Response of temperature and sea surface circulation to a Sirocco-wind event in the Adriatic basin: a model simulation


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Abstract

A fully coupled atmosphere-ocean model, endowed with a feedback of the ocean model on the atmospheric one, was applied in order to simulate the variations of temperature and sea currents induced by the occurrence of a late-fall episode of intense Sirocco wind over the Adriatic Sea. The coupled model was made up of the RAMS atmospheric model coupled with the DieCAST ocean model with the purpose to obtain more realistic forcing conditions of the lower winds on the underlying sea surface.

The two main phenomena highlighted by the simulation are: the genesis of a 10 cm s$^{-1}$ north-westward current along the Italian coastline and a general cooling of the entire basin of approximately 1°C limited to the upper 40 m. The same current shows an offshore anti-cyclonic pattern at different latitude in the whole basin.

The results generally agree with experimental data collected by surface drifters released in different regions of the Adriatic Sea as a part of the international DOLCEVITA project, which also includes the same Sirocco episode considered here. The simulated currents represent the drifter trajectories quite accurately, with only few exceptions in the northernmost region of the basin, characterized by shallow water conditions. The simulated SST fields fully agree with the temperature values observed by the same drifters.

Keywords: Surface currents, Temperature profiles, Drifting data buoys, Sirocco, Ocean-atmosphere coupled model, Adriatic Sea.

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1 Introduction

The Adriatic Sea is an elongated basin with a roughly rectangular shape, whose extension is about 800 km in the NW-SE direction, from 46°N to 40°N, and about 200 km in the SW-NW direction, from 12.5°E to 19.5°E. It is surrounded by the Italian coasts on its northern and western side and by the Istrian, Dalmatian and Albanian coasts on its eastern one. The southernmost boundary is connected to the Mediterranean Sea through the Channel of Otranto (Fig.1).

![Figure 1 The Adriatic region geography, sea bathymetry (depths are in m b.s.l.) and latitudinal position of the vertical sections (45° N, 43.25° N and 41° N).](image)

The bathymetric configuration of the basin is split into three parts (Orlic et al., 1992): a northern region, where the depth is less than 100 m; a central region with a bathymetric depression named “Pomo/Jabuka Pit” (280 m); and a southern region, with the deepest bathymetric depression named “South Adriatic Pit” (1200 m). At the southernmost latitudes, in proximity of the Channel of Otranto, the sea bed rises again up to 780 m. Along the western coast, isobaths are parallel to each other and to the continental coast, while along the eastern coast they are more indented and irregular.

Trade has always been the main activity of people living in the towns along the Adriatic coasts; for this reason, the surface current patterns of this sea were explored as far back as the ancient times by experienced and skilled seamen and navigators.
During the last decade of the nineteenth century and the whole twentieth century, experimental data of water temperature, salinity and current direction were collected; this quantitative information was summarized in a paper by Orlic et al. (1992).

In the nineteen-nineties, measurement campaigns performed by using drifters produced a quite complete description of the mean seasonal and yearly surface circulation in the Adriatic Sea (Poulain, 1999, Poulain and Cushman-Roisin, 2001, Poulain, 2001). In particular, Poulain (2001) used 201 drifters from August 1990 to July 1999 to estimate the velocity of the surface currents. The mean surface circulation in the whole Adriatic is characterized by two steady vortices, located respectively in the central and southern Adriatic Sea, where the circulation is controlled by the bathymetry of the two marine pits (Dietrich et al., 2007).

The northern area of the basin, characterized by a flat and shallow shelf, cannot support a stable circulation: sometimes the patterns of sea circulation are shaped like two small cyclonic vortices, but they are unsteady, and the seasonal fluctuations can reverse the sense of rotation of the surface vortices on all space and time scales of motion (Brana and Krajcar, 1995, Supic et al., 2000, Mauri and Poulain, 2001, Supic et al., 2003, Rachev et al., 2006).

The mean coastal current flows north-westward along the Albanian, Dalmatian and Istrian coasts up to the Gulf of Venice, and from there veers back to the Southeast following the Italian coast. The water exchange between Ionian and Adriatic sea occurs across the Channel of Otranto; at the upper levels the flow enters the basin close to the eastern coast while the outflow prevails along the western coast.

The features of the general circulation of the Adriatic Sea outlined above represent the result of the actions, simultaneous or not, of different processes on different time scales. The most relevant ones are: 1) wind forcing, 2) fresh water discharge, and 3) convective mixing (Poulain and Raicich, 2001). Obviously, the bottom topography of the basin is also relevant, chiefly as regards its more stationary features.

The present study aims to inspect the role of the first kind of processes, with special emphasis on
short-lived, strong air outbreaks over the basin.

