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Regarding the Spontaneous Mechanism of Atmospheric Whirlwind Generation in Narrow Mountain Canyons

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ABSTRACT

In a narrow, rather deep mountain canyons, under certain conditions, an irregular thermal mechanism can be activated, leading to the spontaneous convective movement of the air mass. This effect differs from the well-known phenomenon caused by the diurnal variation of the solar heat flux in large, broad valleys, where the regular diurnal variation in the direction of onshore winds is systematically suppressed. A specific hydrodynamic picture corresponds to spontaneous convection. In particular, there is a change of direction (inversion) in the vertical profile of the horizontal movement of air along the slope of the canyon at a certain height. At that time, Ludwig Prandtl developed the theoretical model through which it is possible to analytically determine the level of velocity inversion compared to the base of the valley. At this height, due to the instability of the velocity profile, the formation of atmospheric vortexes of a certain size is likely. It is natural that the dissolution (dissipation) of such vortexes will affect the temperature field.Therefore, the breakup of whirlwinds is related to the violation of thermodynamic equilibrium, meaning that there will be an impulsive change in the meteorological regime in the local area due to the spontaneous turbulence of air masses in the areas of velocity inversion. The characteristic time of this event will depend on the duration of the temperature field disturbance. It is likely that such a location will become a dangerous opportunity for hang gliding or paragliding enthusiasts. It should be noted that this type of sport has become an important component of tourism in Georgia, particularly in the mountainous regions of the country. Therefore, there is a need to focus on ensuring the safe flight conditions of individual aircraft in narrow valleys. Their formation, among other measures, requires an assessment of the probability of the operation of a thermal mechanism causing stochastic atmospheric disturbances in narrow canyons. This task can be carried out only as a result of a special investigation, based on the monitoring of seasonal and short-term hourly indicators of the mentioned physical event in a specially selected canyon, which can be considered typical for the mountainous regions of Georgia.

Key woods: *vertical profile, velocity iinversion, turbulence, paragliding, narrow canyons.*

Introduction.

The Earth's atmosphere is a global, open thermodynamic system whose functioning is intricately determined by the sun. It comprises from regional and local subsystems, the existence of which is influenced by geographic factors. In mountainous regions, such as the Caucasus, these subsystems are manifested in local atmospheric configurations associated with narrow, relatively deep valleys interspersed between high ridges. While any physical system is only truly isolated in specific cases, the Earth's atmosphere, as a single, closed global system, maintains a continuous interaction with cosmic electromagnetic radiation and cosmic matter. In theory, an isolated system may exist in a thermodynamically unstable but mechanically balanced state for an extended period. Under certain conditions, a portion of the atmosphere in a mountainous region may be found in such a state, adhering to isolation criteria. These subsystems can sometimes be regarded as formations with stable thermodynamic characteristics. However, over time, their physical attributes, including the quantity of atmospheric particles, energy, temperature, and barotropic fields, inevitably undergo fluctuations under the influence of solar radiation.

A narrow, deep valley can be conceptualized as a channel through which the air mass flows.

It is known that, under calm atmospheric conditions, during specific periods of the year, both day and night, a disruptive convective movement of the regular air mass can occur along the ridges bordering any valley. For instance, a noteworthy example of such a low atmospheric flow is observed in the section of the Vere River valley from Bethany to Mtkvari River [1]. A suitable physical analogy for this canyon and others with similar orography is the disturbance of the slow laminar motion of the fluid caused by the interaction of relatively high walls in a rectangular channel. In the case of a canyon, as the height increases to 200-250 meters, the wind speed of concern also rises. However, its magnitude, reaching a maximum at a certain height, gradually decreases, leading to the so-called "inversion" level where the wind direction changes in the opposite direction. This effect is qualitatively similar, although potentially quantitatively different, in many narrow valleys. It is noteworthy that a convective effect similar to a spontaneously active disturbing heat source may regularly operate in some wide valleys, such as along the ridges bordering the Alazni River valley [2]. In the first case, the effect is spontaneous, occurring only rarely, while in the second case, it signifies the peculiarity of the action of a regular thermal mechanism, possibly related to the dimensions of the valley and the orography of its surface.

