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Development of an atmosphere-ocean coupled model and its application over the Adriatic Sea during a severe weather event of Bora wind

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[1] This study presents the results of an application to a Bora severe weather episode (January 1995) in the northern Adriatic Sea of the regional two-way atmosphere-ocean coupled model (RAMS-DieCAST), developed jointly by the Università di Torino and the Istituto Sperimentale Talassografico del CNR, Trieste. RAMS-DieCAST showed significantly better ability to predict the sea surface temperature (SST) and its time evolution during the above mentioned episode using a full two-way coupling as opposed to simpler one-way forcing of the ocean. In this context, we found out that even in the high-frequency variability conditions that are typical of Bora events, heat fluxes from the sea must be taken into account for a better description of air-sea interaction processes in a dynamical framework. The SST evolution has been chosen as a validation parameter, owing to its availability and relevance for the characterization of the marine environment and local weather and climate studies. The simulations carried out with RAMS-DieCAST present a small systematic error in calculating the SST evolution; however, a sensitivity analysis of the model to the preparation of initial conditions of the simulation suggested that climatological initialization could be partly responsible for this error, which might be reduced by assimilating satellite-derived SSTs into the preparation of the initial conditions of the model. *INDEX TERMS:* 0312 Atmospheric Composition and Structure: Air/sea constituent fluxes (3339, 4504); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4504 Oceanography: Physical: Air/sea interactions (0312); *KEYWORDS:* Bora, ocean-atmosphere coupled model, RAMS-DieCast

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1. Introduction

[2] Air-sea interface exchanges represent the pathways through which atmospheric signals are transferred to the ocean, and vice versa. The aim of this study is to investigate a few of the most relevant physical processes playing a role in the air-sea interaction, especially during strong wind situations. The northern region of the Adriatic Sea has been selected as a particularly suitable natural laboratory for this kind of study, due to the noticeable occurrence of intense outbreaks of Bora winds.

[3] The Adriatic Sea is a semi-enclosed basin connected to the Mediterranean Sea by the Otranto Channel. It can be divided into three parts (Figure 1), each increasing in depth and in proximity to the Otranto Strait [*Orlic et al.*, 1992]. The first is the northern part of the basin which includes the Gulfs of Venice and Trieste. It is shallow and has a fairly even slope gradually deepening to 100 m. The second part (near Pescara) has its main feature in the Jabuka Pit, a bathymetric variation about 200 m deep, able to induce a bifurcation in the Croatian coastal current [*Carnevale et al.*, 1999]. The third part is the southern area of the Adriatic Sea, which is deeper than the other two parts, and reaches a maximum depth of almost 1200 m (South Adriatic Pit).

[4] In winter, the dominant winds blowing over the Adriatic Sea are the Bora (from northeast) and the Sirocco (from southeast), while in summer the Etesian winds (from northwest) occur. In this study, we focused our attention on the effects of the Bora wind on the dynamics and thermodynamics of the Adriatic basin.

[5] The Bora wind has attracted the attention of scientists for over one hundred years for various reasons including its dramatic social impacts. The earliest studies of the Bora were mainly descriptive, categorizing the Bora

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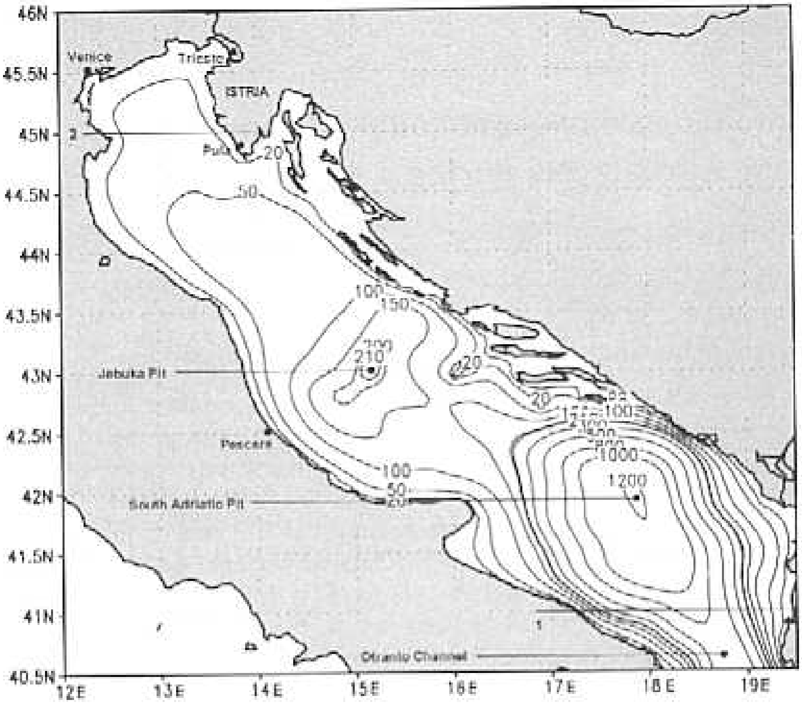

Figure 1. The Adriatic Sea and its bathymetry (in m bsl) and the coordinates of the two stations mentioned in the text: Trieste (45°39′N, 13°36′E) and Venice (45°26′N, 12°20′E).

as a cold and dry wind greatly influenced by local orography (J. Prettner [1866], as dissuced by *Yoshino* [1976]): the gusts of this wind were reported to reach more than 40 m/s. At a later date, some special field observations were carried out, wind tunnel experiments were performed and, after that, the Bora was considered to be a "fall wind" [*Yoshino*, 1976]. However, this last idea was questioned after aircraft observations of the ALPEX Project in 1982, which showed that the wind accelerates on upward mountain slopes [*Smith*, 1987]. This evidence suggested that the Bora might be a "downslope wind" like the well-known Boulder windstorm. Later, it was suggested that the Bora might have a multiscale nature [*Camuffo*, 1981, 1990]. The speed and direction of the Bora largely depend on orographic details, hence mountain and coastal features are clearly responsible for daily variation in wind speed and direction during Bora periods. In spite of these local effects, the onset of the Bora, (its longevity and its severity) have been shown to be closely related to larger subsynoptic features, in particular, those resulting from the interaction processes of synoptic scale flow with the Alpine massif [*Jurcev and Vishovic*, 1994; *Ivancan-Picek and Tutis*, 1996].

[6] It must be emphasized that the Bora directly affects the circulation, sea level and pattern of sea surface temperature (SST) of both the northern Adriatic Sea (because of its shallow bathymetry) and along the Albanian coast, where intense upwelling events, or marked variability in the SST resulting from large heat and momentum exchanges, are observed.

[7] These facts have recently led to several ongoing studies, the purpose of which are to highlight both the experimental aspects and the theoretical interpretation of the main features of the Adriatic Sea circulation (for a general review of this argument, see *Cushman-Roisin et al.* [2001]). In particular, theoretical studies [*Orlic et al.*, 1994; *Bergamasco and Gacic*, 1996; *Bergamasco et al.*, 1999; *Rachev and Purini*, 2001], together with observations [*Kuzmic*, 1991], found that one of the effects of the Bora wind was the reduction of the Levantine Intermediate Water (LIW) inflow and the induction of the above mentioned upwelling event along the Albanian coast. Finally, *Vested et al.* [1998] analyzed dense water formation in the Northern Adriatic with the help of a three-dimensional numerical model, using either climatological or instantaneous data as initial conditions.

[8] However, it must be pointed out that these theoretical studies mainly dealt with simplified or climatological one-way forcings of the ocean model, and only a few of them with instantaneous forcing obtained from atmospheric limited area models (LAM). Because of their higher resolution, LAMs are able to capture with sufficient accuracy spatial and temporal variability of meteorological patterns in regions characterized by complex orography, like the Adriatic basin. For example, *Raicich et al.* [1999] and *Wakelin et al.* [2000] studied an intense storm surge observed in Trieste by coupling two different simple barotropic marine models with two limited area models (DALAM and BOLAM, respectively). Concerning the Bora wind, *Paklar et al.* [2001] carried out a simulation by means of a three-dimensional ocean model (Princeton Ocean Model (POM)) forced by wind stress and heat fluxes obtained by the atmospheric mesoscale model MM5. Their objective was to understand and predict the Bora- driven evolution of the Po River discharge observed by the advanced very high resolution radiometer (AVHRR).

