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Anomalously Strong Bora over the Black Sea: Observations from Space and Numerical Modeling

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Abstract—An anomalously strong Novorossiysk bora (strong coastal wind) observed in January–February 2012 with synthetic aperture radar (SAR) images from the *Radarsat-1* and *Radarsat-2* satellites is studied using the high resolution Weather Research and Forecasting Model (WRF). The bora was reliably reproduced not only in the narrow coastal zone, but also far in the open part of the Black Sea. As a result of modeling we demonstrated that an optimally configured WRF–ARW model with nested grids and horizontal resolution equal to 9/3/1 km quite well qualitatively and quantitatively reproduces the bora events. The details and structure of the bora (for example, wind strips and other peculiarities) seen on the SAR images were clearly reproduced by numerical modeling. Coupled analysis allowed us to conclude that these two alternative methods of investigating this dangerous meteorological phenomenon are highly effective.

Keywords: Black Sea, Novorossiysk bora, WRF-ARW model, numerical modeling, SAR images, coupled analysis

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1. INTRODUCTION

Novorossiysk bora is the Black Sea term for a strong cold katabatic wind. It appears in locations where not very high mountain ridge separates the continent from relatively warm sea. In the cold period of the year, a region of high pressure is formed over the cold continent whose air begins to move in the direction to the warm sea, which is a region of low pressure. If the air flow has sufficient energy, the cold air overflows the obstacle being, compressed in the vertical plane. The overflow of the air occurs over the passes in the mountains. Here, the air is subjected to additional compression in the horizontal plane because it is surrounded by higher mountains from both sides. Naturally, this narrowing of the airflow leads to an increase in the velocity. Then, the cold air directs downwards along the valleys, increasing in speed under the influence of gravity and baric gradients [1]. Owing to its origin, the bora has a small vertical scale, usually not exceeding 2 km. In general, the bora is related to mesoscale processes [2].

Such a phenomenon is observed in different regions of the planet. The Adriatic and Novaya Zemlya bora, mistral, sarma, and other local winds are widely known. The bora on the Adriatic Sea is studied best of all; however, owing to the climatic and topographic peculiarities, it is often not accompanied by such a strong temperature decrease and wind speed like the Novorossiysk bora. On average, the bora in the city of Novorossiysk occurs 45 days per year with maximal occurence in November. In half of these days the wind speed exceeds stormy values (20 m/s) and approximately 5 days the wind has a hurricane speed (greater than 33 m/s). The duration of an individual bora is usually 1–3 days and it rarely exceeds 7 days [3]. Approximately once in 5–10 years an anomalous bora occurs in Novorossiysk and its vicinities with a wind speed of 35–45 m/s, leading to natural disasters.

In this work we analyze the bora event that occurred in the end of January—beginning of February 2012. The wind speed in Novorossiysk and surroundings reached 30–40 m/s with gusts up to 40–50 m/s; the air temperature dropped from +10° to −19°C. Waves 2–4 m in height were observed in the sea; a cold stormy wind in the coastal zone blew water droplets from the wave crests, which caused mass ice accretion on vessels, port constructions, and embankments. Judging from these characteristics, this bora was distinguished for its anomalous force and had catastrophic consequences [4].

Despite numerous attempts to study the bora, the existing methods of research and forecast are not always effective. For example, the application of the synoptic method allows forecasting large-scale meteorological phenomena. In this case, a local forecast is possible only on the qualitative level. Empirical methods based on the statistical analysis of the data of observations can appear more successful. However, such an approach requires a large number of stations and long time series of observations. Unfortunately, the study region does not correspond to these requirements. Thus, it seems numerically modeling the atmospheric state during the bora event to be the most effective method.

For this reason, we used the Weather Research and Forecasting Model (WRF) with investigation core Advanced WRF (ARW). This is a nonhydrostatic regional model of high resolution which has a powerful dynamic core; it takes into account the inhomogeneity of the underlying surface. It has been continuously improved, and now it is widely used for weather modeling both in the applied and research fields. The output product contains all the information needed to solve the formulated problem. The main advantage of the WRF–ARW is a wide set of parameterizations of the physical processes that allows to select the configuration of the model on the basis of the solved problem. A detailed description of the model is given in [5] as well as in the user's manual [6] and at http://www.wrf-model.org.

The first works, in which attempts of numerical modeling of the Novorossiysk bora using the WRF were undertaken, are [7] and [8], they gave promising results.

Finally, recent attention of the researchers has been focused on the satellite monitoring of the meteorological processes including the bora using synthetic aperture radar (SAR) surveys. Some specific results were obtained in this field [9–13]. The basic methods of analysis and interpretation of the SAR and satellite images with manifestations of local winds, in particular, the bora and foehn, are described in [9, 11, 13, 14].

In 2012, the operational monitoring organized by the SCANEX Research and Development Center allowed us to see the development of the bora event in the northeastern part of the Black Sea from space. A detailed analysis of the series of images obtained during the bora is presented in [4, 15]. In the general case, the analysis of the satellite images gives qualitative information; however, modern methods of processing the calibrated SAR data allow to restore the wind fields over the sea using the model of the National Center for Atmospheric Research (NCEP) for wind directions and the C-band Model (CMOD) function for wind speed [11–14].

In this paper we present and discuss the results of a numerical experiment conducted using the WRF–ARW mesoscale model confirmed by the coupled analysis of a series of satellite images taken by *Radarsat-1* and *Radarsat-2* (which can be reliably considered the data for model verification) obtained during anomalously strong bora of January–February 2012. Eventually, this allowed us to characterize this dangerous meteorological phenomenon qualitatively and quantitatively.

THE WRF–ARW MODEL

The 3.5.0 version of the WRF–ARW model to reproduce the bora in January–February 2012 with the nested domains without feedback has been selected and used. The configuration of the domains is shown in Fig. 1. The spatial resolution for domains d01, d02, and d03 was 9, 3, and 1 km, respectively. The vertical resolution for all grids was 36 levels (the upper boundary was specified at a level of 50 hPa). The time digitization was 1 h. According to the meteorological observations in the period from January 24 to February 10, 2012, several cases of wind intensification occurred (there were actually two consecutive bora events). Therefore, for the complete description of the bora development stages, we decided to reproduce the entire time interval.

