საქართველოს მეცნიერებათა ეროვნული აკადემიის მოამბე, ტ. 7, №2, 2013
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 7, no. 2, 2013

Geophysics

A Modeling Study of Meso-Scale Air Flow Over the Mountainous Relief with Variable-in-Time Large-Scale Background Flow

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ABSTRACT. The paper presents the numerical investigation of some orographic effects in the troposphere taking place in conditions of nonstationarity of large-scale undisturbed background air flow. With this purpose a 3-D hydrostatic nonstationary model of meso-scale atmospheric processes is used. The upper boundary of the calculated domain is simulated by the free surface and on the lower boundary the condition of slipping of air particles has been used along the relief. The problem is solved numerically by the two-step Lax-Wendroff method. Performed numerical experiments in case of both model and real relief of Georgia have promoted some regularities of orographic effects caused by the non-stationary character of the background flow. *© 2013 Bull. Georg. Natl. Acad. Sci.*

Key words: *numerical simulation, orographic effects, nonstationary flow, troposphere, system of equations.*

It is well known that large-scale (synoptic) atmospheric processes have nonstationary character and alternation of different circulating modes permanently takes place in the atmosphere. Clearly, the question arises as to how the meso-scale flow over the complex terrain responds to the variability of large-scale processes. Such investigations were partially performed in [1, 2] in the framework of the 2-D hydrostatic model.

The main goal of this paper is to investigate numerically the influence of nonstationarity of the large-scale background flow on the structure of disturbed mesoscale flow in the troposphere over the orographically inhomogeneous Earth's surface. To achieve the specified goal, we used a 3-D hydrostatic nonstationary model of meso-scale atmospheric processes for "dry atmosphere" [3, 4].

Description of the Model

Let us consider moving air masses in the troposphere, which from below is limited by orographically inhomogeneous underlying earth's surface $\delta(x, y)$, and from above, at height of the tropopause by the free surface

$H(x,y,t)$, changeability of which is defined during integration of the model equations. At the first stage we shall neglect the condensation and radiation processes in the atmosphere.

According to the ideas offered in [5, 6], using simplifications of the free convection theory, the problem is formulated in terms of a deviation from the background values of meteorological parameters. After transition from Cartesian coordinate system (x, y, z) (the axes x, y and z are directed eastward, northward and vertically upward, respectively) to the terrain-following system x_1, y_1, ζ, where

$$x_1 = x,\ y_1 = y,\ \zeta = \frac{z - \delta(x,y)}{h(x,y,t)},$$
$$h = H(x,y,t) - \delta(x,y)$$

the model equation system has the following form:

$$\frac{du}{dt} = -\Theta_0 \frac{\partial \varphi'}{\partial x} + \lambda \vartheta' \left(\zeta \frac{\partial h}{\partial x} + \frac{\partial \delta}{\partial x} \right) + l\,\mathrm{v} + \mu \Delta u + F_u, \tag{1}$$

$$\frac{d\,\mathrm{v}}{dt} = -\Theta_0 \frac{\partial \varphi'}{\partial y} + \lambda \vartheta' \left(\zeta \frac{\partial h}{\partial y} + \frac{\partial \delta}{\partial y} \right) - lu + \mu \Delta \mathrm{v} + F_v, \tag{2}$$

$$\Theta_0 \frac{\partial \varphi'}{\partial \zeta} = \lambda \vartheta' h,\ \varphi = c_p (p/1000)^{R/C_p}, \tag{3}$$

$$\frac{d\,\vartheta'}{dt} + Sw = \mu \Delta \vartheta' - u' \frac{\partial \Theta}{\partial x} - \mathrm{v}' \frac{\partial \Theta}{\partial y}, \tag{4}$$

$$\frac{\partial h}{\partial t} = e^{\sigma h} \int_0^1 E\, e^{-\sigma h \zeta} d\zeta, \qquad \tilde{w} = \frac{1}{h} \left[e^{\sigma h \zeta} \int_0^{\zeta} E e^{-\sigma h \zeta} d\zeta - \zeta\, e^{\sigma h} \int_0^1 E\, e^{-\sigma h \zeta} d\zeta \right], \tag{5}$$

