Spatial-Temporal Structure of Bora in Yalta

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Using a numerical model of the regional atmospheric circulation *WRF-ARW*, evolution of a strong bora in winter, 2013 (December, 2–3) near the Southern coast of the Crimea was reproduced. The features of the wind speed and temperature fields that describe formation of intensive atmospheric near-surface airflow over the leeward slope of the mountain ridge are considered. According to the results of numerical simulations carried out at high temporal resolution, strong temporal variability of the wind speed and temperature fields is observed, especially at the foot of the mountains near the coast. Vertical structure of the wind speed and temperature fields for bora is calculated. Quantitative estimates of the temperature, wind speed, stability frequency and the Froude number vertical profiles conditioning the mode of the airflow around the Crimea Mountains ridge are obtained. Fluctuations of the wind speed which are of the character of stationary internal gravity waves induced in the atmosphere behind a leeward slope of the mountains, are shown in a form of wave disturbances of the near-surface wind speed field over the sea. It is shown that the wind speed and temperature fields are conditioned by the post-critical wave mode of the airflow in the Crimea Mountains ridge. Spatial-temporal variability of these fields is a characteristic feature of the Black Sea bora.

Keywords: bora, Southern coast of the Crimea, numerical model of regional atmospheric circulation *WRF-ARW*.

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Introduction. Bora is a strong cold and gusty off-shore wind blowing along the leeward slopes of the Crimean Mountains (the Southern coast of the Crimea (SCC)) and on the coast stretch from Anapa to Tuapse with the speed 15 – 20 m/s, and sometimes – up to 40 – 50 m/s. The most known are the Novorossiysk bora which is observed on average 46 days per year, and the Yalta one observed 7 – 8 days per year [1]. As a rule, they are accompanied by temperature decrease by 10 – 15 °C and by so strong gusts that they can result in breaks of power transmission lines, sinking of vessels and other destructions.

At present two physical mechanisms of bora (a kind of mountain winds characterized by attaining maximum speeds over the leeward slope) formation are considered to be basic. The first mechanism is a resonant inducing of waves in a stably stratified area which is located below the zone of internal waves' breaking formed over the leeward mountain slope [2]. The second one consists in intrusion of the stratified air jet into the boundary layer over the mountain; it is described by a nonlinear hydrodynamic model. In this case increase of speed over the leeward slope is a result of interaction between the stratified air layer and the well-mixed turbulent area which is formed over it due to breaking of gravity internal waves [3]. Thus, significant wind speed increase over the leeward slope is induced by the nonlinear effects and it strongly complicates analytical description of the bora development. Therefore the basic advances in studying the orography-induced disturbances that entered the thermodynamic processes in the atmosphere are related to application of numerical models.

The Novorossiysk bora is considered in [1] which up to now remains the most comprehensive review of studies of the phenomenon in the Black Sea region. The first results of the Novorossiysk bora numerical modeling are given in [4, 5], and those of the Yalta bora – in [6]. In these papers the bora development was numerically reproduced for specific weather conditions; and the results were interpreted with allowance for the well-known physical notions. It is shown in particular, that the main criterion determining spatial-temporal structure of the wind speed field is the hydrodynamic mode of the coastal mountains' airflow by the running up cold air stream. The airflow wave mode or the air stream blocking by a mountain are the characteristic features of the post-critical and pre-critical airflow regimes, respectively.

In this paper another recent case of strong bora in the region of the Crimea Southern coast is considered in details. The bora spatial-temporal structure is shown and the air stream mode significantly different from that previously considered in [6], is evaluated. Having developed the results of [6], we numerically reproduced (on the minute scales) high-frequency variability of the wind speed field during the bora which is especially strongly pronounced nearby the coastal boundary at the Crimean Mountains' foot.

Numerical model. The model of regional atmospheric circulation *WRF-ARW*, version 3.4, with four nested domains (horizontal resolution in the internal domain is 333×333 m) [7] was used for numerical calculations. This well-known model is used for various purposes in simulating the atmospheric phenomena in the preset regions. Therefore the basic tuning parameters chosen from a large set of parameterization variants will be briefly listed.