The Adriatic Sea basin may in fact experience the onset and growth of short episodes of very strong winds superimposed over more regular atmospheric flow regimes. An example of these phenomena are some short-lived winds blowing over the Adriatic Sea, such as the Bora from north-east, the Sirocco from south-east, and the Etesian (also called Maestro) from north-west; under their drag forcing at the air-sea interface, the conditions of circulation and temperature distribution in the surface layers of the sea can change abruptly during short spells of a few days.

In these circumstances, the knowledge of long-term features of sea surface circulation in the basin is not always sufficient to reveal the relative role played by each of the main physical processes driving the circulation itself, among which we can mention, as an example, the mechanical and thermal energy exchanges forced by strong wind outbreaks at the air-sea separation interface (Bergamasco et al., 1999).

Among the efforts made in the past years to investigate these physical processes, we can mention the high resolution (1 km x 1 km) atmospheric mesoscale model, used by Qian and Giraud (2000) to simulate the main features, such as the mountain upstream acceleration and the strong downstream descent of the flow during a short Bora case occurred on 4 January 1995.

A series of numerical experiments, based on the use of an eddy-resolving primitive general ocean circulation model, was carried out by Bergamasco et al. (1999) in order to examine the sea circulation produced in the Adriatic basin by various combinations of different forcing mechanisms, such as Sirocco and Bora wind stresses (representative of the mean conditions over the winter season), surface thermohaline fluxes and fresh water discharges.

Another example of this methodology can be found in the paper of Rachev and Purini (2001), who studied the relative effect of the Bora wind on the Adriatic Sea circulation by means of a 3-D, z-level, hydrostatic, Boussinesq, incompressible, rigid-lid numerical ocean code, forced by an idealized wind stress field pattern similar to that used by Bergamasco et al. (1999). This last study, together with other contributions by Kuzmic et al. (1988), Kuzmic et al. (1991), Orlic et al. (1994)
and Kourafalou (2001), is worth mentioning also for the Sirocco wind. In these cases, simplified and schematic surface wind data were still used to drive the ocean models.

More recently, Russo et al. (2003) studied the response of the sea surface conditions to the forcing of short-lived Bora wind events, using a non-hydrostatic ocean model forced by the actual wind in order to investigate an extreme summer event of Bora-induced cooling which gave rise to shallow convection conditions.

Cushman-Roisin and Korotenko (in press) employed DieCAST model to study the Adriatic Sea response to Bora wind events. The oceanic model was initialized with seasonally averaged temperature and salinity data and forced with climatological winds. Martin et al. (2006) conducted numerical simulations of the Adriatic Sea with NCOM model forced by atmospheric fluxes computed by COAMPS model.

Another kind of approach to the problem of the air-sea interaction in the Adriatic Basin is instead represented by the application of two-way, or fully coupled, ocean-atmospheric models.

While in the previously mentioned approaches, where the sea was only forced by real or schematic surface winds, it would have been impossible to get any description of the actual changes of the sea circulation corresponding to actual changes of the meteorological conditions, in the studies using air-ocean fully coupled models it becomes possible to investigate the mutual, two-way fast-response interactions between the atmosphere and the sea in situations of strong winds, so as to model actual space and time evolutions of both systems (Paklar et al., 2001, Loglisci et al., 2004, Pullen et al., 2006, Pullen et al., 2007).

In this paper, we endeavoured to achieve a more detailed description of the circulation variability of the Adriatic sea on daily or weekly time scales, based on full coupled ocean-atmospheric models.

Starting from the state of knowledge described above, we carried out a more localized and realistic study of the sea-surface circulation during an intense Sirocco event. Our purpose was to achieve an improvement in the knowledge of the effects of strong Sirocco winds as driving mechanisms of
the basin circulation, and its impact on the temperature fields at surface and in the sea.

With this end in view, we chose to study a real, intense Sirocco event: this episode occurred from 14 to 18 November 2002. We used the fully coupled atmosphere-ocean RAMS-DieCAST model with horizontal resolution of 7 km (Loglisci et al., 2004), driven by the initial and boundary conditions provided by the atmospheric TL511 ECMWF global analyses, with a resolution of 0.5x0.5 degrees and an advection time step of 15 minutes.

The surface wind field simulated by the coupled model was then used at the sea interface, in place of the ECMWF wind field, so as to achieve a more realistic representation of the actual surface wind and its forcing action on the sea surface of the Adriatic basin. This kind of down-scaling for the meteorological forcing when using the RAMS wind field obtained from the ECMWF analysis outputs represented a crucial point to improve the quality of our marine simulations.

In order to achieve a further check on the reliability of the coupled model, the simulated surface currents were compared with drifter trajectories collected at the same time of the simulation in the Adriatic basin, within the DOLCEVITA (Dynamics Of Localized Currents and Eddy Variability In The Adriatic) project. The same drifters collected also temperature measurements and these data were used to check the simulated surface temperature.