[9] From the more general perspective of performance of coupled regional models, it is worth mentioning a number of efforts on coupling regional atmosphere-ocean models. For example, Coupled Ocean + Atmospheric Mesoscale Prediction System (COAMPS), developed by *Hodur* [1997] at NRL in Monterey as a nonhydrostatic atmospheric model, to hindcast and forecast the atmosphere at medium to high resolution, currently running operationally at the U.S. Navy's FNMOC in Monterey on several regional domains and NCOM (an ocean model studied by *Haidvogel et al.*, 2000] which is currently part of COAMPS can be paired together even if they are currently run separately. Regional Ocean Model System (ROMS) (A. F. Shchepetkin and J. C. Mcwilliams, The Regional Ocean Modeling System: A split-explicit, free-surface, topography-following-coordinate ocean model, unpublished manuscript, 2003; see http://www.ocean-modeling.org/Papers/roms.pdf) is a free-surface, hydrostatic, primitive equation ocean model that uses stretched, terrain following coordinates in the vertical and orthogonal curvilinear coordinates in the horizontal. Worth of mention is also the contribution given by Julie McClean (Naval Postgraduate School, Monterey, CA) who studied local to global-scale high-resolution ocean, ocean/ice and ocean/atmosphere coupled models, and by Isaac Ginis (University of Rhode Island), who studied atmosphere-ocean coupling with special attention to hurricane forecast.

[10] Even though we could have made a selection from among several excellent atmosphere and ocean coupled models, nevertheless we choose to develop a new "ad hoc" coupled model, taking advantage of previous experience we gained by specific and positive applications to the Adriatic Sea [*Qian and Giraud*, 2000; *Rachev and Purini*, 2001] of both the atmospheric model Regional Atmospheric Modeling System (RAMS [*Pielke et al.*, 1992]; see section 2) and the ocean three-dimensional code Dietrich Center for Air Sea Technology (DieCAST [*Dietrich et al.*, 1975]; see section 2).

[11] The RAMS model actually proved to be particularly capable in downscaling the meteorological fields from synoptic to regional scale, and therefore mimicing detailed features of the Bora, such as acceleration of wind upstream of the mountains, its strong descent within the Bora layer, and a strong turbulent zone just downstream [*Qian and Giraud*, 2000].

[12] As for the DieCAST model, thanks to its particularly low numerical dissipation and reduced computing time (since it is based on the rigid lid approximation), it proved to have an excellent and realistic performance in the simulation of sudden changes of surface currents, especially in the northern Adriatic basin, under a schematic stress of Bora wind-forcing [*Rachev and Purini*, 2001].

[13] Because of the strong cold advection in the planetary boundary layer generally present during Bora episodes, SST has been chosen to be an easy-to-monitor "tracer" of the dynamic and thermal response of the Sea to the Bora forcing, which permits a fast quantitative comparison between observed data and model simulations. In addition, as will be shown later (section 6.3), SST appeared closely related to the dynamic and thermal structure of the entire subsurface water, both in the northern shallow area and in the southern deeper basin of the Adriatic Sea.

[14] With respect to the above context of the sole one-way forcing of the Adriatic Sea, the primary novel features of the present study include (1) successful development of a two-way coupling of atmosphere and ocean regional models, (2) application of this two-way coupled model to a case study of air-sea interaction during a Bora event, (3) sensitivity analysis of initialization of the two-way coupled atmosphere-ocean model, and (4) significantly better prediction of SST using two-way coupling as opposed to one-way forcing of the ocean model.

[15] Section 2 of this study briefly presents the atmospheric and the oceanic models used for the coupling. Section 3 explains in detail the settings and parameterizations of the numerical models. Section 4 introduces the one and two-way couplings of atmosphere-ocean model, the preparation of their boundary and initial conditions, and their initialization. Section 5 describes the meteorological condition when the Bora case study was analyzed. In section 6, the results of the one-way forcing and their deficiencies are briefly presented, together with a more detailed analysis of the results of the two-way forcing and of the sensitivity to the initial conditions. Section 7 summarizes the conclusions.

2. Description of the Atmosphere and Ocean Models Used in This Study

[16] The RAMS model [*Pielke et al.*, 1992; *Walko et al.*, 1995] is a highly versatile numerical code for simulating and forecasting meteorological phenomena based on the full set of primitive dynamical equations which govern atmospheric motions, integrated on the standard C staggered grid [*Mesinger and Arakawa*, 1976]. These equations are supplemented with [*Walko et al.*, 1995]: optional parameterizations for turbulent diffusion, solar and terrestrial radiation, moist processes including microphysics (formation and interaction of clouds and precipitating liquid and iced hydrometeors), cumulus convection, kinematic effects of terrain, sensible and latent heat exchange between atmosphere and surface, multiple soil layers, vegetation canopy and surface water (see also first paragraph of section 4). The radiation schemes used in RAMS, which take into account the effects of condensation, are described by *Chen and Cotton* [1983]. The longwave radiation scheme is a full solution of the radiative transfer equation using an emissivity approach while the shortwave radiation scheme is a 3-band scheme. RAMS is a multigrid model allowing simulations by means of one or more grids nested to the main grid, so it has a better resolution in regions of particular interest.

[17] The DieCAST model [*Dietrich et al.*, 1975] was derived from the modified Arakawa C grid Sandia Ocean Modeling System (SOMS) model [*Dietrich et al.*, 1975; *Dietrich and Ko*, 1994]. It is a three-dimensional model in a rotating frame, z-level, hydrostatic, Boussinesq, incompressible, rigid-lid model. Because of its rigid-lid imposition at the ocean surface, the model sets the surface height to zero, eliminating the wave modes associated with the vertical displacements of the full water column. Because these wave modes are connected to the very fast external

Table 1. Settings of Coupled Atmosphere-Ocean Model

	RAMS	DieCAST
Horizontal grid points	101 × 101	101 × 101
Horizontal resolution	7 km	7 km
Number of vertical levels	35	20
Time step	30 s	10 min (one-way coupling) 30 s (two-way coupling)

Table 3. Main Numerical Parameters for DieCAST in the Simulations

Parameter	Value
Input data	MODB-MED4-MED5 (Monthly or Seasonal Climatology)
Momentum diffusivity	Horizontal 65 m^2/s
Momentum diffusivity	Vertical 10 cm^2/s plus contributions proportional to vertical velocity
Bottom friction	$\vec{\tau}_b = -C_d|\vec{V}|\vec{V}$
Drag coefficient	$C_d = 0.002$

mode of the gravity wave, their elimination allows for a relatively large momentum time step. Two methods can be used to impose a rigid lid: a barotropic stream function [*Bryan*, 1969], or the top-level pressure adjustment [*Smith et al.*, 1992]. The DieCAST uses the latter, more suitable for steep topography, and adopts the conservative flux-based centered approximations in control volumes, together with a weakly filtered "leapfrog" time integration scheme. A fourth-order approximation is used to communicate data between collocated A and staggered C Arakawa grid [*Dietrich*, 1997]. Coriolis and vertical diffusion terms are coupled with an implicit treatment. Coriolis terms are of primary importance for ocean modeling, because of the approximate geostrophic balance between Coriolis acceleration and pressure gradient force. The implicit trapezoidal treatment of the Coriolis term chosen for the DieCAST model makes it possible to conserve (from the numerical view point) kinetic energy if the above mentioned balance is verified.

3. Settings of Atmosphere and Ocean Models

[18] The two models (RAMS and DieCAST) were set up with the same horizontal geometry in a common area, including the entire Adriatic Sea from its northern border to the Otranto Strait. All settings used in the present work are summarized in Table 1.

[19] The numerical integration was performed for both models over 101 × 101 horizontal grid points, with a resolution of 7 km. The origin of the DieCAST and RAMS grids are both at longitude 12 E and latitude 40.5 N, so that the horizontal grid extends up to longitude 19.5 E and latitude 46 N. The initial and lateral boundary conditions of the atmospheric model were provided for all simulations by 6-hour ECMWF analyses (wind speed vector, geopotential height, relative humidity, temperature) at 10 standard pressure levels (1000, 850,700, 500, 400, 300, 250, 200, 150, 100 hPa) with a nudging procedure. Both models use a vertical stretching that allows for a better resolution near their separation interface. The numerical parameterizations used for the two models are summarized in table 2 (RAMS) and 3 (DieCAST), where the vector $\vec{V}$ in Table 3 represents the bottom velocity. The reader is referred to *Mellor and Yamada* [1974, 1982] for the vertical parameterization of turbulent diffusion and *Ferrero et al.* [2002] for the diffusivity parametrisation of RAMS.

