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Numerical simulation of Novorossiysk bora and related wind waves using the WRF-ARW and SWAN models

P. A. Toropov[1], *S. A. Myslenkov*[2,3], *A. A. Shestakova*[1]

[1]Lomonosov Moscow State University, Faculty of Geography, Department of Meteorology and Climatology, Moscow, Russia

[2]Lomonosov Moscow State University, Faculty of Geography, Department of Oceanology, Moscow, Russia

[3]Hydrometeorological Research Centre of the Russian Federation, Marine forecast division, Moscow, Russia

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Abstract. Bora in Novorossysk (coastal zone of Black Sea) was investigated by using Regional hydrodynamic model WRF-ARW. We have analized bora event which was obtained in January 2012. The experimental model results are compared with observations from regular stations of Hydromet and own data from AMS during the winter expedition Department of Meteorology and Climatology, Faculty of Geography Moscow State University.Performed as a qualitative (visual analysis) and quantitative evaluation of the results (comparison of forecasting and the real average and modal values of wind speed for the selected area). The results of modeling the wind velocity field is used as initial data for the wave model SWAN (Simulating WAves Near shore), be used to calculate wave height over the north-eastern part of the Black Sea.

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Introduction

Bora is a strong cold and gusty wind blowing from the low mountain ranges in the direction of the warm sea. Bora is the result of large-scale flow over the flow of orographic barriers [*Barry*, 2008; *Durran*, 2003a; *Kojevnikov*, 1999; *Markowski and Richardson*, 2010; *Pearce*, 2002; *Smith*, 1987]. Genetically, this phenomenon is akin to the foehn. In some studies, in particular, in [*Barry*, 2008; *Durran*, 2003a; *Reinecke*, 2008], such phenomena are called a "downslope wind." Bora observed, usually in the cold season, from October to April. The phenomenon occurs in the case of advection of cold air into the southern regions of European Russia. Bora is formed in certain synoptic conditions, most often, in two cases. Firstly, on the southern periphery of the cold anticyclone dominated by the north-east wind flow. Secondly, in the rear of the cyclone, which is also dominated by northern or north-easterly winds, or in the area of a cold front.

During bora, temperature for 2–3 hours may decrease by 15°C and the wind velocity may reach 60 m/s. Bora usually lasts 1–2 days, but in some individual cases, it continues for 10 days. The horizontal scale of the phenomenon concerned is several dozens of kilometers, the vertical, few hundred meters (usually no more than 1 km). Based on stations data [*National Climatic Data Center*, 2005], the following conclusions can be made. In Novorossiysk the north-east winds are recurrent the most frequently (about 33%, Figure 1a). In this case bora is observed, on average, 75 days a year. Of these, 20–22 days storm winds (gusts of 20–25 m s^{-1}) blow, and 5–7 days a year, a strong storm (gusts 26–32 m s^{-1} occurs). Approximately 1–2 days a year there is a hurricane (over 33 m s^{-1}) (Figure 1b). Once in 10 years in Novorossiysk a catastrophic bora blows, characterized by an average wind speeds of 35–40 m s^{-1} and gusts of 60–65 m s^{-1}. In this case, "bora" results in significant destructions and casualties, and the operation of the seaport is almost completely paralyzed.

The phenomena described occurs in other regions ("novozemelskaya bora", "north of Baku", "Baikal Barguzine", "Adriatic bora", "Mistral (French Riviera)". The hydrodynamic model of circulation of the foehn and downslope wind was considered in [*Gill*, 1986], while in Russia a respective mathematical model was proposed in [*Gutman and Frankl*, 1960]. However, sparse and patchy data available on the three-dimensional structure of falling circulation and