Under normal (calm) less cloudy natural conditions, in both cases, about half an hour after sunset, the wind flow on the mountainside takes place in the lower direction of the valley. In warm conditions, after sunrise, the wind continues to blow in the same direction for about an hour before changing from downslope to upslope. Under calm conditions, the minimum characteristic speed of such wind is (1 - 3) m/s [3]. The inversion of air mass convection speed should qualitatively develop in the same manner for all small mountain rivers. We consider the section of the Iori River valley between the extreme eastern part of the Saguramo-Ialno range and the extreme western end of the Gombor range as a suitable object for further research into this event. The choice of this canyon is due to the contrast in relief over a relatively small area: the highest place (mountain Ialno 1874 m.) and the lowest one River Iori bed at 700-750 m. This canyon overlooks the Iori Plateau, which experiences severe thermal overheating during the summer season. To the north is the Ertso depression, with an average height of 1000-1100 meters. Such a variety of terrain and landscapes determine the complexity of the formation of meteorological elements, making this place interesting for long-term research. Additionally, the Vere River canyon will be utilized for the research, where the inversion of convection speed can also be a frequent occurrence [4]. The mathematical model of this process belongs to the creator of the boundary layer theory L. Prandtl [3].

Prandtl's model.

According to Prandtl's model, the non-uniformity of the temperature field in the lower atmosphere is the cause of the inversion effect on the direction of air convection speed by the heat source in narrow canyons. There, this phenomenon is induced by the local orographic feature—the height of the ridges bordering the valley. Usually, the temperature of the surface of the mountain slopes in the canyon varies widely during the day and night, although air convection along the slopes of the valley occurs only under certain conditions.This analytical model is built on the basis of several simplifying assumptions. Specifically, only the developed convective movement in the vertical plane xz is considered (the x-axis is directed along the valley, z-vertically upwards). Due to the small linear scales of convective motion, the Coriolis effect is neglected. The slope of the mountain is inclined to the horizon at a rather small angle α. Directly along the ridge, there is no place for the formation of convection currents because the air mass moving at a low speed does not stop at its surface; the movement is so slow that acceleration can be neglected. Accordingly, the mathematical basis of the model consists of the simplified equations of motion (the same signs as in [3] are used)

$$\frac{\partial p}{\partial x} = \eta \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2}\right), \qquad (1)$$

$$\frac{\partial p}{\partial z} = \eta\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial z^2}\right) - g\rho, \qquad (2)$$

where p is the pressure, u and w are the horizontal and vertical components of the velocity, η- is the coefficient of turbulent viscosity, and g is the acceleration due to gravity. The temperature in the free atmosphere is assumed to increase linearly with height, and the heating slope introduces a perturbation that is a function of height.

Through ingenious mathematical transformations, in the approximation of a weakly turbulent atmosphere, where the coefficients of temperature transfer and kinematic viscosity can be assumed to be equal to each other, Prandtl demonstrated the relationship of the boundary layer on the canyon slope to the perturbation of the temperature field. In particular, as the temperature θ in the free atmosphere increases linearly with height, and the surface of the ridge slope introduces a small perturbation θ' into the temperature field, the keystone equation of the model was obtained

$$\frac{\partial^4 \theta'(n)}{\partial n^4} + \frac{g\beta B \sin^2\alpha}{\nu^2}\theta'(n) = 0, \qquad (3)$$

Where n- is the height calculated from the slope of the canyon, β- is the coefficient of temperature expansion of air, $B = const$ - is the vertical temperature gradient, and ν is the coefficient of kinematic viscosity of air. Due to physical considerations, Prandtl used only one of the solutions of equation (3)

$$\theta' = \theta'_0 \exp\left(-\frac{n}{L}\right)\cos\frac{n}{L}, \qquad (4)$$

which satisfies the following boundary conditions [3]

$$\theta' = \theta'_0, \quad \text{when } n = 0; \quad \theta' = 0, \quad \text{when } n = \infty. \qquad (5)$$