Table 2. Main Numerical Parameters for RAMS in the Simulations

Parameter	Value
Input data	ECMWF
Frequency of input data	6 hours
Lateral boundary conditions	Klemp-Wilhelmson
Dimensionless momentum diffusivity parameter	Horizontal (CSX) 0.2
Dimensionless momentum diffusivity parameter	Vertical (CSZ) 0.2
Parameterization for turbulent diffusion	Horizontal Deformation scheme
Parameterization for turbulent diffusion	Vertical Mellor-Yamada
Parameterization for radiation	Chen-Cotton

[20] For the purpose of this work our interest was concentrated only in a small area (the Adriatic Sea), so nesting was not necessary and only one grid with high resolution was used (as can be seen from Table 1). The lateral boundary conditions used in the RAMS are the general C-grid staggered radiative condition, given by:

$$\frac{\partial u}{\partial t} = -(u - c)\frac{\partial u}{\partial x} \tag{1}$$

where u is the wind component along the x direction, which is normal to the boundary. The form of c, the phase velocity, was the one given by the *Klemp and Wilhelmson* [1978] scheme and reported by *Walko et al.* [1995], which specifies a constant value as a typical gravity wave phase velocity, from 10 to 30 m/s (the intermediate value of 20 m/s was chosen for this application, in order to allow the propagation of gravity waves out of the domain).

[21] As far as the DieCAST model is concerned, a quite crude parameterization of the vertical mixed layer of the ocean, yet able to capture its main features, was used. This parameterization is based on the Peclet number criterion, which calculates the vertical viscosity and diffusivity by setting a constant value of the Peclet number:

$$Pe = \frac{w\Delta z}{K_{m,h}} \tag{2}$$

where Δz is the depth of the mixed layer, $K_{m,h}$ are the vertical viscosity and diffusivity respectively, and w is the vertical velocity in the mixed layer. Pe was set, in this study, equal to the constant value of 10. This numerical value was evaluated on the basis of the scale values of the quantities on which it depends, i.e., $w = 0.001$ m/s [*Russo et al.*, 2003, D. Dietrich, private communication, 2002], $\Delta z = 5$m, $K_{m,h} = 0.0005$ m^2/s. In this way, the viscosity and diffusivity (mentioned before) are a function of the actual vertical velocity w and of the vertical depth Δz.

4. One- and Two-Way Coupling of Atmosphere-Ocean Models

[22] The RAMS and DieCAST models were coupled through an interaction scheme including wind stress,

short-wave and long-wave radiation and sensible and latent heat fluxes. Conservation of fluxes was achieved because both RAMS and DieCAST models are fully flux conserving, and in their coupling their numerical structure was not modified (particularly as far as the subroutines calculating fluxes were concerned).

[23] In the present case study, the parameterizations for turbulent diffusion, solar and terrestrial radiation and multiple soil layers (8 layers) were turned on, while the microphysics option was not activated since there was no rain during the simulated Bora period (see section 5). The coupled model will hereafter be referred to as RAMS-DieCAST.

[24] The initial SST conditions for RAMS-DieCAST were the output of a 3-month "stand-alone" run of DieCAST over the entire Adriatic Basin, initialized and forced by the following climatologies: MODB-MED4 [*Brasseur et al.*, 1996] for ocean currents, MODB-MED5 [*Wu and Haines*, 1998] for ocean temperature and salinity, and *May* [1982] for wind stresses. These climatologies, is available on a seasonal basis for the ocean data, and on a monthly basis for the wind-forcing (input data in Table 3), represent interpolated averages of observations. "Stand alone" means that there was no coupling between DieCAST and RAMS. Initial conditions obtained in this way are expected to approach the actual initial conditions of the case study quite well, although not always exactly equaling it.

[25] Therefore, in order to avoid this discrepancy, once the simulation of the Bora with the coupled model was started, the ocean model DieCAST no longer used the climatological data, but was completely forced by the real time atmospheric fields provided by RAMS, hence constituting the boundary conditions during the model run.

[26] In order to minimize the differences between climatological and real data at the beginning of simulation, we checked to determine that the initial climatologically forced field of SST was as close as possible to the SST field obtained from satellite images of the simulation domain, in particular over the northern part of the Adriatic Sea, where local SST observations were available at the beginning of the Bora episode. Among the different Bora episodes available for simulation, we could retrieve a Bora case from 3 to 10 January 1995, for which an accurate meteorological analysis was already carried out [*Qian and Giraud*, 2000] and a meaningful set of satellite SST observations and temperature measurements at two sites of the northern Adriatic Sea (Trieste and Venice) were available. These were the reasons why this episode was elected as the case study of air-sea interaction to be simulated in this study.

[27] This episode was analyzed with two different levels of coupling between the atmospheric model RAMS and the ocean model DieCAST. First, we started with a one-way coupling scheme, corresponding to the ocean model DieCAST forced by the atmospheric model RAMS. With this interaction scheme, the ocean DieCAST model was restored to the surface forcing (wind stress, radiation, sensible and latent heat fluxes) provided by RAMS, without giving feedback to the same, every 10 minutes, which is the time step of DieCAST, while RAMS had a time step of 30 s. This time step frequency guaranteed RAMS's numerical stability at a space resolution of 7 km (Table 1), while DieCAST is stable at a time step rate of 10 minutes. We chose the lowest time step rate of DieCAST because it was stable and reduced the computation time. However, this procedure's drawback was that it used a climatological value of SST taken from RAMS archives, in the computation of the heat fluxes by the atmospheric model RAMS.

[28] In the second stage of the study, we used a two-way coupling procedure, in which the DieCAST model became a subroutine of RAMS, giving its calculated SST values back to the atmospheric model RAMS, in order to allow it to compute net heat fluxes in a more realistic way ("net" means that the forcing heat flux of RAMS results from the difference between the incoming and outgoing heat fluxes at the sea surface). With this procedure, DieCAST was restored to the surface forcing at each time step of integration of RAMS (i.e., every 30 s).

5. Meteorological Analysis of the Bora Case

[29] During the few first days of January 1995, the synoptic meteorological situation was characterized by a trough extending from the north of Europe to the Iberian peninsula. The trough moved eastward on 4 January and a cutoff occurred near the northeastern region of the Alpine mountains. This cutoff remained in that region until 9 January.

[30] The mean sea level pressure and the front maps indicate that the main features on 1 January include a vast zone of high pressure on the European Atlantic coasts (Azores high pressure) and a low pressure over the northeast of Europe. At the same time, a low pressure over the Adriatic Sea was also present, with an associated frontal system moving southward. The cold part of the frontal system passed over the Adriatic Sea on 3 January. After its passage, the high pressure present over eastern Europe strengthened and moved westward, and joined the Azores anticyclone, inducing a northeasterly flow of cold air, favored also by the presence of the depression. This circulation pattern caused a decisive cooling of the air over the northeast of Italy, Slovenia and Croatia and created a strong pressure gradient over the Adriatic Sea. In the following days the minimum moved to the south, pushed by the high pressure, over the east of Europe, but it remained near the south of Italy blocked by the presence of another area of high pressure present over the north of Africa.

[31] The meteorological situation described above, resulting in a strong pressure gradient over the Adriatic basin, created a condition typical of the onset of the Bora. The cold air masses were forced to rise up to the Carso plateau and then to descend and accelerate toward the sea. The Bora wind reached its maximum velocity early on 4 January (16 m/s, one hour averaged).

6. Results of Application of the One- and Two-Way Coupled Simulation Models to the Bora Event

[32] The selected Bora event took place from 3 to 5 January 1995. Its simulation with the RAMS-DieCAST

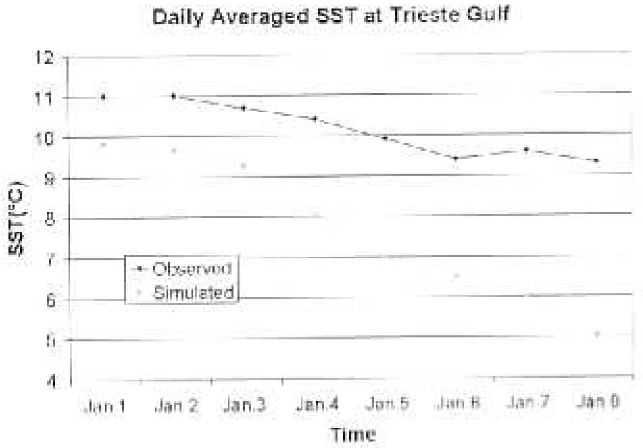

Figure 2. Comparison between simulated daily average SST and the observed one (both in °C) during 1–8 January 1995 at Gulf of Trieste (meteorological station of Istituto Sperimentale Talassografico del CNR of Trieste) (one-way forcing).

model started on 1 January, and covered an eight day period up to 8 January 1995. As previously mentioned, a three-month "stand-alone" run of the DieCAST model was performed before starting the simulation, in order to provide better initial condition for the coupled model. Except section 6.1 in which the one-way coupling was used, all other simulations adopted the two-way coupling.