These data are available at [http://doga.ogs.trieste.it/doga/sire/dolcevita/database_dolcevita].

2 The method

The coupled ocean-atmosphere model RAMS-DieCAST has previously been described in detail by Loglisci et al (2004). Table 1 provides detailed information on the main physical parameterizations of the model, while key aspects of the model will be reviewed here.

The atmospheric processes were simulated by the RAMS model. It is based on the full set of primitive dynamical equations integrated on the standard Arakawa C staggered grid. The vertical structure of the grid uses the terrain-following coordinate system. The turbulence, the radiation fluxes, the microphysics, the interaction with the surface, the sensible and latent heat fluxes are

Table 1

<table>
<thead>
<tr>
<th></th>
<th>DieCAST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input data (frequency)</td>
<td>MODB-MED4 –ocean currents (seasonal climatology)</td>
</tr>
<tr>
<td></td>
<td>MODB-MED5 –ocean temperature and salinity (seasonal climatology)</td>
</tr>
<tr>
<td></td>
<td>May – stress wind (monthly climatology)</td>
</tr>
<tr>
<td>momentum diffusivity</td>
<td>Horizontal: 65 m²/s</td>
</tr>
<tr>
<td></td>
<td>Vertical 10 m²/s plus contributions proportional to vertical velocity</td>
</tr>
<tr>
<td>drag coefficient</td>
<td>Cₖ=0.002</td>
</tr>
<tr>
<td>bottom friction</td>
<td>(\vec{f}_b = -C_d</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>RAMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input data (frequency)</td>
<td>ECMWF (6 hours)</td>
</tr>
<tr>
<td>Lateral boundary conditions</td>
<td>Klemp-Wilhelmson</td>
</tr>
<tr>
<td>Dimensionless momentum diffusivity parameter</td>
<td>Horizontal: 0.2</td>
</tr>
<tr>
<td></td>
<td>Vertical: 0.2</td>
</tr>
<tr>
<td>Parameterization for turbulent diffusion</td>
<td>Horizontal: Deformation scheme</td>
</tr>
<tr>
<td></td>
<td>Vertical: Mellor-Yamada</td>
</tr>
<tr>
<td>Parameterization for radiation</td>
<td>Chen-Cotton</td>
</tr>
</tbody>
</table>

Table 1 Main numerical parameterizations for the RAMS-DieCAST coupled model

The ocean processes were simulated by the DieCAST tri-dimensional, z-level, hydrostatic, Boussinesq, incompressible, rigid-lid model (Dietrich et al., 1975, Dietrich and Ko, 1994, Dietrich, 1997 and Staneva et al., 2001).

The coupling between the two models is described in Loglisci et al. (2004): at every time step of integration, the two fluid domains fully communicated with each other, swapping fluxes of dynamic and thermodynamic quantities such as wind stress, latent and sensible heat, long and short wave radiation.

In the coupled model, RAMS and DieCAST were set up with the same horizontal geometry from 12.0°E to 19.5°E longitude and from 40.3°N to 46.0°N latitude, in order to simulate the whole Adriatic sea. The numerical integration was performed for both models over 101x101 horizontal grid points corresponding to 7 km of resolution. Table 2 of this paper summarizes the main settings of the coupled model. RAMS-DieCAST was driven by initial and boundary conditions provided by 6-hours ECMWF analyses.
Table 2

<table>
<thead>
<tr>
<th></th>
<th>DieCAST</th>
<th>RAMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of horizontal grid points</td>
<td>101x101</td>
<td>101x101</td>
</tr>
<tr>
<td>Number of vertical levels</td>
<td>20</td>
<td>35</td>
</tr>
<tr>
<td>Boundary north-south</td>
<td>46°N-40.3°N</td>
<td>46°N – 40.3°N</td>
</tr>
<tr>
<td>Boundary east-west</td>
<td>12°E – 19.5°E</td>
<td>12°E – 19.5°E</td>
</tr>
<tr>
<td>Time step</td>
<td>10 min (stand alone)</td>
<td>30 s (coupled model)</td>
</tr>
</tbody>
</table>

Table 2 Numerical scheme for the RAMS-DieCAST coupled model

The simulation procedure was divided in two phases as in Loglisci et al. (2004). The first phase was devoted to the preparation of the marine initial conditions of the simulation, and consisted of a preliminary run of the DieCAST model in stand-alone mode, i.e. not coupled with the RAMS atmospheric model, for a temporal period of 90 days. During this stand-alone mode run, the model was initialized with the MODB-MED5 climatological sea temperature and salinity field data (Brasseur et al., 1996), MODB-MED4 climatological ocean currents (Wu and Haines, 1998), and May (1982) wind stress. The MODB data are organized in seasonal fields, whereas the wind stresses are filed in monthly data. The purpose of this run was to homogenize the values representing the average autumn ocean conditions and to spin up the ocean components in the whole volume of the basin. Therefore these results did not claim to represent the ocean conditions on a specific day of the year, but were only meant to describe the mean situation in that period of the year. In particular the sea surface temperatures were comparable to the real temperatures during the first ten days of November 2002.

