Atmospheric Disturbances in the Airflow around Mountains and the Problem of Flight Safety in the Mountains of the Republic of Adygeya

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Abstract
This article considers airflow around mountain systems as a meso-scale atmospheric phenomenon. It presents a non-linear stationary dimensional theoretical model of the airflow of the North-West Caucasus Mountains, taking into account characteristics of a real mountain terrain. The article further discusses the results of the calculations of the speed field of the airflow and general regularities of the origin and the scale of the rotary-wave deformation of the airflow over the mountains. The calculation results have shown that for the model scenario I at wind speed $U=15$ m/s the disturbances are the most intense over the ridge crests, where they are characterized by the zone with rotors. The total length of the rotor zone downwind is more than the length of its nucleus and is close enough in value to the extent of the lee part of the terrain (downwind from the main top). The area of maximum amplitudes is located in the windward side of the rotor zone. These amplitudes are several times higher than the maximum height of the mountains. For the model scenario II ($U=19$ m/s) wave disturbances slightly increased in length downwind, but minimally changed in amplitude. The rotary zone changed and moved downstream. The model scenario III ($U=22$ m/s) is accompanied by sharp transformation of the rotor zone. Closed vortices disappear; there is no purely vertical and backward motion. The flow over the mountain greatly smoothed, and the rotor area completely disappeared. Flight safety indicators over the mountains of the Republic of Adygeya for two types of aircrafts (light-engine and speed) were calculated on the basis of the obtained data. In certain conditions, flights for both high-speed and single-engine aircrafts can be considered dangerous.

Key words: Republic of Adygeya, atmospheric physics, hydrodynamics, internal gravity waves, flow over mountain systems, rotary-wave deformation, flight safety.

Introduction

Among meteorological phenomena that have a significant impact on the operation of aircraft, atmospheric turbulence causing intense aircraft bumpiness is one of the most dangerous. The main reason for air current turbulence is contrast in wind and temperature fields originating in the atmosphere (Wyngaard 2010). These contrasts create the following processes:

- airflow friction against the Earth surface;
- deformation of air currents by orographic obstacles;
- uneven heating of different parts of the underlying surface;
- cloud formation processes, which cause condensation heat separation and change the character of temperature and wind fields;
- interaction of air masses of different properties, at the borders of which horizontal gradients of temperature and wind are very pronounced;
- presence of atmospheric inversion layers where internal gravity waves can occur that lose stability under certain conditions.

All the processes listed above can operate simultaneously in the same or opposite direction and thereby increase or decrease the degree of atmospheric turbulence.

Orographic turbulence depends on the wind speed at the Earth surface, terrain unevenness, as well as on mutual disposition of the wind and ridge direction. Airflow gets deformed during the flow around mountain obstacles. The degree and nature of this deformation depends on the nature of the oncoming flow – its speed, direction, and temperature stratification, as well as on the ridge shape and dimensions (Wyngaard 2010).

Interaction between a moving air stream and terrain unevenness refers to medium-scale or local atmospheric processes. Atmospheric disturbances under consideration are of a wave nature. This is because the atmosphere is steadily stratified with respect to rapid vertical displacements of its particles and terrain unevenness affects the airflow as a driving force in an elastic medium. The resulting waves are an example of internal gravity waves. In case of mountain airflow, atmospheric disturbances can be classified as internal gravity waves of an orographic nature (Wyngaard 2010). They are characterized by spatial asymmetry, because they are observed only over the mountains and downstream of them. This is why they are usually called lee or mountain waves (Kozhevnikov 1999). In the recommendations of the International Civil Aviation Organization, strong mountain waves are included in the list of stormy weather events along the flight route.