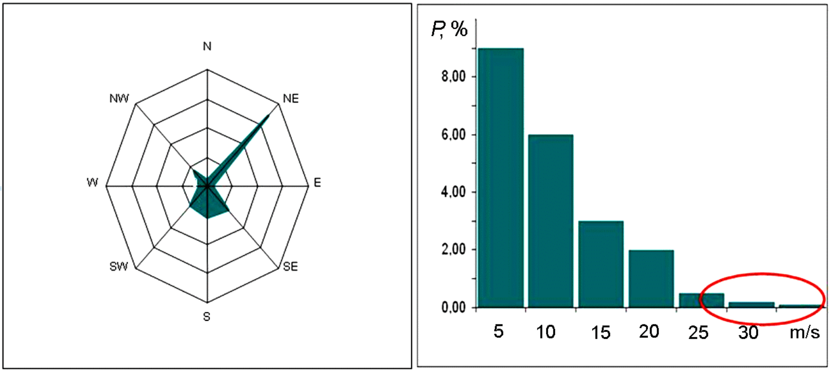

Figure 1. The mean annual wind characteristics in Novorossiysk: a) the probability (%) of different wind directions, b) the probability (%) of some particular wind speeds during "bora".

foehn is insufficient to develope a theory. The active development of remote measurements allowed us to obtain a large amount of data on the 3-D structure of downslope winds. Currently, the most Adriatic bora, and similar events in the USA [*Alpers et al.*, 2010, 2011; *Durran*, 2003a; *Gohm and Mayr*, 2005; *Jiang et al.*, 2005; *Smith*, 1987] have been studied in greatest detail. The resulting information provided the basis for the theory of downslope winds which is actively developing in recent decades [*Durran*, 2003a, 2003b]. There are two hypotheses of the genesis of the bora: hydraulic and wave [*Barry*,

2008; *Durran*, 2003a]. The former describes the bora like a katabatic wind, or as a "supercritical flow" that occurs in a thin layer bounded by a strong temperature inversion top. The second hypothesis describes bora as a nonlinear wave process [*Nappo*, 2002; *Reinecke*, 2008]. The modern study of the "downslope wind" is a synthesis of observation data [*Alpers et al.*, 2010; *Belusic et al.*, 2004; *Ivanov*, 2008; http://www.comet.ucar.edu/class/comap/06_Aug2_1999/downslope_wind_lab/bogar/downslope.html], the results of the analytical solution of the flow of orographic obstacles [*Durran*, 2003a, 2003b; *Gill*, 1986; *Gutman and Frankl*, 1960; *Klemph and Lilly*, 1978; *Kojevnikov*, 1999; *Markowski and Richardson*, 2010], as well as numerical simulations [*Klemph and Lilly*, 1978; *Koch et al.*, 2006; *Nappo*, 2002; http://www.comet.ucar.edu/class/comap/06_Aug2_1999/downslope_wind_lab/bogar/downslope.html].
The modern study of the "downslope wind" is a synthesis of measurement data [*Alpers et al.*, 2010, 2011; *Belusic et al.*, 2004; *Grisogono and Belusic*, 2008; *Ivanov*, 2008; *Jiang and Doyle*, 2005], the results of the analytical solutions of equations describing the flow of orographic barriers, and also numerical simulations [*Jiang et al.*, 2005; *Klemph and Lilly*,

1978; *Koch et al.*, 2006; *Nappo*, 2002]. These results are suggestive that the main physical mechanism of bora is the fall of downwind waves.

The most effective method for studying and forecasting downslope wind is a numerical simulation. It provides a high spatial and temporal resolution forecast fields. The present study uses the regional hydrodynamic model WRF-ARW (version 3) [http://www.mmm.ucar.edu/wrf] as a diagnostic tool. The experimental results are compared with observations made by a network of stations Federal Service of Russia for Hydrometeorology and Monitoring of the Environment (hereinafter referred to as FSRHME) [*National Climatic Data Center*, 2005], and also during the winter expedition of the Department of Meteorology and Climatology, Geography Faculty of Moscow State University.

Both qualitative (visual analysis) and quantitative evaluation of the results (comparison of forecasting and the real average and modal values of wind speed for the selected area) was performed. The results of simulating the wind velocity field are used as initial data for the wave model SWAN (Simulating Waves Near shore) [*SWAN Technical Documentation*, 2007], be used to calculate wave height over the north-eastern part of the

Black Sea. By choosing the method for the numerical forecast of the territory with complicated topography, along with errors in the initial data, we have to allow for the inaccurate description of the characteristics of the terrain, shoreline and land use types in the boundary conditions of the model. These inaccuracies can lead to significant errors in the forecast.