Subsequently, the second phase was dedicated to the simulation of the case study with the RAMS-DieCAST coupled model. The coupled model was initialised by the outputs of DieCAST in stand-alone mode as regards the oceanic fields and by the ECMWF analysis of 11 November 2002 for the atmospheric fields; then, during the whole simulation, it was driven by the 6-hours ECMWF analysis (wind speed,
temperature, relative humidity and geopotential) as boundary conditions by the technique defined as analysis nudging (Walko et al., 1995).

We also decided to simulate the three days before the case study, in order to obtain more homogenous initial conditions and to adjust the 3-D structure of the sea circulation and temperature fields to the actual initial conditions at the beginning of the case study (spinup problem).

The simulation performed with the RAMS-DieCAST coupled model started on 11 November 2002 (three days before the onset of the event) and it ended on 18 November 2002 (when the Sirocco wind event terminated).

3 The Sirocco wind event

The Sirocco wind usually blows over the Adriatic basin from SSE. Its customary place of origin is located over the deserts of northern Africa. Along the coasts from Libya to Syria, the Sirocco typically appears as a warm and dry southerly wind that carries sand and dust.

During its subsequent northward course crossing the Mediterranean Sea, it takes up humidity from the warm water: as a result, when it goes past the latitude of Malta, it gradually turns into a warm and humid wind.

The main consequences of the passage of the Sirocco over the Adriatic sea are: 1) the piling up of water near the northernmost coasts (which in some cases may cause the flooding of Venice, a phenomenon commonly known as “acqua alta”, which means “high water”); 2) strong rainfalls and sometimes severe thunderstorms over the northern Italian regions (and, in case of very strong wind, also over central Italy).

A strong wind event is defined as a wind having an intensity $\geq 13 \text{ m s}^{-1}$ and lasting for 6 hours or more (Conte et al., 1996).

The Sirocco event selected as our case study occurred from 14 to 18 November 2002 and exhibited some oscillations in its strength from day to day. Our choice was suggested by the
particular intensity of the episode. Table 3 reports the wind speeds and directions at about 900 hPa, extracted from meteorological vertical radio soundings carried out at the Brindisi station – Italy (Fig. 1), in the period from 11 to 20 November 2002. As the data of Table 3 show, the 13th was the date of the onset of the Sirocco wind, and the 19th that of its end. An inspection of the ECMWF surface (1000 hPa) wind fields makes it possible to determine the onset and duration of the event more precisely. In fact, the Sirocco was absent on the morning of the 11 November (Figure 2a), and started blowing during the afternoon of the 12th (Figure 2b), reaching its highest values on the 14th (Figure 2c) and 16th (Figure 2d). This is confirmed by the 900 hPa observations at the Brindisi station (Table 3) which show that, on the 13th, the flow had rotated and increased with respect to that of the previous day and, on the days from the 14th to the 18th, wind intensity was higher than 15 ms⁻¹.

Table 3

<table>
<thead>
<tr>
<th>Date</th>
<th>Wind intensity (m/s)</th>
<th>Wind direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 NOV 2002</td>
<td>2.6</td>
<td>NW</td>
</tr>
<tr>
<td>12 NOV 2002</td>
<td>2.6</td>
<td>E</td>
</tr>
<tr>
<td>13 NOV 2002</td>
<td>10.3</td>
<td>SW</td>
</tr>
<tr>
<td>14 NOV 2002</td>
<td>15.4</td>
<td>S</td>
</tr>
<tr>
<td>15 NOV 2002</td>
<td>18.0</td>
<td>S</td>
</tr>
<tr>
<td>16 NOV 2002</td>
<td>20.6</td>
<td>S</td>
</tr>
<tr>
<td>17 NOV 2002</td>
<td>15.4</td>
<td>S</td>
</tr>
<tr>
<td>18 NOV 2002</td>
<td>15.4</td>
<td>S</td>
</tr>
<tr>
<td>19 NOV 2002</td>
<td>7.7</td>
<td>SW</td>
</tr>
<tr>
<td>20 NOV 2002</td>
<td>7.7</td>
<td>SW</td>
</tr>
</tbody>
</table>

Table 3 Wind speeds and directions recorded at about 900 hPa at the Brindisi meteorological radiosounding station (from the European Meteorological Bulletin, published by DWD, Deutscher Wetterdienst, Offenbach, Germany)

Table 4, which lists the values of the sea level anomalies (“high water” or “acqua alta”) measured by tide gauge in Venice during the analyzed period and available on the web site
http://www.comune.venezia.it/maree, shows that the threshold of 80 cm above the normal sea surface level was exceeded several times. In particular, on 16 and 18 November 2002, the “acqua alta” observations showed the highest water levels among all those recorded during the whole of that year: this event was filed as the fifth severest “high water” episode over the last 100 years.