6.1. One-Way Forcing

[33] Model results of the one-way coupled approach gave very low simulated SST after the Bora episode, compared with the observations collected at the meteorological station of the IST of Trieste, whose location and coordinates are shown in Figure 1. In fact, SST on the Gulf of Trieste side of the Adriatic Sea, was shown to drop by 4°C within the five days of the Bora, while observations showed a drop of approximately only 1°C (Figure 2). In addition, the overestimate did not keep constant, but was accentuated with the passing of time. The reason for this error in the simulated SST might be that the one-way coupled model DieCAST overestimated both sensible and latent heat fluxes from atmosphere to ocean and the stirring effect induced by the wind stress on the marine mixed layer.

6.2. Two-Way Forcing

[34] Figures 3a, 4a, and 5a show the simulated SST pattern in the whole basin of the Adriatic Sea immediately before, during, and after the Bora episode, respectively. These simulations were performed only by the two-way RAMS-DieCAST model with real time dynamical forcing. Figures 3b, 4b, and 5b show the simulated surface currents corresponding to Figures 3a, 4a, and 5a.

[35] From Figure 5a, it can be clearly seen that SST decreased after Bora event by almost 2°C on the Venetian side of the Adriatic Sea, by only about 1°C at the Gulf of Trieste side, and by 0.5°C on the Istrian side (Pula). In the central part of the Southern Adriatic Sea, SST only decreased by about 0.5°C for two main reasons: first, the Bora wind in that area was not as intense as in the northern area; second, the deep bathymetry of that part of the Adriatic Sea gave it a higher heat capacity than the northern part. SST even increased by about 0.5°C south of the Istrian Peninsula due to strong water advection along the Croatia coast (Figures 4b and 5b).

[36] The more rapid decrease of the SST on the Venetian side with respect to the easternmost one (Trieste) can be ascribed to two main reasons. First, the shallowness of the former area (18 m approximately) compared with the latter (25 m approximately). Second, the advection of warm waters due to the marine currents flowing along the Croatian coast and then curving cyclonically (without affecting the Venice gulf).

[37] In fact, Figures 3b, 4b, and 5b show that the surface current increased dramatically during the Bora

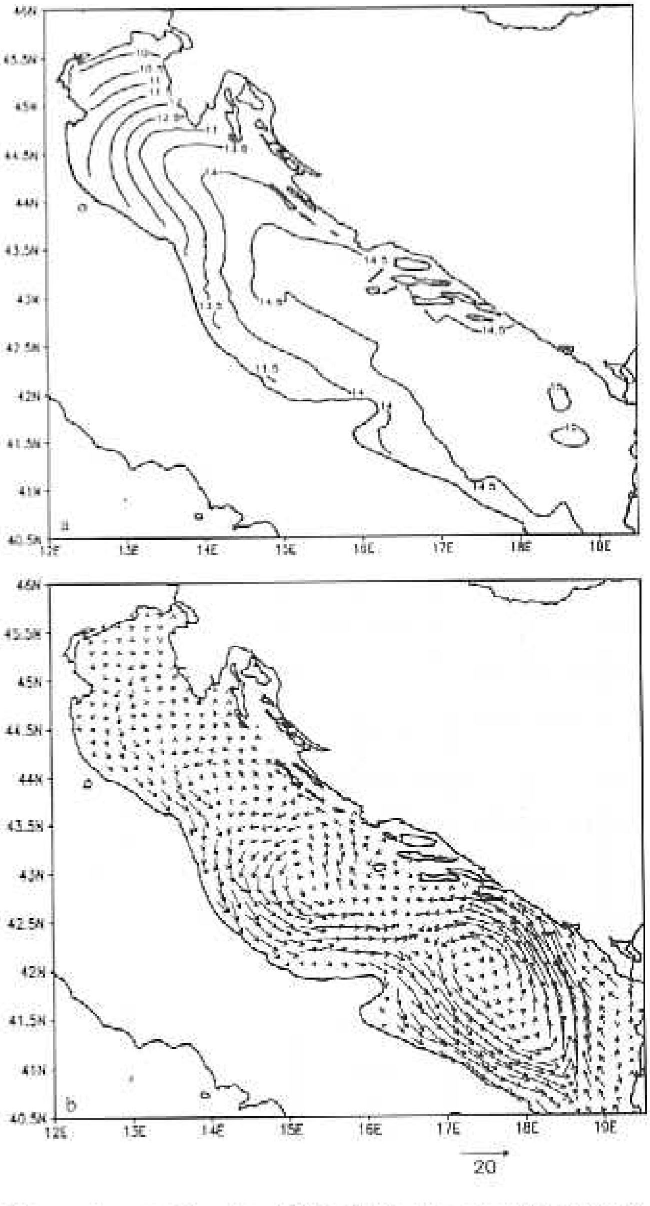

Figure 3. (a) Simulated SST (°C) with two-way coupled model RAMS/DieCAST at 00:00 3 January 1995. (b) Simulated surface current (cm/s) with two-way coupled model RAMS/DieCAST at 00:00 3 January 1995.

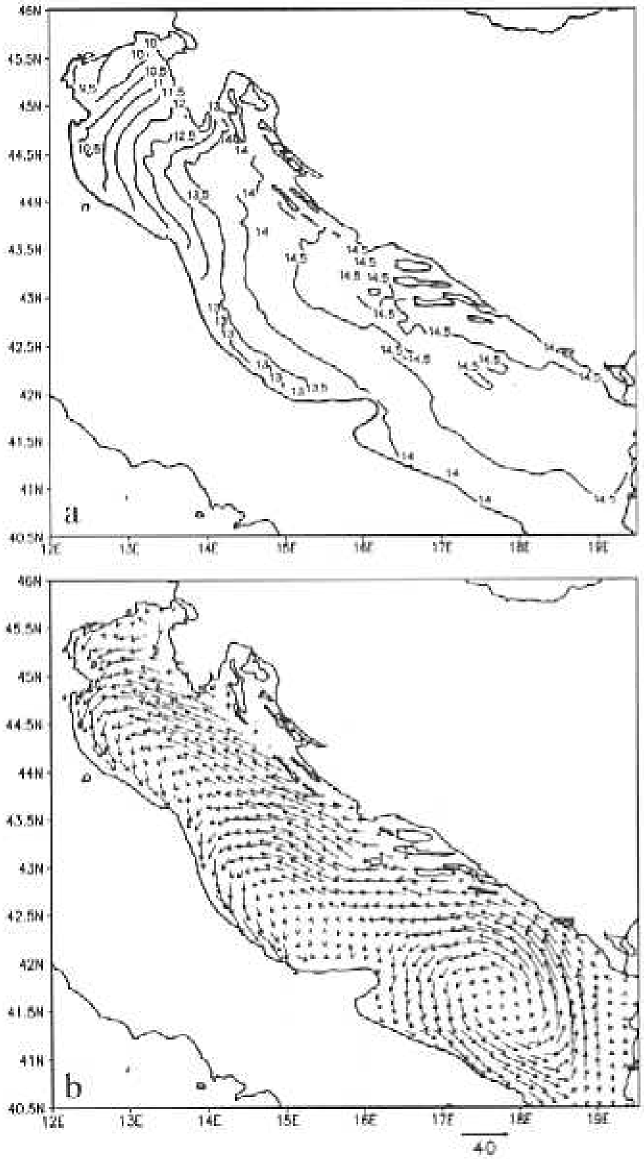

Figure 4. (a) Simulated SST (°C) with two-way coupled model RAMS/DieCAST at 00:00 4 January 1995. (b) Simulated surface current (cm/s) with two-way coupled model RAMS/DieCAST at 00:00 4 January 1995.

episode, especially in the north of the Adriatic Sea, as indicated by both observations and previous studies [*Orlic et al.*, 1992; *Bergamasco and Gacic*, 1996; *Paklar et al.*, 2001, *Rachev and Purini*, 2001]. In this context, it is necessary to underline that the DieCAST is able to reproduce accurately the dynamics of the Adriatic Sea, as it is evident by both the cyclonic circulation of the southern Adriatic and the bifurcation induced by the Jabuka Pit [*Carnevale et al.*, 1999].