$$w = \zeta \frac{\partial h}{\partial t} + u \left(\zeta \frac{\partial h}{\partial x} + \frac{\partial \delta}{\partial x} \right) + \mathrm{v} \left(\zeta \frac{\partial h}{\partial y} + \frac{\partial \delta}{\partial y} \right) + \tilde{w} h \tag{6}$$

$$E(x,y,t) = \sigma u h \left(\zeta \frac{\partial h}{\partial x} + \frac{\partial \delta}{\partial x} \right) + \sigma \mathrm{v} h \left(\zeta \frac{\partial h}{\partial y} + \frac{\partial \delta}{\partial y} \right) - \frac{\partial u h}{\partial x} - \frac{\partial \mathrm{v} h}{\partial y} \tag{7}$$

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + \mathrm{v} \frac{\partial}{\partial y} + \tilde{w} \frac{\partial}{\partial \varsigma},\ \Delta = \frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2}$$

$$u = U + u',\ \mathrm{v} = \mathrm{V} + v',\ \mathrm{w} = w',\ \vartheta = \Theta + \vartheta',\ \varphi = \Phi + \varphi',\ F_u = -lV + \frac{\partial U}{\partial t},\ F_v = lU + \frac{\partial V}{\partial t},\ \mathrm{S} = \frac{\partial \Theta}{\partial z},$$

$$\frac{\partial \Theta}{\partial x} = \frac{l}{\lambda} \frac{\partial V}{\partial z},\ \frac{\partial \Theta}{\partial y} = -\frac{l}{\lambda} \frac{\partial U}{\partial z}.$$

Here the following notations are used: u, v and w are the air velocity components in the Cartesian coordinate system along the axes x, y and z, respectively; $\tilde{w}$ is the analogue of the velocity vertical component in the terrain-following coordinate system; ϑ' and φ' are deviations of the potential temperature and analogue of the pressure from the corresponding background values Θ and Φ, respectivally; U and V are the background velocity components along the axes x, y, respectively; g, Θ_0, l are the gravitational acceleration, the average potential temperature and the Coriolis parameter, respectively; c_P, R, λ are the specific heat capacity at constant pressure P, the gas constant for dry air and the buoyancy parameter; σ is the parameter describing reduction of the density with height; F_u and F_v are given functions of time and space describing the influence of the large-scale synoptic process on the meso-scale process.

The equation system (1-7) is solved under the following boundary and initial conditions :

$$\tilde{w} = 0\,,\ \left(w = u\frac{\partial\delta}{\partial x} + v\frac{\partial\delta}{\partial y}, z = \delta(x,y) \right) \ \text{if}\ \varsigma = 0\,, \tag{8}$$

$$\tilde{w} = 0\ \left(w = \frac{\partial H}{\partial t} + u\frac{\partial H}{\partial x} + \mathrm{v}\frac{\partial H}{\partial y},\ z = \delta(x,y) \right), \quad \varphi' = 0, \quad \text{if}\ \varsigma = 1, \tag{9}$$

$$\frac{\partial u}{\partial x} = 0,\ \ \frac{\partial v}{\partial x} = 0,\ \ \frac{\partial \vartheta'}{\partial x} = 0,\ \ \frac{\partial h}{\partial x} = 0,\ \ \text{if}\ x = 0, L_x, \tag{10}$$

$$\frac{\partial u}{\partial y} = 0,\ \ \frac{\partial v}{\partial y} = 0,\ \ \frac{\partial \vartheta'}{\partial y} = 0,\ \ \frac{\partial h}{\partial y} = 0,\ \ \text{if}\ y = 0,\ L_y, \tag{11}$$

$$u = u^0,\ \mathrm{v} = \mathrm{v}^0, \vartheta' = \vartheta'^0,\ h = H_0 - \delta\ (x,y)\ \ \text{if}\ t = 0, \tag{12}$$

where H_0 is the initial height of the free surface; L_x and L_y are horizontal scales of the calculated domain along x and y, respectively. The basic requirement to the lateral conditions (10) and (11) consists in that they should provide passing of perturbations, generated inside the solution domain, through lateral boundaries without essential reflection.

