatic (not shown) the temperature declines since 3rd of January and then it decreases dramatically on 4th of January even if its variation is limited to the first 60 m (Figures 3c and 3d). The isotherms become very irregular when the Bora wind reaches its maximum value (Figure 3d).

The simulated temperature data in the Northern Adriatic Sea have been compared with satellite observations (available at the web site: http://podaac.jpl.nasa.gov). Figure 4a shows the comparison in one site, representative of the Northern Adriatic. The trends of simulated and measured data are similar, even if the differences can reach 1 °C.

Simulated temperatures are compared with the observations at the meteorological stations in Trieste Gulf and in Venice site (Figure 4b). A systematic error lower than 1 °C appears, likely due to the initial conditions set in the model (Loglisci et al., 2004). The agreement between simulated temperature and *in situ* observations is better than one with satellite observations. This is likely due to the fact that the simulated temperature is a mean in a model box, the *in situ* observation is punctual and the satellite temperature is a skin measure.

The temperature patterns are confirmed by the postbora maps of SST computed by Pullen et al. (2006).

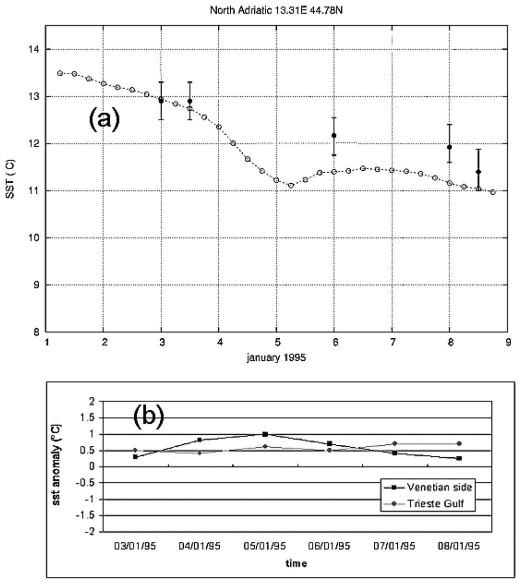

Figure 4. (a) Comparison between simulated by RAMS-DieCAST sea surface temperature and satellite observed temperature in North Adriatic basin (longitude: 13.31° E, latitude: 44.78° N), error bars: ±0.4 °C, (b) Temperature differences between the simulated results and the *in situ* observation at Trieste and Venice stations.

3.2. Sirocco wind event

The Sirocco wind episode started in the afternoon of November 12th 2002, and has reached its highest values on the 14th and 16th (Ferrarese at al., 2008). Its onset and evolution is confirmed by observations: ECMWF surface (1000 hPa) wind data and wind speeds and directions at about 900 hPa from the Brindisi meteorological radiosoundings station (latitude:40.7° N, longitude:18.0° E). The Sirocco wind event is also confirmed by a "acqua alta" (flood) occurrence in Venice during the analysed period: the sea level anomalies measured by tide gauge exceeded every days the value of 80 cm (http://www.comune.venezia.it/maree).

The RAMS-DieCAST simulation started on November 11th and ended on November 18th 2002. The simulation outputs show that, before the onset of the Sirocco event (November 11th at 12 a.m. – Figure 5a) in the southern and central area of the basin there were two cyclonic gyres connected to the bathymetry, with respectively water speeds of about 15 cm s^{-1} and 10 cm s^{-1}. In the northern region of the Adriatic basin, the model has simulated a weak current which could barely reach the value of 5 cm s^{-1}. Along the Dalmatian coast, the current flows north-westward, but along its course gets involved in the two cyclonic gyres present in the Middle and South Adriatic, which make it turn southward; the same behavior happens in the northern Adriatic basin, where the weak cyclonic vortex is also able to cause a turning of the current. Along the Italian coast, the current is south-eastward.

