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INFLUENCE OF TOPOGRAPHY AND THERMAL FACTORS IN THE PBL ON CYCLONE AND ANTICYCLONE SURFACE TRAJECTORIES

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Abstract. It is explored the influence of orographic and thermal nonhomogeneities and the friction in PBL on the trajectories of the baric formations (cyclones and anticyclones). It is explored their deviation from the conventional rule of the leading flow at level 500 hPa. On the basis of comparison with real synoptic situations it is shown that the used parameterization of PBL significantly improves the results.

Key words: orographic and thermal nonhomogeneities, parameterization, trajectories of the baric formations.

Introduction

In the case of flat and horizontally homogeneous earth surface the trajectory of the baric formations is determined to a great degree by the leading flow at level 500 hPa. It is known that biggest errors are made over regions with orographic and thermal nonhomogeneities, which is not taken into account at the method of the leading flow. In such case the problem is significantly more complex because of taking into account the complex processes of interaction with the earth surface. In this case in each point (local area) of the earth surface significant role plays a group of factors like form and spatial position of the relief , structure of the thermal nonhomogeneities, the friction, the baroclinic factors in the Planetary boundary layer (PBL).

The purpose of the work is to explore the trajectories of the baric centers accounting these complicated effects for a number of real synoptic situations. This includes proper parameterization of these complex effects in PBL and their incorporation in the equations of movement of the baric centers.

Theoretical background

To obtain the equation for the movement of the baric centers (cyclones or anticyclones) we will use the conditions for extremum of geopotencial Φ in the center of baric formation

$$\frac{d}{dt}\left(\frac{\partial\Phi}{\partial x}\right)=0, \frac{d}{dt}\left(\frac{\partial\Phi}{\partial y}\right)=0 \qquad (1)$$

and the following generalized formula for the vertical velocity w_H at the top of orographic and thermal horizontally inhomogeneous PBL:

$$w_H = w_I + c\Omega_g + \Delta w,\ \Delta w = \Delta w_{or} + \Delta w_{\delta\theta} + \Delta w_{BC}\ , \qquad (2)$$

where: $w_I = u_{go}\frac{\partial z_0}{\partial x} + v_{go}\frac{\partial z_0}{\partial y} = \left(\vec{\nabla} z_0 \vec{c}_{go}\right)$ is “ideal fluid” velocity , $c\boldsymbol{\Omega}_g$ - friction in a horizontal homogeneous PBL and

$$\Delta w_{or} = a(\vec{\nabla} z_0.\vec{c}_{g0}) + b(\vec{\nabla} z_0 \times \vec{c}_{g0})_z - dG_0^2\nabla^2 z_0 - e(u_{g0}^2 - v_{g0}^2)\partial^2 z_0 \frac{\partial^2 z_0}{\partial x \partial y} \qquad (3)$$

is correction describing the orographic effects (Godev 1970),

$$\Delta w_{\delta\theta} = a_1\left(\vec{\nabla}\,\delta\theta.\vec{c}_{g0}\right) + b_1\left(\vec{\nabla}\,\delta\theta \times \vec{c}_{g0}\right)_z - d_1 G_0^2 \nabla^2 \delta\theta - e_1\frac{\partial^2 \delta\theta}{\partial x \partial y}\left(u_{g0}^2 - v_{go}^2\right) \qquad (4)$$

considers the effects caused by the thermal horizontal nonhomogeneities (Syrakov 1979, 1985) and

$$\Delta w_{BC} = -f_1\left(u_{g0}\frac{\partial \overline{T}}{\partial x} + v_{g0}\frac{\partial \overline{T}}{\partial y}\right) \equiv -f_1\left(\vec{\nabla}\overline{T}.\vec{c}_{g0}\right), \qquad (5)$$

describes the baroclinic effect connected with warm or cold thermal advection (Syrakov 1979, 1985), here $\vec{c}_{g0} = \left(u_{g0}, v_{g0}\right)$ is the surface geostrophic wind, $G_0 = \left(u_{g0}^2 + v_{g0}^2\right)^{1/2}$ is its modul, $\Omega_g = \frac{\partial v_{g0}}{\partial x} - \frac{\partial u_{g0}}{\partial y}$ is surface geostrophic vortex, $c = \sqrt{2k/f}$, f is Coriolis’s parameter, k is average with the height, coefficient of vertical turbulent exchange and depends on $z_0(x,y)$ and $\delta\theta(x,y)$, $f_1 = (\pi/T)c$, T is averaged with height mean temperature in PBL, a,b,d,e are positive and a_1, b_1, d_1, e_1 are negative weight coefficients, whose explicit form is determined in (Syrakov 1979, 1985), $z_0(x,y)$ is Earth’s orography and $\delta\theta(x,y)$ is horizontal thermal inhomogeneity.