The configuration of the model was generally determined by the parameterization of submesoscale processes used in the model. According to the problem considered in the investigation, the key problem is selecting the schemes for the microphysical processes, convection, surface, and boundary layers. Finally, in order to take into account the microphysical properties, we selected the WSM6 scheme, in which the mixed phase of the clouds and precipitation is described most fully [16]. The scheme of convection parameterization was used only in the domains with resolutions of 9 and 3 km (d01 and d02). We used an improved scheme of Kain–Fritsch [17, 18] because it has a good feedback with the mesoscale atmospheric dynamics. Parameterization of convection was not used in domain d03. We used the MM5 parameterization scheme based on the Monin–Oboukhov simulation theory [19] as the model of the surface layer, underlying surface, and soil. This scheme earned a good reputation among researchers. The planetary boundary layer was specified using the scheme developed in the Yonsei University in South Korea [20].

As the initial conditions and input data we used the data of the NCEP FNL operative analysis on 1° × 1° grid with 26 vertical levels and a time step of 6 h. The WRF model adopts these data well, moreover they have a high resolution and possess the necessary information for modeling.

RESULTS OF MODELING

The available meteorological and synoptic information (the data of weather stations in Temryuk, Anapa, Novorossiysk, Gelendzhik, and Dzhubga) has been collected to validate the model. These meteorological data and also the charts of the surface analysis of the Krasnodar Regional Hydrometeorological Center became the main material that allowed us to analyze the synoptic situation during the bora event.

It is most interesting to compare the wind speed at a height of 10 m between the WRF and data at the stations obtained using the standard method. Regular wind measurements (with a time interval of 3 h) are shown in Fig. 2 with triangles; the modeling results at the nearest node of the calculation grid are shown with

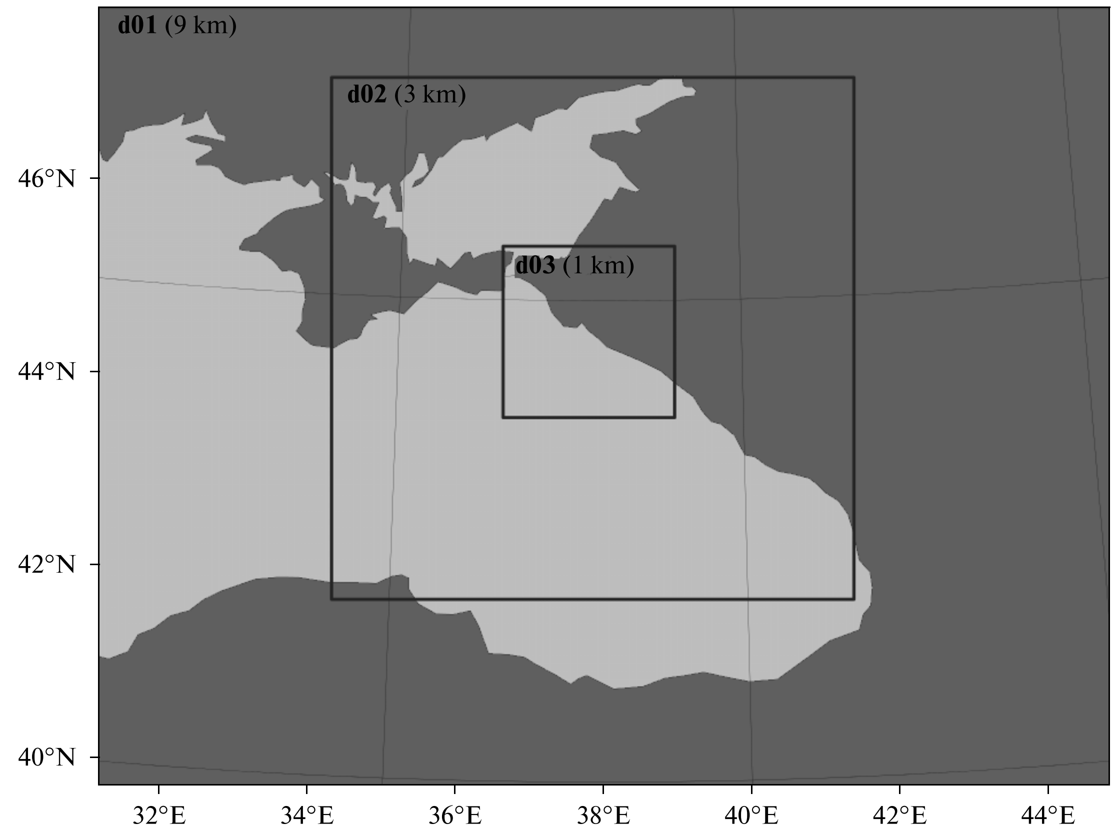

Fig. 1. Calculation domains used in the modeling.

a solid line (with a time interval of 1 h). It is known that the data of meteorological stations are presented in the measurement in one point, while the model results are presented as the collected and acquired information in the grid square. In order to increase the efficiency of such a comparison as much as possible, only the model result of calculation using a grid with a resolution of 1 km is used (d03). It is worth noting that the model successfully reproduced the bora both at the qualitative and quantitative levels. Nevertheless, the model systematically overestimated the wind speeds, the mean difference from the station's measurements was approximately 2 m/s. A similar result was obtained in [7]. However, it is well seen that if the terrain topography becomes rougher and the wind speed increase, the discrepancies increase too. For example, the stations in Temryuk and Dzhubga are located in wide valleys; therefore, the mean difference between these stations was the smallest, i.e., approximately 1 m/s (Fig. 2 on the right).