The simulated surface current field during the Sirocco event is shown in Figure 5b. The two cyclonic gyres in the South and Middle Adriatic are still present because they are driven by the bathymetry, but the Sirocco wind has modified the course of the current near the coasts. Figure 5b shows in fact that the current near the central and northern Italian coasts has reversed its direction towards north-west. The same current has veered anti-cyclonically in the Northern, Middle and South Adriatic. Along the eastern coast, the North-westward current is weaker than before the Sirocco event. At the end of the episode, the sea surface circulation pattern becomes similar to the initial conditions before the onset of the Sirocco event.

Orlić et al. (1994) and Bergamasco at al. (1999) have simulated the north westward current along the Italian coast and a less intense current along the Dalmatian side; Kourafalou et al. (2001) simulations with the POM ocean model have captured also the anti-cyclonically currents near the Italian coast. The main differences between these simulations and ours are in the Middle and South Adriatic, where they did not capture the cyclonic gyres. The above differences could be due to the fact that those authors used theoretical wind fields instead of the actual ones.

The comparison between the simulation results and the observations involves the mean surface marine circulation in the period from November 14th to November 18th, and 22 drifter trajectories in the same period.

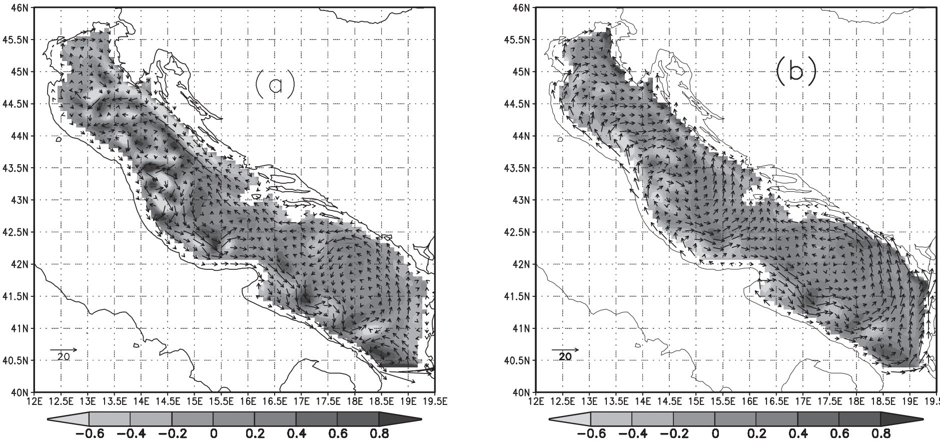

Figure 5. Surface currents computed by RAMS-DieCAST: vorticity map ($10^{-5}\,s^{-1}$) and water velocity (cm s^{-1}) (a) at 12 a.m. on 11 November 2002, (b) at 12 a.m. on 14 November 2002.

During the episode, 22 drifters were released in the Adriatic Sea as a part of DOLCEVITA (Dynamics Of Localized Currents and Eddy variability In The Adriatic) project.

The comparison between the surface current field and drifter trajectories is described in detail in Ferrarese et al., 2008. The agreement is quite satisfactory: only two short trajectories did not to follow the computed current.

Figure 6a shows the modelled surface temperature before the Sirocco event. The coldest temperature values (17 °C) are observed near the coast of the extreme northern Adriatic basin, while the warmest values (18 °C) are

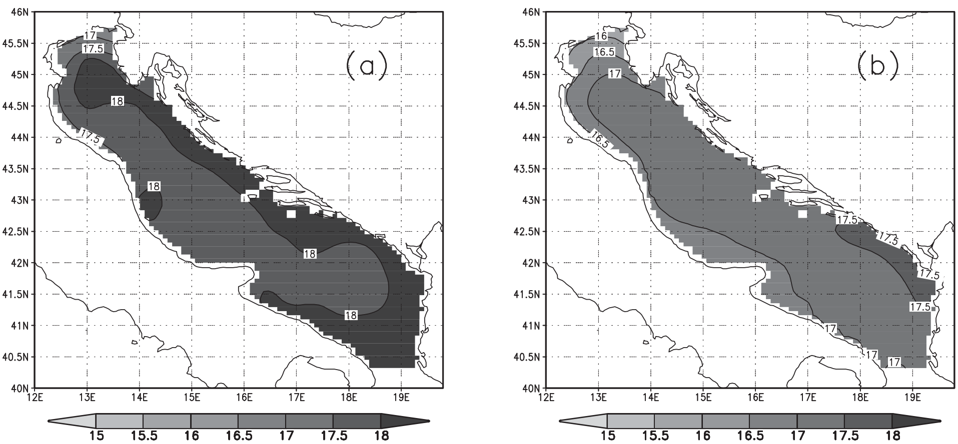

Figure 6. Surface temperature computed by RAMS-DieCAST: (a) at 12 a.m. on 11 November 2002 (b) at 6 p.m. on 18 November 2002.

