Formation of the Novaya Zemlya bora

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Structure of the atmospheric fields for a few cases of strong southeast and west winds is reproduced and considered based on the *WRF-ARW* high-resolution numerical model of atmospheric circulation. Typical distribution of the wind speed and temperature fields for these cases is presented. It is shown that the main condition of bora occurring consists in stable stratification in the atmosphere low layer above the Kara Sea under the east and southeast winds. Blocking of an air flow on the windward eastern slope of the mountains is followed by arising of a strong near-surface wind – the bora – on the western slope and in the nearshore area of the Barents Sea. As a result, in case of a bora the air temperature above the Barents Sea significantly exceeds that above the Kara Sea on the same heights. Under the west winds, a weakly stable atmospheric boundary layer above the Barents Sea does not constitute a considerable block (by mountains) for a running flow which is one of the basic conditions of the bora development. Thus, as for the west wind, Novaya Zemlya is not a barrier separating the atmosphere lower layers between the Kara and Barents seas in winter.

Keywords: Novaya Zemlya, bora, *WRF-ARW* atmospheric circulation model, baroclinic stream, stability frequency.

DOI: 10.22449/1573-160X-2017-2-3-10

Introduction. Novaya Zemlya is an archipelago located between the Barents and Kara Seas, affecting the water circulation system in the Arctic Basin. About half of the Atlantic Ocean waters entering the basin passes through the Barents Sea. The shallow part of the sea, adjacent to the western coast of Novaya Zemlya, is one of the centers of cold deep water formation in winter being a result of heat loss through the surface due to the sensible and latent heat flows. In the same area the ice cover is formed in winter. It concurs to the increase of salinity and cold water formation rate [1 – 4]. The regime of the Kara Sea, located to the east of Novaya Zemlya is significantly different from the one of the Barents Sea: in winter it is almost completely covered by ice, and the near-surface air temperature is lower by 5 – 15 °C. One of the reasons for such differences is the location of Novaya Zemlya Archipelago. It is situated between these two seas stretching northward and is a natural obstacle to the flow of relatively warm Atlantic waters that as a result do not enter the Kara Sea. However, the different temperature regime of the atmosphere over these two seas is also important. It largely arises from the presence of the mountainous Novaya Zemlya. A characteristic feature of atmospheric circulation in this region is the occurrence of the strong coastal winds, defined as bora, near the western coast of Novaya Zemlya in the winter period.

The occurrence of strong winds on the slopes of coastal mountains is well-known (for example, the Novorossiysk bora [5 – 8]). Among the few references to Novaya Zemlya bora, it is possible to single out only the work [9]. It is the first work where a general analysis of the statistics of strong winds in the Barents Sea is carried out, and, particularly, the increased heat losses of the sea, associated with the bora, through the surface in the vicinity of the western coast of Novaya Zemlya, are noted. In the present paper, some features of the hydrodynamic regime of bora development are also considered. It should be noted that the work was based on data from the 11-year *Interim Arctic System Reanalysis (ASRI)* with a spatial resolution of 30 km. Generally speaking, it is not sufficient for a more detailed study of the spatiotemporal structure of the Novaya Zemlya bora.

The numerical calculations made in this work using the *WRF-ARW* model with a high spatial resolution of 1 km allowed to single out a small-scale bora structure, to estimate the features of the interaction of the air flow with the mountain ridge of Novaya Zemlya and perturbations introduced by the bora into the temperature field of the atmosphere over the eastern edge of the Barents Sea.

Numerical model. The known *WRF-ARW* regional model of atmospheric circulation [10] with the spatial resolution in the nested domains 1 × 1 km, 3 × 3 km and 9 × 9 km was used (Fig. 1). Twenty eight unevenly located vertical σ-levels with the increased resolution in the planetary boundary layer were specified. To compute the radiation balance of long- and short-wave radiation, the *RRTM* (*Rapid Radiative Transfer Model*) and *Dudhia's* parameterization schemes, respectively, were used; to compute the cumulus convection the *Kain-Fritsch* parameterization was used. To describe phase transitions in the atmosphere (microphysical processes), the *Single-Moment 3-class* scheme was used.