The equations (5) for definition $\tilde{w}$ and h are obtained from the continuity equation

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial \mathrm{v}h}{\partial y} + \frac{\partial \tilde{w}h}{\partial z} = \sigma\, wh\,,$$

with use of boundary conditions (8) and (9) for $\tilde{w}$.

Thus, the problem is reduced to solution of the equations (1)-(7) with use of the boundary and initial conditions (8)-(12) in the rectangular parallelepiped $M(0 \le \varsigma \le 1,\ \ 0 \le x \le L_x, 0 \le y \le L_y)$. The problem is solved numerically by the two-step Lax-Wendroff method [7].

Numerical Experiments

Before carrying out numerical experiments on simulation of air flow over the real relief, we have considered the air flow over the isolated obstacle of a circular form. The obstacle was given by formula

$$\delta(x,y) = \begin{cases} a_0(1 - r^2/r^2{}_0)^3, & r = \sqrt{(x-x_0)^2 + (y-y_0)^2} \le r_0 \\ 0, & r > r_0, \end{cases},$$

where a_0 and r_0 are maximum heights and half-width of the obstacle, x_0 and y_0 are the horizontal coordinates of the top.

On a vertical 21 levels were taken by regular vertical steps $\Delta\varsigma = 0.05$. On each level there were 46 x 66 grid points with a grid step 10 km. Other parameters had the following numerical values: a_0=1 km, r_0=75 km, H_0 = 12 km, $S = 0.003\,K/m$, σ = 10^{-4} m^{-1}, l = 10^{-4} s^{-1}, λ = 0.033 m/s^2K, $\Theta_0 = 300K$. The time step $\Delta t = 60$ s.

In the numerical experiments with the real relief of Georgia and its vicinities taken into consideration the solution domain with horizontal sizes 830 x 690 km was covered with a grid having 30 levels on a vertical and 84 x 70 points on each horizons. The other parameters were the same as in the previous case.

In Fig.1 the heights of the relief of Georgia and its vicinities (counted from sea level) used in numerical experiments are shown, from which it is well visible that the territory of Georgia is characterized by rather complex and original orography.

