IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

Energy modeling of Novorossiysk bora

To cite this article: R B Berzegova *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **231** 012010

IOP Conf. Series: Earth and Environmental Science 231 (2019) 012010 doi:10.1088/1755-1315/231/1/012010

Energy modeling of Novorossiysk bora

R B Berzegova[1], M K Bedanokov[1], V N Kozhevnikov[2], I A Repina[3,1]

[1]Maikop state technological university, Maikop, Russia
[2]Lomonosov Moscow State University, Moscow, Russia
[3]A.M. Obukhov Institute of Atmospheric Physics, Moscow, Russia

E-mail: rozaberzegova@yandex.ru

Abstract. The hydrothermodynamics of the flow over a mountain range under the Novorossiysk bora is investigated. A nonlinear, stationary, two-dimensional, analytical model is used. Vertical unlimitedness of the atmosphere is taken into account by representing it in the form of three layers with different hydrostatic stability. The properties of the unperturbed incindent flotation are taken into account throughout the real range of its changes. The characteristics of the air flow at the leeward slope of the streamlined relief are studied. A hypothesis is made that the intensity of bora can be estimated from the speed at the leeward slope of the mountains.

1. Introduction

The Novorossiysk bora is one of the most striking manifestations of downslope winds. It occurs on the lee side of the mountain ranges Caucasus and Markhotsky, on the coast of the Black Sea, which are aligned mainly in the north-west to south-east direction. Bora is observed mainly during the cold season between the Russian cities of Anapa and Tuapse, but the highest wind speeds (10-min average speed up to 35–40m s−1) usually occur in the Novorossiysk and Gelendzhik region. Such intense windstorms pose a great threat to the population in the area and can be catastrophic to vessels moored in the Novorossiysk harbour.

Similar models have been created and improved for almost a hundred years, but the problem remains unresolved to the full extent. In the early years, analytical models were created and used, in which the equations describing the flow laws were solved by standard mathematical means. In this case, all laws were not fully taken into account, so that only the real properties of the process could be modeled approximately [1-5]. In the works [3, 6 - 11], this phenomenon was studied on the basis of the application of a nonlinear, stationary, two-dimensional, open, mesoscale, analytical model. In the model: air was considered as an ideal fluid, the processes were assumed to be adiabatic, the nonlinearity of the advective terms in equations was fully taken into account, the shape of the relief was accurately taken into account. The model took into account approximately the influence of the upper atmosphere on perturbations in the troposphere, namely by representing a flowing stream in the form of three layers having the same velocity but different stability. Comparison of calculations with the results of a number of measurements has shown that the model describes qualitatively the characteristics of atmospheric perturbations over mountains at altitudes outside the boundary layer. It was shown how important in modeling to take into account the actual shape of the mountains and their extent. In [12], recently on the basis of this model, a detailed research of the flow of one more case of real mountains, namely, the mountains characterizing the relief in the region of the city of Novorossiysk, was carried out.

This study was carried out not for one or two states of a flowing current, as is usually done, but for a very wide range of such states. Some of the results obtained in this connection will be used in this study of bora characteristics.

In [13-18] the bora in Novorossiysk was investigated to solve the problem of predicting this dangerous phenomenon by using a numerical mesoscale non-hydrostatic model WRF-ARW. This model includes accounting for many more physical phenomenon factors than analytical models, however, as usual, this is done through the use of parametrization methods. The quality of the results obtained is checked by comparing them with the data of individual measurements at the ground. This is clearly not enough. For the present estimation of the quality of a numerical model, it is necessary to evaluate the reliability of the methods of parametrization of complex physical processes used for the phenomenon under study. To obtain such an estimate, it is necessary to compare the results of the calculation with measurements at sufficiently many points at the ground, and even more importantly with measurements at many altitude levels. There are almost no such measurements. The following became even clearer. 1. Bora should be considered as a process of development in time. 2. At the first steps, the initial, culminating and final stages of its development should be identified. 3. The shape of streamlined mountains generates the presence of a two-dimensional component in the spatial variations of the perturbations. 4. In all cases, the greatest increase in wind should be expected at the leeward slope of the streamlined mountains.