Description of Numerical Experiments With the WRF Model and Real Data

In this work we analyze the results of the numerical experiment on 26.01.2012 00:00 to 27.01.2012 00:00. During this period there was a strong anticyclonic bora and also during this period the most complete observations were performed. The experiments were carried out in the pattern of a four-dimensional assimilation. Used as initial data were the results of the analysis FNL (NCEP/NCAR), which were assimilated every 6 hours. The boundaries of the computational domain are as follows: 44–45 N and 37–39 E. The spatial step was 2 km, and the number of vertical levels of 27 (the upper limit at 50 hPa). In accordance with our objective we used nonhydrostatic version of the model WRF-ARW.

Integration over time was carried out for 72 hours.

As already mentioned, the WRF-ARW model supports a large number of parameterizations that allows selecting the configuration that best matches the case under stud [http://www.mmm.ucar.edu/wrf].

1. Non-hydrostatic version;

2. The number of vertical levels – 27 (the top level is a 50 hPa);

3. Parameterization of microphysical processes in clouds under the Thompson scheme (considering s into account the content in the air like a cloud of water droplets and ice particles and snow);

4. Parametrization of shortwave radiation fluxes under the RRTM scheme (Rapid Radiation Transfer Model, predicted an influx of shortwave radiation, taking into account the atmospheric gases);

5. Parametrization of longwave radiation fluxes at the Goddard scheme (accounts for the effect of clouds and ozone);

6. Parametrization of turbulence in the surface layer in accordance with the theories of Monin-Obukhov and Zilitinkevich;

7. Land surface parametrization scheme of NCEP/NCAR (takes into account temperature and soil moisture on 4 levels, as well as snow cover and frozen soil);

8. Parametrization of the planetary boundary layer scheme Mellor-Yamada-Zhanzhina (calculates the turbulent kinetic energy and vertical mixing).

Measurements include (Figure 2):

1. The results of measurements of speed, gusts and wind direction at a height of 10 meters, made on network of weather stations Novorossiysk sea port (FSRHME), the time discreteness in these 2 minutes, the number of observation points – 5;

2. The results of measurements of basic meteorological variables on network stations Roshydromet (Novorossiysk, Gelendzhik, Tuapse, Anapa, Dzhubga, Krymsk), temporal discreteness 3:00;

3. Data forwarding observations of the Department of Meteorology, Moscow State University, the results of measurements by means of automatic weather stations Davis (USA), the temporal discreteness of the measurements – 5 minutes. The similar data

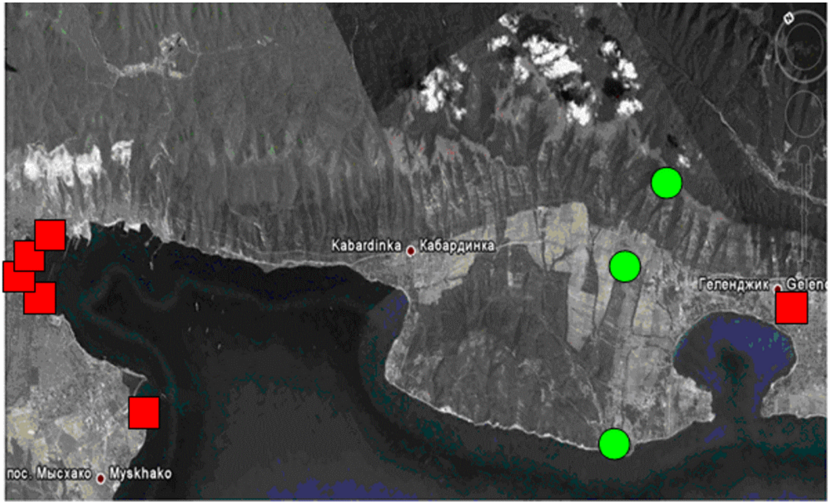

Figure 2. The region with the highest wind speeds during bora (Tsemess Bay, Gelendzhik Bay) part of the computational domain model WRF-ARW; points on the map: green circles – points of automatic weather observations in the expeditions of Geography Faculty of Moscow State University, red squares – network of weather stations of FSRHME.