Since Novorossiysk lies in the zone of the maximum intensity of the bora, the measurements at this point are most significant. Here, the mean difference is also not high (1.4 m/s); however, the root-mean-square deviation (RMSD) was ±5.7 m/s. If we focus our attention on the evolution of wind speed in Novorossiysk (Fig. 2 on the left) we see that the model underestimates the maximum values, but agrees well in the trend. It is also worth noting that the three stages of the maximum development of the bora agree with the measurements: the first on January 27–28; the second on February 1; and the concluding one, which was the most intense on February 7–8. Thus, the WRF model with the selected configuration successfully solves the formulated problem and can be used in the research.

Along with the wind speed, the evolution of the air temperature at the surface is an important parameter for the bora description. The data of the model together with the data at stations are presented in Fig. 3. On average, the model slightly overestimates the temperature values: on average less than by 1°C, which is a very good result. It is noteworthy that at all weather stations where the influence of the bora was recorded, the increase in the wind speed was always accompanied by a preliminary temperature drop at all stages of intensification. Such a dependence is characteristic only of the bora.

Then the modeling results were compared with the satellite SAR images. It was shown above that during the study time of the bora development, the first phase (January 27–28) and the final one (February 7–8) can be considered extreme. The last phase was anomalously intense. Due to many causes, only the final

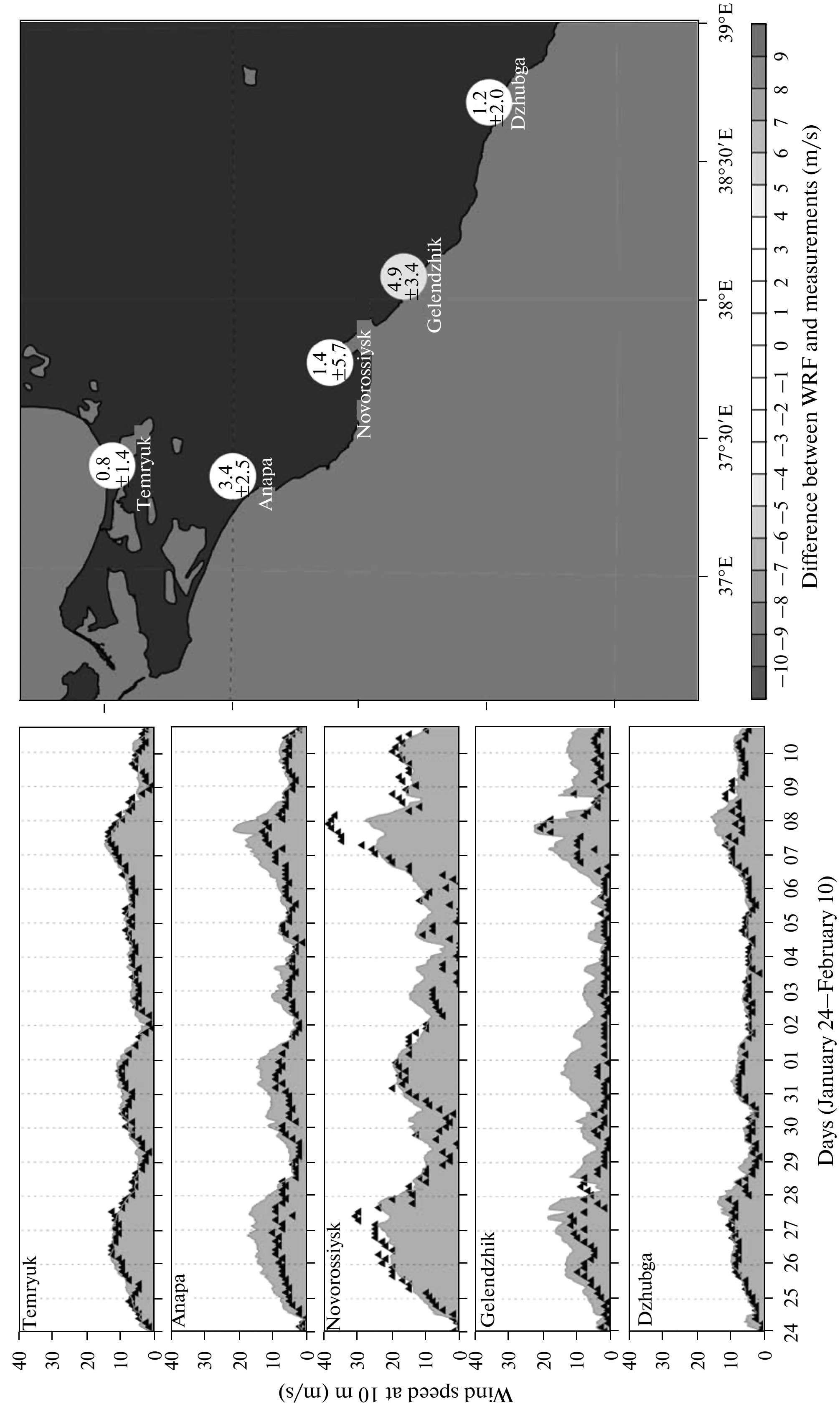

Fig. 2. Comparison of modeling results (gray filled plots) and observed values (triangles) for wind speed at a height of 10 m at the weather stations Temryuk, Anapa, Novorossiysk, Gelendzhik, and Dzhubga. Mean velocities and root-mean-square deviations between WRF and observations are given on the right in white circles.