2. Theoretical model

Simulation of the flow past the mountains was carried out, as in [3.8-10], within the framework of a stationary, two-dimensional, nonlinear, non-hydrostatic approximation based on the solution of the Helmholtz equation for perturbations of the stream function ψ'. The magnitude of the coefficient of the equation is inversely proportional to the Lyra scale λ_c [3, 19]:

$$\lambda_c = 2\pi \frac{U}{N}, \quad N^2 = \frac{g(\gamma_a - \gamma)}{T_1}, \tag{1}$$

where U, N - the speed and frequency of the Brent-Väisälä in the flowing stream in front of the mountains, γ and γ_a - the vertical and dry-adiabatic temperature gradients, T_1 - the characteristic temperature of the layer, g - the acceleration of gravity (in foreign publications, the Scorer parameter is used instead of the Lyra scale). The possibility of reducing the nonlinear problem to the solution of a linear equation was determined by the fact that a particular variant of the properties of the flowing flow was considered, namely, when it was assumed that the velocity and the gradient do not depend on the altitude in it: γ:

$$U = const, \quad \gamma = const. \tag{2}$$

This way of accurately accounting for the nonlinearity of the equations of motion is very close to that used in Long's model [4]. The stream function in the incoming flow was determined as a linear dependence on the height $\psi_0 = -Uz$, and the total current function by means of adding perturbations to the written value ψ'. The perturbations of temperature were determined with ψ' in full accordance with the assumption of adiabatic vertical displacements of air particles according to the formula:

$$T' = -\frac{(\gamma_a - \gamma)\psi'}{U}. \tag{3}$$

The horizontal and vertical velocity components were determined by the derivatives of the current function, respectively, in the vertical and horizontal directions. The lower layer in the model represented the troposphere, the middle layer - the lower part of the stratosphere, and the upper layer - the rest of the atmosphere. The velocity of the flow was assumed to be the same in all layers, and the temperature gradients were different. Two-dimensional characteristics of the relief of the mountains in the Novorossiysk area were studied in detail in [12]. It was shown that the main properties of the perturbations can be investigated by modeling the flow around the average section of the relief, and the entire wide range of states of the inflowing stream is reduced to the next range of values of the Lyra scale in the troposphere and layer by layer setting the values of the temperature gradient from the bottom up (j = 1, 2, 3):

$$\lambda_c = 3, 4, 5, 6, 6.66, 7, 7.5, 7.8, 9.5, 10, 12.2 \text{ km}, \quad \gamma_j = 6, 0, 3 \text{ degr/km}. \tag{4}$$

It was assumed that in the troposphere N is approximately equal to $4\pi \cdot 10^{-3}$ 1/s, from which it follows that U is determined by the relation $2\lambda_c \cdot 10^{-3} \cdot 1/c$, i.e. in m/s the speed is twice the value λ_c in km. Hence it is easy to see that setting values λ_c in (4) is equivalent to setting values U in the range from 6 до 24.4 m/s. Further, for brevity, the values λ_c, γ, U will be given respectively in km, deg / km, m/s. The heights of the interfaces in the model were set equal to 10 and 18 km. Steps of the computational grid in calculating the field of trajectories were 50 m in coordinate x and 250 m - in z.

3. Results

3.1. Field of trajectories.

In [12], many variants of flow around the mountains were analyzed, including - for 4 different reliefs using the parameter range (4). The first and the main was the relief obtained by averaging the heights according to the method, tested in [3, 7-11] (we will call it the average). Averaging was carried out for 10 specific vertical sections of the terrain, perpendicular to the middle direction of the mountains. The second was a relief characterizing the profile of the mountains for one of these particular sections, the most seriously different from the average. Two more reliefs were created artificially in order to study the general physical laws of flow around real mountains. When they were created, the requirements were met. 1. They had one, and not two main ridge. 2. The leeward slope was steep, roughly coinciding with the steepness of the middle relief. 3. The cross-sectional area with an accuracy of at least 7.6% coincided with the cross-sectional area of the middle relief. In the third relief, the maximum height was set equal to the height of the average relief, i.e. 541 m, and in the fourth relief - equal to 350 m. The above reliefs will be denoted as sr, ch, iskV and iskN, respectively.