Theory and field observations carried out in mountainous regions, showed great airflow disturbances in the flow around mountains (Kozhevnikov 1963). Vertical displacement of air particles are comparable to mountain heights, and may even significantly exceed them. Wave energy of orographic disturbances is comparable to kinetic energy of incident fluctation. It often exceeds the energy spent to overcome surface friction, which is taken into account in usual schemes of weather forecast. For this reason, we now see development of nonlinear models that do not take into account assumptions of small perturbation (Kozhevnikov 1999). With the development of numerical methods and computer technology it is now possible to more widely use the non-linear approach in solving problems of airflow over obstacles. This allowed for taking into account the shape of real mountains as a source of disturbances in the capacity of the lower boundary condition and obtaining numerical estimates for specific geographical areas (Kozhevnikov 1963; Kozhevnikov & Kozoderov 1970; Kozhevnikov, Pavlenko 1993; Kozhevnikov 1999; Kozhevnikov 2004).

**Geographical features of the Republic of Adygeya**

The Republic of Adygeya is located on the plains, in the foothills and in the mountains of the Greater Caucasus. The mountainous part of the Republic of Adygeya is presented by the system of the Great, the Front, the Lateral and the Rocky Ridges of the Greater Caucasus.

The Greater Caucasian Ridge borders the territory of the Republic from the south and consists of a system of echelon ridges with various absolute altitudes of 3–25 km in width. The main peaks of the Greater Caucasian Ridge within Adygeya are Chugush (3238 m) and Tybga (3064 m). These are the highest mountains of the Republic of Adygeya and they are located on the territory of the Caucasian State Wildlife Biosphere Reserve.

Lago-Naki Plateau with the average height 2000 m takes up the most part of the mountains of Adygeya (Fig. 1). It stretches from the north to the south and from the west to the east for about 40–45 km and includes the Murzikao Ridge, which comprises Abadzesh Mountain (2287 m), the Kamennyoe More (Stone Sea) Ridge, and the Nagoy-Chuk Ridge. The mountain group of Mount Fisht (2867 m) is the center of the mountainous part of Lago-Naki Plateau, which is a part of the Greater Caucasus Range. In the west, Mount Fisht joins the Pshekha-Su mountain mass (2743 m). The Oshten mountain mass (2804 m) is located to the north of Psheka-Su Mountain. Major orographic elements located outside the plateau are: the Lago-Naki Ridge, the Azish-Tau (Azishtau) Ridge and Chernogorje Plateau.
The Front Range is located to the north of the Greater Caucasus Range and stretches in the south-eastern direction outside Adygeya. The width of the Front Range varies between 5 and 15 km. Its length is more than 100 km. At the same time, it has soft and flat topography. The highest point of the Front Range within the Republic of Adygeya is Acheshbok Mountain (2486 m).

Between the Greater Caucasus Ridge and the Front Ridge lies the Lateral Ridge. On the territory of Adygeya it has Pshekish (2242 m) and Abago Mountains (2689 m), which are located in the Caucasus State Wildlife Biosphere Reserve.

The wind regime of the Republic of Adygeya depends on the orographic terrain. For example, in Dakhovskaya stanitsa, winds of the northern and southeastern directions prevail. In Guzeripl village, which is situated in the Belaya River Valley, there are mostly winds of the northern, northeastern, southern, and southwestern directions. A characteristic feature of the wind regime in mountain and foothill zones is the presence of mountain-valley winds.

In the Republic of Adygeya there is a high frequency of strong winds with the speed of more than 15 m/s. The average number of days with strong winds is between 13 and 20 days, and the maximum number of them in some years can vary between 36 and 68. The highest frequency of winds is recorded in early spring, specifically in February and March.
Material and Methods

The theoretical model (Kozhevnikov & Bedanokov 1993, 1998; Bedanokov et al. 2008; Bedanokov & Kobleva 2009), developed in the Maykop State Technological University, was used to investigate airflow disturbances in the flow around the Greater Caucasus Range in the Republic of Adygeya. The selected area of the Greater Caucasian Ridge (Mount Fisht) has two features: a sufficient probability of lee wave formation and a rather good justification for the use of a two-dimensional theoretical model.