32 σ-levels unevenly located over height with the increased resolution in the planetary boundary layer were preset over vertical. The following parameterization schemes were used: *RRTM* (*Rapid Radiative Transfer Model*) and *Dudhia* – for calculating radiation balance of long- and short-wave radiations, respectively; *Kain – Fritch* – for calculating cumulus convection in the domains with the resolution 9 and 3 km (in the domains with the resolution 1 and 0.3 km, cumulus convection was calculated without parameterization). Phase transitions in the atmosphere (microphysical processes) were described by the scheme *Single-Moment* 3-*class*.

The scheme *MM*5 *similarity* was applied to parameterize the surface boundary friction layer. The planetary boundary layer was parameterized using the Mellor – Yamada – Janjic scheme (level 2.5) in which one of the prognostic variables was the turbulence kinetic energy [7].

The *FNL* operational analysis (*Global Final Analyses*) data with the resolution 0.5×0.5° updated every 6 h were used as the input information. After the model was adapted to the preset initial conditions, development of the atmospheric processes in all four domains was governed only by the periodically updated boundary conditions for the external domain.

The model calculations' discreteness was about 30 s, the output data were recorded each hour (for some calculations discreteness was 2 min). The horizontal grid spacing Δx = 0.3 km permitted to resolve spatial inhomogeneities of $7\times\Delta x$ ~2 km scale [7]. The database on relief *SRTM* with discreteness 3" (about 90 m) was used; some points on the steep slopes of the Crimean Mountains were characterized by significantly differing heights. Therefore, stability of the model numerical scheme *WRF-ARW* in the σ-coordinates was provided by the smoothing procedure in the vicinity of such points. Besides, spatially more rough data on soil characteristics (*landuse* parameter) were interpolated to the internal domain nodes with the coastline having been correctly taken into account.

Development of bora. The case under examination, i. e. strong Yalta bora, took place in the region of the Crimea Southern coast on December 2 – 3, 2013. Fig. 1 shows the baric map (based on the *NCEP Reanalysis* archive; www.wetterzentrale.de) for the European region on 00 h December 3, 2013 – just the time of the bora maximum development in the SCC region; the phenomena started to develop 12 hours earlier (hereinafter *GMT*). The anticyclone with its center in the Carpathian region, the cyclone in the region of the Ural Mountains, and concentration of the isobars in the Crimean Peninsula region are clearly seen. Such a picture of baric topography is accompanied by a cold front and strong north wind over the Crimea. In 10 – 12 hours the anticyclone center displaced to the northeast, and the cold front has left the Crimea territory.

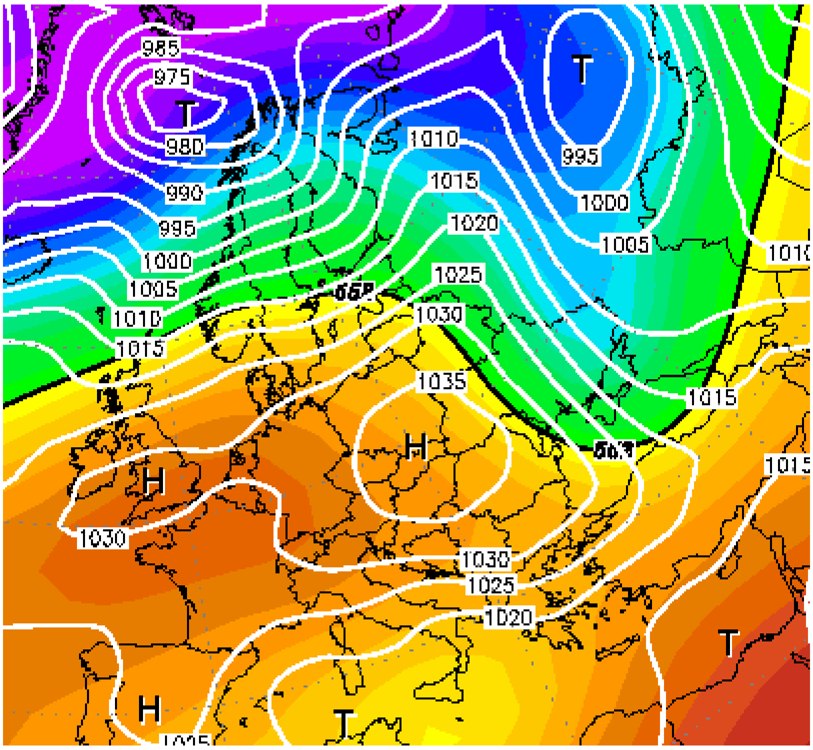

Fig. 1. Map of baric topography (hPA) for the European region on 00 h December 3, 2013 based on the *NCEP Reanalysis* archive (www.wetterzentrale.de) for the period of the Yalta bora maximum development (H is high pressure, T is low pressure)