In the literature (see, for example, [3, 5, 20-22]), it is customary to characterize the variants of flow around the values of the Froude number F the dimensionless mountain height L_b, equal to the reciprocal value F. In this as a scale the maximum height of the mountain h_m is used, so:

$$F = \frac{U}{Nh_m} = \frac{\frac{1}{2}\pi\lambda_c}{h_m}, \quad L_b = \frac{1}{F} = \frac{Nh_m}{U} = \frac{2\pi h_m}{\lambda_c}. \tag{5}$$

From this it follows that the studies were carried out for the following parameter ranges:

$$0.87 < F < 3.59, \quad 1.14 > L_b > 0.28. \tag{6}$$

The process of flow is most graphically illustrated by the trajectories of the motion of air particles. Fig. 1 shows one of the results of [12], namely the trajectory of motion over the middle relief at $\lambda_c = 4$. Trajectories are identified with the values of their heights in the inflowing current z_0 (in km). The motion of particles is directed from left to right. The figure shows trajectories with $z_0 = 0$, 0.35, 0.5 and further higher with values increasing with an interval of 0.25 km. The terrestrial trajectory, as is easy to see, has two ridges almost equal in height. Over the mountains, the disturbances are so large that the trajectories with z_0, variations in the range from 2 to 2.75 have a rotary character (according to [4]) in the altitude region 1.5 - 3.5 km (i.e, the amplitude of the vertical vibrations is about 1 km). It is not difficult to see that the trajectory with $z_0 = 3.5$ to some extent follows the shape of the relief. In this there are two regularities: the periodicity of changes along the vertical and the influence of the scale of the shape of the relief. In the leeward region, the perturbations have the form of periodic waves.

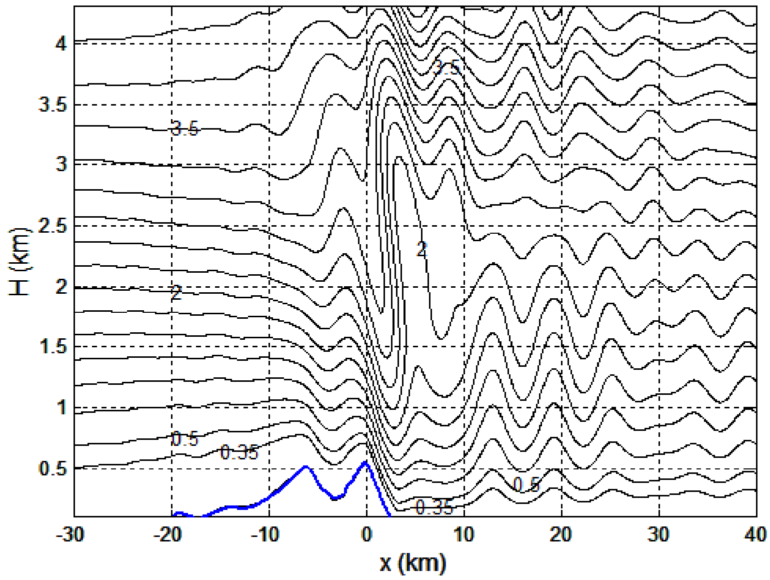

Figure 1. Trajectory of motion over the middle relief at $\lambda_c = 4$, $\gamma = 6$, $U = 8$, that corresponds to the values $F = 1.18$, $L_b = 0.85$.

At low altitudes of 1 to 1.5 km, their amplitudes are about 250 m, they decrease rapidly, remaining significant in the surface layer - the trajectories with $z_0 = 0.35$ the amplitudes above the sea make up at least 50 m at distances up to 20 km.

3.2. Perturbations at the leeward slope of the mountains

Earlier it was shown that in the zone of perturbations always appear the regions of sharp condensation of the motion trajectories that are jet streams. In the upper and lower parts of the jets, the convergence of the trajectories has different signs. This means that the velocities in the jet at some average altitude are always maximal. It is established in the same way that the highest velocities are observed at the leeward slope of mountains and their values can be used as a measure of the intensity of disturbances. In Fig. 1 three such jets can be seen.

The first is located at the leeward slope of the mountains in the region of lowering the air particles down, the second is above the mountains at an altitude of about 2.5 km in the region of the upward lift, the third is even higher and close in characteristics to the first jet. When investigating bora, we will be interested only in the first stream. In addition to the trajectories at the leeward slope, the velocity and temperature perturbations fields were calculated, with the steps of the calculation grid decreasing – with x up to 25, with z up to -10 m. The calculations were carried out for all the reliefs and for all the parameters (4, 6). It was found that the disturbance patterns in all variants are qualitatively close; this made it possible to illustrate what was said by one Fig. 2. Here are the isolines of the temperature perturbations at the leeward slope for one of the variants, namely for $\lambda_c = 5$. Simultaneously, these isolines qualitatively characterize the motion trajectories. For example, an isoline for a temperature perturbation of 2.5 degrees reproduces well the trajectory with $z_0 = 0.9$. The figure shows that the jet along the slope is almost uniform and has a thickness of less than 800 m. At a sufficient distance from the slope of the motion of air particles acquire a wave character.