Table 4

<table>
<thead>
<tr>
<th>Day</th>
<th>Hour [local time]</th>
<th>High water [Acqua alta] [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>14th November 2002</td>
<td>20.05</td>
<td>89</td>
</tr>
<tr>
<td>15th November 2002</td>
<td>8.10</td>
<td>103</td>
</tr>
<tr>
<td>15th November 2002</td>
<td>20.25</td>
<td>102</td>
</tr>
<tr>
<td>16th November 2002</td>
<td>9.45</td>
<td>147</td>
</tr>
<tr>
<td>16th November 2002</td>
<td>19.55</td>
<td>126</td>
</tr>
<tr>
<td>17th November 2002</td>
<td>9.10</td>
<td>86</td>
</tr>
<tr>
<td>17th November 2002</td>
<td>21.05</td>
<td>83</td>
</tr>
<tr>
<td>18th November 2002</td>
<td>10.25</td>
<td>123</td>
</tr>
</tbody>
</table>

Table 4 Sea level anomaly data (“high water”, or “acqua alta” data) measured by the CPSM (Centro Previsioni e Segnalazioni Maree) at Punta Salute (Venice). These data represent the extreme tidal values that are higher than or equal to 80 cm with respect to the fundamental level of the “Rete Altimetrica dello Stato” (Italian Altimetrical Network) The data were measured by a water level sensor (accuracy 1 cm).

Figure 2 ECMWF analyses at 1000 hPa: horizontal wind speed field (m s\(^{-1}\)) on (a) 11 November 2002 at 6 a.m., (b) 12 November 2002 at 6 p.m., (c) 14 November 2002 at 12 a.m., (d) 16 November 2002 at 12 a.m.
4 Results

The results of the RAMS-DieCAST simulation are shown in this Section by analysing the sea-surface current patterns, the surface temperature and the temperature distributions in three specific vertical west-to-east sections.

4.1 Current patterns

Figure 3a shows the surface circulation pattern simulated by the DieCAST stand-alone run which was used as an initial condition for the RAMS-DieCAST coupled model.

![Initial conditions computed by DieCAST in stand-alone mode: (a) sea surface currents (cm s\(^{-1}\)) and vorticity field (10\(^{-5}\) s\(^{-1}\)), (b) sea surface temperature (°C).](image)

The northern area of the basin, characterized by a shallow, flat shelf, can be divided into two regions, respectively north and south of the Po River Delta (latitude 45°N) (Fig. 1).

In the former region, the northernmost part of the Adriatic basin, the model simulated a weak current which could barely reach the value 5 cm s\(^{-1}\). In the latter region, along the Istrian and Dalmatian coasts, there was a cyclonic north-eastward gyre: the associated flow approached the Italian coast, where it rotated southwards. In this region, and particularly along the Istrian and Dalmatian coasts, the water speed was more intense than in the other region, reaching values up to 10 cm s\(^{-1}\).

In the central area of the basin, approximately at latitude 43.5N, the current along the Dalmatian
coast is split up into two streams, according to the dynamic process described by Carnevale et al. (1999). The one nearest the Dalmatian coast continued its course northwards, while the off-coast one turned and merged into a cyclonic gyre whose typical speed was around 10 cm s\(^{-1}\).

In the southern area of the basin, finally, there was a cyclonic gyre connected to the bathymetry, with typical water speeds of about 15 cm s\(^{-1}\).

The surface currents presented in Figures 4a-d show the surface circulation and vorticity patterns in the whole basin during the period from 11 to 18 November 2002 as simulated by RAMS-DieCAST coupled model. Every map is the result of a mean over 2 days, carried out in order to filter inertial oscillations. As expected, the vorticity field appears to be well correlated with the horizontal shear of the flow over short distances.

![Figure 4 Surface currents](image)

Figure 4 Surface currents computed by RAMS-DieCAST: vorticity map (10\(^{-5}\) s\(^{-1}\)) and water velocity (cm s\(^{-1}\)) averaged (a) from 6 a.m. on 11 November to 12 p.m. on 12 November 2002, (b) from 6 a.m. on 13 November to 12 p.m. on 14 November 2002, (c) from 6 a.m. on 15 November to 12 p.m. on 16 November 2002, (d) from 6 a.m. on 17 November to 12 p.m. on 18 November 2002.