Fig. 2 shows both the results of the wind speed (at the 10 m height) and temperature (at the 2 m height) calculations for the point nearby the location of the hydrometeorological station (GMS) Ai-Petri (44° 26' N, 34° 05' E.) and the values of these parameters measured at this weather station. Note that the wind direction in this period was close to normal relative to the Crimean Mountains ridge; hence the wind speed meridian component will be considered hereinafter as the basic determinative parameter. Almost monotonic decrease of surface temperature which in course of the bora development period constituted about 14 °C, and increase of the wind speed up to 21 – 22 m/s are seen. Due to their occasional character, the data on the wind speed and temperature obtained at GMS do not allow more detailed comparison with the numerical calculations; although the general trend and the very values both of the temperature monotonic decrease and the wind speed changes are rather close.

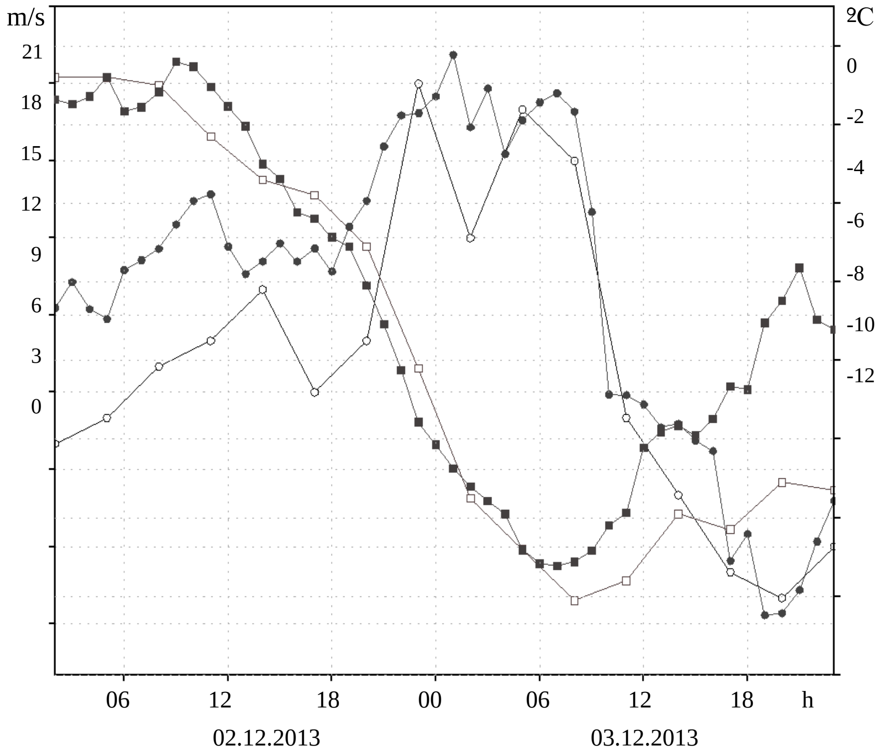

Fig. 2. The calculated values of wind speed on the 10 m height (—●—) and temperature on the 2 m height (—■—) for the point close to HMS Ai-Petri, and also the measured at HMS Ai-Petri values of wind speed on the 10 m height (—o—) and temperature on the 2 m height (—□—)

Fig. 3, *a*, *b* shows time realizations of the calculated wind speed values on the 10 m height and those of the temperature ones on the 2 m height with the increased time resolution 2 min for the period of the bora maximum development in two locations: on the mountain Ai-Petri top, and at its foot. Significant temporal variability both of temperature and wind speed is seen. Especially strong variability on the minute-hour scales is observed on the lower part of the slope close to the mountain foot and in the coastal part of the sea. It will be shown below that it is related to the character of the mountain airflow, to formation of a strong jet stream on the mountain slope and its separation from the surface at the mountain foot. Significant variability of the speed field is the bora characteristic feature.

