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Synoptic Conditions for the Novorossiysk Bora Formation in Modern Climate

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Abstract—The authors have developed a classification of the conditions for the Novorossiysk bora formation based on the data on the synoptic conditions preceding the phenomenon and contributing to its development. The Azores, North Atlantic, Siberian, and Arctic classes of the Novorossiysk bora have been identified. The authors also has developed a synoptic and climatic method for classifying the cases of the Novorossiysk bora, which consists in transition from analyzing typical schemes of synoptic processes to analyzing directly the fields of surface pressure and geopotential height that characterize each synoptic class of the Novorossiysk bora. The use of this method made it possible to use the data of modeling pressure fields, which are simulated by models much better than wind fields, for the forecast of the phenomenon. Due to this method, it became possible not only to detect cases of the Novorossiysk bora, but also to identify their classes for a long period from 1979 to the present and also to make a forecast of the frequency of the Novorossiysk bora in the 21st century. It has been found that the number of the bora events of the Siberian class, against which the bora of the frontal and monsoon types belonging to the most extreme ones in terms of their meteorological characteristics and consequences is more often observed, will increase in the periods of climate warming.

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INTRODUCTION

The Novorossiysk bora is a strong gusty wind directed down mountain slopes toward the sea in the area from Anapa to Tuapse and causing a fast and sharp cooling in winter. In Novorossiysk, the bora is manifested most strongly: the average annual number of days with the bora is above 30–40, and their maximum frequency is registered in November–March [6, 8–10]. The wind gusts accompanying the bora can exceed 40–50 m/s. During the bora, a fast air temperature drop for several hours is often accompanied by the formation of heavy glaze on coastal facilities and ships, sometimes leading to their demolition and flooding and to a significant economic damage for the region. The combination of a strong and durable cold wind, high air humidity, and a dramatic temperature drop creates extremely uncomfortable conditions for the population and the environment, sometimes leading to irreversible loss. In view of this, despite the local nature of the phenomenon, the exploration of the bora is still relevant from both fundamental and applied points of view, making it possible to reveal the patterns of the long-term dynamics of the frequency of high wind speeds typical of the bora and to get closer to understanding the role of climate change in these processes. The climate forecast of the Novorossiysk bora is also of practical importance, since the information

[†] Deceased.

about the bora obtained from the forecast will allow assessing the wind impacts and consequences of the bora and, if necessary, taking early measures to mitigate a potential damage.

The exploration of the Novorossiysk bora became more active in the late 19th century. For example, based on analyzing the data for 1891–1900, N.A. Korostelev revealed an important pattern: the bora happens "…when the air pressure in the country rises quickly, forming the barometric maximum, and, as a result, there is a strong pressure fall towards the sea, where the conditions favorable for the formation of barometric minima are constantly present" [7]. This means that he was the first to conclude that the bora is mainly formed under a certain type of large-scale circulation in the presence of local factors that are favorable for its development.

A detailed and frequently used genetic classification of the Novorossiysk bora was presented in the papers by A.M. Gusev et al. [8] based on the observations in 1891–1900 and 1952–1954. According to this classification, four types of the Novorossiysk bora are distinguished: downslope, airmass, monsoon, and frontal one. For explicit consideration of large-scale atmospheric processes and their type, E.K. Semenov et al. [10] developed a synoptic classification that does not contradict the genetic one but complements it in terms of the features of general atmospheric circulation and mutual position of pressure systems in the surface and lower atmospheric layers. According to the classification of E.K. Semenov et al., the following synoptic types of the Novorossiysk bora are distinguished: the Azores, North Atlantic, Siberian, and Arctic ones. For identifying the types of the Novorossiysk bora, other approaches using the methods of cluster analysis applied to surface pressure fields were also used. For example, V.V. Efimov et al. [6] distinguished two types of the surface pressure field configuration for the cases of the Novorossiysk bora. Other authors basically paid attention to case studies and their modeling in limited areas [12, 13].

The novelty of the present paper consists in revealing a connection of synoptic conditions and the configuration of a large-scale pressure field with the Novorossiysk bora occurrence for a long period, which makes it possible to estimate the trends in its frequency. The ten-year period 1998–2007 was analyzed to produce the synoptic classification of the Novorossiysk bora in [10], while the long-term analysis in the present study used the ERA-Interim reanalysis data on surface pressure and 850 hPa geopotential height over the cold season (October–April) for 1979–2015.