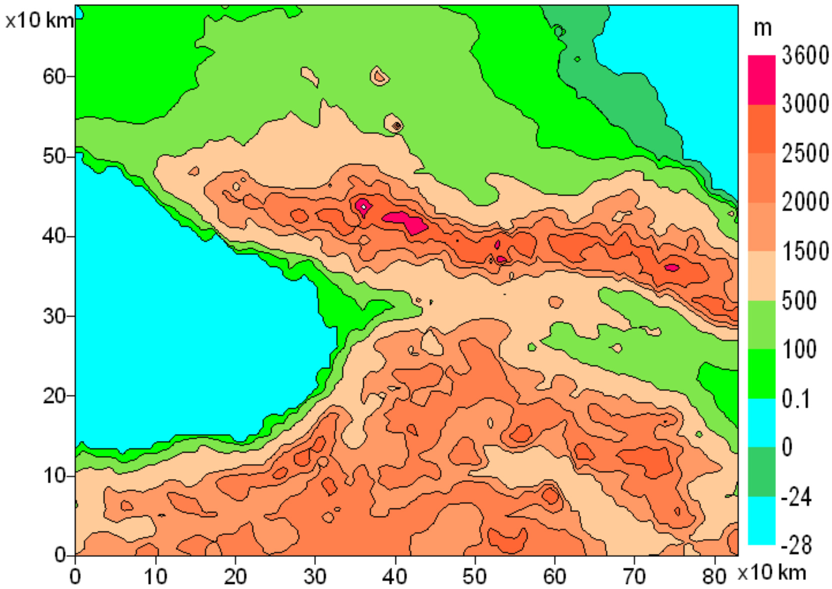

Fig.1. The relief of the Caucasus (in meters) used in the model

Simulation of Air Flow Above the Isolated Obstacle. In the numerical experiment the uniform undisturbed background current was directed along the axis x and it changed in time as follows: the background current arose at t = 0 and within two hours reached 12 m/s. After that it did not change up to t = 10 h. After t = 10 h it was transformed during 12 hours and obtained opposite direction with speed U = -12 m/s.

This numerical experiment was performed with the purpose of researching the character of transformation of meso-scale flow above the obstacle at attenuation of background current (U $\rightarrow$ 0 during time period 10 ÷ 16 hrs) with change of its direction to opposite. Fig. 2. illustrates transformation of air flow over the isolated obstacle on horizon z = 500 m and Fig. 3 – in the vertical plane zx passing through the centre of the obstacle during change of the direction of the background flow to opposite. The analysis of these Figures indicates that during decreasing of air motion of synoptic scales (10 ÷ 16 h) meso-scale disturbed flow is considerably transformed. In particular, from Fig. 2 it is well visible that during reduction of background current speed deviation of the dersturbed flow from the basic undisturbed direction is increased, at achievement of the background calm conditions the disturbed mesoscale flow exists again and has the disorder character with tendency of eddy