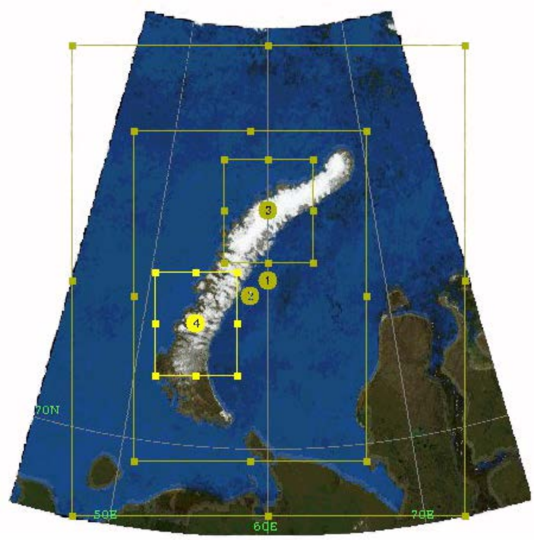

Fig. 1. Location of the domains to the bora computation

For the parameterization of the surface boundary layer the *MM5 similarity* scheme was used. The planetary boundary layer is parameterized using the Mellor–Yamada-Janjic scheme in the first two domains and by *YSU* (*Yon Sei University*) scheme in the last one. There the linear parabolic profile of vertical turbulent viscosity coefficient is defined. To take into account the sub-grid flows of momentum, heat and moisture that are not resoluted in the model, the parameterization of the counter-gradient flows is introduced, and the value of the entrainment flux is specified.

The data of *FNL (Global Final Analysis)* operational analysis with the resolution of 0.5 × 0.5° being updated every six hours were used as the input data for the external domain. After the adaptation of the model to the specified initial conditions, the development of atmospheric processes in all four domains was defined only by the periodically updating boundary conditions in the external domain.

Spatial structure of the bora. According to [9], in winter in the Barents Sea, the strong southeastern winds with speeds over 14 m/s have a fairly high frequency (~ 10 %). Therefore, several cases of such strong winds of the autumn-winter period lasting more than a day were singled out from the *FNL* operational reanalysis data array. Typical computed fields of speed and temperature related to the bora, i.e. to a strong southeastern wind on the western slope of the mountains, are considered below. The cases when the wind blows from the opposite, western or northwestern direction in winter, are additionally considered.

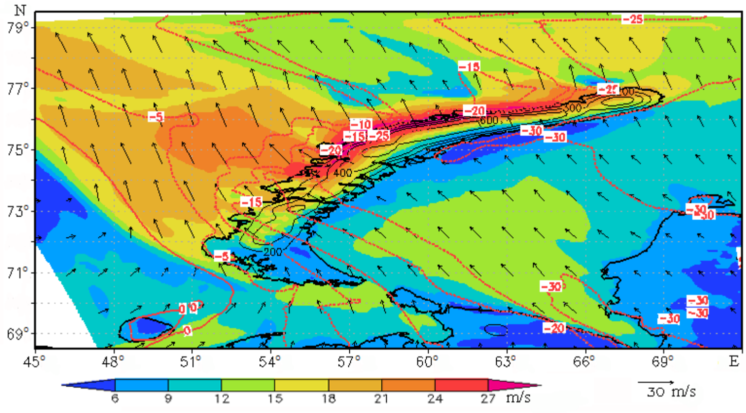

Fig. 2. Fields of the potential temperature θ at 2 m height and wind speed at 10 m height for 2 pm Dec 6, 2014 according to the computational data in the second domain (3 × 3 km resolution)

Based on the simulation results for the bora for the period December 6 – 7, 2014 the computed potential temperature of the atmosphere (θ) at 2 m height (for short hereinafter, the scale of the potential temperature is shifted: θ = θ(°K) – 273.15) and the wind speed vector (*U*10) at 10 m height are shown in Fig. 2. The main feature of θ distribution consists in low temperatures over the Kara Sea and on the eastern slopes of the mountains. At that, over the Barents Sea and above the western slopes of the mountains, the temperature is much higher (by 7 – 11°). This feature is typical for all terms of computation and, as it will be noted later, is essential for the Novaya Zemlya bora. At the western slope of the mountains and in the nearshore part of the Barents Sea, the area of great speeds of near-surface wind over 24 m/s had been formed. In addition, the wind speeds are not high over the eastern windward slope of the mountain range and in the nearshore area of the sea. And they are generally smaller over the Barents Sea than over the Kara Sea. Fig. 2 is based on the data from an external, large-scale domain with 3 km resolution, so the distribution and speed values do not reproduce the small-scale structure of the wind speed field over the mountains.