3.3. Energy of bora

In [3, 6-11] it was shown that the model used in this paper characterizes quite well the perturbations at altitudes of more than 2 km. However, it is clear that it cannot claim the high reliability of describing the characteristics of disturbances in the surface layer behind the mountains, since it does not take into account the viscosity and, especially, the turbulent viscosity of the medium. At the same time, the results of previous and present calculations show that in all cases a jet stream with high velocities is predicted at the leeward slope of the mountains. This allows us to believe that in nature the turbulence in the stream at the slope is suppressed and concentrated only in its very thin layer near the earth. Hence, we can hope that our model describes the perturbation properties in this part of space quite well. On this basis, we will further assume that the intensity of bora in the city and in the bay can be estimated from the value of the energy of the flow in this zone.

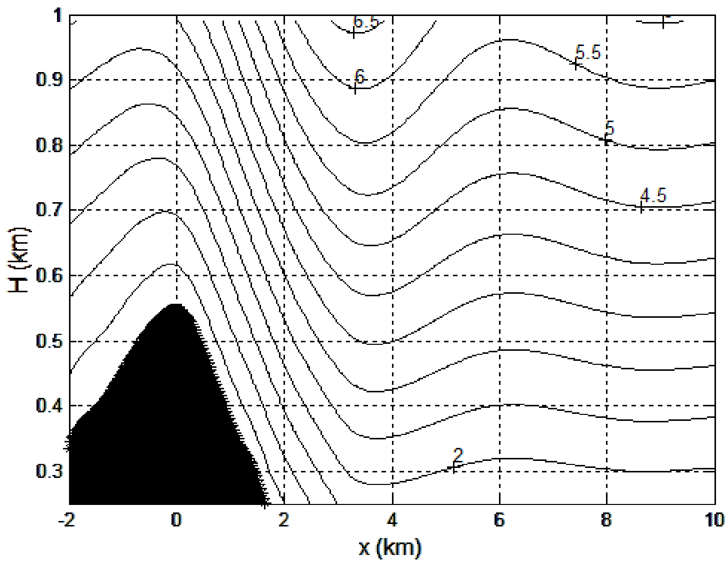

Figure 2. Temperature perturbations at the leeward slope at $\lambda_c = 5$, $\gamma = 6$, $U = 10$. The relief is blackened. The isolines are digitized in 0.5-degree increments.

The velocity field at the slope was studied in detail for the mean relief at all λ_c. First of all, the changes in the values of the velocity modulus $V(z,x)$ depending on x at the level $z = 300$ m were calculated (it can be considered characteristic). The corresponding curves shown in Fig. 3 show that the nature of the changes $V(z,x)$ is the same with the distance from the mountain. At first, the velocity decreases monotonically (by about 1 to 2.5 m/s in the range of deletions up to 200 m). Then, its values begin to change wavy with amplitudes of about 1.5 m/s and a period of order λ_c. For simplicity, the energy of the jet at the leeward slope was decided to be estimated from the average value $V(z,x)$ in a layer 200 m thick. This value should obviously characterize the properties of the jet at a specific altitude. If the averaging is carried out at the maximum speed level, the resulting value will characterize the maximum jet velocity for a particular value λ_c. The resulting quantity will be denoted as V_b, and called the characteristic velocity of the jet. It will give an idea of the energy flow at the slope, and also with this the intensity of all perturbations. The ones shown in Fig. 1, 2 data, draw attention to the fact that air particles as they descend along the slope from the uppermost layers of the jet do not reach the ground clearly and, therefore, form a transitional layer between the free atmosphere and the surface layer that we are interested in. Particles of air from the lowest layers of the jet, obviously, directly participate in the formation of this layer and its turbulents. It becomes clear that the energy of turbulent gusts in it is directly proportional to the kinetic energy of the jet, and, therefore, to the value V_b.

Calculations of the value V_b were carried out for all variants. In this case, the averaging $V(z,x)$ along the horizontal coordinate was carried out each time at two altitude levels at which they had the maximum values. According to the two values obtained in this way, the mean value V_b and range of variation dV were determined. It was found that the value dV did not exceed 0.17 m/s. The results are illustrated in Fig. 4, 5. For the average relief, the curves with asterisks are represented by smoothed data.