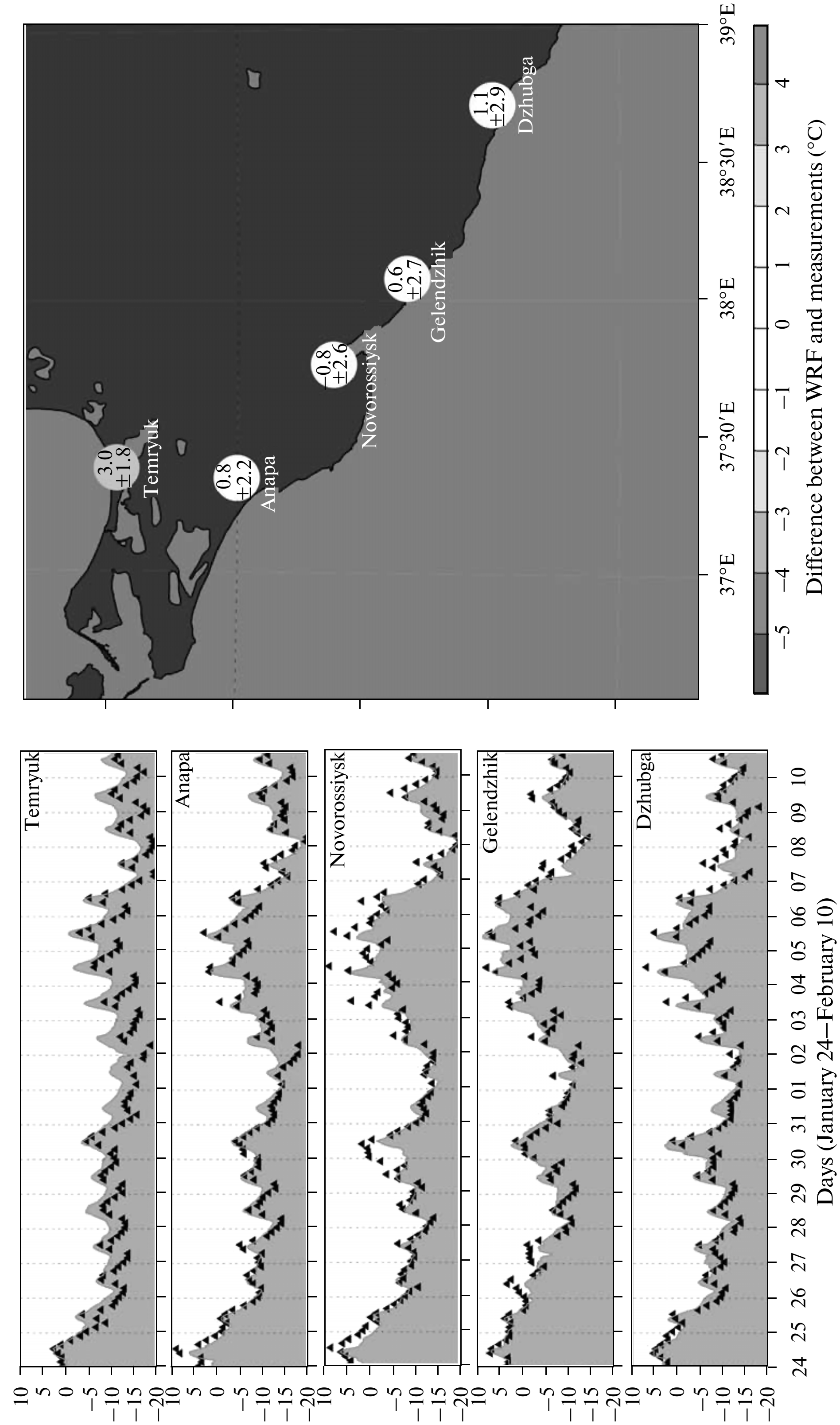

Fig. 3. Comparison of modeling results (gray filled plots) and observed values (triangles) for air temperature at a height of 2 m at the Temryuk, Anapa, Novorossiysk, Gelendzhik, and Dzhubga weather stations. Mean temperatures and root-mean-square deviations between WRF and observations are given on the right in white circles.

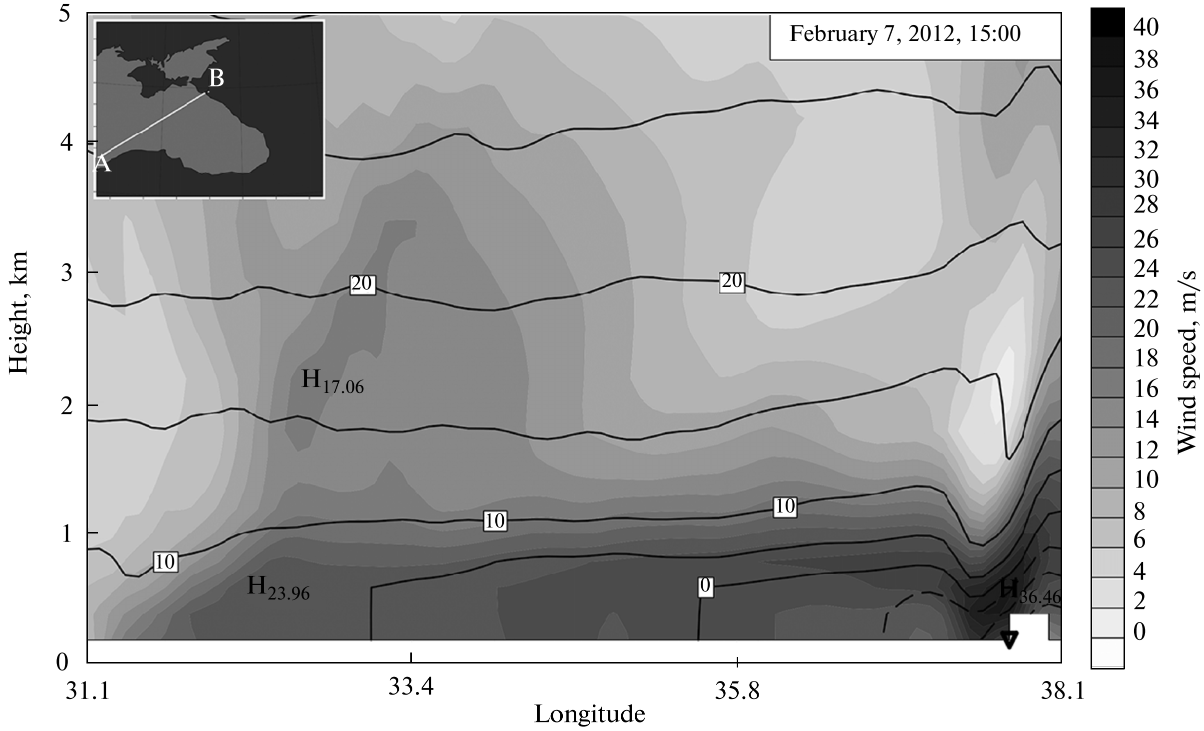

Fig. 4. A vertical section of the atmosphere along the direction of wind-jets observed on the *Radarsat-2* SAR image on February 7, 2012 (along the A–B line in the inset in the upper left corner), plotted from the results of modeling (the contour lines with numerals in the squares show the distribution of potential temperature (°C); the gray tones indicate the wind speed with the maximum value of 36.5 m/s).

stage of the bora was covered most fully by the images from many satellites. This is why we considered only the time interval from February 6 to February 9, 2012 to compare the results of modeling with the satellite SAR images.