The objective of the present study is to investigate the average long-term features characterizing the frequency of different types of the Novorossiysk bora events according to the synoptic classification against the background of modern and projected climate change using observations and modeling based on typing of large-scale atmospheric processes.

DATA AND METHODS

Estimation of the probability of a severe weather event and investigation of its future dynamics requires knowledge of physical conditions that are favorable for the development of this phenomenon, its characteristic structure and life cycle, as well as the local features affecting its evolution. This is particularly valid for events whose mathematical modeling is complicated at the current stage of scientific development. In other words, "it is necessary to develop a conceptual model of a phenomenon, the knowledge of which gives a forecaster confidence in a need for introducing certain changes in forecast products of the model" [2].

The uniqueness of the synoptic classification consists in a comprehensive approach used to understand the essence of large-scale atmospheric processes that contribute to the formation of the Novorossiysk bora. The synoptic classification continues and strengthens in details the genetic classification by A.M. Gusev et al. [8].

The following data were used for a long-term synoptic systematization of the Novorossiysk bora events in 1979–2015: (1) the synoptic classification of the Novorossiysk bora events for the cold season (November–April) [10] for 1998–2007 (95 cases) according to surface, radiosonde, satellite, and radar observations; (2) the results of the ERA-Interim global reanalysis; (3) the numerical experiments with the WRF-ARW mesoscale model that were held during the study for individual cases of the Novorossiysk bora [4–6, 8, 13–15]. The set of diverse data made it possible to proceed to a conceptual synoptic model of the Novorossiysk bora [2, 10].

Despite the fact that according to the Beaufort scale, a storm wind is a wind whose speed at a height of 10 m above the ground exceeds 20.8 m/s, the present study considers a wind with a speed of 10 m/s and more as the Novorossiysk bora event (with the compliance of other characteristics). This threshold value was obtained in [10], where the quantitative criteria for identification of the bora were developed: pressure tendency, surface pressure, air temperature, wind speed, and precipitation. Each episode of the bora during

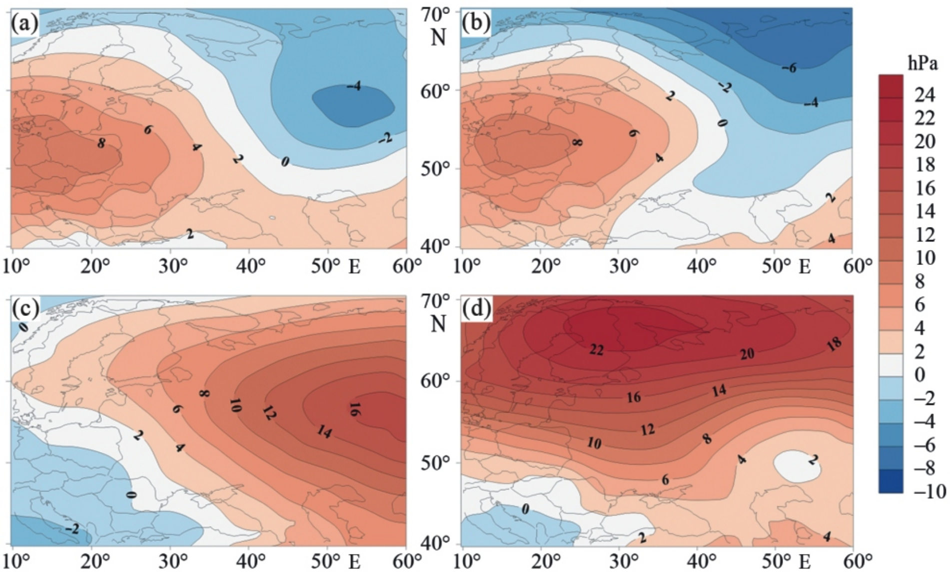

Fig. 1. The composite maps of the surface pressure deviation from the multiyear means (1979–2015) for different classes of the Novorossiysk bora: (a) the Azores, (b) North Atlantic, (c) Siberian, and (d) Arctic classes.

1998–2007 was classified at first according to the genetic classification [8] and then according to the synoptic classification based on the quantitative criteria proposed in [10].

The ERA-Interim reanalysis data [16] on the sea-level pressure and 850 hPa geopotential height in the cold season (October–April) for 1979–2015 for the territory of 40 –70 N, 10 –60 E with a horizontal spatial resolution of 0.75 0.75 were used to get an idea of long-term variations in the frequency of the Novorossiysk bora. The time period from 1998 to 2007 was analyzed separately since it corresponded to the calendar of the Novorossiysk bora from [10], which included 95 cases of the bora.