for summer have been described in [*Surkova et al.*, 2006]

Results of Numerical Simulation

Figure 3 shows the results of numerical experiment. It should be noted that the model reproduces exactly

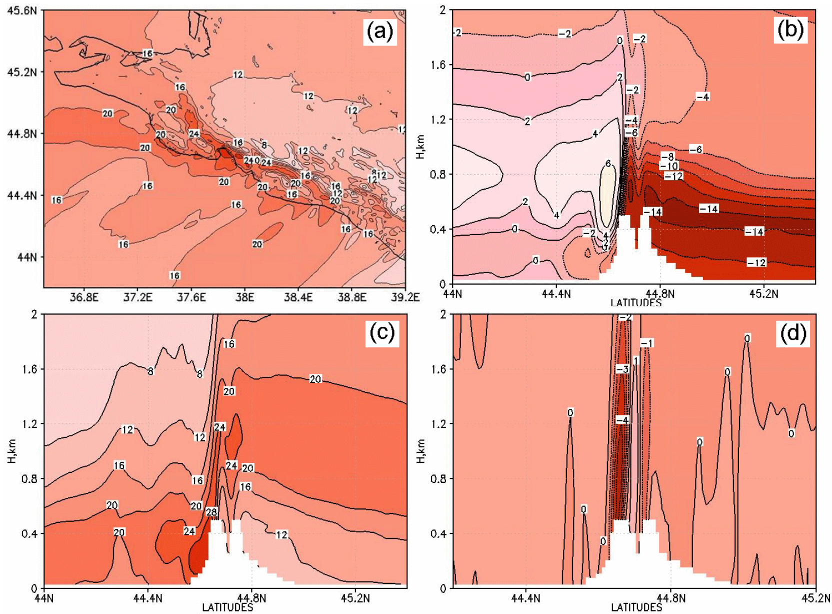

Figure 3. The results of the numerical prediction of Novorossiysk bora daily averaging of 26.01.2012: a) the field of wind speed solid black line – the coastline), and b) vertical section of temperature along the 38th parallel (light area with two peaks designates the spurs of the Great Caucasus), c) vertical section wind speed, d) section of the vertical component of wind velocity.

the Novorossiysk bora, and not any other phenomenon. This is evidenced by the following facts.

The vertical scale of the phenomenon is about 1 km. This thin layer is characterized by low temperature (Figure 3b), and high wind speeds (Figure 3c).

Well seen an increase in wind speed on the downwind slope. In particular, the analytical solutions of the Bernoulli equation follows that the wind speed at the foot of the mountain should be twice as high at its apex [*Barry*, 2008; *Gill*, 1986; *Kojevnikov*, 1999]. These theoretical findings are consistent with the simulation results: Figure 4c shows clearly that the wind speed at the bottom of the slope in the 1.8–2.2 times higher than over the top of the ridge Markotkhsky. It is possible, however, that strong winds may be associated with the fall of orographic waves. This effect is noted as one of the physical mechanisms of cold foehn [*Durran*, 2003a; *Nappo*, 2002]. Correctly simulated are the horizontal scale of the phenomenon (Figure 3a) and its spatial structure. Maximum wind speed reached at the foot of the ridge Markotkhsky, and in the coastal zone, especially in Tsemess bay. Here, even the average daily wind speed was 20–25 m s^{-1}. This agrees well with the field data obtained by Alpers [*Alpers et al.*, 2010, 2011]. As the distance from the coastline bora weakens, and at a distance of 100 km of coastline average daily wind speed exceeds 15 m s^{-1}. On the windward side of ridges, that is, in the northern regions, as well as in the east, where the height of the ridges of the Caucasus has more than 1000 meters the average wind speed is 8–13 m s^{-1} (Figure 3a). There are strong positive values of the vertical component of wind velocity on the windward side of the ridge and negative on the downwind (Figure 3d), which also corresponds to the foehn (wind flow up the windward side of the slope and descends on the downwind). In addition, (Figure 3a) shows some visible linear structure, characterized by high velocity winds, interspersed with areas of lower velocities. By the end of the physical mechanism of formation of such structures is not clear. There is reason to assume that this increased hydraulic flow in the crevices and canyons. In the mouths of the slots and bays the wind speed are higher than it observed before the high parts of the ridges and high banks. Olso, the same kind of structure was revealed by the results of satellite measurements [*Alpers et al.*, 2010, 2011; *Ivanov*, 2008].