The study began with the identification of the heights along the middle of the Greater Caucasus Range. This closely matches the direction from the northwest to the southeast. The airflow around the mountains, perpendicular to it, passes in the direction from the southwest to the northeast (shown as the dashed line in Fig. 1).

On the basis of the numerical terrain model of the Republic of Adygeya, the desired two-dimensional terrain was calculated. For this, real data of incident flotation in the Greater Caucasus Range area for August 2001 were used. They were obtained from nearby weather stations and by radiosonde stations, located practically on the windward and leeward side of the Greater Caucasian Ridge.

Results

Analysis of the airflow around Mount Fisht included several model scenarios. This chapter presents the results of three model scenarios.

The calculation results have shown that for the model scenario I at wind speed \( U=15 \) m/s (Fig. 2a) the disturbances are the most intense over the ridge crests, where they are characterized by a zone with rotors and extended portions of vertical movements. Lee-wave disturbances are strong enough just above and below this zone. The core of the rotor zone, where disturbances are especially large, is located in a region similar to a rectangle. The total length of the rotor zone downwind is more than the length of its nucleus and is close enough in value to the extent of the lee part of the terrain (downwind from the main top). The area of maximum amplitudes is located in the windward side of the rotor zone. These amplitudes are several times higher than the maximum height of the mountains. This phenomenon may depend both on the size of Lyra scale, shape and height of the mountains.

Such substantial disturbances suggest that a part of rotor disturbances obtained in the calculations can be transformed into high intensity turbulent zones in the nature. If there is a lack of moisture, these areas will manifest in clouds. Meteorologists call this phenomenon “clear air turbulence” (Astapenko et al. 1985).

Fig. 2b clearly shows that when Lyra scale was zoomed (model scenario II – \( U=19 \) m/s) lee-wave disturbances slightly increased in length along the wind, but little changed in amplitude. The rotary zone changed and moved downstream. The dimensions of the main part of this zone along the vertical increased approximately twice.

The model scenario III (\( U=22 \) m/s) is accompanied by sharp transformation of the rotor zone (Fig 2c). Closed vortices disappear; there is no purely vertical and especially backward motion. The flow over the mountain greatly smoothed, and the rotor area completely disappeared.

Discussion

Scientists have known about the flight danger in mountainous areas for a long time, and relevant data are used in practice when laying regular air routes. However, these studies rarely take into account the fact that aviation security depends essentially on the state of the atmosphere and on orographic features of the mountains. Even less often theoretical calculations are linked to the stability of flights of real airplanes (Nikolaev 1990; Kozhevnikov & Kozoderov 1970). The aircraft falls into a “special situation”, which is understood as a set of conditions that lead to reduction in flight safety due to environmental influences. Various hazard situations can occur in different meteorological processes: in conditions of intense turbulence, near fronts, near the surface layer, characterized by a strong wind speed shift, and so on (Nikolaev 1990). One of the first attempts to take into account all of these factors was made in the research (Kozhevnikov & Pavlenko 1993). This study analyzed flight safety in specific mountain regions, such as the
North Urals mountain mass, the Crimea peninsula mountain mass, the Kuznetsky Alatau mountain mass, the Dzhudgzhur mountain mass, and the Karatau mountain mass.

**Figure 2.** Pattern of the Mount Fisht airflow for the model (a) – scenario I ($U=15$ m/s), (b) – scenario II ($U=19$ m/s) and (c) – scenario III ($U=22$ m/s).
The results of the model calculations presented above can be used to determine the degree of danger of flights over the mountainous region of the Republic of Adygeya (Lago-Naki Plateau).

The decrease in the safety level in a steady horizontal flight in the zone of atmospheric disturbances may be due to two factors. The first one is the loss of stability due to a sharp increase in the angle of attack of the aircraft wing. This increase may exceed the maximum permissible value, which will cause the wing stall. As a result, the aircraft will start to “fall down”, that is, it will start to unpredictably fall and rotate. The exit out of this situation is only possible by reducing the angle of attack. The second factor is acceleration that occurs when an aircraft gets into a zone of abrupt change in the wind speed, especially of its vertical component. Loads on the load-carrying structures of an aircraft increase, passengers feel uncomfortable (Nikolaev 1990).