[38] Figure 6 shows a comparison of simulated and observed daily average SSTs in the Gulf of Trieste from 1 to 8 January. It can be seen that the RAMS-DieCAST model accurately simulated the decrease in SST, with only a small systematic error (≈0.5°C). Such an error might be due to the fact that the model used an initial condition that did not perfectly match to the observed one. This interpretation is suggested by the fact that the systematic error in the two-way coupled model was not accentuated with the passing of time, as was the case in the one-way model, but remained almost constant during the whole simulation.

[39] In the same way as Figure 6, Figure 7 shows a comparison of simulated and observed SSTs on the Venetian side of the Adriatic Sea. The observed data, provided by the "Istituto per lo Studio della Dinamica delle Grandi Masse, CNR, Venezia", were available starting on January 3. For this place, whose location and coordinates are shown in Figure 1, simulation was again very accurate, but the results of observations were still underestimated as in the Trieste Gulf area.

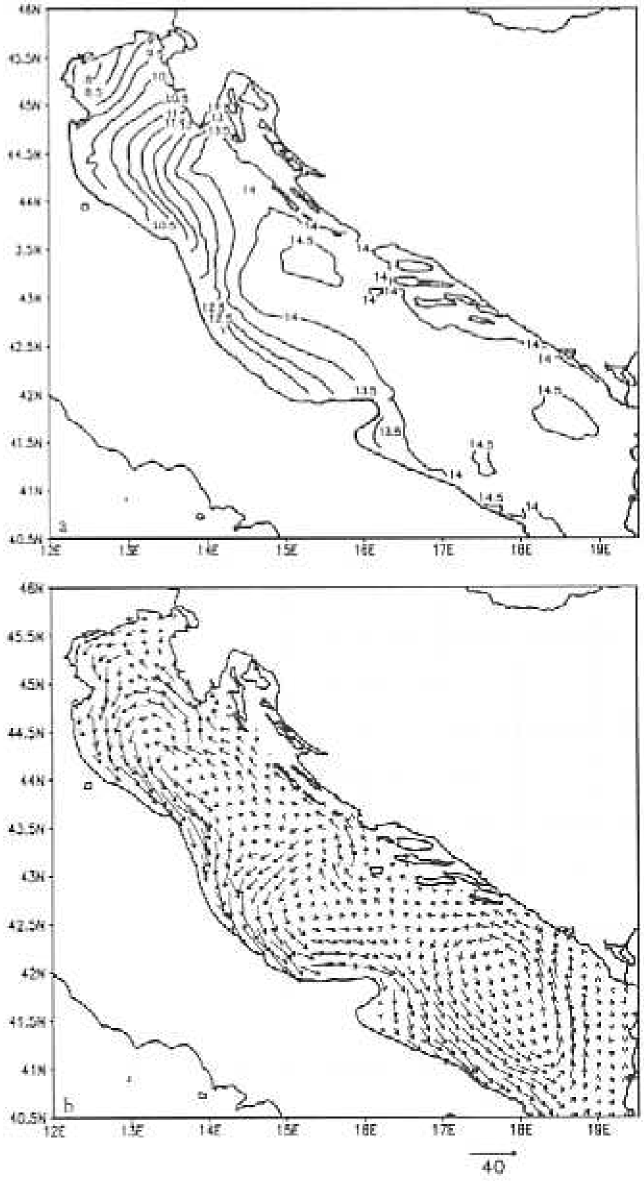

Figure 5. (a) Simulated SST (°C) with two-way coupled model RAMS/DieCAST at 00:00 6 January 1995. (b) Simulated surface current (cm/s) with two-way coupled model RAMS/DieCAST at 00:00 6 January 1995.

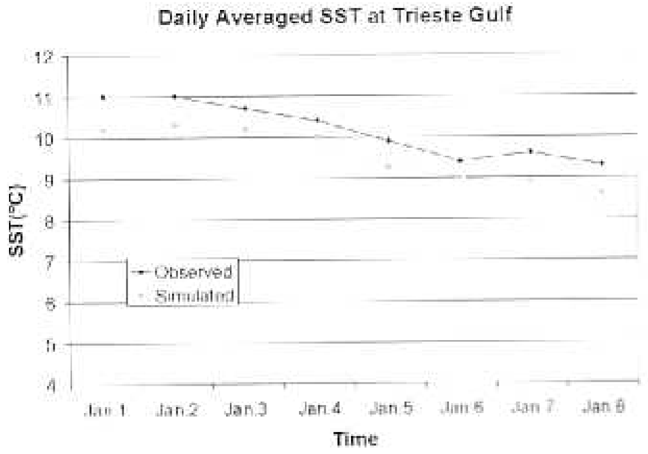

Figure 6. Comparison between simulated daily average SST and the observed one at the Gulf of Trieste during 1–8 January (two way coupling), both in °C.

[40] In conclusion, whatever the reason for this residual systematic departure between simulated and observed SSTs may be, it is a fact that the improvement of the prediction skill shown by the two-way coupled model reveals that the air-sea interaction mechanism entails a forcing of the ocean by the atmosphere and a contemporary forcing of the atmosphere by the ocean, notwithstanding the small scale of the Northern Adriatic Sea.

6.3. Sensitivity Analysis With Respect to Initial Conditions

[41] The residual systematic underestimation of the SST simulated by the two-way coupled model raised the important issue of the spatial and temporal propagation of error affecting the initialization of the ocean model. To clarify this point, a new climatologically forced run of the same type and duration (91 days) as the previous simulation (called the reference simulation) has been made by integrating the DieCAST model starting one month before (on 1 September 1994 instead of 1 October) and then terminating on 30 November of the same year. Seasonal climatological SST, gridded profiles of temperature and salinity and currents in the ocean used to spin up DieCAST were the same as those used to obtain the OIC, while the wind-forcing was referred to the months of September, October, and November. The Bora episode has been simulated with these new initial conditions (NIC) that show some differences, at the surface, from the old initial conditions (OIC) of the reference run.

[42] The results of the simulations affect thermal and kinematic fields of seawater, represented by distributions of isotherms and isotachs in zonal vertical sections of the Adriatic Sea. The sensitivity analysis also pointed to establishing the penetration depth of the perturbation produced by different preparations of initial conditions. To this end, two sections of different depths were selected: a northern section, representative of air-sea interaction processes in shallow water (which is the main object of this study), and a southern deeper one.

[43] Figures 8a and 8b show the distribution of seawater temperature, simulated by the RAMS-DieCAST (two-way coupled) model forced with OIC and NIC respectively, at the beginning of the Bora episode, i.e., at 12.00 a.m. of 4 January 1995, in the zonal vertical section at 45° North stretching from longitude12.53°E to longitude 13.75°E.

[44] This section is very shallow (maximum depth about 30 m); nevertheless, Figure 8a exhibits the doming of the isotherms characterizing the cyclonic gyre that affects the northern Adriatic circulation in the reference run (Figure 4b) and which is absent in Figure 8b.

[45] Figures 8c and 8d show the same distributions of Figures 8a and 8b, respectively, but referring to one and half days later. We can see that in both cases, the thermal structure keeps some memory of the OIC and NIC. In particular, the pattern of Figure 8c still shows the above mentioned doming of the isotherms, absent in Figure 8d.

[46] For the southernmost section at 41°N and stretching from longitude17.35°E to longitude 19.35°E, we analyzed the isotherms (Figures 9a–9d) and the isotach distributions of meridional (Figures 10a–10d) and zonal (Figures 11a–11d) components of seawater simulated with the OIC and NIC.

[47] This section is deeper than the previous one and has a symmetric shape, from the east to the west coast, its bottom reaching a maximum depth of more than 750 m bsl at the center of the basin. In this region the Adriatic Sea is not directly influenced by the mechanical and thermal effects of the Bora wind, nevertheless, the surface waters respond to its strong dynamical forcing, while for deeper waters, the temperatures show a marked steadiness.