Described below are the results of the estimate of the accuracy of simulating the wind speed. Despite the fact that the of bora simulated model is successful, the error at specific points in the computational domain may be quite significant. In Figure 4a presents the empirical distribution function of the error model (compared with the observational data described above). The maximum error values reaches 15 m s^{-1}. There

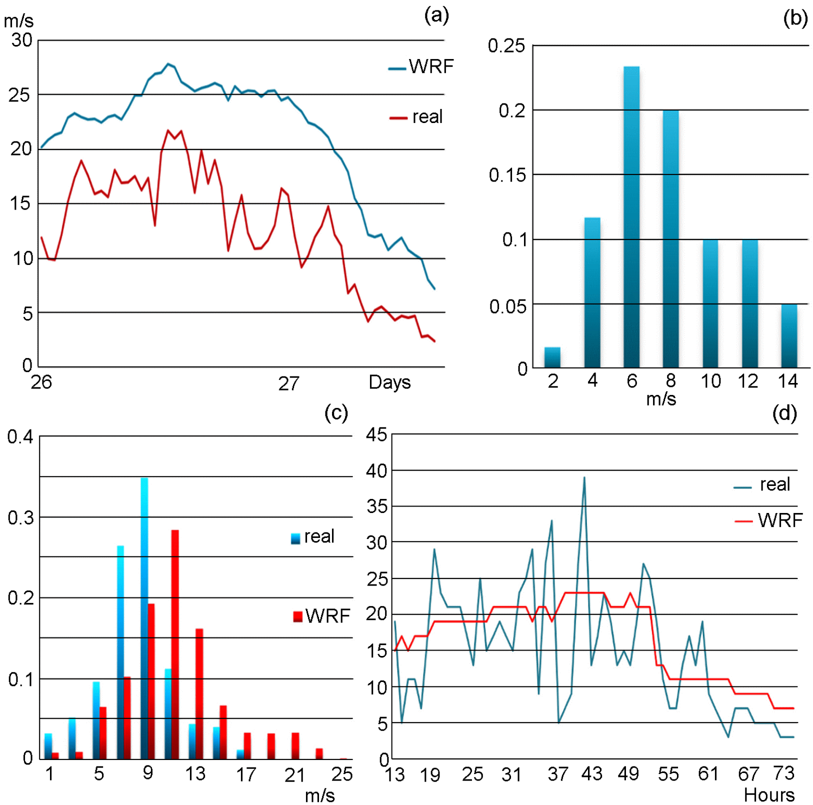

Figure 4. Some results of the statistical evaluation of forecast accuracy: a) the average course of forecast (blue line) and observed (red line) wind speed, averaged over the "field test" (on the abscissa – days (26–28.01.2012), the ordinate values of wind velocities); b) the empirical distribution function of the forecast errors (on the horizontal axis – the interval in m/s); c) the empirical distribution function forecast (red bars) and actual (blue bars) wind speeds to

"test area" (along the horizontal axis – the intervals in m/s), d) the status of the modal forecast of wind speed (red line) and the actual value of the modal (blue line) for the "test area" (along the horizontal axis – hours forecast).

have also been identified modal forecast values of wind speed within the computational domain and modal values estimated from the observed data.

The modal values were determined as follows: the selection of a rectangular area, which includes n nodes, which are written forward-looking information. According to these data was based empirical distribution function and fashion stood out – the most repeated value. This operation is repeated for all time slices. To select a mode in the observed data are used by field data obtained from the points of the stations in the nodes of a regular grid by Kressmann's objective analysis.