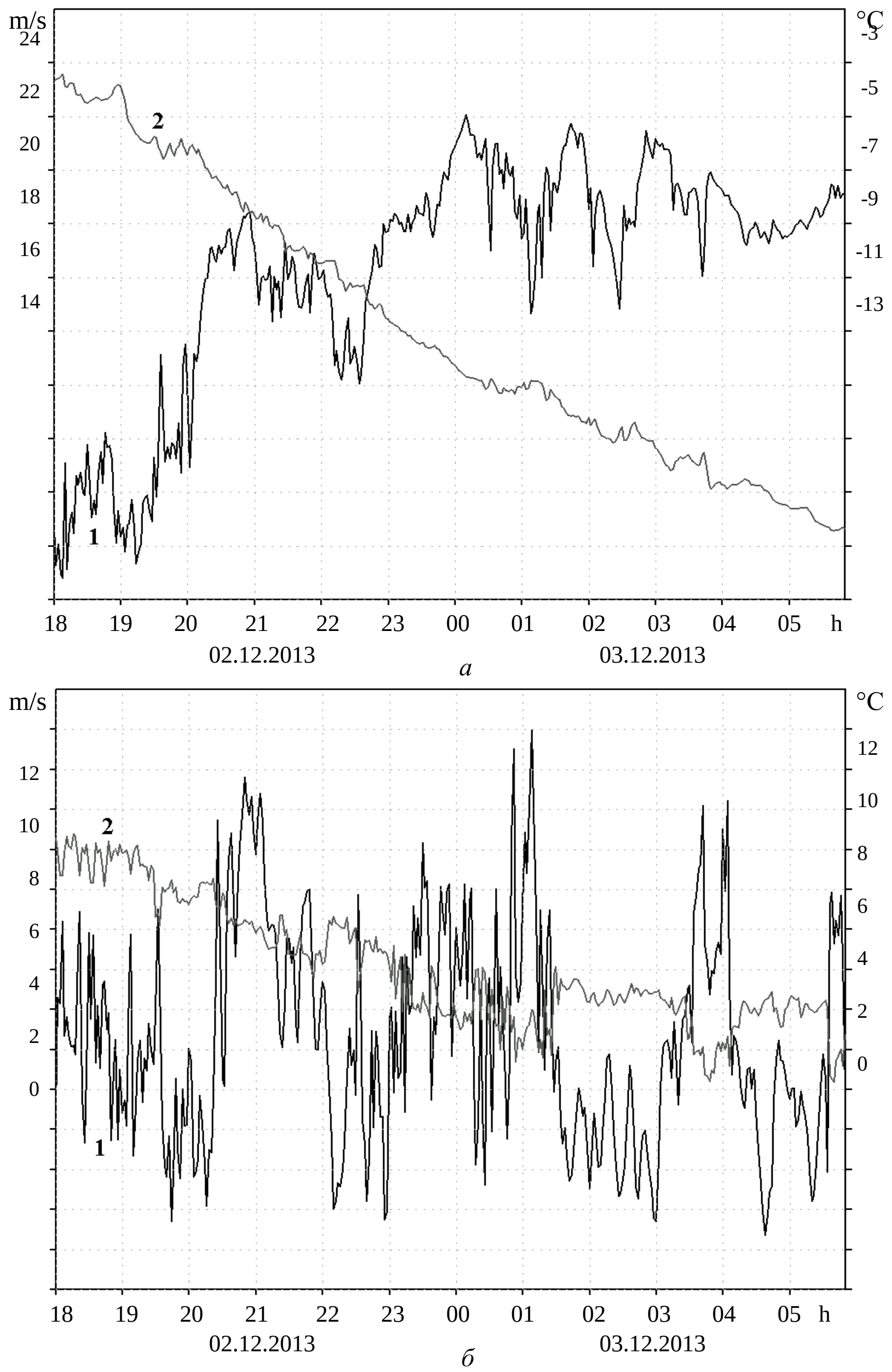

Fig. 3. Time realizations of the calculated values of wind speed on the 10 m height (*1*) and temperature on the 2 m height (*2*) with the increased time resolution 2 min for the period of the bora maximum development in two points – on the mountain Ai-Petri top (*a*) and at its foot (*b*)