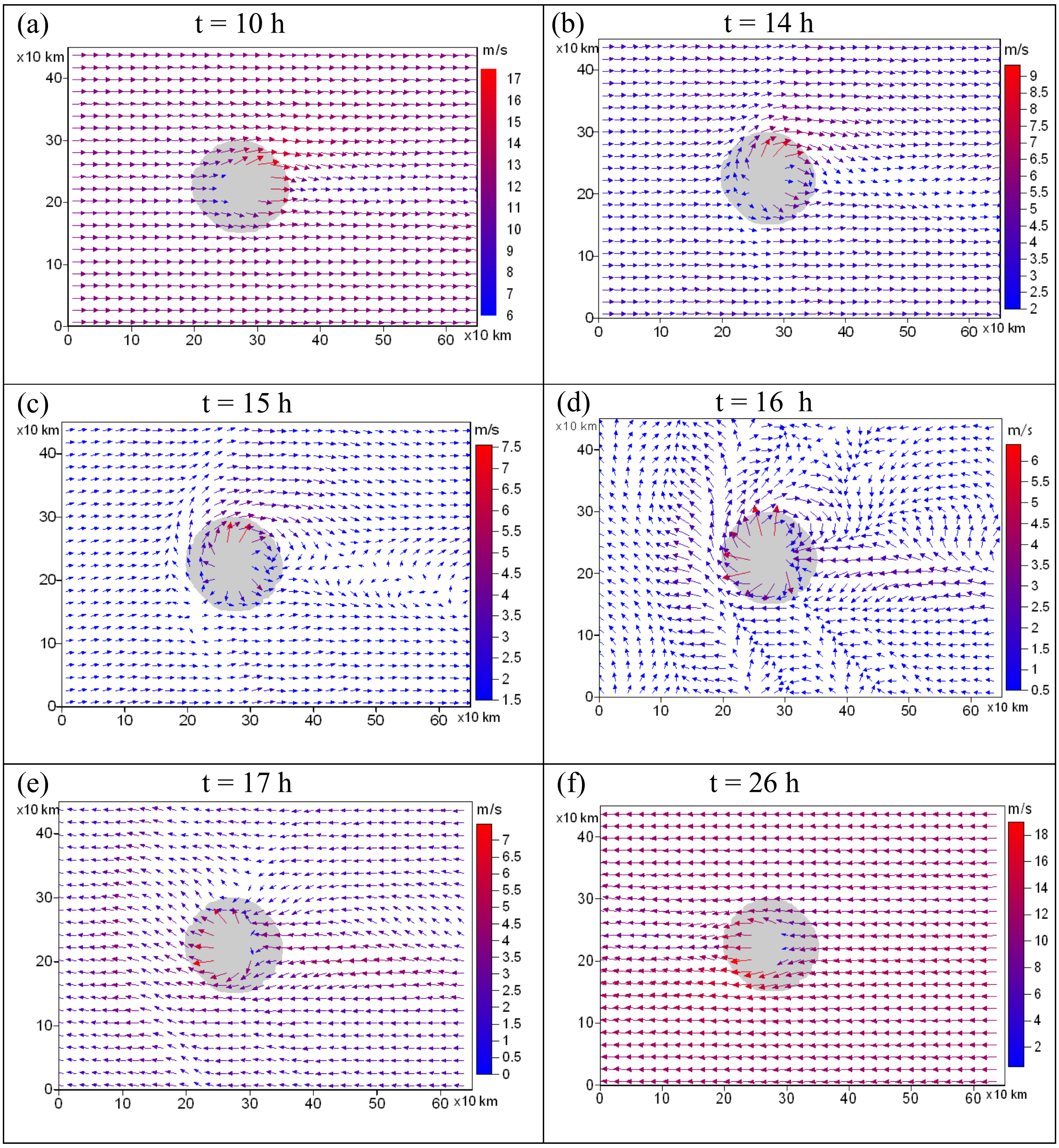

Fig. 2. Transformation of the meso-scale flow on a height z = 500 m during change of a direction of the background flow to opposite. (a) – 10 h, (b) – 14 h, (c) – 15 h, (d) – 16 h, (e) – 17 h, (f) – 26 h.

formation in the horizontal plane near the obstacle (Fig.2d). Amplitudes of wave current above the obstacle considerably grow in the entire troposphere and the wave current is gradually transformed into a vortical current over the obstacle at disappearance of the background current (Fig. 3). It is important to note that similar result was received in the framework of the 2-D model [1]. Under influence of occurrence and amplification of the background opposite current (16 ÷ 22 h) the disorder meso-scale movement becomes ordered again and a current of an opposite direction over the obstacle is gradually formed.

Simulation of Air Flow Above the Caucasian Relief. A similar numerical experiment was carried out in the case of the real Caucasian relief (Fig.1), when the western background flow with speed U = 12 m/s was