The characteristic in the form of a vertical scale, in (4), represents the height corresponding to the maximum convection speed, which depends on the environmental parameters

$$L = \sqrt[4]{\frac{4\nu^2}{g\beta B \sin^2\alpha}} \ . \qquad (6)$$

According to Prandtl, the disturbance of the temperature field along the slope of the canyon leads to the convective movement of the air mass (disturbance), the speed of which is determined by the expression

$$V_1 = \theta'_0\sqrt{\frac{g\beta}{B}} \exp\left(-\frac{n}{L}\right)\sin\frac{n}{L} \ . \qquad (7)$$

The formula (7) image provides a vertical profile of the convective movement speed. An inversion point (level) the speed changes direction (Fig.1). This concept can be envisioned as an abstraction of a tangential-discontinuity surface, where a velocity shift occurs, serving as a prerequisite for the development of Kelvin-Helmholtz or Rayleigh-Taylor hydrodynamic instability in a liquid (gas) medium. Fig.1 displays the vertical profile of convection velocity for a typical set of atmospheric parameters. The velocity profile, in addition to the inversion point, also includes the inflection point (V_{max}), where the development of hydrodynamic instability and the generation of atmospheric vortices are also possible.

Therefore, in the Prandtl model, the height of the velocity maximum is $n_m = \frac{L\pi}{4}$. The height of the inversion level corresponding to the first minimum of the trigonometric function ($n_m = \pi L$) are clearly defined. But we contend that the utilization of only one specific solution of equation (3) confines the potential of the Prandtl model as a tool for representing real atmospheric phenomena. Embracing the principle of synergy, the physical depiction becomes more comprehensive when considering the time-varying impact of boundary conditions, a characteristic generally inherent in atmospheric processes. This approach is recognized for enabling substantial quantitative corrections in long-term prognostic meteorological tasks. The variation of boundary conditions is anticipated to be beneficial in modeling short-term local atmospheric processes. For instance, the disturbance of the temperature field in the lower part of the Vere River Canyon, which traverses Tbilisi, is expected to be influenced not only by natural factors but also by anthropogenic pressure [4].

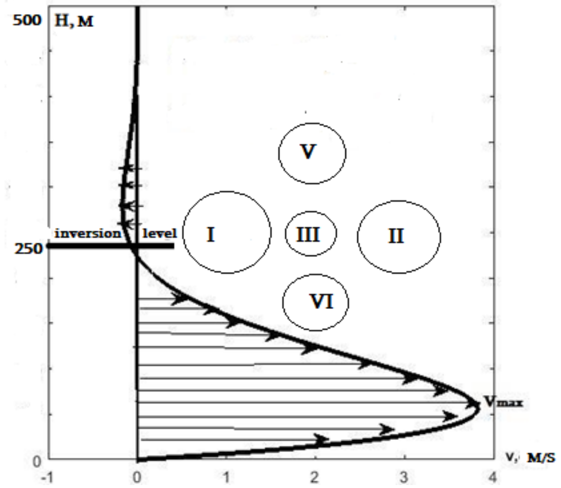

Fig. 1. Convection speed profile and atmospheric vortexes.

Therefore, to account for the urban effect on the local temperature field within the Prandtl model, a different pair of boundary conditions, distinct from (4), was employed

$$\theta' = \theta'_0 \ , \quad \text{when } n = 0 \ ; \qquad \theta' = \infty, \quad \text{when } n = \infty. \qquad (8)$$

These boundary conditions are met by the specific solution of equation (3), which also encompasses the inversion effect, and (4) differs from the image only by the sign of the power of the exponential multiplier

$$\theta' = \theta'_0 \exp\left(\frac{n}{L}\right)\cos\frac{n}{L} \ , \qquad (9)$$

to which the velocity profile also corresponds, differing from the profile in image (7)

$$V_2 = -\theta'_0\sqrt{\frac{g\beta}{B}}\exp\left(\frac{n}{L}\right)\sin\frac{n}{L} \ . \qquad (10)$$