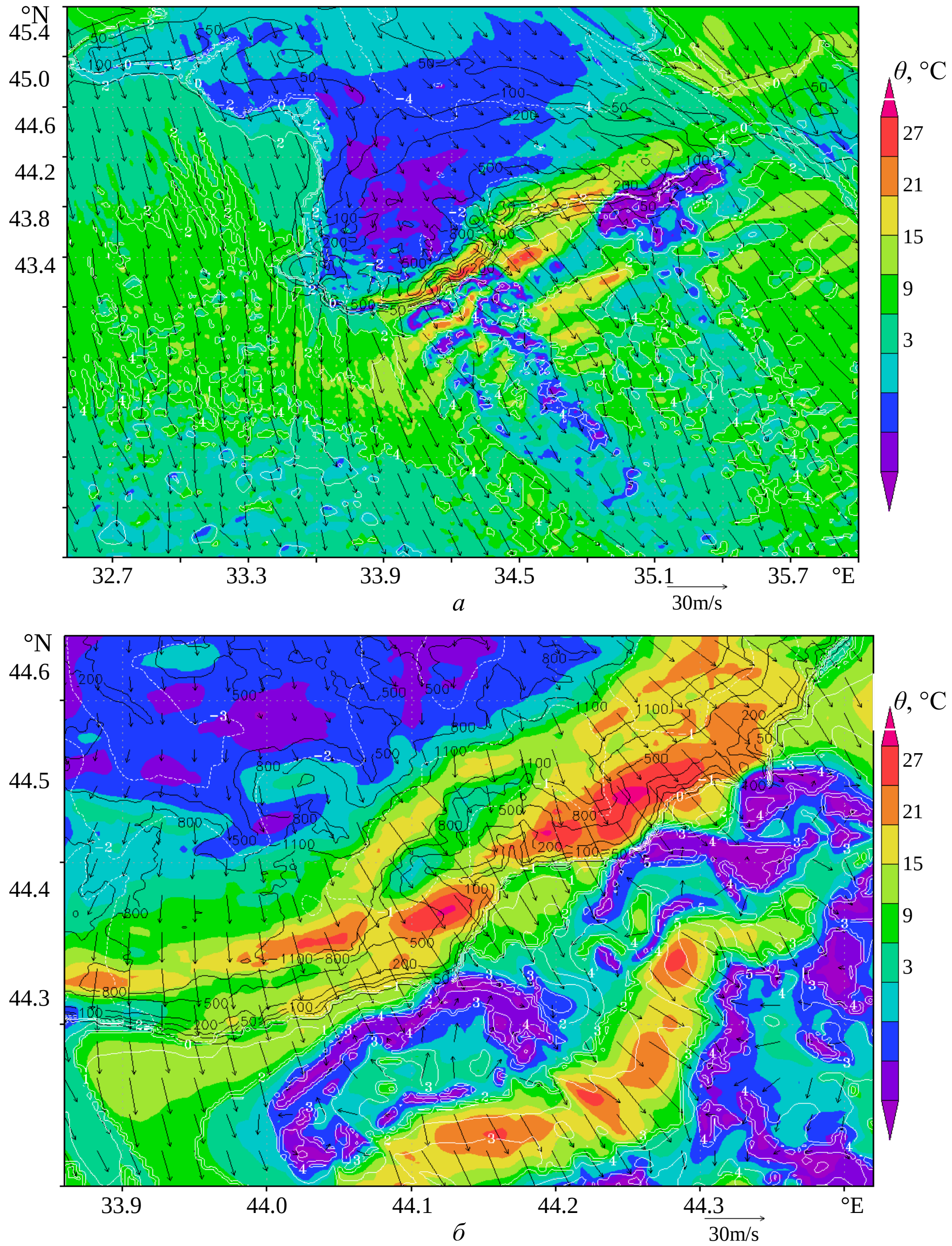

Fig. 4. The calculated fields of wind speed on the 10 m height and the potential temperature θ on the 2 m height for the period of the bora maximum development (00 h, December 3, 2013) in the third (resolution is 1 × 1 km) – *a* and in the fourth (resolution is 333 × 333 m) – *b* domains (the numbers on the isolines denote relief, m)