In Figure 4a (surface mean currents from 6 a.m. of the 11\(^{th}\) to 12 p.m. of the 12\(^{th}\)), the Sirocco event had not started yet: the model simulations showed current patterns almost similar to those calculated by DieCAST in stand-alone mode (Figure 3a).
On the contrary, snapshots of the model (not shown here) revealed that, during the night of the 12\textsuperscript{th}, the current near the Italian coast in the northern part of the basin reversed its direction (with respect to the previous day), following the wind direction and moving towards north-west along the coast. This could be expected, because the Sirocco wind, absent on the 10\textsuperscript{th} and on the 11\textsuperscript{th}, started to blow during the last hours of the 12\textsuperscript{th}, as observed in ECMWF analyses (Figure 2b).

Figure 4b shows the pattern of sea surface currents flowing from 6 a.m. of the 13\textsuperscript{th} to 12 p.m. of the 14\textsuperscript{th}; this figure exhibits, in the northern and central areas of the Adriatic basin, a north-westward coastal current along the Italian coast, reaching a mean speed of about 10 cm s\textsuperscript{-1}. The same current in the north veered anti-cyclonically, subsequently flowing towards south-east and crossing the Adriatic basin from the North Italian to the Istrian and Dalmatian coasts; in the central Adriatic area it followed a anticyclonic gyre and it was involved in the stable central cyclone. In addition, the two large cyclonic gyres induced by the bathymetry were still present in the central and southern areas of the basin.

During the period from 6 a.m. of the 15\textsuperscript{th} to 12 p.m. of the 16\textsuperscript{th} (Figure 4c), the current in the extreme northern part of the Adriatic basin was very slow, but it is possible to recognize two northwards coastal currents near Trieste gulf and Venice lagoon. In the remaining area of northern Adriatic sea, the coastal Italian north-westward current revolved to the eastern coast and then turned to South in the central part of the basin. The intensities were lower than in the two previous days (figure 4b). In the central Adriatic sea an anticyclonic gyre was recognizable near the western coast and a wide cyclone driven by the bathymetry was present in the centre of the basin. In the south area the vorticity map show that the stable widest vortex still persisted and became stronger with time: the highest simulated speeds were found near the Albanian coasts (about 15 cm s\textsuperscript{-1}).

On the next two days (Figure 4d, from 6 a.m. of the 17\textsuperscript{th} to 12 p.m. of the 18\textsuperscript{th}), the sea surface circulation pattern looked similar to the initial conditions before the onset of the Sirocco event (Figure 4a) marking the end of the Sirocco influence upon the sea surface currents in the Adriatic basin. In fact, in addition to the two stable cyclones driven by the bathymetry and not influenced...
by Sirocco wind, there were again an anticyclonic flow in the extreme northern area, a weak cyclonic current in the northern part (below 45°N) and a south-eastward flow along the whole Italian coast. According to the ECMWF maps of the horizontal wind speed at 1000 hPa, during this period the Sirocco was intense over the whole basin only at 12 a.m. of 18 November, and the variations in wind direction chiefly affected the northern area of the Adriatic Sea. However, according to Table 4, the “high water” phenomenon in Venice was still present on 18 November (the sea level at Venice descended on 17 November and rose again on 18 November). This apparent mismatching can be explained if we consider the phenomenon of “seiches”, a long-period residual oscillation of the sea water in a basin that occurs when the forcing of a strong wind producing water elevation at one of its boundaries stops suddenly. The rigid-lid approximation in the DieCAST model, by smoothing the residual vertical sea oscillations, prevented our simulation from representing completely the actual phenomenology, in particular the formation of positive and negative vorticity regions consequent to the conservation principle of the potential vorticity.

In order to highlight the circulation pattern during this Sirocco event, the mean circulation calculated by averaging the model simulations in the period from 14 to 18 November is summarized in Figure 5. In this figure, in addition to the two typical gyres in the central and southern areas, other characteristics can be pointed out: 1) a weak cyclonic flux in the northern extremity of the sea near Trieste and, on the contrary, a weak anticyclonic flux near Venice; 2) the north-westward current flowing along the Italian coast and a very weak current along the Istrian and Dalmatian coast; 3) three narrow anti-cyclonic gyres near the Italian coast, in the northern area of the basin (latitude 44.5°N) in the central (latitude 43°N) and in the southern one (latitude 41.5°N).

This result was then compared with the available literature results. Kuzmic et al. (1991) had calculated, by means of a simple 3-D numerical model, the Adriatic Sea surface circulation forced by several Sirocco wind patterns. Their results pointed out the constant presence of two vortices: the first one, cyclonic, covered most of the Adriatic shelf; the second
one, anti-cyclonic, was located in the proximity of the Italian coast.

Figure 5 shows that the RAMS-DieCAST model was able to simulate all the gyres mentioned by Kuzmic et al. (1991), i.e. the cyclonic circulation in the basin and the three anti-cyclonic gyres near the Italian coast south of the Po River delta, the Conero Promontory and the Gargano Peninsula.