In this case, the velocity inversion event will occur at the height $n_m = \frac{3L\pi}{4}$. Additionally, the vertical profile of convection speed will be different. Naturally, the combination of both solutions results in a change in the level of velocity inversion. However, it should be noted that, since a different model of temperature field change was used to derive equation (1), an apparent contradiction has emerged. In particular, the boundary condition (8) formally allows an unlimited increase in temperature with the increase in height

$$\theta = \theta_0 + Bz + \theta'(n). \qquad (11)$$

Therefore, it is logical to ask: Does a solution to the Prandtl problem have practical value when its asymptotic behavior does not satisfy the condition of the tube disturbance of the temperature field as height increase? It should be considered that the validity of the boundary conditions (8), like (5), is limited to small heights. If this condition is satisfied, the value of the Prandtl model as a mathematical abstraction of a physical process is further enhanced by incorporating another specific solution to equation (3).

Temperature Field Considerations. Kinematic Model of Atmospheric Wortex.

The vertical profile of the convection speed exhibits a critical point, enhancing the likelihood of Kelvin-Helmholtz hydrodynamic instability development at the inversion level. This results in the formation of atmospheric eddies, whose decay is associated with Rayleigh-Taylor instability. Consequently, mechanical energy transforms into thermal energy, leading to the disturbance of the temperature field in the inversion area. This factor may contribute to the disturbance of the locally balanced, but unstable, thermodynamic state. During the process of restoration, a change in the meteorological regime in the valley becomes possible, with the characteristic duration depending on the nature of the disturbance of the temperature field. In cases of strong turbulence, this process can be nonlinear, as the disturbance of the temperature field in the area of velocity inversion may trigger the "dynamo-effect," an impulsive strengthening of turbulence. Given that the generation of a chain of eddies should occur in a specific direction within limited space, the structure of the temperature field in the area of velocity inversion is likely to be non-uniform and asymmetric. In the hydrodynamic approximation, this effect can be modeled using the temperature conduction equation [5].

To simplify the mathematical problem, let's consider a stationary atmospheric vortex of cylindrical or spherical shape. In the case of a cylinder, its symmetry axis is collinear with the x-coordinate. Let's examine the intersection of the vortex with the xz plane and utilize the polar coordinate system, where the stationary equation for temperature conduction takes the following form

$$V_r \frac{\partial \overline{T}}{\partial r} + V_\varphi \frac{1}{r}\frac{\partial \overline{T}}{\partial \varphi} = \eta \left[\frac{1}{r^2}\frac{\partial^2 \overline{T}}{\partial \varphi^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial \overline{T}}{\partial r} \right) \right], \tag{12}$$

where $\overline{T}$ - is the temperature, η -is the temperature conductivity coefficient, V_r ,V_φ - are the radial and azimuthal components of velocity.

Assuming that the perturbation of the temperature field depends linearly on the radial coordinate: $\overline{T} = \frac{r}{R_0} T(\varphi) + T_0$, where T_0 - is a constant on the vortex boundary: $r=R_0$ for any φ. Such a representation of the search function allows us to use the so-called separation method of variables to solve (12) in the Karman scheme. Since we will observe the cross-section of the unstable vortex with the directed plane of its axis, the following kinematic model of non-uniform rotation is suitable to represent the velocity field [6]

$$V_r = \frac{1}{2} u_0 \left(\frac{r}{R_0} \right) (\cos\varphi + \sin\varphi),\ V_\varphi = u_0 \left(\frac{r}{R_0} \right) (cos\,\varphi - sin\varphi). \tag{13}$$

where u_0- is the characteristic linear speed of rotation.

Model (13) satisfies the environmental continuity equation and offers a correct scheme for the decomposition of an unstable vortex [6]. Utilizing this model, (12) is transformed into a non-linear equation

$$\frac{d^2 T}{d\varphi^2} - \frac{u_0 r^2}{\kappa R_0}(\cos\varphi - \sin\varphi)\frac{dT}{d\varphi} = -\left[1 - \frac{u_0 r^2}{2\kappa R_0}(\cos\varphi + \sin\varphi) \right] T\,. \tag{14}$$

The equation (14) involves an non dimensional combination: $\delta = \frac{u_0 r^2}{\kappa R_0}$, which, like the parameters Reynolds number and Prandtl number, can be referred to as the criterion of thermohydrodynamic similarity. This implies that, owing to the presence of this characteristic, the solution of equation (14) is universal within certain limits for vortexes with different sizes and speeds.