Fig. 4, *a* shows a large-scale spatial structure of the fields of wind speed on the 10 m height and potential temperature θ on the 2 m height in the SCC region in the period of the bora maximum development when the surface wind speed on the mountains' slope exceeded 30 m/s. Fig. 4, *b* represents the same fields with higher spatial resolution for the Yalta region. The large-scale structure of cold airflow of the Crimean Mountains is clearly seen in Fig. 4, *a*: high wind speeds over the sea in the western part of the region with no influence of the mountains; almost zero values of surface wind speeds in the sub-mountain area and simultaneously small values of the surface temperature which are the features of blocking the baroclinic air stream on the windward slopes of the mountains; gradual increase of the wind speed and temperature over the sea with moving off the coast. At that heterogeneities in distribution of the wind speed behind the mountains over the sea related to the relief features (mountain valleys and high peaks of the Crimean Mountains) are clearly seen. The wave disturbances (periodicity is about 10 km) are also observed over the sea to the south off the Crimean Mountains. The surface temperature in the SCC sub-mountain part is 5 – 10 °C lower than that over the sea that is natural for a bora being considered a cold air stream flowing from the coastal mountains.

The distinguishing feature of the wind speed field during the period of the bora maximum development (Fig. 4, *b*) is a distinct localization of wind with the speed up to 25 – 30 m/s over the leeward slopes of the mountains. At that the wind speed in the coastal zone did not exceed 5 m/s. Only in the south-western part of the area under examination where the mountains are lower, and in the northeastern part where the pass between the mountains is also lower the wind speed over the sea attained larger values. Significant drop between the temperature values on the windward and leeward mountain's slopes is a characteristic feature: potential temperature on the windward slope was about – 12° and over the sea — 0 – 2° (hereinafter, the potential temperature θ, °C is calculated by the formula $\theta = T - 273.15$ where T is the initial value of potential temperature in K°).

Note that the previous simulation of the Novorossiysk and Yalta boras [4 – 6] shows a similar character in the wind speed and temperature variations: monotonous significant decrease of temperature throughout the region and episodic, i. e. lasting almost a day, abrupt increase of the surface wind speed on the windward slope of the ridge. In both cases, significant spatial heterogeneities of speed and temperature fields conditioned by local peculiarities of the land relief are observed. The latter circumstance hampers comparison of the simulation results with the available data of standard measurements performed at HMS, i. e. with the values of average wind speeds and the values of maximum wind gust speeds measured in the preset periods in course of 10-minute intervals. More correct comparison requires special measurements which at present are extremely few [8, 9]. The calculated and measured temperature values showing its significant and almost monotonic decrease (Fig. 2) are rather close.

Vertical structure of bora. Let us consider vertical structure of the thermodynamic fields for the period of the bora maximum development. Fig. 5 shows potential temperature θ and the wind meridian speed on the vertical section along 34.08 °E. It is seen that the bora in the lower atmosphere constitutes rather thin cold air gravity current streaming down the mountain to the warm atmosphere above the sea. The important feature accompanying propagation of the gravity current is its separation from the surface just above the mountain foot. At that the area with nearly zero wind speeds is formed in the atmosphere lower layer above the sea behind the mountain foot. Such areas are well distinguished in Fig. 4, *b*.