A model vertical section of the low atmosphere along the direction of the wind jets observed on February 7, 2012, on the SAR images from *Radarsat-2* (Fig. 7) is shown in Fig. 4. The marked contour lines show the vertical distribution of potential temperature (°C); the gray tones show wind speed (with a maximum of 36.5 m/s at a height of 300 m). The main peculiarity of this section is a characteristic "tongue," which is seen in the atmospheric layer over the water up to altitudes of 1000–1200 m. It is traced over a distance of almost 400 km along the section. As the distance from the coast increases, the wind (bora) decreases and then decays to the velocities less than 15 m/s. We note that from the analysis of the SAR images we found that usually the horizontal scale of the bora changes from 50 to 250 km; it depends on the synoptic situation, intensity of the bora, and some other less known factors [4, 9]. It is also clearly seen from Fig. 4 that when the descending air flow hits the water surface in the coastal zone, it reflects and as the distance from the shore increases at least two more shocks are observed. Such a behavior resembles the phenomenon known as a hydraulic jump. Finally, the distribution of the potential temperature reflects the inflow of the cold air mass. The fact that the region of the maximum intensity of the winds concentrates in the lower atmospheric layer (1–1.5 km) is characteristic only of the bora and indicates that the model successfully reproduced this phenomenon precisely.

Figure 5 shows the results of the wind field modeling in domain d03 (resolution 1 km) for the time moments close to the moments when the SAR images from *Radarsat-1* and *Radarsat-2* were acquired, namely: February 6, 2012 (03:43 UTC); February 7, 2012 (15:26 UTC); and February 9, 2012 (15:15 UTC) (see also Fig. 7). The spatial variability (fine structure of the wind field) in the initial, maximum, and final phases of the bora development, respectively, is clearly seen. Note that the full representation of the results of the bora modeling can be seen only from the sequential patterns collected in an animation file (see http://sail.msk.ru/gulev black_sea/novorossiysk).

Aerological diagrams plotted as a result of WRF modeling for Novorossiysk at the times close to the time moments of the SAR image acquisitions are presented in Fig. 6. One can see that, on February 6, an inversion was observed in the surface layer, which reached an altitude of 1300–1400 m (Fig. 6 on the

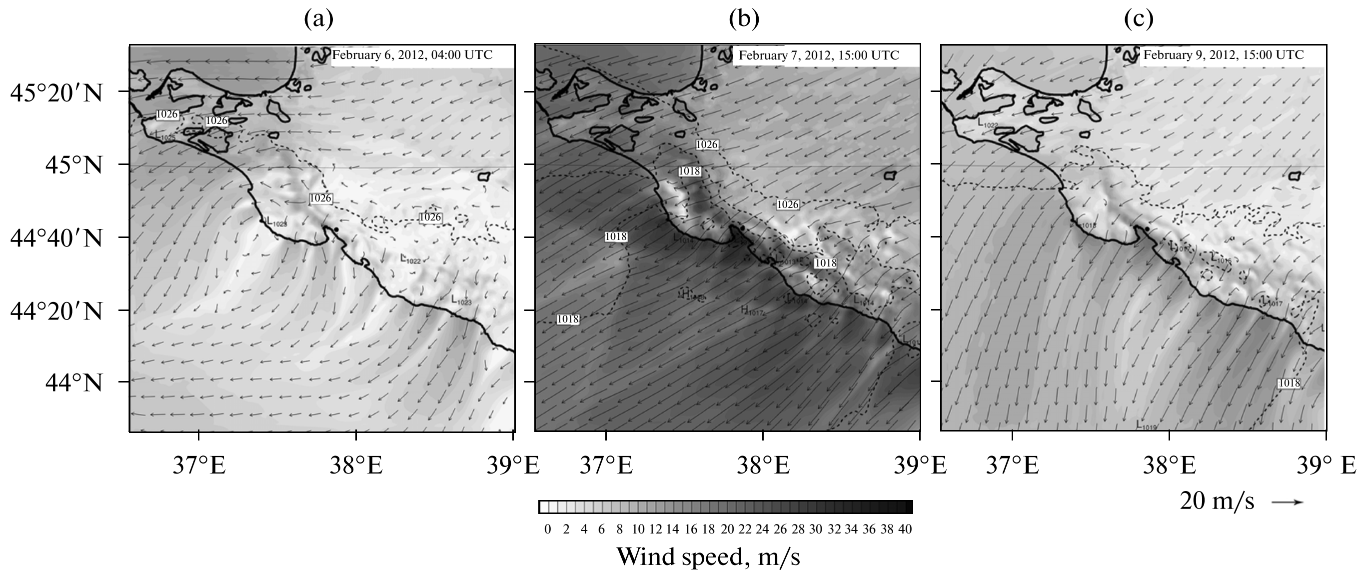

Fig. 5. Simulated wind fields in domain d03 at time moments close to the time of the SAR image acquisitions from the *Radarsat-1* and *Radarsat-2* satellites: (a) February 6, 2012 (04:00 UTC); (b) February 7, 2012 (15:00 UTC); and (c) February 9, 2012 (15:00 UTC). Dashed lines with numerals show isobars.