Equation (14) belongs to the type of second-order differential equations with variable coefficients

$$y'' + f(\varphi)y' + g(\varphi)y = 0\,. \tag{15}$$

In general, obtaining an analytical solution for equation (15) is challenging due to its non-linear nature, making approximate solutions more feasible. Depending on the nature of the problem, various simplifying assumptions are employed. One such assumption is embodied in the kinematic model (13), allowing the representation of the velocity field without explicitly solving the equation of motion. For instance, in a paper [5] modeling the temperature field in the polar ionosphere, the kinematic model (13) facilitated the use of the Wetzel-Kramer-Brillouin (VKB) method to approximate the solution of equation (14). It is known that equation (15), by introducing a new variable

$$y = z(\varphi)\cdot p(\varphi), \tag{16}$$

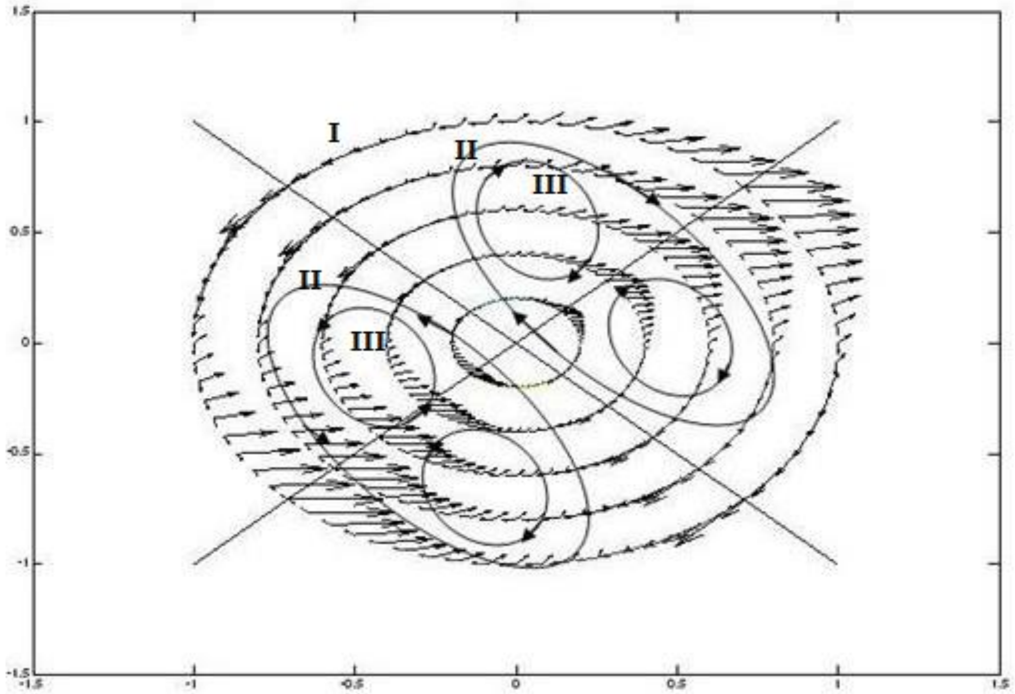

Fig. 2. The dissipation of normalized vortex according to the non-uniform rotation model.

can be transformed into an oscillation equation with a variable coefficient [7]

$$\frac{d^2 z}{d\varphi^2} + h(\varphi)z=0, \tag{17}$$

Where $h(\varphi) = \dfrac{P'' + fP' + gP}{P}$,

$$P = e^{-\frac{1}{2}\int f(x)dx}, P' = -\frac{1}{2} fe^{-\frac{1}{2}\int f(x)dx}, P'' = -\frac{1}{2} f' e^{-\frac{1}{2}\int f(x)dx} + \frac{1}{4} f^2 e^{-\frac{1}{2}\int f(x)dx}. \tag{18}$$