Based on the 36-year sample obtained, the mean values of both parameters (sea-level pressure and 850 hPa geopotential height) were computed. Additionally, for greater clarity, the deviations from the multiyear mean (1981–2015) pressure and geopotential height were calculated.

The INMCM 4 Earth climate system model developed at the Marchuk Institute of Numerical Mathematics of the Russian Academy of Sciences [3] was used for the climate forecast of the Novorossiysk bora for 2016–2100. The frequency of different synoptic classes of the Novorossiysk bora was calculated based on the results of the numerical experiments within the Coupled Model Intercomparison Project, Phase 5 (CMIP5). The advantage of the INMCM 4 model is that it is one of the best CMIP5 ensemble models in simulating the Northern Hemisphere air pressure field. The calculations were performed for the results of the CMIP5 experiment [18] under the RCP8.5 scenario [17]. The air pressure field for each “model day” was compared with the composite field for a certain synoptic class of the bora. For the comparison, the spatial correlation of these two fields was estimated. If the correlation coefficient was above 0.95, it was assumed that the spatial structure of the pressure field is favorable for the bora formation on that day. The choice of the value of 0.95 as an indicator of the similarity of fields demonstrated a good consistency of the frequency of the bora events according to the reanalysis and the model.

RESULTS AND DISCUSSION

The results have been obtained based on the synoptic classification of the Novorossiysk bora developed by E.K. Semenov et al. applied for a longer (as compared to [10]) time period 1979–2015. This gives a basis for a greater insight into long-term climatic pattern of synoptic features in the development of the Novorossiysk bora.

The analysis of the computed composite fields of sea-level pressure for the types distinguished in the synoptic classification has shown that the Azores type is characterized by the presence of an elongated sublatitudinal high-pressure area over the central part of Europe (about 1025 hPa in the center). The pressure difference with Novorossiysk, which is located in a col in this case, is about 6–8 hPa. Over northern European Russia and Scandinavia, a vast low-pressure zone is observed. On the map of the surface pressure deviations from the long-term means for the chosen territory (Fig. 1a), the positive maximum is marked over Germany and the Czech Republic.

A similar pattern is observed in the distribution of the averaged surface pressure field that forms the Novorossiysk bora of the North Atlantic type. In this case, the high-pressure zone is also situated over the center of Europe, but the pressure at the center is lower than for the Azores class, and the pressure deviations from the multiyear means are smaller (Fig. 1b).

In case of the bora of the Siberian class, the center of a large anticyclone is on average located over the southern part of the Ural Mountains (with the pressure above 1034 hPa), and its ridge occupies almost entire European Russia. This situation is also preserved at the level of 850 hPa. The main difference from the first two classes is the fact that positive anomalies in the east of the analyzed territory are almost two times greater (Fig. 1c).

The anticyclone accompanying the Novorossiysk bora of the Arctic class is situated over the Barents and Kara seas. This is the most powerful anticyclone. The positive pressure anomalies occupy more than a half of the study area with the maxima in the north (Fig. 1d).

The use of the synoptic-climatic approach allowed obtaining new data on the frequency of the Novorossiysk bora as a whole and of each of its types. It should be noted that according to the reanalysis, the number of cases of the Siberian bora increased (almost two times!) in 2008–2015 as compared to 1998–2007, while the number of the bora events of the Azores and North Atlantic classes decreased, although the total number of the Novorossiysk bora events almost did not change (a figure is not presented).

Earlier [10], the comparison of the synoptic and genetic [8] classifications revealed that the strongest bora according to the genetic classification (the bora of the frontal and monsoon types [8]) is most often observed for the Siberian or Arctic classes of the synoptic classification. This complements the results presented in [6], where the prevalence of the frontal bora in the cold season is also noted.

The frontal type of the bora [10] is characterized by high values of the pressure tendency (to –4 hPa per past three hours), a low pressure at the observation point (not more than 1015 hPa), a dramatic temperature drop, and precipitation. A wind speed for this type of the bora can reach 20–35 m/s. The frontal bora is never localized only in Novorossiysk. It always affects a significant part of the coast and can continue up to ten days. The monsoon type of the bora is accompanied by a significant horizontal temperature contrast, which increases in the Black Sea area, the temperature drops dramatically (to –10…–20 C), and the wind speed reaches 40 m/s! The monsoon bora can last from three to eleven days, i.e., this type of the bora is most durable [10].