In the calculations, the field of perturbations of the trajectories of motion obtained from the flow simulation and the speed field data were used. Calculations were carried out for rotor zones, as the highest values of the vertical speed were forecasted specifically for them. Below are our calculations for the model scenario I, that is, for the case when the largest disturbances may be expected by visual assessment (Fig. 2a). Two variants of flights at an altitude of 7 km and 5 km were considered.

For a high-speed aircraft flight at an altitude of 7 km, results of calculations indicate slight turbulence and low hazard changes in the angle of attack.

In case of a flight at the altitude of 5 km, the situation worsens for both high-speed and single-engine planes. Increase in overloads for both types is not very noticeable, and bumping should not come out of the “weak” category. However, change in the angle of attack is more indicative. For a high-speed aircraft, these changes double compared to a flight at a higher altitude and reach 2.7 degrees. This may be considered as entering a dangerous situation. For a single-engine aircraft, change in the angle of attack can considerably exceed 6 and even 8 degrees, which is more than the maximum value of the maximum permissible increase in the angle of attack (Nikolaev 1990). The situation can be considered as reaching the critical level.

However, the obtained data on the angle of attack and vertical acceleration do not cover the whole problem of flight safety assessment over mountains. Let us consider in more detail the character of movements in the rotor zone in Fig. 2a. There are four rotors in the trajectory field, i.e., there are areas where both speed components abruptly change. At 4.5 km, there is one rotor formation and the air therein rotates counterclockwise. During a horizontal flight through such area, the plane will be affected by vertical movements of the atmosphere, which rapidly reverse sign. According to the instructions, when flying in such conditions, a pilot must use manual control, which means that his skills should be really advanced. The worst situation seems to be the case when an airplane, after falling into the descending stream, unexpectedly meets the ascending one.

In this case, a pilot focused on the need to increase the angle of attack in the zone of descending air stream, may miss the moment when the maneuver should be reversed. Because of this, he may not notice the excess of the permissible change of the angle of attack. At an altitude of 5 km (Fig. 2a), the most critical area appears to be the one from the first rotor to the second one. At an altitude of 4.5 km, the most critical area is the area in front of the rotor between the ascending and descending branches of the streamline with a height of 5 km in incidence flotation. The duration of a flight in these dangerous areas may be up to 1 sec (Kozhevnikov 1999).

This research analyzed the risks during the horizontal flight when a pilot does not perform maneuvers to change the height. In the case of such maneuvers, the risk of achieving the critical angle of attack may considerably increase.

The presented method of determining the danger level of flying over the mountains of the Republic of Adygeya is currently used in the Adygeya Republican Center of Hydrometeorology and Environmental Monitoring.

Conclusions

This research studied atmospheric disturbances in the flow of the mountains of the Republic of Adygeya. For this purpose, a hydrodynamic model of orographic disturbances of airflow was developed. This was done on the basis of the non-linear three-layer analytical model that takes into account layered gaps of stability. At the same time, it takes into account the vertical and horizontal infinity of the atmosphere. Two-dimensional
characteristics of the real mountains were determined from a geographical map and used in the calculations with high accuracy.

Model calculations were used to obtain motion trajectories and speed disturbance fields in the troposphere for the real range of Lyra scale values in the atmosphere. Flight safety over the considered mountainous region was assessed for two types of aircrafts using the obtained disturbances. Location of high-risk areas in the space over the mountains and the way they depend on the properties of incident flotation were determined. It is shown that in certain parts of the space this danger can be critical.

The danger level of orographic disturbances near the Earth’s surface for the mountains of the Republic of Adygeya was assessed for the first time.

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