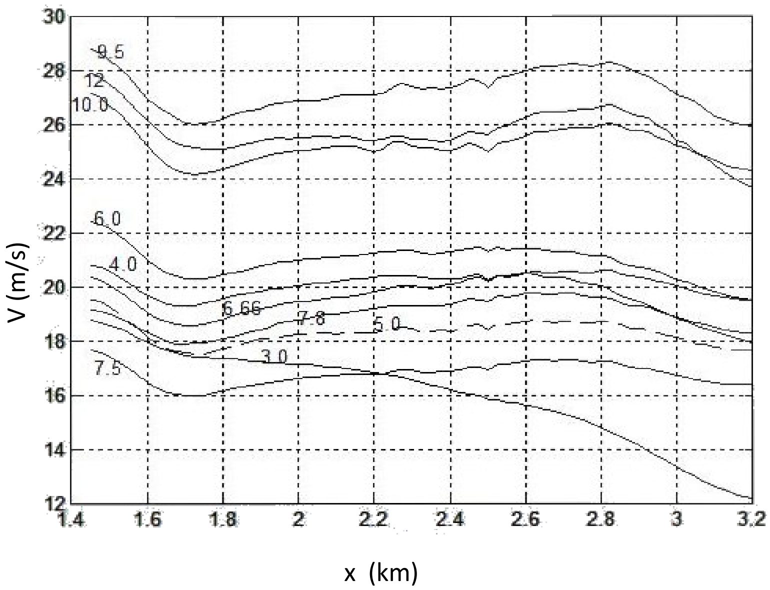

Figure 3. Modifications of the flow velocity module as you move away from the slope. The numbers in the curves give the meanings λ_c.

Fig. 4 shows the changes in the values V_b/U. They allow us to note the following. 1) For all λ_c the value V_b/U is greater than 1. Consequently, the wind near the ground with bora is always stronger than the wind in front of the mountains. 2) On average, there is a decrease V_b/U with increasing λ_c, i.e. the previously formulated law of smoothing is fulfilled. 3) In some parts of the range λ_c, the smoothing law is not monotonous. This is particularly noticeable in the vicinity of the values $\lambda_c = 5$, 7.5, 9.5. For very large λ_c values V_b/U approach unity.
4) The curve for a particular relief does not qualitatively differ from the curve for the average relief; it differs quantitatively only in that it does not reproduce an increase V_b/U in the region of the point $\lambda_c = 6$. Hence, the results for the middle relief are quite suitable for studying the intensity of bora. 5) The reliability of the revealed dependencies is confirmed by smallness dV.

Figure 5 shows how the absolute values V_b change with increasing λ_c (and velocity U). It is easy to see that the changes take the form of appreciable oscillations with respect to the law of linear increasing in the mean. These changes V_b require detailed analysis. In [3, 6, 7, 10, 11] it was shown that the intensity of disturbances is determined by the joint influence of three factors - the perturbing effect of the relief, the intrinsic wave properties of the layers and the dynamics of interaction between them.

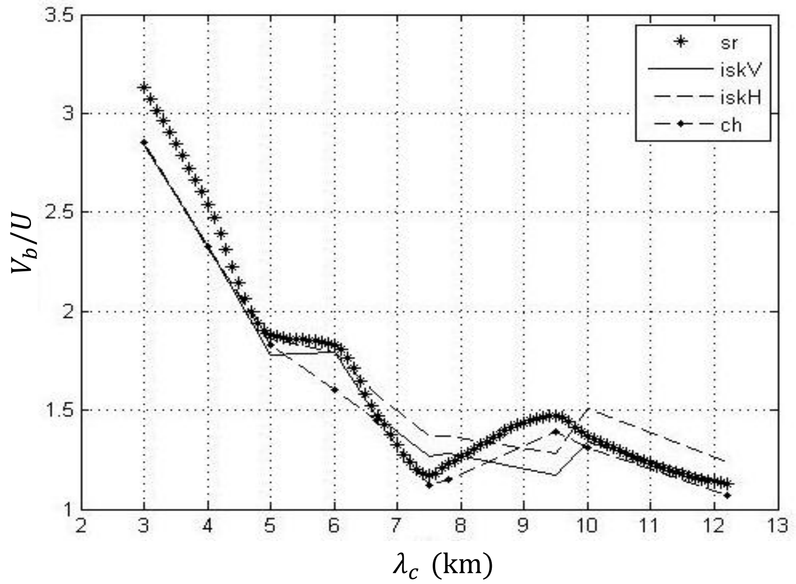

Figure 4. Dependence V_b/U on λ_c for various reliefs.