Let us consider one of the most striking cases of the bora for the 21st century as an example of the structure of a large-scale pressure field during the Novorossiysk bora and of the evolution of such structure. Such synoptic approach makes it possible to understand the characteristic features of a large-scale pressure field before, during, and after the bora, which can help in forecasting the phenomenon.

In the winter of 2012, the frontal Novorossiysk bora was observed against the synoptic conditions of the Siberian class. This episode was studied and simulated by different research groups [1, 6, 12]. During this bora, severe frosts in southern European Russia on the Black Sea coast were accompanied by strengthening of northeastern wind during the period from January 25 to February 10. Sea smoke and rapid icing of ships occurred in the Krasnodar krai (Kerch Strait) at wind speeds up to 26 m/s on January 27–28 and in Novorossiysk at hurricane winds to 38 m/s on January 27. On February 7–8, wind speeds reached 26–29 m/s in the Kerch Strait, 33–44 m/s in Novorossiysk, and 32–39 m/s in Gelendzhik. Hurricane and close wind speeds led to a large-scale power failure, damage to roofs and buildings, falling of trees, so the emergency regime was introduced (https://meteoinfo.ru/novosti/8520-28012014).

The formation of such strong bora in January 2012 was associated with a large-scale transformation of atmospheric circulation, which led to an abnormal warm weather in the Russian Arctic and an extremely cold weather in Southern Europe (this situation was analyzed in detail in [11]).

This large-scale transformation was caused by the movement of the ridge of the Siberian High to the southern Urals and the Lower Volga, where it had formed an independent center with a maximum pressure of 1055–1058 hPa by mid-January 2018. As a result, favorable conditions were formed for an intense advection of warm air from Western Europe and the Atlantic Ocean to the central Arctic Basin. The eastern transport of the cold air from Siberia and Northern Kazakhstan intensified along the southern periphery of this anticyclone, which finally led to formation of high cold cyclones over the northern Caspian Sea.

At the same time, another high cold cyclone, which enhanced still more the advection of continental air from Siberia to the Black Sea and the Balkans, was formed over Turkey. This is a vivid example of the formation of the frontal Novorossiysk bora against the background of the synoptic processes of the Siberian class.

As mentioned above, the INMCM 4 model results were used to produce the climate forecast of the Novorossiysk bora frequency in the 21st century both for the total number of episodes and with their division to synoptic types. The sea-level pressure fields, which are quite accurately simulated by climate models, were used to detect the bora events. At the preliminary stage, the INMCM 4 air pressure fields that corresponded to the synoptic classes favorable for the Novorossiysk bora formation were identified [10]. The verification has shown that the spatial configuration of the pressure field can be used as a sign of the risk of the Novorossiysk bora development.

The following conclusions can be made from the results of the stage of climate forecast. During the warming in the 21st century, the total number of the Novorossiysk bora events is expected to increase (by 9% as compared to 1979–2015). More detailed analysis for 20-year periods has shown that the most noticeable increase in the total number of the Novorossiysk bora events (26%) is expected in 2021–2040 and 2041–2060 (14%), and the return to the modern mean values will occur in the late 21st century. Model simulations of individual types of synoptic conditions under which the Novorossiysk bora is formed demonstrate that the greatest changes (by 50%) are associated with the North Atlantic type, the frequency of the Azores type is decreasing insignificantly (by 7%), the one for the Arctic type remains close to modern one, and the frequency of the Siberian type is increasing by 18%. This is associated with the fact that against the background of climate warming, the greatest changes are observed in the Arctic (a temperature rise), which contributes to the strengthening of anticyclones in the north and northeast of European Russia.

CONCLUSIONS

The use of the synoptic-climatic method made it possible not only to detect the cases of the Novorossiysk bora but also to determine their synoptic types for the period from 1979 to 2015, to use the data of modeling pressure fields until the end of the 21st century for a climatic long-term forecast of the frequency of the Novorossiysk bora events, and to produce the forecast of the Novorossiysk bora frequency in the 21st century as a whole and for individual synoptic types.

It has been found that in the period of climate warming in the 21st century, against an increase in the average number of the bora episodes by 9%, the number of the episodes of the North Atlantic type will increase (by 50%), the frequency of the bora events of the Azores type will decrease (by 7%), and the frequency of the bora of the Siberian type, during which the cases of the frontal and monsoon bora, which are the most extreme in terms of their meteorological characteristics and consequences, are most often observed, will increase (by 18%).

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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