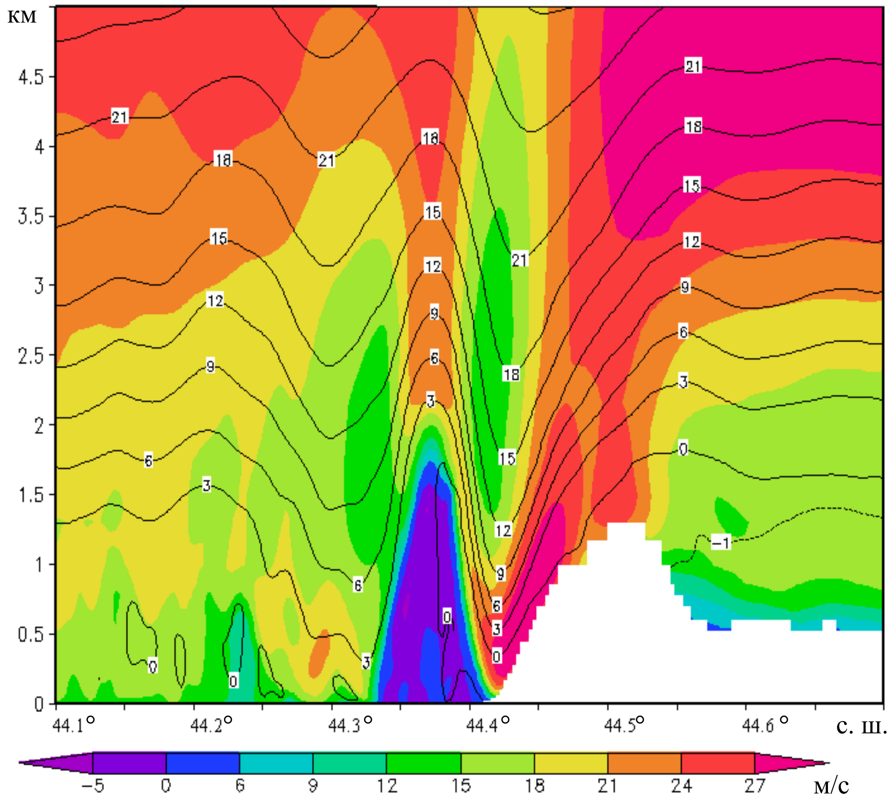

Fig. 5. Vertical section of the fields of meridian wind speed and potential temperature θ, °C (isolines) along 34.08 °E for the period of the bora maximum development (02 h December 3, 2013)

Internal gravity waves induced at the mountain airflow occupy the entire troposphere up to the heights 7 – 9 km; their wavelength is about 10 km. The wave-like structures in the wind speed field over the sea represented in Fig. 4, *a* were connected exactly with them.

It was noted above that there were different modes of airflow of an obstacle in a form of a ridge. It is known that if the height of the wind speed *V* is constant and the atmosphere is hydrostatically stable with constant Brent – Vaisala frequency *N*, the airflow mode is conditioned by the Froude number $Fr = V / Nh$ where *h* is the mountain height, $N^2 = g\theta' / \theta_0$, *g* is gravity acceleration, θ_0 is average potential temperature and θ' is the height derivative *z*. At the supercritical regime when $Fr \geq 1$ (more precisely, $Fr \geq 1.18$ [10, 11]), the wind kinetic energy is sufficient for the air to transfer the ridge. At small Fr numbers, the running up air stream is blocked on the windward slope. The transition process is accompanied by the propagating upstream gravitational density drop [12]. Just such mode was represented in [6] for the case of the Yalta bora.

Generally speaking, in the examined case of the atmospheric processes including values *V* (*z*) and *N* (*z*) which are substantially variable over height, assessment of the Froude number becomes rather conditional.

Fig. 6 shows vertical profiles of the normal to the ridge wind speed component *V* (*z*), potential temperature *θ* (*z*) and frequency *N* (*z*) in the atmosphere over the windward slope. The Froude number profile Fr (*z*) is also shown; its local values were calculated using the meridian velocity and stability frequency values on the height under consideration and on h = 1100 m. It is seen that the Fr values vary over height, but almost on all the heights they exceed the critical value that clearly testify to the post-critical mode of the mountain airflow. Thus, the stream stability in the whole atmospheric layer was insufficient to block it completely at the given large values of the meridian speed achieving 40 m/s in the middle troposphere. The air stream blocking manifested in intersection of the windward slope surface with the potential temperature isotherms (Fig. 4), shows itself only in the lowest layer – up to the heights about 200 – 500 m.