Combining (1) and (2) after series of transformation we determined the velocity components (u_C, v_C) of the baric center (see Syrakov 1985, 1990):

$$u_C = c_0 (g/f)\left[u_{C1} + u_{CZ_0} + u_{C\delta\theta} + u_{CBC}\right]$$
$$v_C = c_0 (g/f)\left[v_{C1} + v_{CZ_0} + v_{C\delta\theta} + v_{CBC}\right], \tag{6}$$

where $c_0 = 0.3$ and:

$$u_{C1} = -\frac{\partial z_0}{\partial y}, \; v_{C1} = \frac{\partial z_0}{\partial x}$$
$$u_{CZ_0} = -a\frac{\partial z_0}{\partial y} - b\frac{\partial z_0}{\partial x}, v_{CZ_0} = a\frac{\partial z_0}{\partial x} - b\frac{\partial z_0}{\partial y} \tag{7}$$
$$u_{C\delta\theta} = -a_1\frac{\partial \delta\theta}{\partial y} - b_1\frac{\partial \delta\theta}{\partial x}, v_{C\delta\theta} = a_1\frac{\partial \delta\theta}{\partial x} - b_1\frac{\partial \delta\theta}{\partial y}$$
$$u_{CBC} = f_1\frac{\partial \overline{T}}{\partial y}, v_{CBC} = -f_1\frac{\partial \overline{T}}{\partial x}.$$

The components (u_{C1}, v_{C1}) describe respectively kinematic effects connected with orography $z_0(x,y)$; (u_{CZ_0}, v_{CZ_0}) - the PBL friction, $(u_{C\delta\theta}, v_{C\delta\theta})$ – effect connected with thermal heterogeneity $\delta\theta(x,y)$ and (u_{CBC}, v_{CBC}) baroclinicity effect.

The first terms u_{C1}, v_{C1} in (6) are given by Gandin and Dubov (1968). The second terms u_{CZ_0}, v_{CZ_0} are given by Godev (1976) and last terms u_{CBC}, v_{CBC} and $u_{C\delta\theta}, v_{\delta\theta}$ by Syrakov (1985).

Let's explain the physical meaning of separate components in (6). Obviously:

$$u_{C1}\frac{\partial z_0}{\partial x} + v_{C1}\frac{\partial z_0}{\partial y} = 0. \tag{8}$$

According to (8), the baric center moving with velocity components (u_{C1}, v_{C1}) takes part in "geostrophic" movement perpendicular to $grad(z_0)$ (the role of the isobars plays the isohypes of the relief). This means that the movement is along the isohypes with declining values of orography to the left. In the case of linear isohypes the disposition of the components $u'_{C1} = -a\frac{\partial z_0}{\partial y}$ and $v''_{C1} = -b\frac{\partial z_0}{\partial y}$ connected with the interaction of the orography and friction and deviating the movement to the decreasing values of the height of the obstacle, is shown in Fig. 1a).

Let's analyze the thermal effects connected with the influence of $\delta\theta$ - topography and the baroclinic effects. We can introduce the following terms:

$$u'_{C2} = -a_1\frac{\partial \delta\theta}{\partial y}, \quad u''_{C2} = -b_1\frac{\partial \delta\theta}{\partial x}, \quad v'_{C2} = a_1\frac{\partial \delta\theta}{\partial x}, \quad v''_{C2} = -b_1\frac{\partial \delta\theta}{\partial y}$$

It is easy to check that:

$$u'_{C2}\frac{\partial\delta\theta}{\partial x}+v'_{C2}\frac{\partial\delta\theta}{\partial y}=0, \qquad (9)$$

which allows (u'_{C2}, v'_{C2}) to be interpreted as a kind of "geostrophic" wind perpendicular to $grad(\delta\theta)$ i.e. the movement is along the isotherms of the $\delta\theta$ - topography. In the case of linear $\delta\theta$ isotherms, shown in Fig 1b), the movement is at such direction, that the increasing value of $\delta\theta$ are located to left side (i.e. to the areas with increased thermal stability).