![Figure 5 Mean surface marine circulation in the period from 14 to 18 November 2002 (cms$^{-1}$): comparison between the mean surface circulation (vectors) and the drifter trajectories (thick lines starting at the black points).](image)

The current patterns simulated by RAMS-DieCAST confirmed those obtained by Bergamasco et al. (1999), who had used an oceanic model driven by a spatially homogeneous Sirocco. In fact, both models simulated the water crossing from the Italian coast to the Dalmatian one, the cyclonic gyre located in the central area of the basin, and the north-westward currents alongside the Italian coast of the basin. In Bergamasco et al. (1999) simulation, the current along the Italian coast was more intense than the one along the Dalmatian coast; our simulation confirms this result.

However, a difference can be found, in the southern part of the basin, where Kuzmic et al. (1991) and Bergamasco et al. (1999) had not detected a cyclonic gyre related to the bathymetric configuration of the sea floor.

Kourafalou (2001) simulated with the POM model the Adriatic surface currents driven by a theoretical south-easterly wind. His simulation showed a north-westward current along the Italian coast that anti-cyclonically turned round in the centre of the basin like in our simulation, but the
current along Dalmatian coast was more intense than the one along Italian coast. The southern vortex was hardly visible.

A further comparison was made with the results obtained by Orlic et al. (1994). These authors had computed a surface sea circulation pattern which exhibited the north-westward coastal Italian current mentioned above and a less intense current along the Dalmatian side, but they were unable to simulate the cyclonic and anti-cyclonic gyres in the basin.

The above differences could perhaps be due to the fact that Kuzmic et al. (1991), Bergamasco et al. (1999), Kourafalou (2001) and Orlic et al. (1994) used theoretical wind stresses to analyse a case study, while we used ECMWF data to drive the wind fields during an actual Sirocco event.

In order to obtain more quantitative results from our simulation, we made a comparison between simulated fields and experimental data; for this reason the mean fields of simulated current patterns were compared with drifter trajectories in the same period.

The drifters were released in the Adriatic sea as a part of the previously mentioned international DOLCEVITA project, carried out between 21 September 2002 and 29 February 2004.

Figure 5 shows a comparison between the currents simulated by RAMS-DieCAST, averaged over the period 14-18 November 2002, and the stretches of 22 drifter trajectories during the same period (thick lines starting from the black points, which represent the drift position at the beginning of the Sirocco event, i.e. at 0 a.m. of 14 November). The comparison confirmed that the RAMS-DieCAST ocean-atmosphere coupled model was able to simulate the surface marine currents in the whole Adriatic sea quite well. A few differences can be found in the northern area at latitudes higher than 45°N, where the amplitude of the anti-cyclonic gyre is overestimated and it would let the Dalmatian coastal current through as it is suggested by the drifter trajectories. This inconsistence could be explained considering that the extreme North Adriatic basin presents shallow water conditions and the current pattern in these areas are critical to be simulated by the ocean models.

Another difference can be found in the northern and central area of the Adriatic sea: two south-
eastward drifters trajectories are coupled with two short trajectories (starting at points 42.9°N – 14.5°E and 44.2°N – 13.8°E) which have opposite directions; this feature was not revealed by the RAMS-DieCAST model. These inconsistencies might be considered compatible with the vertical model resolution at the air-ocean interface: the depth of the surface marine layer was about 5 m, and the currents shown in Figures 4a-d refer to that depth; the drifters, on the contrary, were driven by the sea surface currents and winds.

Considering the drifter trajectories below 45°N, where the simulated sea surface currents are more intense, the inconsistence between observed and simulated data appear only in 2 cases out of 12: this confirms the reliability of the model prediction. In the same area the average correlation coefficient between simulated sea surface currents and drifter trajectories in the period of the Sirocco event is 0.64.

4.2 Temperature fields

Figure 3b shows the surface temperature field computed by DieCAST in stand-alone mode. The coldest temperature values (16.5°C) are observed near the coast of the extreme northern Adriatic basin, while the warmest values (18°C) are computed in the South or offshore. The mean temperatures are comparable with the real values recorded at the beginning of November 2002, before Sirocco onset.

The simulated temperature fields (figure 6a-d) show the surface temperatures computed by RAMS-DieCAST at 12 a.m. of the 12th, 14th, 16th and 18th November 2002.

The temporal sequence of the figures shows a general surface cooling of approximately 1°C in the northern Adriatic and between 0.5°C and 1°C in the central and southern part of the basin. Cooling trend is constant throughout the time. At the end of the sirocco event (figure 6d), the coldest areas were located at the North: the Italian coast was colder than the Dalmatian one and the previously discussed warm areas in the offshore zone disappeared.

To investigate the temperature variations beneath the sea surface due to Sirocco, three zonal
sections, respectively at the latitudes of 45°N, 43.25°N and 41°N, have then been selected (Fig. 1): their positions are relative to the northern, the central and the southern Adriatic Sea.