The influence of the relief depends on the spectral composition of the disturbances, which in turn depends on λ_c, the shape and height of the relief. Consider the behavior of the curves sr and ch in Fig. 5, and then - iskV and iskN. These pairs of curves refer to two fundamentally different in form reliefs - the first to the variant of two ridges and a trough between them, the second to a variant of a sufficiently smooth relief with one ridge.

It should also be noted that in three of these reliefs, the maximum heights are practically the same and exceed the height of the iskN relief by 190 m. Pair-wise comparison of the curves shows that they have the same qualitative dependence on λ_c. Simultaneously, one should note the discrepancy between the oscillations in the amplitudes. It is noteworthy that in the first pair the differences are least noticeable. All this makes it possible to assume that the oscillations are related to a considerable extent with changes in the spectral composition of the perturbations upon changing λ_c.

Comparing the curves for the reliefs iskV and iskN, we see that at $\lambda_c > 6.3$ the curve for the higher of them lies lower everywhere. This is probably due to the fact that, the law of smoothing out perturbations begins to overcome the flow effect earlier for a lower relief than for a high one, and this leads to a decrease in the amplitudes of the individual wave components of the perturbation spectrum over the iskV relief.

Comparison of the curves sr and iskV makes it possible to reveal in some way the role of the presence of a trough between the two main ridges. The figure shows that the relief sr practically at all λ_c perturbs the atmosphere stronger. When comparing the results for these reliefs at $\lambda_c = 5$, it was noted in [12] that the maximum range of vertical displacements in the rotor region in the second case decreased by 38%. The data in Fig. 5 show that in the region $\lambda_c < 6.7$ the signs of the difference in velocities remain the same, but the magnitude of the discrepancy is almost 7 times smaller (of the order of 5%). This indicates that the presence of a trough in the relief has a much greater effect on perturbations in the middle troposphere than on the leeward slope.

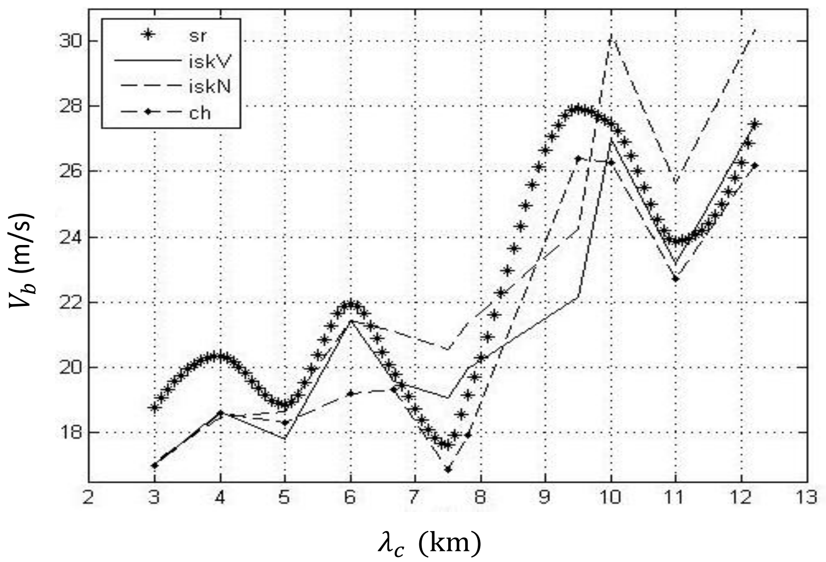

Figure 5. Dependence V_b on λ_c for various reliefs.

It is difficult to judge the influence of the wave properties of layers on oscillations. It is known (see [3, 6, 7]) that these properties in the model depend on λ_c, the thickness of the layers and on the processes of their dynamic interaction. In [12], the role of the dynamic interaction of the layers was partially revealed when the results of calculating trajectories at $\lambda_c = 5$ were compared for three variants of specifying a gradient in the troposphere: = 5, 6, and 7. The analysis showed that in the transition from variant $\gamma = 6$ to case $\gamma = 5$, the reflection coefficient of wave energy on the tropopause decreased significantly. This effect was observed by increasing the amplitudes of waves in the stratosphere. Now it has been tested for changes in value V_b. Corresponding calculations showed that in these variants the values V_b in comparison with the value of 18.8, which is seen in Fig. 5, increased by 4 in the case $\gamma = 7$ and decreased by 2.8 - in the case $\gamma = 5$. Consequently, the characteristic velocity at the slope reacts to changes in the energy exchange between the layers more clearly than the field of trajectories.