WRF-ARW model systematically overestimates the wind speed, and error fashion amounts to 6 m s^{-1} (Figure 4b). The maximum values of errors at some points reaches 15 m s^{-1}. However, the correlation coefficient between the two graphs is quite high: 0.7. This is due to the fact that this problem is a 4-D assimilation – updated every 6 hours initial data FNL-analysis

However, the accuracy of the modal forecast of wind speed in space is quite high. Thus, for the actual data the mode corresponds to the wind speed of 9 m s^{-1}, while according to the WRF-ARW data, 11 m s^{-1}. Apparently, a probabilistic approach to forecasting is more correct. The temporal evolution of the modal forecast is also well reproduced: WRF results look like the average values of the actual modes in space.

Analysis of the Results of Calculation of Wind Waves

The results of wind speed and direction calculations using the WRF-ARW model were used as initial data for the model SWAN (Simulating WAves Near shore) [*SWAN Technical Documentation*, 2007], which provides adequate information about sea wave's parameters. The model successfully simulates the parameters of wind waves in the open sea and coastal areas [*Efimov and Komarovskaya*, 2009; *Efimov et al.*, 2000; *Willis et al.*, 2010]. It is important that the SWAN model successfully simulates sea waves in the shelf zone. Numerical experiments were performed in the Numerical Center of Lomonosov Moscow State University in supercomputer "Lomonosov" MSU. Calculations were performed in a parallel mode. Quantitative estimates of the accuracy of model wave height were carried out by the authors. Estimates of the summer storms on the Black Sea in June 2010 were made. The results of SWAN simulation were compared with wave sensor LogaLevel 5 Hz, which was installed on the long pier of the P. P. Shirshov Institute of Oceanology RAS in Blue Bay near the Novorossiysk. Errors for significant wave height did not exceed 0.2 m and qualitative comparison with satellite data were also made. Estimates of sea waves from the north-eastern shores of the Black Sea had been carried out before [*Efimov and Komarovskaya*, 2009; *Efimov et al.*, 2000]. However, as an input to the wind low-resolution reanalysis was commonly used. Naturally, such data do not describe the complex spatial structure of wind speed during bora. The experiments whose results are discussed in [*Efimov and Komarovskaya*, 2009; *Efimov et al.*, 2000] have been mainly focused on the study of regime characteristics of sea waves.

We used SWAN for modeling of sea waves in coastal zone during a heavy bora. The boundaries of the computational domain were 37–39°E, 44–45°N. The spatial step was 0.02°and 0.01°latitude by longitude. The integration time is 12 hours, with wind data were given

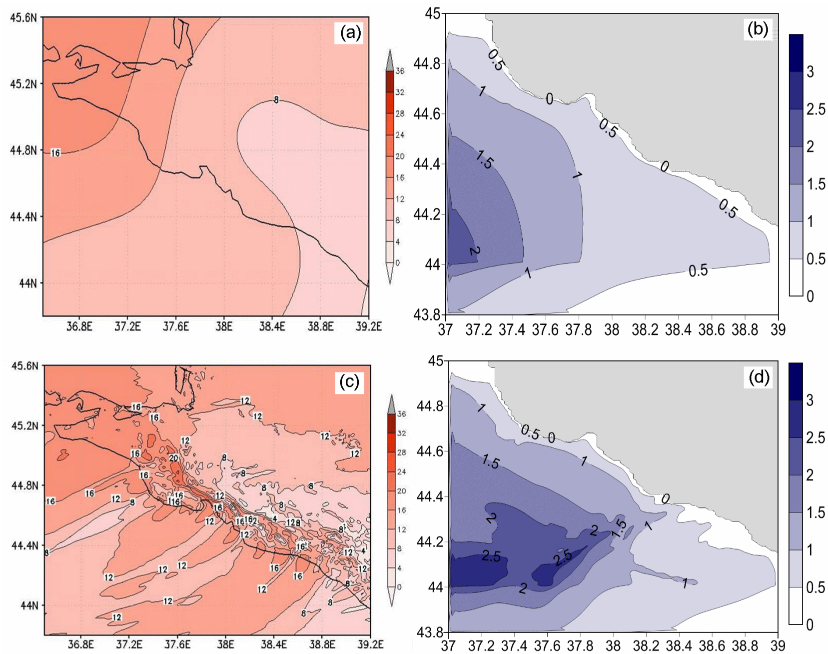

Figure 5. Wind speed averaged over 01/26/2012 According to a) the analysis of NCEP/NCAR 1 × 1, c) model WRF-ARW; and their corresponding significant wave height (b, d), calculated by the model SWAN.

hourly. In order to assess the need for mesoscale atmospheric models such as sphere WRF-ARW, was carried out two experiments. The first type of wind field used FNL NCEP/NCAR (1 × 1 degrees). In the second experiment were used the results of WRF-ARW.