The prime in formulas (18) signifiers the derivative by φ. Particularly in case the equation (14) we will have

$$P = e^{-\frac{1}{2}\int f\varphi d\varphi}, \; f(\varphi) = \delta(\sin\varphi - \cos\varphi), \; h = 1 - \frac{\delta^2}{4}(1-\sin 2\varphi) - \frac{3\delta}{4}(\cos\varphi + \sin\varphi). \tag{19}$$

The solution of equation (17) obtained by the VKB method is accurate when $\delta < 1$ and $h > 0$, which does not qualitatively limit the value of the model in terms of its physical significance [7]. However, depending on the boundary conditions of the problem, the approximate analytical solution can take different forms.

Let's estimate the value of the parameter δ, for which we use the maximum characteristic speed of atmospheric convection related to the action of the spontaneous heat source: V_0 = (3-5) m/s and the value of the air temperature conductivity coefficient at normal atmospheric temperature $\eta \approx 2.10^{-5}$ m^2/s. For example, suppose that the initial size of the atmospheric vortex generated in the area of velocity inversion is: $R_0 \approx$ 10m and the characteristic size of small vortex cells obtained after its decay is: $r \approx 5.10^{-3}$ m. In such a case, we will have: $\delta \approx$/0.4-0.6/, which means that the first criterion for using the VKB method is satisfied. For such values of the parameter δ, in any φ case, the second criterion is also satisfied- $h > 0$. Thus, assuming that the initial temperature of the air at the boundary of the atmospheric vortex T_0 =const, the approximate analytical solution of equation (14) for the dimensionless temperature: $T' = \bar{T}/T_0$ in general can be represented by the following expression

$$T' = 2\frac{r}{R_0}\left(\frac{e^{-\frac{1}{2}\int f d\varphi}}{h^{1/4}}\cos\left(\int\sqrt{h}d\varphi\right)\right)+1. \quad (20)$$

The formula (20) provides a reasonably accurate model representation of the asymmetric temperature field, qualitatively capturing the dissipative nature of the process of disintegration of non-uniform atmospheric vortexes.

Conclusion

1. According to the formula (20), local change of the structure of atmospheric movement should be accompanied by a perturbation of the atmospheric temperature field, the scale of which should depend on the size of the velocity inversion. This observation is crucial for determining the approximate time and thermodynamic conditions of the generation of gyral formations in narrow canyons, with potential implications for the safety of activities like hang gliding or paragliding. To meet this demand, it becomes essential to assess the probability of the development of dangerous atmospheric events characteristic of narrow deep canyons, particularly referring to the convective movement of air caused by the action of an irregular heat source, which can be the reason for the generation of gyral formations.

2. Monitoring conducted under natural conditions demonstrates the effectiveness of the Prandtl model and its modification, theoretically allowing the formation of atmospheric vortexes at the level of convection velocity inversion. The kinematic model of non-uniform rotation provides a qualitative representation of the mechanism of the process of generation and decay of atmospheric vortexes. With its help, the disturbance of the atmospheric temperature field can be modeled using a specific solution of the temperature conduction equation.

3. Beyond theoretical interpretation, there is a natural need to quantify the results of the spontaneous convection effect in the canyons. Long-term monitoring of atmospheric vortexes and temperature fields in a specific canyon, such as the section of the Iori River valley between the extreme eastern part of the Saguramo-Ialno ridge and the extreme western end of the Gombor ridge, is expected to contribute to solving this task.