In the model, the reflection coefficient at the interfaces for a particular value λ_c is determined only by the break in the temperature gradients. The dependence of this coefficient on λ_c was not determined, but it can be assumed that it is not so great. In this case, it can be expected that when the values of the layer-by-layer values γ in (4) change to the values V_b presented in Fig. 5 they will basically only shift vertically. This means that in the first approximation the characteristics of the energy of the bora are elucidated.

In the literature (see, for example, [5]), the phenomenon of collapse of waves over mountains is widely discussed. In this case, it is assumed that it is primarily realized in the form of destruction of the rotor circulations. Specifically, the appearance of rotors is considered as a sign of inapplicability of the theoretical model used in the calculations. The model applicability boundary is estimated from the values F and L_b introduced in (5). In nonlinear, open, non-hydrostatic models [20-22], devoted to flow around a mountain-semicircle, the radius of the mountain was used as the quality h_m, and the value L_b was considered as the main parameter of the problem. In [21, 22] the results were analyzed for L_b = 1, 2, 3 and L_b = 0.5, 1, 1.27, 1.5, respectively. It was found that for large values L_b above the mountain wave perturbations acquire a rotary character and this occurs when the value L_b lies in the range between the values 1 and 2 according to [21] or 1 and 1.27 - according to [22]. In [21], in addition, it was shown that two regions always appear in the rotor zone, differing sharply in hydrostatic stability. In one of them, the temperature gradient decreases substantially in comparison with γ, and in the other, it increases to such an extent that it can even exceed γ_a. With the growing L_b the intensity of the rotor increases, particles appear that move towards the incoming flow, and finally a closed vortex appears in the flow [21]. Both these regions are continually approaching, and the contrast in the magnitude of hydrostatic stability between them increases so much that the inevitability of the transition of the flow from the laminar regime to the turbulent regime becomes evident. From this it was concluded that the model can be used for sufficiently small values λ_b, or large values F, namely, approximately at L_b <1.2 (or F > 0.83). If we carry out a similar estimate for the considered case of flow around concrete real mountains, then according to [12] we use the values $\lambda_c = 5$ and $h_m = 0.54$. Then we get that the model by this estimate is obviously can be used at L_b<0.68 (or F >1.47). The detected change in the critical value L_b cannot be associated only with h_m, it is obviously connected with the entire energy of the interaction of the incoming flow with the relief irregularities, including the presence of upper layers of the flow. It is even more important to pay attention to the following. In [4] Long expressed the opinion that the rotary current can not be realized in nature at all. However, his experiments on the flow around the unevenness of the lower boundary in the channel showed the opposite. In one experiment, a rotor was observed in the flow above the unevenness, in which the particles moved towards the incoming flow, and there was no doubt about the stability of its existence. This established the fact that the flow of a stratified fluid can be noticeably more stable than that of a homogeneous fluid.

4. Conclusions

It was confirmed that the characteristic flow velocity at the leeward slope of the mountains is the most important quantitative characteristic of atmospheric perturbations during flow. It is shown that it depends essentially on the Lyra scale. Two variants of bora should be considered. The main (more frequent) can be considered the option when the values of the Lyra scale are less than 8 km (the flow velocity is less than 16 m / s). In this case, as the Lyra scale increases, the values of the characteristic velocity change nonlinearly, but in a rather narrow range of values of 17-24 m/s. The second variant of bora should be considered more rare and, therefore, less interesting. Changes in air temperature during bora depend little on the flow effect and are determined practically by how much the temperature of the incoming air mass differs from the temperature of the displaced mass. The speed of gusts in the bora is determined by the energy of the air flow at the leeward slope of the mountains and the subsequent processes of turbulence of the atmosphere in the surface layer. These processes were not modeled, but it can be assumed that in the case of bora, the force of these gusts always exceeds the characteristic velocity - by two or more times.

The work was carried out within the framework of the task No. 5.9533.2017 / BC for the project "The study of the geoecology of the Northwest Caucasus environment and specially protected natural areas".