The distribution of wind speed *U*10 and temperature θ according to the internal domain data with 1 km resolution is shown in Fig. 3. The small-scale variability of the module and direction of wind speed, determined by the relief of the mountains, is well-represented. High speed values are distinguished on the leeward slope of the mountains (up to 35 m/s) and small ones on the windward slope, especially over the Kara Sea coast. The formation of the along-coastal current of air directed to the southwest with the velocities of ~ 6 – 10 m/s on the eastern windward slope of the mountains should be also noted. This is the result of air blocking on the windward slope: a baroclinic air stream running onto the mountains does not have enough kinetic energy to pass through them and, as a result, spreads along the ridge.

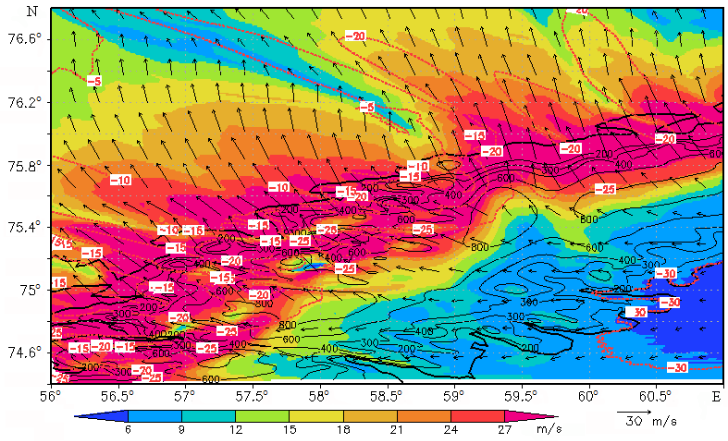

Fig. 3. Fields of the potential temperature θ at 2 m height and wind speed at 10 m height for 2 pm Dec 6, 2014 according to the computational data in the third domain (1 × 1 km resolution)

As is known, the Froude number Fr = *U/Nh* is the main parameter to set the regime of the air flowing around the mountain, where the vertical constants are as follows: *U* is the air flow velocity, *N* is the stability frequency and *h* is the height of the mountain. The barotropic stream freely flows around the mountain from above at any speed, the baroclinic one only at a speed of $U > Nh$ [11 – 13]. For variable height values of wind speed and stability frequency, this simple criterion becomes rather conditional. For significantly height varying and non-monotonous profiles of temperature and wind speed, the determination of such characteristic features of the air flowing around the mountain, as the blocking height on the windward slope and the formation of the critical layer, becomes possible only in numerical simulation [12, 13].

The blocking effect is well-presented in Fig. 4, showing the vertical structure of the speed and potential temperature at the meridional cross section along 59.5 °E through the mountain range, passing through the high-mountainous part of Novaya Zemlya. In the area of the atmosphere on the windward slope, the isotherms of the potential temperature are almost horizontal. Isotherms θ < 23° cross the windward slope – therein lies the blocking effect. On the leeward north-western slope a well-defined jet stream pressed to a slope is formed, which is actually the bora. Its speed reaches 40 m/s. Without considering the existing physical concepts of the mechanisms of the bora development, all the features that are taken into account in the construction of its analytical or numerical models are well-represented in Fig. 4 [13 – 16]. First of all, this is the formation of a critical layer – a turbulent region with vertical isotherms. In a fairly visual hydraulic model of the bora, the existence of such a region leads to a thickening of the flow lines and a sharp increase of the speed on the leeward slope [13].