The estimated results are shown in Figure 5. It is clear that in both cases (with the initial data FNL, and the initial data WRF-ARW) a maximum wave height is observed in the 50–100 km from the coastline, which corresponds to the scale of dispersal of sea waves. Square area with a maximum sea waves, as well as their position in space at approximately the same. Thus, the region of maximum sea waves in both cases are in the western half of the computational domain. However, the quantitative differences between the experimental results are very high. If the initial data of NCEP/NCAR, the maximum wave height is 1.5–2 meters, whereas according to WRF-ARW 2–2.5 meters. In addition, the area of dangerous sea waves (more than 1 meter) from WRF-ARW approximately one and a half times higher than on the basis of FNL. Unfortunately, it is impossible to perform a detailed quantitative assessment of SWAN model results due to the lack of reliable data monitoring swell conditions. Because LogaLevel 5 Hz wave recorder used does not make sense, since the device is installed on the long pier, it is useful for fixing the sea waves in the tide winds south and west compass points. In case bora events high waves are forming in 5–10 km from the coast. Therefore, the wave recorder data do not allow estimating the wave height during bora. Satellite data can be used only qualitatively as their accuracy today is not high. Nevertheless, satellite data are used to assess the impact of Novorossiysk bora on the sea surface. In work [*Alpers et al.*, 2010], based on image analysis of visible and infrared satellite NOAA and Terra/Aqua, and microwave scatterometer data Quikscat and synthetic aperture radar satellites ERS-2 and Envisat restored interesting features of the spatial hetrogeneity of sea waves in the course of bora. It is shown that the effect of a strong north-easterly wind on the sea surface leads to the formation of characteristic bands in images of the cosmos in visible, infrared and microwave bands. Similar structures appeared in the field of wind speed according to the results of WRF, and to a lesser extent, the results of the model SWAN. The visible, infrared and microwave bands show that the effect of a strong north-easterly wind on the sea surface during bora leads to the formation of characteristic linear structures. Similar structures appeared in the field of wind speed according to the WRF results, and to a lesser extent, according to the SWAN.

Conclusion

This paper presents the results of coupled numerical experiments with using WRF-ARW and SWAN models. We conclude that WRF-ARW model reproduces exactly the Novorossiysk bora, and not some other phenomenon. This is evidenced by the exist strong air current in the underinversion layer, an increase in the wind speed in the coastal zone and its attenuation offshore, and the gravity waves formed after flowing around the ridges. It is shown that WRF-ARW model well reproduce Novorossiysk bora. Similar studies have been made by other authors, but useful numerical simulation in relation to the Novorossiysk bora has never been made before. Nevertheless, quantitative evaluations demonstrate that simulation errors are high: 5–8 m s^{-1}. This is due to the several facts as follows: 1) estimates of the results was based on the records by a few stations only, then spatial model resolution is about 2 km and it not correct to compare station data with the average 2 km mesh data; 2) bora on 25–26 January 2012 was very strong with wind velocities 20–25 s^{-1} and gusts attaining 40 s^{-1}, which means that the errors around 5 s^{-1} is relatively small. Accuracy of the modal forecast of wind speed in space is quite high. For the actual data the mode corresponds to the wind speed of 9 s^{-1}, while according to the WRF-ARW data, 11 s^{-1}. We can see that probabilistic approach to forecasting of bora is more correct.

It is important engineering results when we used the SWAN model with initial data from WRF model for calculating wave parameters during bora. It is shown that using WRF initial data provide more correct significant wave field. But we can not estimate model errors of wave height because the real wave measurements are absence.

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