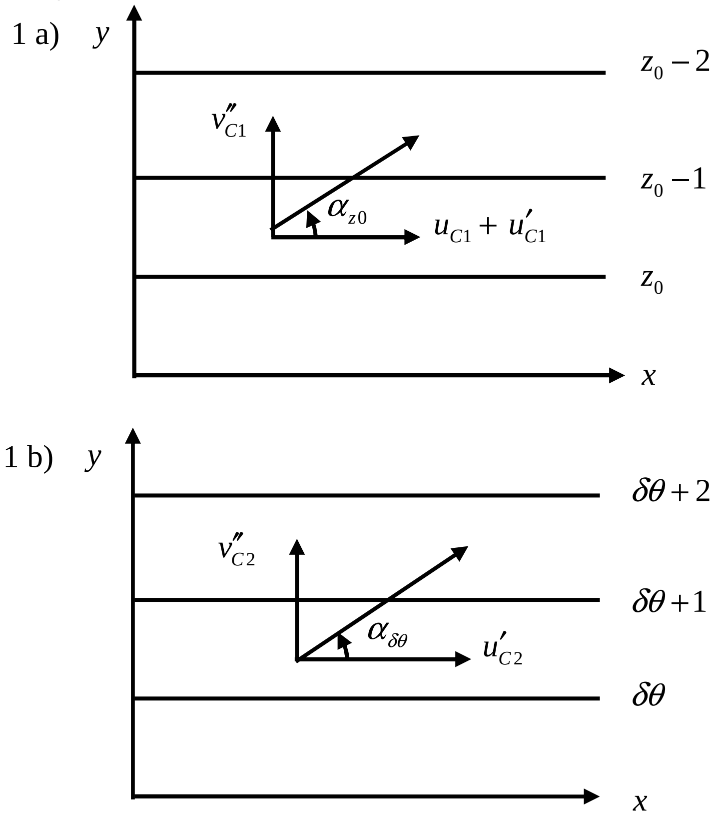

Fig. 1 Location of the different velocity components forming the movement of the surface baric centers in the case of linear isolines the orography $z_0(x,y)$ - a) and of the $\delta\theta(x,y)$- "topography" - b).

The rest components u''_{C2} and v''_{C2} cause additional effects. In the case of linear isotherms (and the x-axes is aligned with them, (Fig 1b)) $u''_{C2}=0$ and it remains only $v''_{C2}=-b_1\frac{\partial\delta\theta}{\partial y}$, $b_1>0$. That component causes movement to the left of the direction of u'_{C2}, which shows that the baric formation directs to the areas with decreasing drag coefficient C_d (these are the areas in which the stability increases). The effect is similar to the orographic effect v''_{C1} shown at Fig. 1a), where the baric formation moves to the decreasing values of C_d (i.e. with decreasing height of the obstacle).

Let's now look at the baroclinic terms in (6) (u_{CBC}, v_{CBC}). It can be easily seen that:

$$u_{CBC}\frac{\partial \overline{T}}{\partial x}+v_{CBC}\frac{\partial \overline{T}}{\partial y}=0 \qquad (10)$$

According to (10) the baric formation moves along the isotherms of the mean temperature $\overline{T}$.

From the obtained results it follows that, because of the effects of orography $z_0(x,y)$, $\delta\theta(x,y)$ - "topography" and baroclinicity in the PBL, the baric formations get additional velocity components which are not taken into account in the rule of the steering flow.

On the basis of the upper formulas we determine the vertical component of the vortex Ω_c of the baric center, $\Omega_c=\partial v_c/\partial x-\partial u_c/\partial y$. After ignoring some small terms we receive:

$$\Omega_c=c_0\frac{g}{f}\left[(1+a)\left(\frac{\partial^2 z_0}{\partial x^2}+\frac{\partial^2 z_0}{\partial y^2}\right)+a_1\left(\frac{\partial^2\delta\theta}{\partial x^2}+\frac{\partial^2\delta\theta}{\partial y^2}\right)-f_1\left(\frac{\partial^2\overline{T}}{\partial x^2}+\frac{\partial^2\overline{T}}{\partial y^2}\right)\right] \qquad (11)$$

The analysis of (11) shows that at $\Omega_c>0$, i.e. over concave surfaces $\Delta z_0>0$ and increasing thermal instability $\delta\theta<0$, according to Fig. 1 cyclone and anticyclone would have to move to these areas. However this is possible only for the cyclone, because at $\Omega_c>0$ cyclones are developing. At the same time at $\Omega_c>0$ the anticyclone fills and breaks down. That's why they move to the areas where $\Omega_c<0$ i.e. to the peaks of the mountains and to areas with decreasing thermal stability, which supports their development.