[48] The temperature distribution shows relevant differences in the initial conditions of the simulation (Figures 9a and 9b represent the situation with OIC and NIC at 12.00 of 4 January) mainly at the surface, i.e., approximately till 70 m depth, while the temperatures of the deeper waters exhibit a close similarity to each other, depending on the steady circulation that characterizes such a basin (Figures 10a, 10b, 11a, and 11b) for the whole year. Therefore, as far as the model temperature is

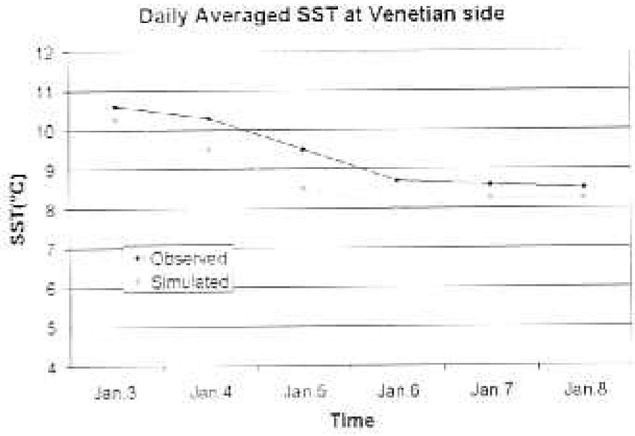

Figure 7. Comparison between simulated daily average SST and the observed one at Venetian side during 3–8 January (two-way coupling), both in °C.

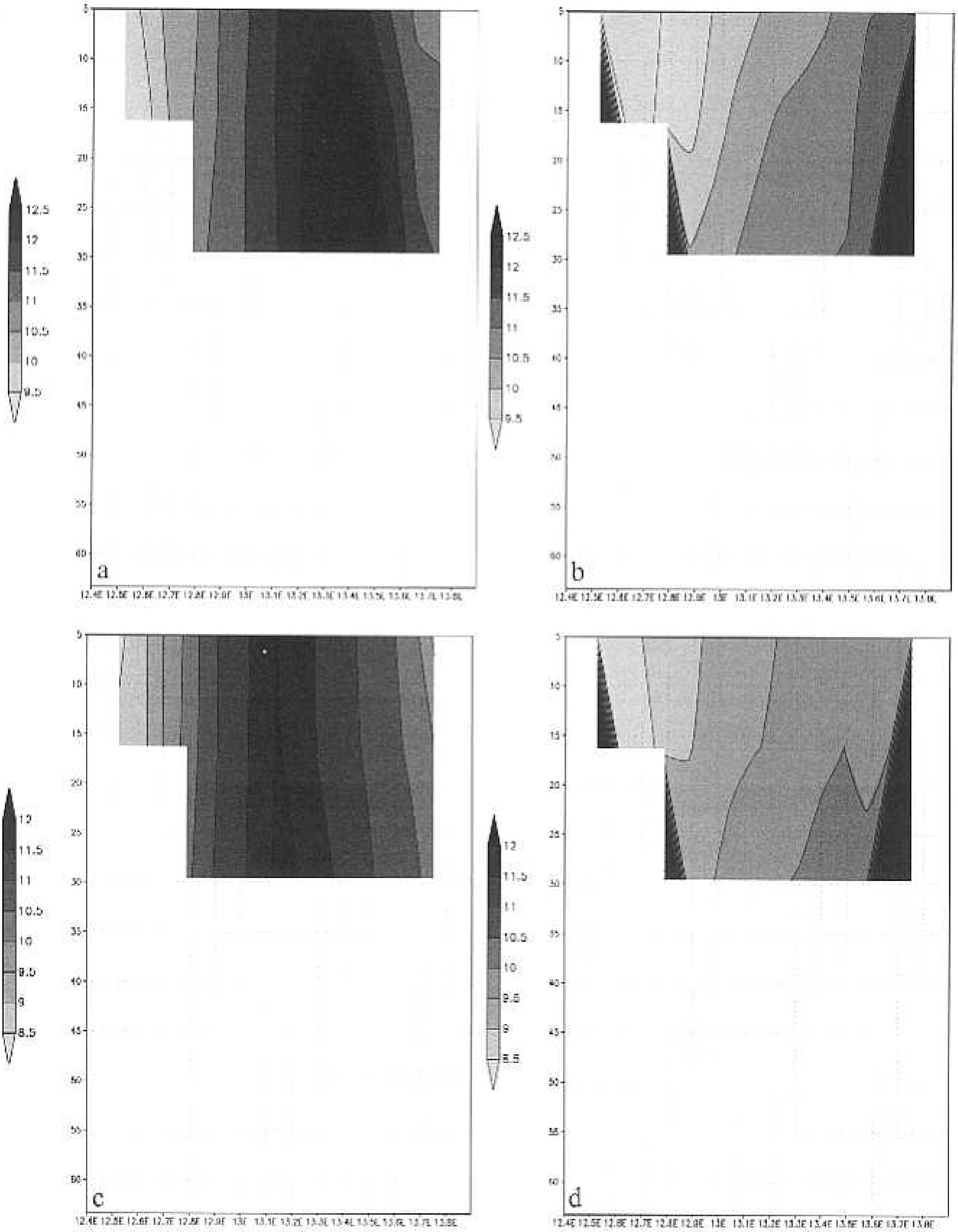

Figure 8. Isotherms of seawater (in °C) in a vertical section of the Adriatic Sea at latitude 45°N, from longitude 12.53°E to longitude 13.75°E at (a) 1200 UTC on 4 January 1995, two-way coupled model forced with OIC; (b) 1200 UTC on 4 January 1995, two-way coupled model forced with NIC; (c) 0000 UTC on 6 January 1995, two-way coupled model forced with OIC; and (d) 0000 UTC on 6 January 1995, two-way coupled model forced with NIC.