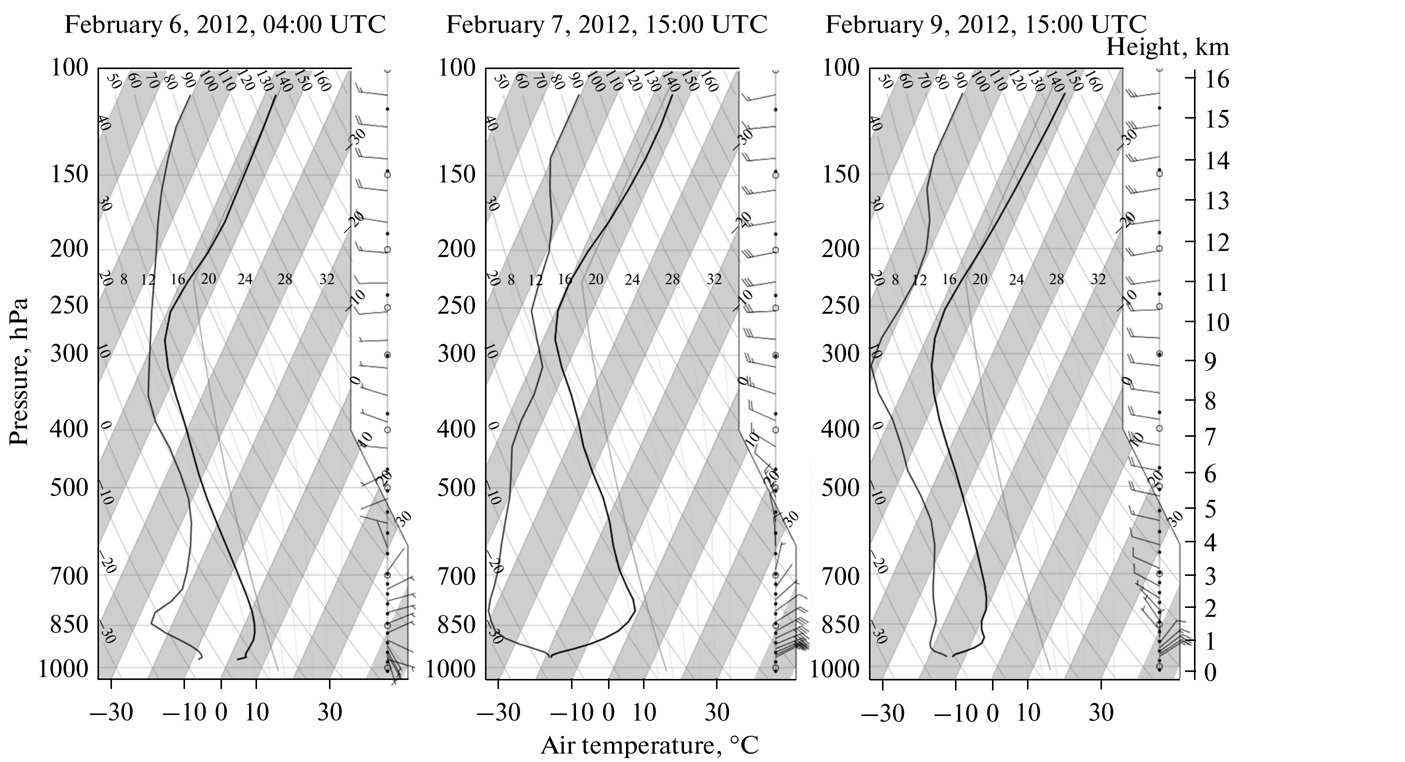

Fig. 6. Simulated aerological diagrams for Novorossiysk: in the beginning of the last stage of the bora in February (left), in the phase of its maximum development (middle), and in the final stage (right); UTC time.

left). In the maximum phase, the inversion was observed at a height of almost 2 km with a temperature difference of almost 20° (–15°C at the surface and 5°C at the inversion altitude) (Fig. 6 in the center). By the time of the end of the bora, the inversion slightly ascended and started to be characterized by negative air temperatures at altitudes of 2100–2300 m (Fig. 6 on the right).

THE BORA ON SATELLITE IMAGES

The SAR and optical images of the remote sensing satellites can be alternative material for validating the modeling results. During the bora in January–February, 2012, the data of remote sensing over the northeastern part of the Black Sea were obtained and provided by the SCANEX. The SAR images of the *Envisat*, *Radarsat-1*, and *Radarsat-2* satellites and the optical images of spectroradiometers MODIS (onboard the *Terra* and *Aqua* satellites) and MERIS (onboard the *Envisat* satellite) were analyzed in detail in [4, 15].

The analysis of the SAR images demonstrated that strong wind forcing the sea surface during the bora leads to the formation of characteristic surface signatures, which are manifested on the SAR images owing to the sea surface roughness (small-scale wind waves) modulated by the wind. Almost always the bora induces surface manifestations in the form of wind jets normal to the shore. Their structure is frequently complicated by transversal perturbations, which are caused by wind gusts and atmospheric gravity waves. This is generally explained by the peculiarities of the topography.

On the optical images, the bora is characterized by a cloudless (or almost cloudless) sky in a wide coastal zone and the further development of the bands of stratocumulus (cloud streets) as the bora becomes weaker and there is a decrease in wind speed, warming of the cold air, and intensification of convection over the open sea.

The analysis of SAR images also allowed us to reveal a number of quantitative characteristics of the phenomenon and determine its scales. For example, the maximum phase of the bora development is reflected on the SAR image from *Radarsat-2* on February 7, 2012; it is shown in Fig. 7 (in the center) (the meteorological station in Novorossiysk recorded a wind speed of 35–36 m/s and gusts up to 40–45 m/s). It is well seen on the image that the hurricane wind was recorded in the coastal region between Anapa and Tuapse (the strongest wind was recorded between Novorossiysk and Gelendzhik). Judging from the length of the wind jets on the SAR image (they are as long as 370 km), the bora spreads over a vast marine area in the northeastern part of the Black Sea up to 350 km long. The wind over the open sea in the region covered by bora reached 25 m/s, decreasing to 15–20 m/s in the direction to the center of the basin. A contrast boundary on this SAR image dividing the light and dark regions near the settlements of Lazarevskoe–Golovinka illustrates the topographic effect: the mountains of the Main Caucasus Ridge, which reach a height of 1000 m and more south of Tuapse, prevent the development of the bora.