Application of the method to real synoptic situations

According to the theoretical background the following main factors have significant influence on the surface trajectories of the baric centers in PBL and cause their possible deviation from the rule of the high steering flow (the wind at level 500 hPa):

- the orography $z_0(x,y)$ - (z_0 - effect)
- the $\delta\theta(x,y)$ topography - ($\delta\theta$ - effect)
- the PBL friction which acts in conjunction with the first two factors
- mean temperature $\overline{T}(x,y)$ - ($\overline{T}$ - effect).

Basic purpose of the present work is on the basis of a series of chosen synoptic situations to analyse the real trajectories of the baric formations and to compare with the theoretical conclusions (6) and (7). It is considered eight synoptic situations for which it is traced the trajectories of Mediterranean cyclones and one synoptic situation of tracing the trajectory of Atlantic anticyclone. The considered cyclone situations are for the respective periods: from 08.11.04 / 00 UTC to 11.11.04 /00 UTC; from 28.12.04 / 00 UTC to 30.12.04 /12 UTC; from 28.12.04 / 00 UTC to 29.12.04 /12 UTC; from 29.12.04 / 06 UTC to 30.12.04 /06 UTC; from 06.05.05 / 06 UTC to 08.05.05 /06 UTC; from 08.05.05 / 00 UTC to 08.05.05 /06 UTC; from 17.05.05 / 00 UTC to 18.05.05 /06 UTC; from 17.05.05 / 12 UTC to 18.05.05 /06 UTC; and anticyclone situation is from 10.07.05 / 00 UTC to 12.07.05 /12 UTC.

We use weather forecast maps provided by the American service for meteorology forecasts (GFS) publicly available at the German meteorological web site www.wetterzentrale.de.

Each situation is divided into consequent intervals of 6 hours $t_i - t_j$ and for each of them it is traced the trajectory of the baric formations in linear approximation. This leads to overall of 37 cases for trajectories of cyclones and 8 cases of trajectories of anticyclones. For each case it is made comparison of the real trajectory, the flow at 500 hPa, $\delta\theta$ and $\overline{T}$ - isotherms, z_0 - isohypses in the region of the trajectory using the following procedure:

For each time interval $t_i - t_j$ on the map it is plotted the real surface trajectory of the cyclone and in its vicinity it is linearly interpolated the isotherms of the fields of $\delta\theta$, $\overline{T}$ and the isohypses of the orography z_0. On the basis of that configuration of the fields of $\delta\theta$ and z_0 it is determined the different angles of deviation of the real surface trajectory respectively from the isolines of $\delta\theta$ (α_θ), from the isotherms of $\overline{T}$ (α_T) and from the isohypses of z_0 (α_{z0}). These angles are taken according to the axes Ox, which for each case is directed along the counted isolines as it is shown on Fig. 1 and are positive at left rotation about Ox (counter-clockwise).

The obtained results for α_θ, α_{z0} and α_T are shown respectively in Fig. 2 a), b) and c) for the cyclonic cases and in Fig. 3 for the anticyclonic situation. On the figures the magnitude of the deviation angle is expressed by vertical bar as the consequent number of each 6 hours interval is shown on the axes Ox. When for a given time interval the vertical bar is missing, it means that the respective angle is zero.

The analysis of the results allows making the following conclusions.

In majority of the cases the $\delta\theta$ - effect is in accordance with the theoretical considerations: the surface trajectories of the cyclones move along the isotherms of $\delta\theta$ or when they deviate from them, this is to the increasing values of $\delta\theta$ (the places with increasing stability) and respectively to the decreasing value of the drag coefficient C_d. This fact confirms the important role of $\delta\theta$ in the behavior of the baric trajectories.

We will note that for some cases the $\delta\theta$ - PBL factor coincides with the rule of the high “steering” flow, but in most cases significant deviations of the trajectories due to the $\delta\theta$ - effects have been observed. The case with the anticyclone fully confirms the theoretical considerations. The deviation of the trajectory is to the decreasing values of $\delta\theta$ i.e. to the places with decreasing stability (increasing instability), on a contrary to cyclones.

In the majority of the cases the z_0 - effect acts according to the theory: the trajectories are along the isolines of $z_0(x,y)$ and they have additional component to the decreasing values of $z_0(x,y)$ i.e. to the zones with decreasing values of C_d for cyclones (for anticyclones is to the increasing values of $z_0(x,y)$). In some cases the effects caused by the $\delta\theta$ and z_0 configurations mutually compensate or intensify.