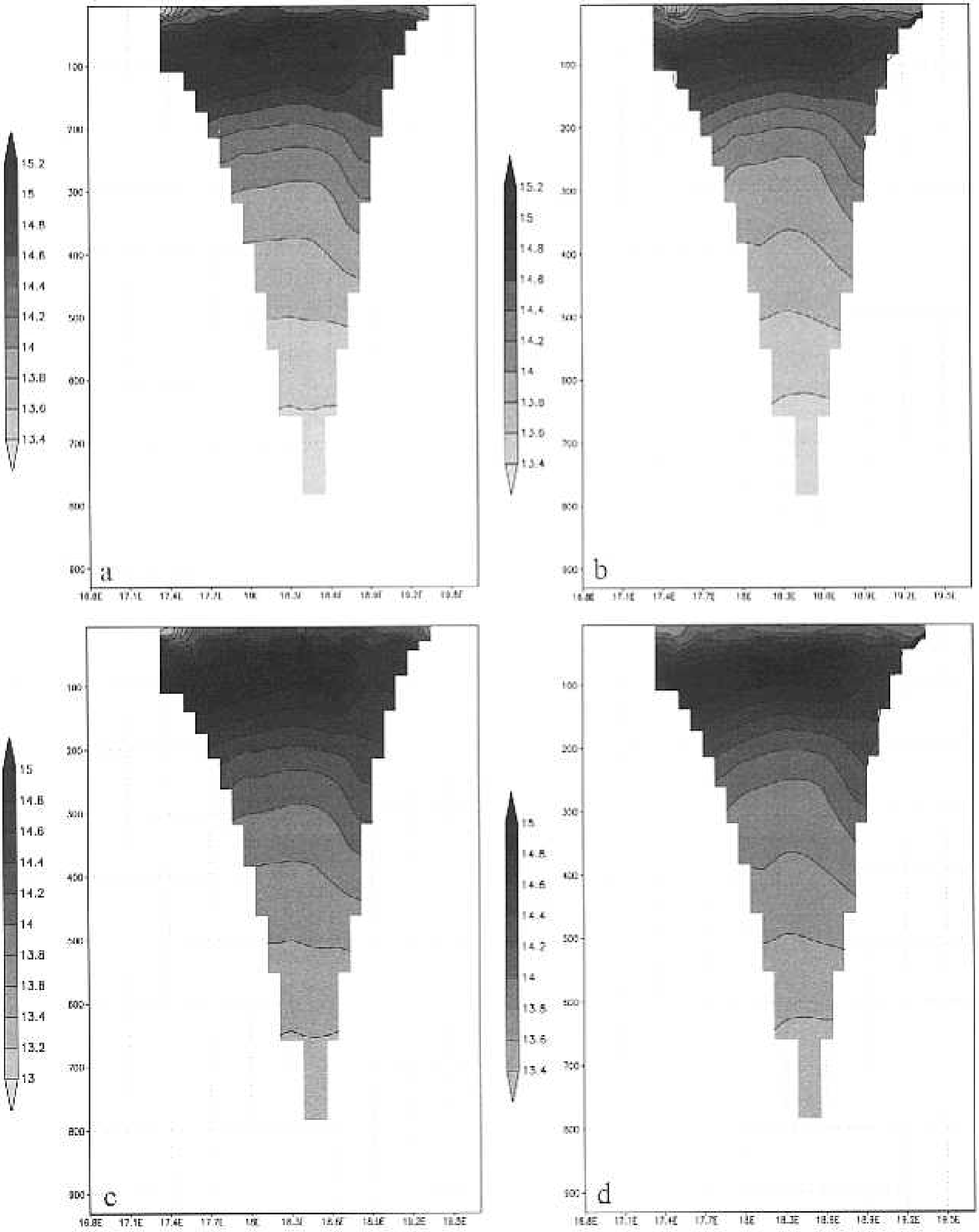

Figure 9. Isotherms of seawater (in °C) in a vertical section of the Adriatic Sea at latitude 41°N, from longitude17.35°E to longitude 19.35°E at (a) 1200 UTC on 4 January 1995, two-way coupled model forced with OIC; (b) 1200 UTC on 4 January 1995, two-way coupled model forced with NIC; (c) 0000 UTC on 6 January 1995, two-way coupled model forced with OIC, and (d) 0000 UTC on 6 January 1995, two-way coupled model forced with NIC.

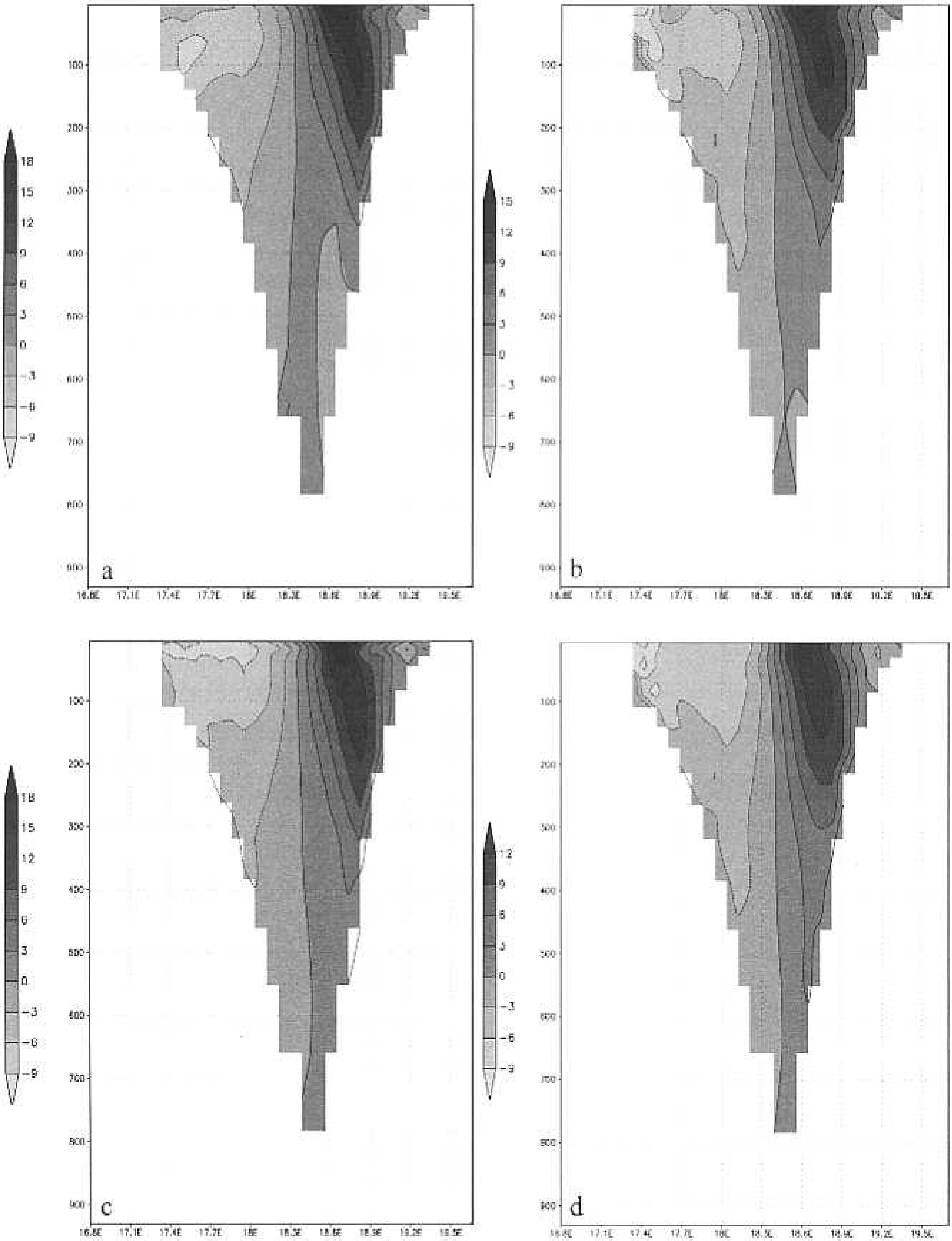

Figure 10. Isotachs of meridional component of seawater speed (in cm/s) in a vertical section of the Adriatic Sea at latitude 41°N, from longitude 17.35°E to longitude 19.35°E at (a) 1200 UTC on 4 January 1995, two-way coupled model forced with OIC; (b) 1200 UTC on 4 January 1995, two-way coupled model forced with NIC; (c) 0000 UTC on 6 January 1995, two-way coupled model forced with OIC; and (d) 0000 UTC on 6 January 1995, two-way coupled model forced with NIC.