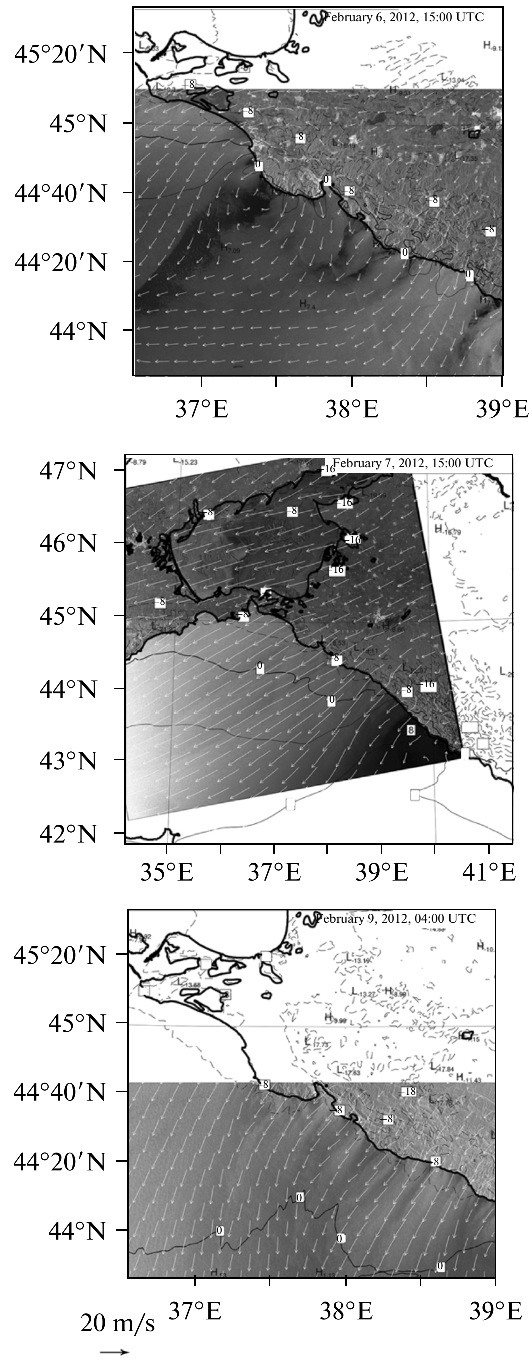

Fig. 7. Matching of the modeling results with the peculiarities of the wind field seen on the SAR images on February 6, 2012, 03:43 UTC (up); February 7, 2012, 15:25 UTC (middle); and February 9, 2012, 15:15 UTC (bottom). © MDA, SCANEX.

COUPLED ANALYSIS OF RADAR IMAGES AND MODELING RESULTS

Since the in situ measurements in the open sea are lacking, the data of remote sensing can be considered as the data for the model verification. A coupled analysis was performed by matching the structures visible

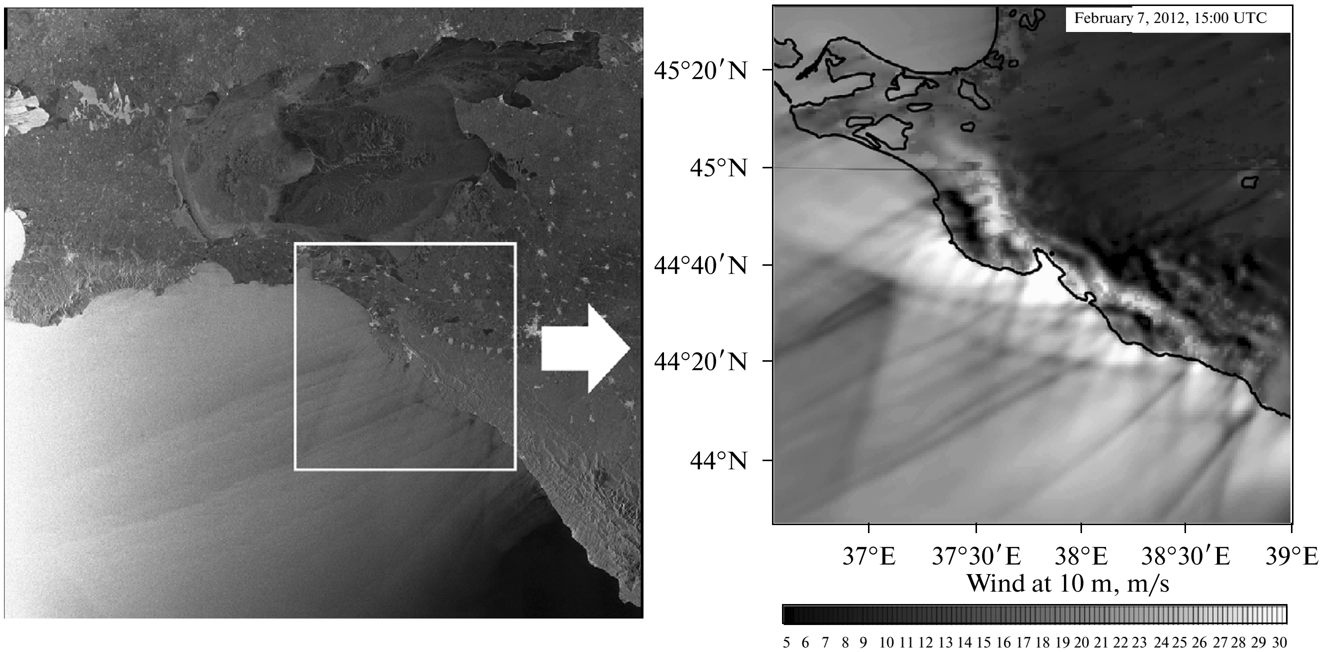

Fig. 8. Wind jets on the SAR image on February 7, 2012, 15:25 UTC, and the jets simulated using modeling of the wind field at a height of 10 m (domain d03).

on the SAR images and modeling results. The results of model wind and temperature fields matching with the brightness of the SAR images acquired by the *Radarsat-1* and *Radarsat-2* satellites on February 6, 7, and 9 are shown in Fig. 7.