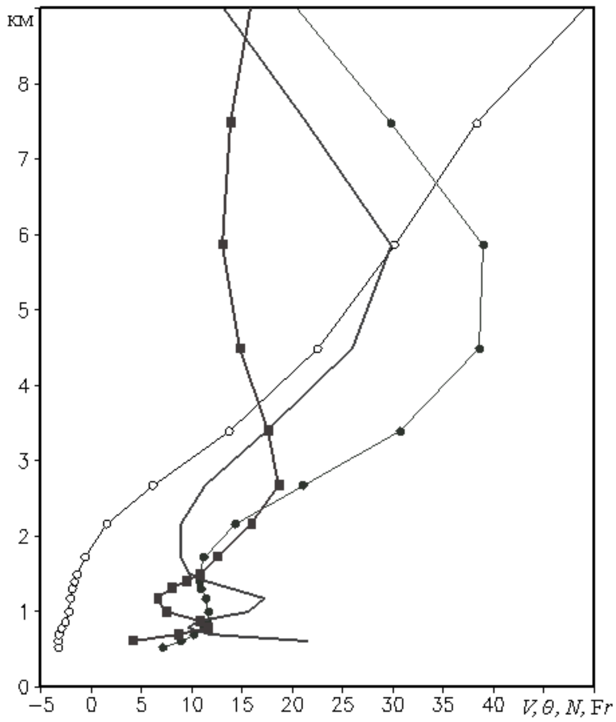

Fig. 6. Vertical profiles of the meridian wind speed, m/s (—●—), potential temperature *θ*, °C (—o—), frequency *N*, c^{-1} (——) and the Froude number Fr (—■—) in the point 44.6° N and 34.08° E

In contrast to the case previously considered in [6], the specified feature is characteristic of the Yalta bora that took place on December 2 – 3, 2013. Comparison of these two cases of strong bora permits to note that significant temperature decrease in the whole region and episodic (lasting about a day) abrupt increase of the surface wind speed in the area of the ridge windward slope are characteristic of both cases. Considerable spatial heterogeneities of the wind speed and temperature fields related to the local features of the land relief are also noted. However, the air stream vertical structures of these two cases of bora were different. In the first case (2006), the pre-critical mode was observed: due to the internal waves' breaking, a well-mixed and homogeneous over height turbulent area and the located from below surface jet stream were formed on the leeward slopes. The bora in 2013 was characterized by post-critical mode of the stream, i. e. in course of the mountain airflow intensive non-breaking gravity internal waves were generated. In such conditions, a strong surface air stream is formed due to the nonlinear effects arising on the leeward slope. It is also promoted by high wind speeds in the atmosphere on the heights exceeding 2 km. Besides, the bora in 2013 was characterized by a strong one-way air stream (40 – 50 m/c) on the heights below 9 – 10 km. During the bora in 2006 a strong air stream normal to the ridge took place only in the lower part of the atmosphere.

Note that the previous simulation of the Novorossiysk bora [4] demonstrates similar character of the temperature change (monotonic decrease by 12 – 15 °C), but the airflow regime varied from the post-critical to pre-critical in course of a two-day episode of the bora development.

Conclusion. The example of the bora that developed in the region of the Crimea Southern coast during the cold front passing on December 2 – 3, 2013 permits to consider the features of its spatial-temporal structure. Significant and abrupt temperature drop in course of the bora development accompanied by substantial wind speed increase on the leeward slope of the Crimean Mountains is a typical feature of the Black Sea bora in winter.

Vertical structure of the wind speed and temperature fields of the bora is calculated. The vertical profiles of temperature, wind speed, stability frequency and the Froude number governing the mode of the Crimea Mountains ridge airflow are quantitatively assessed. It is shown that the air stream vertical structure is conditioned by the post-critical wave mode of the mountain airflow that is a characteristic feature of the bora under consideration.

The wind speed fluctuations are of the character of stationary internal gravity waves induced in the atmosphere behind the mountains' leeward slope. They manifested themselves as wave disturbances (wavelength is about 10 km) of the surface wind speed field over the sea.

Numerical calculations showed a significant spatial-temporal variability of the wind speed field during the bora development. Small-scale features of the mountain relief directly condition spatial variability of the surface wind speed. The results of numerical calculations carried out with high time resolution permit to note strong temporal variability of the wind speed and temperature fields, especially at the mountains' foot near the coast.

Take a notice of the fact that the features of the bora development, such as generation of strong surface wind, rapid temperature drop and significant spatial variability related to the relief peculiarities, are the bora characteristic features irrespective of its mode. At the same time, meso-scale wave oscillations in the atmosphere with a wavelength close to the characteristic transverse dimension of the mountain ridge occur only if the airflow mode is post-post-critical. Allowing for more than twofold difference in the adjacent mountains' heights, such a mode seems to be more frequent for the Novorossiysk bora than for the Yalta one.

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