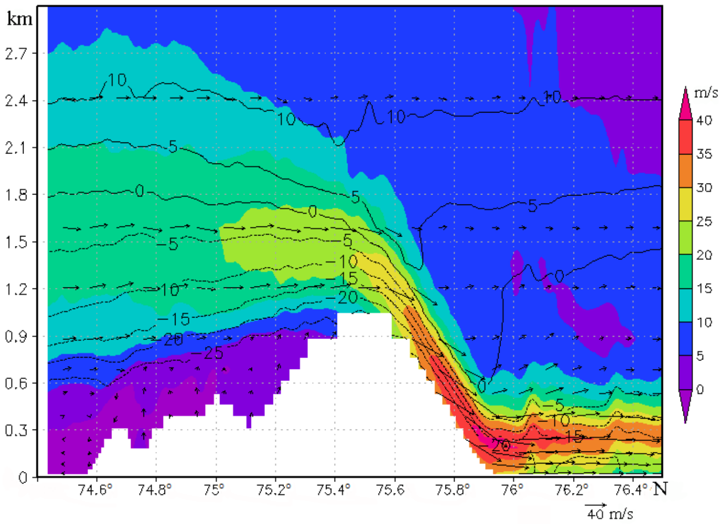

Fig. 4. The vertical structure of the wind speed fields (arrows) with the components (v; w·25), the potential temperature θ (isolines) and the v-component of the wind speed (color) at the meridional cross section along 59.5 °E for 2 pm Dec 6, 2014 according to the computational data in the third domain (1 × 1 km resolution)

An important consequence of the bora development is the formation of a relatively warm air area (in terms of potential temperature) over the leeward slope and in the near-surface atmosphere above the sea. Generally, the air temperature in the nearshore area above the Barents Sea in the layer up to 1 – 1.5 km is higher than the air temperature at the same altitudes above the Kara Sea by 8 – 20 °C. As a result, an interesting feature of the Novaya Zemlya bora development appears. It is a cloudless zone in the atmosphere above the Barents Sea in the high-mountainous region of Novaya Zemlya. This zone is regularly observed on satellite cloud images.

The strong stability of the air flowing on the mountains, which determines the blocking effect, is demonstrated in Fig. 5, showing the vertical temperature profile θ in the Kara Sea coast. A profile of the stability frequency N is also given, since before the windward slope it is the very determining factor for the bora development. As it can be seen, the N values for the heights of up to 1 km are ~ 0.025 – 0.085 s^{-1}, which is insufficient for the air flow to pass over the mountain ridge. Satellite images show that (December 6, 2014) there was no ice cover in the western part of the Kara Sea at this period (http://www.polarview.aq/sic/arctic/). Therefore, above the ice-free surface in the lower part of the atmosphere, a convective boundary layer was formed. However, its height was only 200 – 300 m, which did not change the overall picture: the flow did not pass over a mountain ridge having height of more than 1 km.

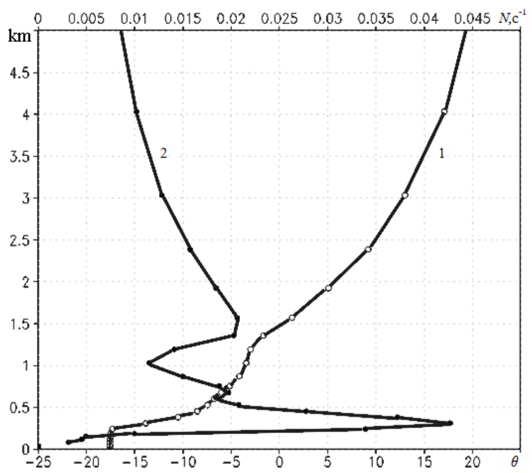

Fig. 5. The vertical structure of the potential temperature θ (*1*) and the frequency of stability *N* (*2*) in the Kara Sea nearshore area in the point of 77 °N, 59 °E for 2 pm Dec 6, 2014 according to the computational data in the third domain (1 × 1 km resolution)

Thus, it can be assumed that the principal condition for the bora development is the high stability of air in the lower atmosphere over the Kara Sea under the eastern and southeastern winds. As is known, stable stratification in the atmosphere is most common for the sea surface covered with ice that is typical for the Kara Sea in winter. Therefore, it is interesting to consider another case – flowing around Novaya Zemlya by the air flow with unstable stratification of the atmosphere boundary layer.