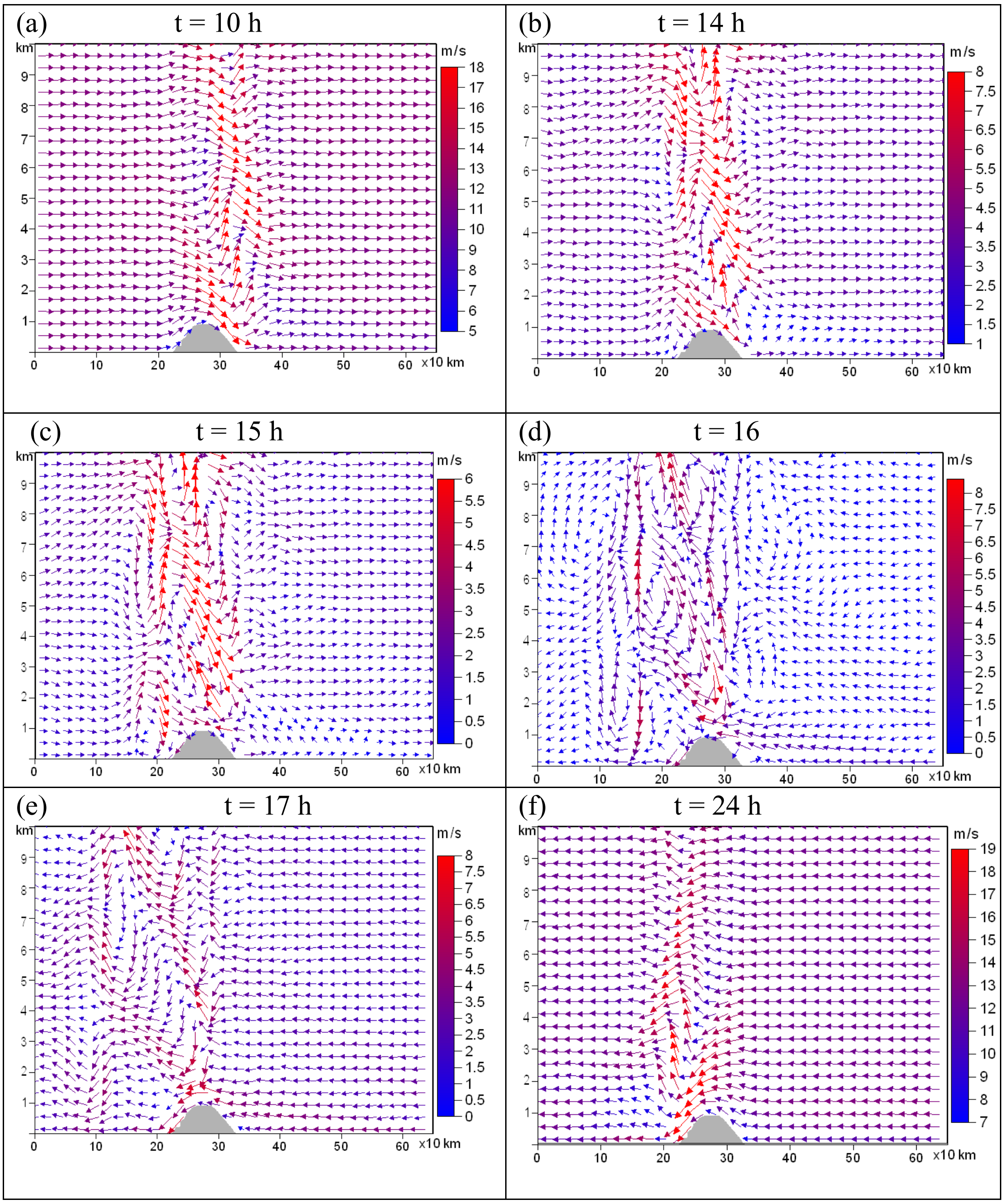

Fig. 3. Transformation of the meso-scale flow in the vertical section during the change of the direction of the background flow to opposite. (a) – 10 h, (b) – 14 h, (c) – 15 h, (d) – 16 h, (e) – 17 h, (f) – 24 h.

transformed into the eastern flow with –12 m/s. Changeability in time of the background flow was the same as in the previous numerical experiment with the model relief.

In Fig. 4 the disturbed flow fields at height z = 200 m (above the Black Sea level) are shown at different time moments, when transformation of background flow was taking place. The numerical experiment showed that during reduction of speed of a background flow from 12 m/s up to 0, orographycally disturbed flow undergoes significant changes. In particular, above the Kolkheti lowland and the east part of the Black Sea turn of a wind counter-clockwise and tendency of generation of vortical formation are clearly observed.