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რეზიუმე

ვიწრო, საკმაოდ ღრმა მთის ხეობებში (კანიონებში) გარკვეულ პირობებში შეიძლება ამოქმედდეს არარეგულარული სითბური მექანიზმი, რომელიც გამოიწვევს ჰაერის მასის სპონტანურ კონვექციურ მოძრაობას. ეს ეფექტი განსხვავებულია კარგად ცნობილი ეფექტისაგან, რომელსაც იწვევს მზის სითბური ნაკადის დღეღამური ცვლილება დიდ, ფართო ხეობებში, სადაც სისტემატურად დაიმზირება მიწისპირა ქარების მიმართულების რეგულარული დღეღამური ცვლილება. კერძოდ, კანიონის ფერდის გასწვრივ ჰაერის ჰორიზონტალური გადაადგილების სიჩქარის ვერტიკალურ პროფილში გარკვეულ სიმაღლეზე ადგილი აქვს მიმართულების ცვლილებას (ინვერსია). ლუდვიგ პრანდტლის მიერ აგებული იყო თეორიული მოდელი, რომლის საშუალებით შესაძლებელია ანალიზურად განისაზღვროს სიჩქარის ინვერსიის დონე ხეობის ფუძესთან შედარებით. ამ სიმაღლეზე, სიჩქარის პროფილის არამდგრადობის გამო, სავარაუდოა გარკვეული ზომის ატმოსფერული გრიგალების წარმოქმნა. ბუნებრივია, რომ ასეთი გრიგალების დაშლა (დისიპაცია) გამოიწვევს ტემპერატურული ველის შეშფოთებას. ამიტომ, გრიგალების დაშლა დაკავშირებულია თერმოდინამიკური წონასწორობის დარღვევასთან, რაც თვისობრივად ნიშნავს, რომ ლოკალურ არეში მოხდება მეტეოროლოგიური რეჟიმის იმპულსური ცვლილება, სიჩქარის ინვერსიის ადგილებში ჰაერის მასების სპონტანური ტურბულიზაციის გამო. სავარაუდოა, რომ ასეთი ადგილები სახიფათო შეიძლება გახდეს დელტაპლანით ან პარაპლანით ფრენის მოყვარულთათვის. ამიტომ, არსებობს აუცილებლობა ყურადღება გამახვილდეს ვიწრო კანონებში ინდივიდუალური საფრენი აპარატების უხიფათოდ ფრენის პირობების უზრუნველყოფაზე. ამ ამოცანის განხორციელება შესაძლებელია მხოლოდ სპეციალური გამოკვლევის შედეგად ისეთ კანიონში, რომელიც თავისი მახასიათებლებით ტიპიურად შეიძლება ჩავთვალოთ საქართველოს მთიანი რეგიონებისათვის.

საკვანძო სიტყვები: ვერტიკალური პროფილი, სიჩქარის ინვერსია, ტურბულენტობა, პარაპლანერიზმი, ვიწრო კანიონები

О спонтанном механизме генерации атмосферных вихрей в узких горных ущельях

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Резюме

В узких, достаточно глубоких, горных ущельях (каньонах) в определенных условиях может придти в действие нерегулярный тепловой механизм, который может вызвать спонтанную конвекцию воздушных масс. Это явление отличается от хорошо известного эффекта, который считается следствием суточного изменения солнечного теплового потока в больших, широких, ущельях, в которых систематически наблюдаются регулярные изменения направления приземных ветров в течение суток. В частности, вдоль склона ущелья в вертикальном профиле на определенной высоте может иметь место изменение направления горизонтальной составляющей скорости ветра (инверсия). Людвиг Прандтль построил теоретическую модель, при помощи которой можно аналитически определить высоту уровня инверсии относительно основания ущелья. На этой высоте, из-за неустойчивости профиля скорости, существует вероятность возникновения атмосферных вихрей различных размеров. Естественно, что распад этих вихрей (диссипация) будет возмущать температурное поле, с которым будет связано нарушение термодинамической устойчивости. На качественном уровне это означает, что в области инверсии скорости возможно локальное изменение метеорологического режима из–за спонтанной турбулизации воздушных масс. Можно предполагать, что такие места могут стать опасными для любителей полетов на парапланах и дельтапланах. Поэтому, существует необходимость обращения должного внимания на обеспечение условий безопасности полетов на индивидуальных летательных аппаратах в узких ущельях. Реализация такой задачи возможна лишь после специальных исследований в одном из ущельи, характеристики которого можно считать типичными для горных регионов Грузии.

Ключевые слова: вертикальный профиль, инверсия скорости, турбулентность, парапланеризм, узкие каньоны.