The results of matching demonstrate that numerical modeling allows reproducing the Novorossiysk bora, its structure, and individual characteristic details not only in the costal zone of the sea. In the initial stages of the bora development, the model clearly reproduces, the so-called outflow cones (zones of wind divergence) in the coastal zone (Fig. 7, up) or the structures caused purely by the gravitational component of the bora. In the maximum phase, the WRF–ARW reproduces the characteristic structures: the wind jets whose genesis is caused by the interaction between the air flow and costal terrain topography and the type of the bora (Fig. 7, center). In the final stage, the wind jets decrease and deviate to the south under the influence of the background airflow (Fig. 7, bottom). The surface temperature field is shown in Fig. 7 with isotherms (the solid lines are positive and the dashed lines are negative). It is clearly seen that, in result of the bora development, the negative temperatures covered a significant part of the northeastern part of the sea from Feodosia to Tuapse.

The coupled analysis of the signatures seen on the SAR images and results of modeling demonstrated that their structure, extension, and scale coincide. This is clearly seen in Fig. 8, which compares the signatures recorded by the SAR on February 7, 2012, and those reproduced by the model. It is clear that the structures coincide well qualitatively; however, the image demonstrates a more detailed pattern than can be explained by the difference in the resolution of the SAR image (50 m) and the model (1 km). Even more, numerical modeling using the WRF–ARW model confirmed the conclusions in [4, 9], which were made only on the basis of the SAR image analysis that the bora has a characteristic structure and scales, which are reflected at the sea surface in the form of specific patterns. Unlike the classical bora, the anomalously strong bora covered almost the entire northeastern basin of the Black Sea, which wasn't previously suggested by Gutman and Frankl [21] and Burman [1]. In February 2012, it covered the sea basin with an approximate size of 240 × 400 km.

Despite the fact that the topographic effect is seen if any model resolution is applied, we found that the higher the resolution, the clearer the structural detailed elaboration. In addition, the resolution of the terrain topography (30') specified in the model does not allow to hope that the further decrease in the horizontal step of the grid (smaller than 1 km) would increase the modeling quality. Hence, the further study of the wind jets and peculiarities of their numerical reproduction requires a higher resolution of the coastal terrain topography, which is included into the boundary conditions of the WRF model.

CONCLUSIONS

Study of an anomalously strong bora occurred over the northeastern Black Sea was performed using numerical methods. The verification of the method was made on the basis of the SAR imaging of the sea surface. The formation and development of the bora was confirmed by land-based observations, synoptic materials, and satellite images. The manifestations reflected on the satellite images were related to the descending flows of cold air and very strong northeastern wind blowing from the land onto the sea.

An analysis of the modeling results demonstrated the following:

(i) the model reproduced the bora exactly, not any other meteorological phenomenon. This is confirmed by the hurricane values of wind speed characteristic of the bora in a narrow coastal zone, which decrease when the bora reaches the sea surface, and also the relatively small (no more than 1.5 km) vertical scale of the phenomenon. Similar conclusions were reported by Toropov et al. [7] who modeled the January phase, and Efimov and Barabanov [8] who modeled the February phase of this bora;

(ii) numerical modeling allowed us to reproduce the fine structure of the Novorossiysk bora, its individual characteristic details, and the spatio-temporal regime. The spatial pattern of the bora reflected on the three SAR images obtained on February 6, 7, and 9, 2012, coincide qualitatively well with the modeling results. For the first time we demonstrated using modeling that the bora, especially the strong one, has a larger scale than was considered before. The peculiarities of the coastal mountainous topography influence the horizontal structure of the wind field during the Novorossiysk bora: the air flowing down the mountainous valleys gains a significant speed and, reaching the sea surface, forms characteristic patterns (wind jets), which are frequently imaged by the SAR [9]. The phenomenon is frequently well seen from space also in the optical bands by the structures of the cloud cover [4, 9]. Depending on the strength and duration of the phenomenon, the wind jets are first localized in the coastal zone 10–20 km wide and then become longer and completely cover the entire northeastern part of the Black Sea. A simulation of the wind jets seen on the SAR images can be considered as one of the main advantages of the work. This result is especially important because not as much attention has been previously paid to the reproduction of the fine (horizontal and vertical) structure of the Novorossiysk bora over a vast sea basin;

(iii) according to the data of modeling and satellite images, the spatial scale of the anomalous event is 400 km long and 200–240 km wide (over the region from Anapa to Tuapse). A relatively thin atmospheric layer over the sea is characterized by high wind speed from 30–40 m/s in the coastal zone. As the bora spreads over the sea, the wind gradually decreases. In the time of the maximum development of the bora, the wind in the open sea is 20–24 m/s.

(iv) a comparison with land-based measurements demonstrated that the model overestimates wind speed. Nevertheless, wind speed and air temperature obtained from numerical modeling are generally in good agreement with the data of observations at the meteorological stations.

Thus, the results of modeling (reconstructing three-dimensional fields of pressure, wind, temperature, and humidity, as well as their vertical distributions) can be considered successful because we selected a complicated meteorological phenomenon for our experiment in which the description of the whole set of the physical processes is possible only with a high degree of approximation.

Finally, we think that in order to improve the bora forecast and develop approaches to decrease the damage, the existing forecast methods should be supplemented by high resolution modeling and operative analysis of the remote sensing data, including the data of spaceborne SARs. This approach would allow to estimate not only the synoptic situation during the bora, but also obtain a number of its parameters over the open sea, which is difficult to obtain using traditional methods.

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