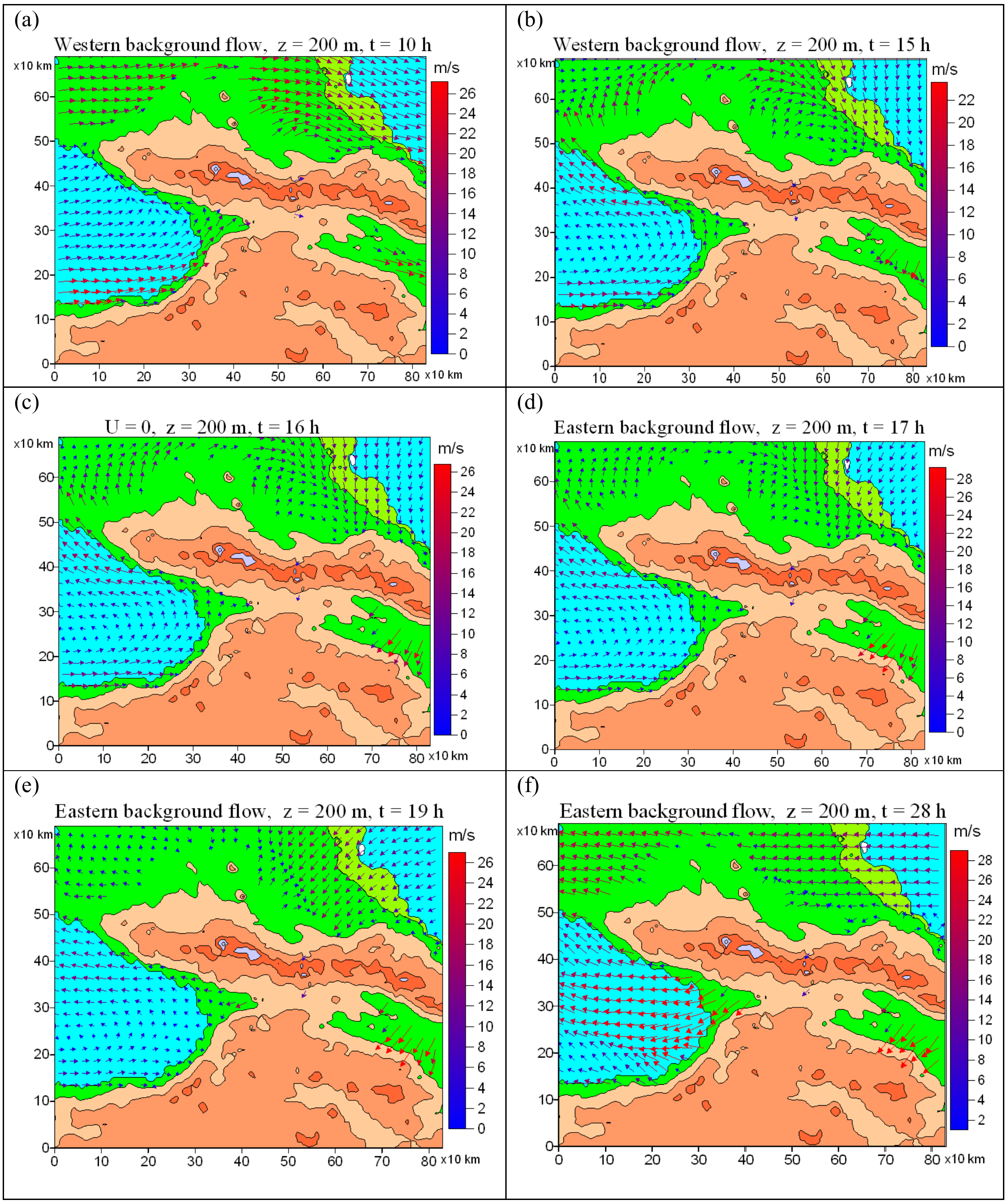

Fig. 4. Simulated current field above the Caucasus relief on z = 200 m at following time moments: (a) – 14 h, (b) – 15 h, (c) – 16 h, (d) – 17 h, (e) – 19 h , (f) – 28 h.

As in the case of the model relief, there is a very interesting phenomenon, when the disturbed meso-scale current exists in the case when the background current is absent (Fig. 4c). Analysis of the flow patterns shows that despite the absence of the background current, in the surface layer the significant winds with speeds approximately 12-16 m/s can be kept. After disappearance of the background current, existence of meso-scale movement over orographically inhomogeneous underlying surface is caused by disturbances of a pressure field, because of which the meso-scale movement is kept at the absence of background pressure gradient.