Reference

[1] Kozhevnikov V N 1970 A review of the current state of the theory of meso-scale orographic inhomogeneities in the field of vertical currents *Trudy TcAO* **98** 3-40

[2] Atkinson B W 1981 Meso-scale atmospheric circulations (*London-New York-Toronto- Sydney-San Francisko: Academic Press*) p 482

[3] Kozhevnikov V N Perturbations of the atmosphere during flow around mountains (Moscow: Nauka) p 160
[4] Long R R 1955 Some aspects of the flow of stratified fluids III. Continuous density gradients *Tellus* **7(3)** 18-35
[5] Lin Y-L 2007 Mesoscale Dynamics (Cambridge, Univercity Press) p 630
[6] Kozhevnikov V N, Bedanokov M K 1993 Nonlinear multilayer model for flow around an arbitrary profile *Izvestiya Atmospheric and Oceanic Physics* **29(6)** 780-92
[7] Kozhevnikov V N and Bedanokov M K 1998 Wave perturbations over the mountains of the Crimea. Theory and Observations *Izvestiya Atmospheric and Oceanic Physics* **34(4)** 546-56
[8] Kozhevnikov V N, Bibikova T N and Zhurba E V 1977 Orographic perturbations of the atmosphere over the North Urals *Izvestiya Atmospheric and Oceanic Physics* **8(5)** 451-61
[9] Kozhevnikov V N, Bibikova T N, Zhurba E V 1986 Orographic waves, clouds and rotors with a horizontal axis above the mountains of the Crimea *Izvestiya Atmospheric and Oceanic Physics* **22(7)** 682-90
[10] Elanskiy N F, Kozhevnikov V N, Kuznetsov G I and Volkov B I 2003 On the influence of orographic disturbances on the redistribution of ozone in the atmosphere on the example of flow around the Antarctic Peninsula *Izvestiya Atmospheric and Oceanic Physics* **39(1)** 105-20
[11] Kozhevnikov V N, Elanskiy N F Moiseenko K B 2017 Variations in the content of ozone and nitrogen dioxide in the field of orographic waves over the Subpolar Urals Doklady RAS 475(6) 691-96
[12] Berzegova R B, Bedanokov M K and Kozhevnikov V N 2018 Orographic disturbances over low mountains of medium scale. Dependence on the shape of the mountains and the properties of the flowing stream *Izvestiya Atmospheric and Oceanic Physics (*in press)
[13] Toporov P A, Myslenkov S A and Samsonov T E 2013 Numerical simulation of Novorossiisk bora and associated wind waves *Bulletin of Moscow University Series 5: Geography* **2** 38-46
[14] Efimov V V and Barabanov V S 2013 Modeling of the Novorossiysk bora *Russ. Meteorol. Hydrol.* **3(3)** 171-76
[15] Toporov P A and Shestakova A A 2014 Quality assessment of Novorossiysk bora simulation by the WRF-ARW model *Russ. Meteorol. Hydrol.* **39 (7)** 458-67
[16] Gavrikov A V and Ivanov A Y 2015 Anomalously strong bora on the Black Sea: observation from space and numerical simulation *Izvestiya Atmospheric and Oceanic Physics* **51(3)** 546-56
[17] Shestakova A A, Moiseenko K B and Toporov P A 2015 Hydrodynamic aspects of the episodes of Novorossiysk bora 2012-2013 *Izvestiya Atmospheric and Oceanic Physics* **51(5)** 534-45
[18] Shestakova A A,. Toporov P A, Stepanenko V M, Sergeev D E and Repina I A 2018 Observations and modelling of downslope windstorm in Novorossiysk *Dynamics of Atmospheres and Oceans* **83** 83–99
[19] Lyra G 1943 Theorie der stationaren Leewellenstromung in freien Atmosphare *Z. Angew. Math. und Mech.* **23(1)** 1–28
[20] Kozhevnikov V N 1967 To one nonlinear problem of orographic disturbance of stratified airflow *Izv. AS USSR, seria geophysicheskaya* **7** 1108-16
[21] Kozhevnikov V N 1968 Orographic perturbations in a two-dimensional stationary problem *Izv. AS USSR, seria geophysicheskaya* **4(1)** 33-52
[22] Miles J W 1968 Lee waves in a stratified flow. Part II. Semi-circular obstacle *J. of fluid mech. 33(4)*