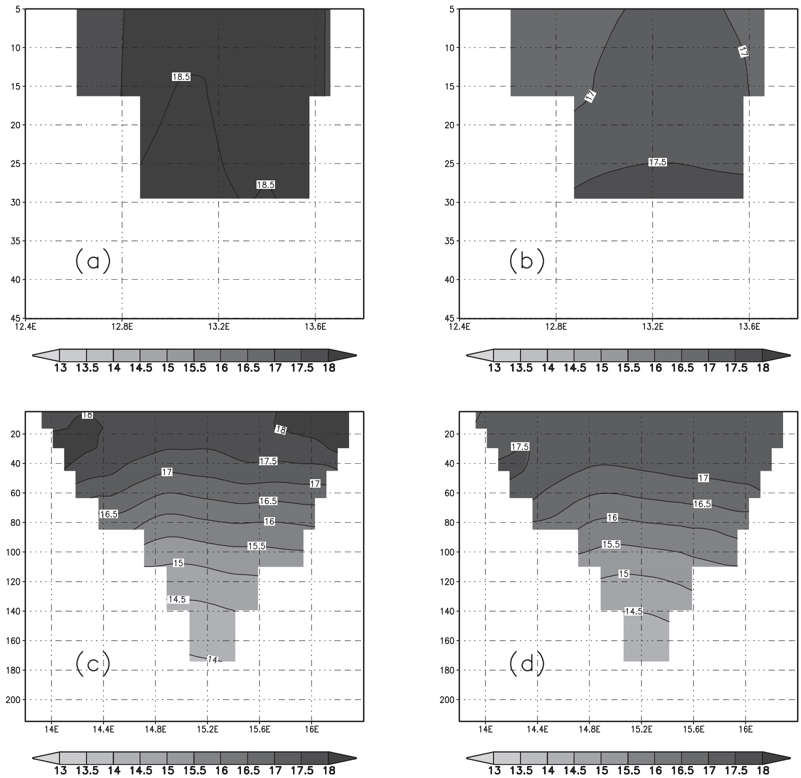

Figure 7. Vertical section of temperature (°C) computed by RAMS-DieCAST at 45° N (a) on 11 November 2002 at 12 a.m., (b) on 18 November 2002 at 18^{th} and at 43.25° N (c) on 11 November 2002 at 12 a.m., (d) on 18 November 2002 at 6 p.m., (vertical scale in meters).

computed near the Dalmatian coast and in the southern area of the basin. The mean temperatures are comparable with the actual values recorded at the beginning of November 2002.

Figure 6b shows the surface temperatures computed by RAMS-DieCAST at the end of the Sirocco event. It shows a general surface cooling of approximately 1 °C in the Northern Adriatic Sea and between 0.5 °C and 1 °C in the central and southern part of the basin, the coldest areas being located in the North: the Italian coast is colder than the Dalmatian one. The intermediate results show that the cooling trend is constant throughout the time.