After t = 16 h, when the eastern background flow arises and reaches speed -12 m/s during 16-22 h, the meso-scale flow is gradually transformed and during the certain time the structure of such current is formed which corresponds to the eastern background flow. The analysis of the flow patterns on different horizons showed that the character of response of the disturbed flow to non-stationary transformation of large-scale processes differs in the lower and upper layers of the troposphere. In the lower layer, where the orographic factor is very significant, the time of the response of the meso-scale flow to changability of synoptic processes is more than in the upper layers of the troposphere and meso-scale flow does not react at once to changes of the background current.

The analysis of the results in a vertical plane has shown that as well as in the case of model relief, above the real relief a significant growth of amplitudes of wave current in the entire troposphere and formation of vortical structures is observed at approach of the background state of the atmosphere to calm conditions.

Conclusion

The air flow over the isolated obstacle and real relief of the Caucasus in conditions of nonstationarity of large-scale background processes is simulated on the basis of the 3-D hydrostatic meso-scale model. The analysis of the results of the performed numerical experiments showed the possibility of some orographic effects in the troposphere, when significant nonstationary transformation of background flow takes place. In particular, it is shown that during attenuation of movement of synoptic scales, the amplitudes on a vertical of meso-scale flow and deviation of air velocity vector across the basic background direction grow considerably. The atmospheric wind with significant speeds above a mountain relief can exist even at the absence of the background current.

გეოფიზიკა

მთიანი რელიეფის ზემოთ მეზომასშტაბური ჰაერის დინების მოდელური შესწავლა დიდმასშტაბიანი ფონური დინების დროში ცვალებადობის პირობებში

დ. დემეტრაშვილი, თ. დავითაშვილი

საქართველოს ტექნიკური უნივერსიტეტის ჰიდრომეტეოროლოგიის ინსტიტუტი

(წარმოდგენილია აკადემიის წევრის თ. ჭელიძის მიერ)

სტატია წარმოადგენს დედამიწის ქვეფენილი ზედაპირის ოროგრაფიული არაერთგვაროვნებით გამოწვეული მეზომასშტაბური პროცესების რიცხვით გამოკვლევას ტროპოსფეროში არასტაციონარული დიდმასშტაბიანი შეუშფოთებელი ფონური დინების პირობებში. ამ მიზნით გამოყენებულია მეზომასშტაბური ატმოსფერული პროცესების სამგანზომილებიანი ჰიდროსტატიკური არასტაციონარული მოდელი. გამოთვლის არის ზედა საზღვარი მოდელირებულია თავისუფალი ზედა-

პირით, ხოლო ქვედა საზღვარზე გამოიყენება რელიეფის გასწვრივ ჰაერის ნაწილაკების სრიალის პირობა. ამოცანა ამოხსნილია რიცხვითი მეთოდით, ლაქს-ვენდროფის ორბიჯიანი მეთოდის გამოყენებით. ჩატარებულმა რიცხვითმა ექსპერიმენტებმა მოდელური და საქართველოს რეალური რელიეფის შემთხვევაში აჩვენა ფონური დინების არასტაციონარული ხასიათით განპირობებული ოროგრაფიული ეფექტების არსებობა.

REFERENCES

1. *D. I. Demetrashvili* (1979), Izv. AN USSR, Fizika Atmosfery i Okeana, **15**, 7: 699–709 (in Russian).
2. *D. I. Demetrashvili, P. Iu. Pushistov* (1981), Trudy Zap.Sib. NII, **55**: 793-803 (in Russian).
3. *D. I. Demetrashvili, A. A. Kordzadze* (1995), Bull. Georg. Acad. Sci., **152**, 1: 87-91 (in Russian).
4. *D. I. Demetrashvili, A. A. Kordzadze* (1996), J. Georgian Geophys. Soc., 1b: 29-42.
5. *I. A. Kibel* (1964), Trudy MMTS, **3**: 3-17 (in Russian).
6. *L. N. Gutman* (1972), Introduction to the Nonlinear Theory of Mesoscale Meteorological Processes. Jerusalem.
7. *R. Richtmayer, K. Morton* (1972), Raznostnye metody resheniia kraevykh zadach, M., 418 p. (in Russian).

Received February, 2013