Figure 6 Sea surface temperature (°C) computed by RAMS-DieCAST on (a) 12 November at 12 a.m., (b) 14 November at 12 a.m., (c) 16 November at 12 a.m., (d) 18 November at 12 a.m..

In figures 7a-d are shown the sections of temperature at the latitude of 45°N at 12 a.m. on the 12th, 14th, 16th and 18th November 2002. In this area the sea bottom is only 30 m deep and thus, during this episode, the whole water column changed its temperature; the cooling was continue and gradual and both the coasts were colder than offshore Adriatic basin.
Figure 7 Vertical section of temperature (°C) computed by RAMS-DieCAST at 45°N latitude on (a) 12 November at 12 a.m., (b) 14 November at 12 a.m., (c) 16 November at 12 a.m., (d) 18 November at 12 a.m. (vertical scale in meters).

Figures 8a-d presents the sections of temperature at the latitude of 43.25°N at 12 a.m. on the 12th, 14th, 16th and 18th November 2002. In these pictures 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.

Figure 8 Vertical section of temperature (°C) computed by RAMS-DieCAST at 43.25°N latitude on (a) 12 November at 12 a.m., (b) 14 November at 12 a.m., (c) 16 November at 12 a.m., (d) 18 November at 12 a.m. (vertical scale in meters).
In the last sections (figure 9a-d), relative to vertical temperature fields at the latitude of 41°N at 12 a.m. of the 12th, 14th, 16th and 18th November 2002, the surface progressive cooling was about 1°C. Also in this area the effects of wind forcing over the Adriatic Sea during this Sirocco event proved to be limited to a shallow water layer, about 40 m deep, below the sea surface.

Figure 9 Vertical section of temperature (°C) computed by RAMS-DieCAST at 41°N latitude on (a) 12 November at 12 a.m., (b) 14 November at 12 a.m., (c) 16 November at 12 a.m., (d) 18 November at 12 a.m. (vertical scale in meters).

To compare the sea surface simulated temperatures with measured data, we used the values collected by the same drifters described in Section 4.1. All drifters were divided into three subsets: in the first we grouped all drifters located in the northern Adriatic basin, in the second one those in the central Adriatic and in the third one those in the southern Adriatic basin. The comparison between the time evolution of the simulated and observed temperature is shown in figure 10a-c. The trends of simulated temperatures are decreasing during time; also the observed temperatures, measured by drifters, follow a decreasing trend in all three Adriatic regions. The bias of the two curves is always lower than ±0.4 °C and the two trends are similar. This discrepancy is acceptable, considering that the simulated data were computed in a spatial and
temporal grid representing the mean values in the model boxes, while the observed measures were punctual data.

For these reasons, we can conclude that the RAMS-DieCAST model accurately simulated the decrease of temperature in the whole Adriatic sea during the Sirocco wind event.

Figure 10 Comparison between simulated (stars) and measured (dots) sea surface temperatures (°C) averaged (a) in the north Adriatic Basin, (b) in the central Adriatic Basin, (c) in the south Adriatic Basin.

5 Conclusions

A fully coupled ocean-atmosphere numerical model RAMS-DieCAST (Loglisci et al., 2004) was applied to a real Sirocco event occurred over the Adriatic sea in the period from 14 to 18 November 2002, with the purpose of studying the response of the sea surface circulation and the evolution of sea temperature.

The simulated marine currents during the event showed:

1) two cyclonic vortices located respectively in central and southern areas of the Adriatic basin, driven by the bathymetry; 2) a north-westward current flowing along the Italian coast and a weak current along the Dalmatian one, and 3) three narrow anti-cyclonic gyres near the Italian coast in
the northern, central and southern areas of the basin, which made the north-westward currents reverse and drift due South.

These model results were compared with other numerical simulation studies in the literature and with some relevant experimental data. The comparison revealed a fairly good agreement, both with the other simulations and with the observations.

During the Sirocco event the simulated surface temperature decreased of about 1°C. The vertical sections of simulated temperature showed that only the upper 40 m were affected by the cooling. The comparison between observed and simulated temperature at the surface confirmed the good skill of the simulation.

It is therefore possible to conclude that a hydrostatic, incompressible, rigid-lid ocean model (DieCAST) coupled with a forecasting atmospheric model based on the full set of primitive dynamical equations (RAMS) is able to reproduce the most meaningful patterns of surface marine currents and temperature variations in the Adriatic sea during strong Sirocco wind events.

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References


Brana, J.H., Krajcar, V., 1995. General circulation of the Northern Adriatic Sea: results of long-
term measurements. Estuarine, Coastal and Shelf Science 40, 421-434.


stresses, NORDA, report 54.


variability. Estuarine, Coastal and Shelf Science 51, 385-397.