Two zonal sections, at the latitudes of 45° N and 43.25° N, have been selected to describe the temperature variations in the sea: their positions are relative to the Northern and Middle Adriatic Sea. In the northern area, where the sea is only about 30 m deep, the whole water column changed its temperature; the cooling is constant in time and both the coasts are colder than the

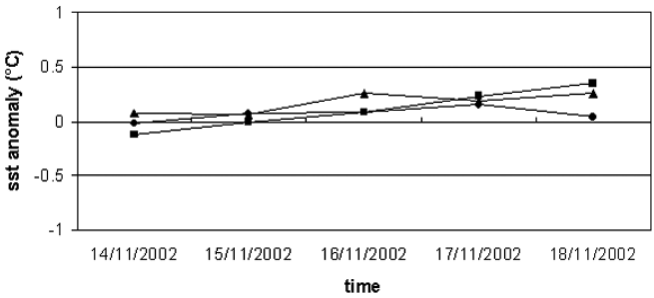

Figure 8. Differences between the simulated and measured sea surface temperatures (°C) averaged in the northern Adriatic basin (squares), in the central Adriatic basin (circles) and in the south Adriatic basin (triangles).

offshore Adriatic basin (Figures 7a–b). In the Middle Adriatic, the cooling (of about 0.5 °C) was limited to the first 40 meters; below this level, the temperature was constant during the whole episode (Figures 7c–d).

Figure 8 shows the time evolution of the differences between the mean values of the simulated and measured sea surface temperatures in the three regions of Adriatic Sea. They have been derived from the measurements collected by the same DOLCEVITA drifters used to compare the simulated and real currents. In the whole Adriatic the anomalies are similar and their values are always lower than 0.4 °C. This discrepancy can be considered acceptable, because the simulated data are computed in a model box, while the observations are punctual data.

4. Conclusions

A coupled ocean-atmosphere numerical model RAMS-DieCAST has been used to simulate two actual Bora and Sirocco episodes over the Adriatic sea, with the purpose of studying the response of the sea surface circulation and the time and space evolution of sea temperature.

During the Bora event, the surface current increased dramatically and the sea surface temperature decreased by almost 2 °C in the extreme northern Adriatic. In the Middle and southern Adriatic, the temperature and current variations are limited to the first 60 m. The comparison with SST measured data have revealed a good agreement, with the only presence of a systematic error which is probably due to the model initialization.

During the Sirocco wind event, the circulation pattern shows: i) two cyclonic vortices in the central and southern Adriatic, both of them driven by the bathymetry; ii) a north-westward current flowing along the Italian coast; iii) a weak current along the Dalmatian coast; iv) three narrow anticyclonic gyres near the Italian coast. The simulated surface temperature has decreased of about 1 °C during the event, and the vertical section has shown that only the upper 40m have been affected by the cooling.

Simulated data at the surface are in good agreement with the observations. Moreover, the currents and temperature fields simulated by RAMS-DieCAST during Bora and Sirocco episodes confirm the results obtained by the ocean models and atmosphere-ocean coupled models used by other authors.

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SAŽETAK

Međudjelovanje atmosfere s morem u Jadranu: simulacije bure i juga

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Dvije simulacije jakog vjetra nad Jadranom koje se simuliraju združenim atmosfersko-oceanografskim modelom se analiziraju i uspoređuju s mjerenjima i drugim objavljenim modeliranim poljima. U tu svrhu se koristi model RAMS-DieCAST za simulaciju promjena morskih struja i temperaturnih profila, od površine prema dnu, uzrokovanih dvjema epizodama intenzivnog vjetra nad Jadranom: *burom* u siječnju 1995. godine i *jugom* u studenom 2002. godine.

Rezultati simulacija se uspoređuju s opažanjima na morskoj površini. Tijekom bure, modelirana površinska temperatura uspoređuje se s temperaturom površine mora dobivene satelitskim mjerenjima i mjerenjima temperature u određenim točkama prostora. Tijekom juga, simulirane površinske struje i temperature se uspoređuju s eksperimentalnim mjerenjima dobivenih na temelju površinskih driftera koji su pušteni u različitim dijelovima Jadrana za istu epizodu.

U obje epizode trendovi simulirane temperature dobro se podudaraju s opažanjima. Također se tijekom juga, površinske struje dobro podudaraju s mjerenjima driftera. Modelirana temperatura mora kao i vektorsko polje brzina pokazuju dobro slaganje s rezultatima sličnih simulacija u literaturi.

Ključne riječi: Jadran, bura, jugo, međudjelovanje oceana s atmosferom, združeni oceanografsko-atmosferski model, površinske struje, površinska temperatura, temperaturni profili

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