Below an opposite case to the bora, when the western wind is blowing on Novaya Zemlya, is considered. One of the numerous examples of that kind, referring to January 3, 2008, was reproduced. Unlike the Kara Sea, the Barents Sea was not covered with ice in this region, the water temperature was ~ 0 °C, and under positive air temperature values, a convective unstable, near-neutral atmospheric boundary layer was formed. The vertical profile of the potential temperature θ and the stability frequency *N* is shown in Fig. 6. There are significant differences from Fig. 5. Up to the height of about 1 km, the atmospheric boundary layer was close to neutral, the values of the stability frequency were small, $N \sim 0.01 - 0.013$ s^{-1}, and this ensured the wind passing over the mountain ridge. The vertical section along the zonal section along 59.5 °N (Fig. 7) shows that the speed and potential temperature fields have a simple form: the flowing around the ridge is a typical mountain wind (as in a mountain wind with Fr numbers > 1). The blocking of the air flow on the mountains is not observed. There are only linear gravitational internal waves over the mountain, no collapse of waves and the jet stream of the bora is not formed behind the mountain. The temperature in the atmospheric boundary layer before and behind the mountain is approximately the same. This has an important practical application and means that the ridge has little effect on the air flowing over it. Thus, as for the western wind, Novaya Zemlya is not a barrier separating the atmosphere lower layers between the Kara and Barents seas.

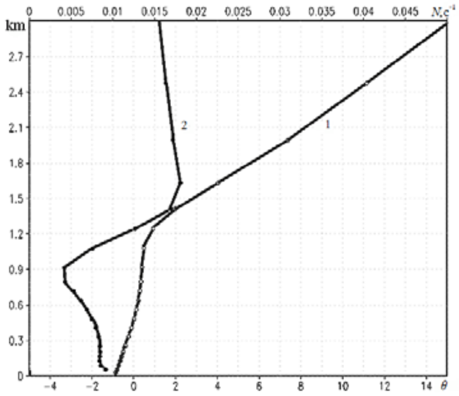

Fig. 6. The vertical profiles of the potential temperature θ (*1*) and the stability frequency *N* (*2*) in the Kara Sea nearshore area in the point of 77 °N, 55 °E for 3 pm Jan 3, 2008 according to the computational data in the fourth domain (1 × 1 km resolution)

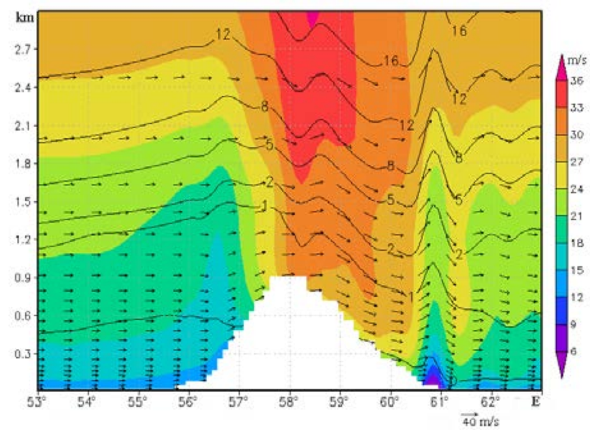

Fig. 7. The vertical structure of the wind speed fields (arrows) with the components (*v*; *w*·25), the potential temperature θ (isolines) and the *v*-component of the wind speed (color) at the zonal cross section along 75°N for 3 pm Jan 3, 2008 according to the computational data in the second domain (3 × 3 km resolution)

Conclusion. Numerical simulation of the atmospheric circulation in the region of Novaya Zemlya allowed to reproduce the structure of atmospheric fields for several cases of strong southeastern and western winds. Typical distribution of the wind speed and temperature fields, showing zones of maximum bora speeds in the region of the western coast of Novaya Zemlya and temperature contrasts between the Barents and Kara Seas is presented. It is shown that blocking of an air stream on the windward eastern slope of the mountains is followed by arising of a strong near-surface wind – the bora – on the western slope and in the nearshore area of the Barents Sea. As a result, in case of a bora the air temperature above the Barents Sea significantly exceeds that above the Kara Sea on the same heights.

An opposite case to the bora with the western wind is also considered. At that, a convective or weakly stable atmosphere boundary layer above the Barents Sea does not constitute a considerable block (by mountains) for a running stream which is one of the basic conditions of the bora development. Thus, as for the west wind, Novaya Zemlya is not a barrier separating the atmosphere lower layers between the Kara and Barents seas in winter in contrast to eastern or southeastern wind.

Acknowledgements. The research was carried out within the framework of State Order No. 0827-2015-0001 “Fundamental research of the processes in the ocean – atmosphere – lithosphere system determining spatial-temporal variability of the global and regional scale environment and climate”.

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