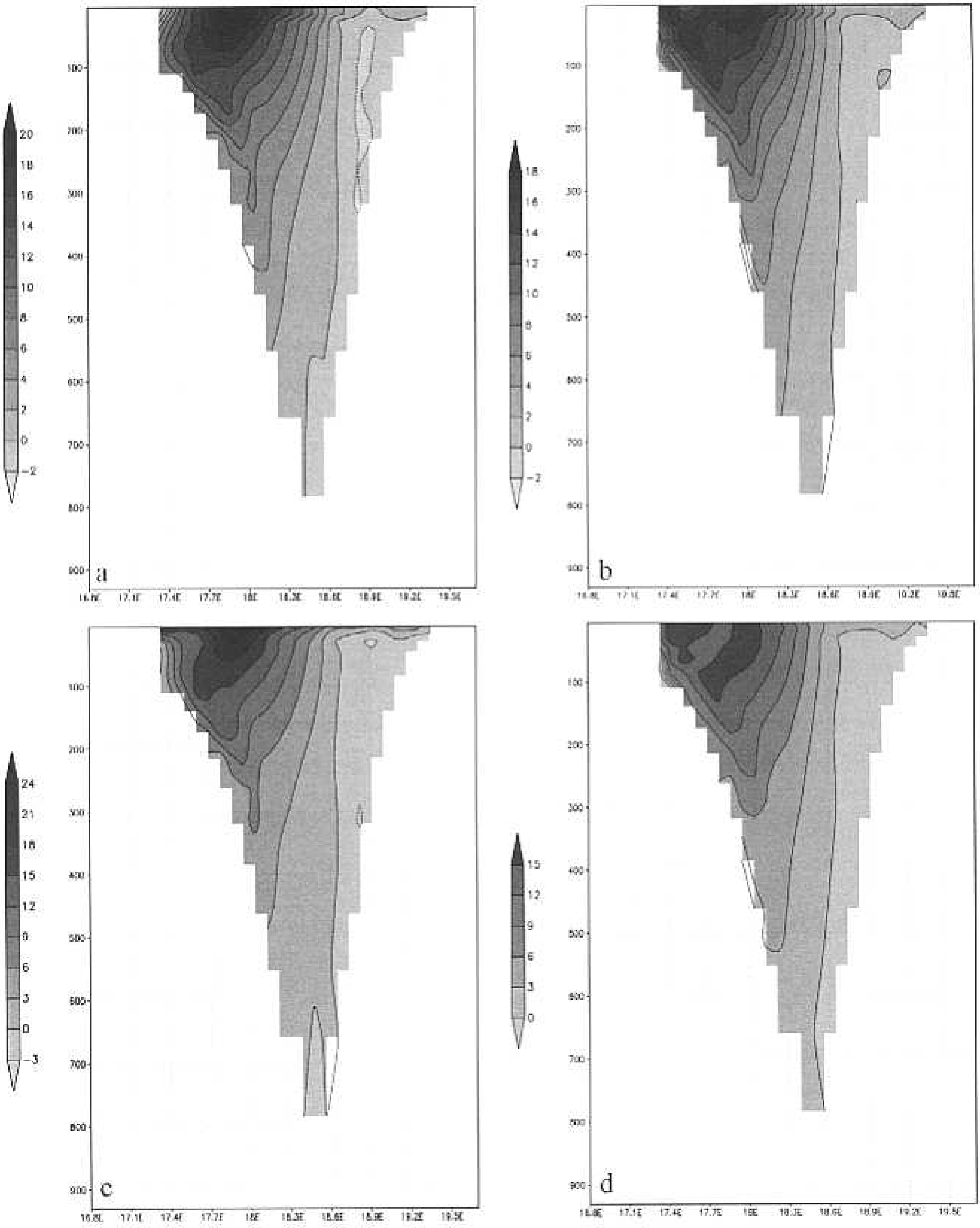

Figure 11. Isotachs of zonal component of seawater speed (in cm/s) in a vertical section of the Adriatic Sea at latitude 41°N, from longitude 17.35°E to longitude 19.35°E at (a) 1200 UTC on 4 January 1995, two-way coupled model forced with OIC; (b) 1200 UTC on 4 January 1995, two-way coupled model forced with NIC; (c) 0000 UTC on 6 January 1995, two-way coupled model forcing with OIC; and (d) 0000 UTC on 6 January 1995, two-way coupled model forcing with NIC.

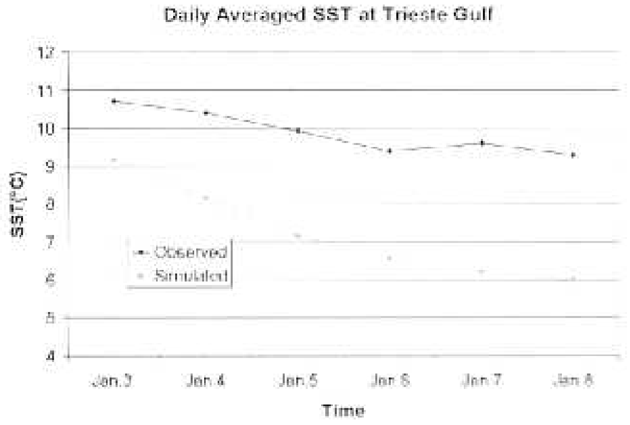

Figure 12. Comparison between simulated daily average SST and the observed one during 3–8 January 1995 at the Gulf of Trieste (two-way coupled model forcing with NIC), both in °C.

concerned, the two different initial conditions yield different results one and half days later (at 00.00 of 6 January), mainly at the surface (Figures 9c and 9d). This behavior should not be surprising because the simulation time (1.5 days) was very short, and also because of the quasi-invariance of the deeper layer for the considered temporal shift of one month between OIC and NIC. In other words, because of the timescale considered in the present study, the meteorological forcing mainly influences the marine surface layer, consequently leaving the subsurface water masses almost unaltered.

[49] Analogous considerations can be made for the dynamical fields. In fact, the initial meridional and zonal velocities (at 12:00 am of 4 January 1995) show noticeable differences in shape and intensity between OIC (Figures 10a and 11a) and NIC (Figures 10b and 11b). After two days of simulation, we can observe that these differences are almost constant and, again, are mainly confined to the surface layer close to the eastern coast (Figures 10c, 10d, 11c, and 11d).

[50] The more intense meridional circulation simulated with the OIC (Figure 10c) appears to support our interpretation of the different cooling rate observed in the Gulf of Venice with respect to the Gulf of Trieste, in terms of advection of warm waters due to the surface marine currents flowing along the Croatian coast (Figures 4b and 5b).

[51] Finally, Figures 12 and 13 show the comparison between the time evolution of the observed and simulated SST at Trieste and Venice marine stations respectively when NIC are taken into consideration for the two-way simulations. By comparing Figures 12 and 13 with the corresponding ones for the reference runs (Figures 6 and 7), it is possible to state that, in the framework of nonclimatological studies such as the present one, initial conditions strongly influence the evolution of the coupled atmosphere-ocean system and therefore the better the matching between observed and initial fields for the runs, the lesser the error between final simulated SST fields and observations.

[52] Therefore, since the NIC case provides worse initial conditions than the OIC ones, then this initial "error" also dramatically propagates itself during the simulated time, in the dynamical coupled system, posing the need for proper assimilation techniques (for instance, with buoy and satellite data) for data initializations.

7. Conclusions

[53] In the framework of setting up a system for the prediction of the Adriatic Sea circulation, we built and tested a two-way regional atmospheric and ocean coupled model. Having in mind this final task, a test of this coupled system was done by simulating a Bora event and its influence on both SST and marine circulation.

[54] The atmospheric limited area model RAMS and the ocean model DieCAST were selected for the two-way coupling. The present case study showed that, notwithstanding the reduced spatial scale of the North Adriatic Bora, only a two-way coupling between the atmospheric and ocean models proved skillful in simulating (quantitatively): SST anomalies, the cyclonic gyre in the northernmost part of the Adriatic Sea, the effect of bathymetry in forcing both the bifurcation in correspondence of the Jabuka Pit and the cyclonic circulation characterizing the Southern Adriatic Sea.

[55] In particular, accurate agreement has been shown between simulated and observed SST in two coastal stations (Venice and Trieste), with only a small systematic error (≈0.5°C). On the contrary, a one-way coupled model showed a significant overestimate of the SST decrease, particularly in the north-eastern Adriatic, because of the unrealistic sensible heat flux from the sea toward the atmosphere.

[56] The sensitivity analysis carried out in section 6.3 also supports the idea that the small systematic error in the predicted SST appears to be due to the nonperfect matching of the initial condition with the observed one used by the model. This interpretation is also strengthened by the fact that the systematic error in the two-way coupled model was not accentuated with the passing of time, as was the case in the one-way model, but remained quite constant during the whole simulation.

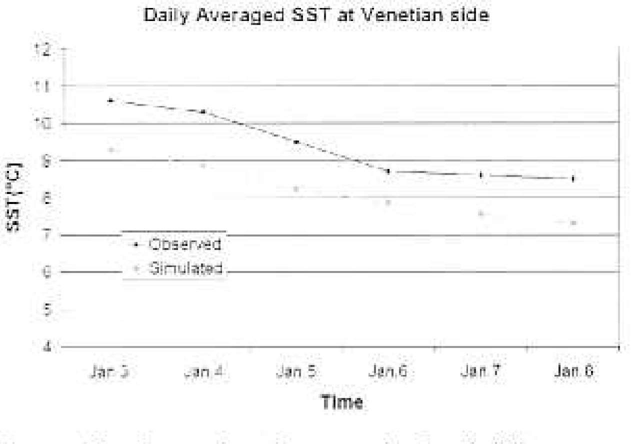

Figure 13. Comparison between simulated daily average SST and the observed one during 3–8 January 1995 at Venetian side (two-way coupled model forcing with NIC), both in °C.

[57] **Acknowledgments.** The authors are grateful to Luigi Cavaleri, Istituto per lo Studio della Dinamica delle Grandi Masse, CNR, Venice, for providing the marine data recorded at the Venetian coast of the Adriatic Sea, and to D. Dietrich and Steve Piacsek for their useful advice. ECMWF is acknowledged for providing the analysis data necessary to drive the models in the simulated period. We also acknowledge the help given by Luigi Alberotanza, Director of the Istituto per lo Studio della Dinamica delle Grandi Masse, CNR, Venice, in satellite data retrieval. This study has been partially financed by the A.S.I. (Agenzia Spaziale Italiana) under contracts I/R/41/00 and I/R/055/01 and Italian Ministry of University and Research, under a COFIN 2000 grant.

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