In most of the cases the surface trajectories have component along the $\overline{T}$ isotherms and in the cases when the trajectories have deviation from them, it is to the increasing value of $\overline{T}$. Generalizing these results, we will note that they coincide with the theoretical considerations (5) and (6), and to significant degree they explain and correlate with the observed deviations of the real surface baric trajectories from the “steer” flow.

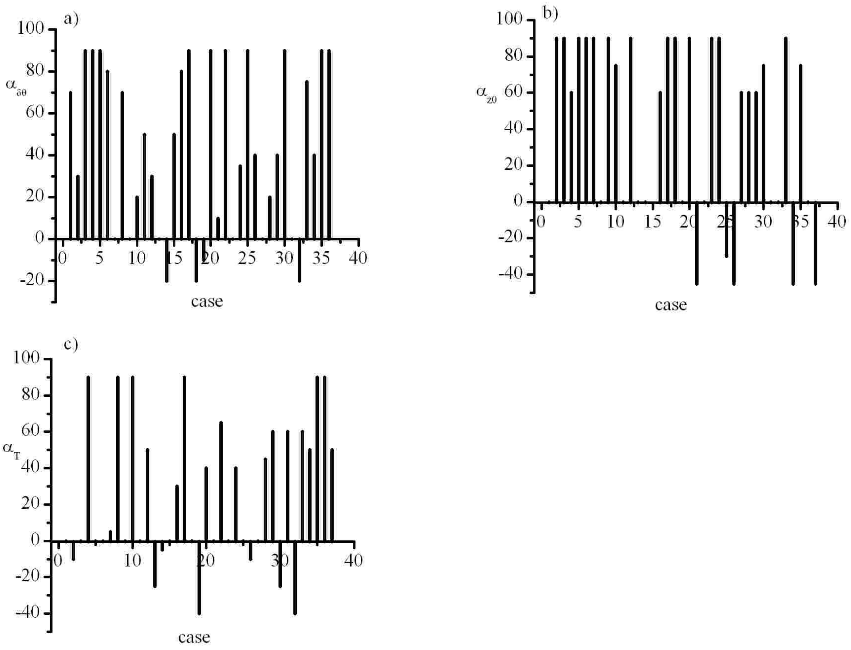

Fig. 2. Results for the angles α_θ - a), α_{z0} - b) and α_T - c) at cyclonic situations.

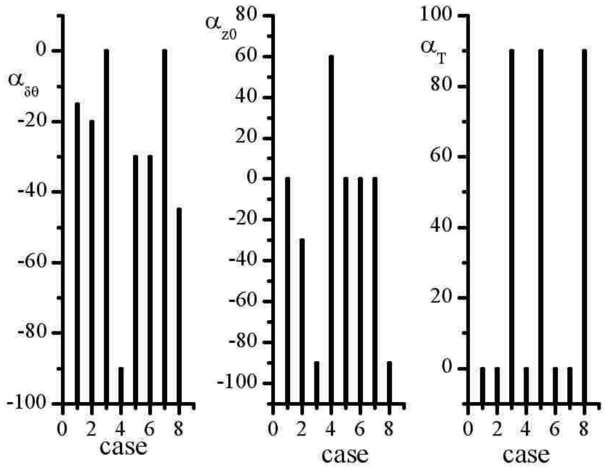

Fig 3. Results for the angles α_θ , α_{z0} and α_T at anticyclonic situation.

Conclusion

The above results show that the given approach for estimation and analyse of the baric trajectories taking into account the mutual influence of the orographic effects, turbulent friction, effects connected with $\delta\theta$ topography, baroclinicity gives good result at comparison with data from real synoptic situations. They show that the counted PBL – forcing factors in series of cases have significant influence on the surface trajectories of the baric formations, which are very significant element of the synoptic forecast. A further development of the task is to increase the number of the considered cases particularly for anticyclones and to study in more details the correlation of the theoretical results with the explored deviations of the surface trajectories from the “steering” flow.

The approach is proper for use for parameterization in numerical forecasting models (Beljaars and Vieterbo, 1998) in order to improve the forecast of the surface baric trajectories particularly over regions characterized with (orographic-thermal) nonhomogeneities where as a rule it is grouped the biggest errors in the forecast (Wollace et al 1982).

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Влияние на топографските и термични фактори в ПГС върху приземните траекториите на циклоните и антициклоните

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Резюме. Изследвано е влиянието на орографските и термични нееднородности и триенето в ПГС върху траекториите на баричните образувания (циклони и антициклони). Изследвано е тяхното отклонение от конвенционалното правило на водещия поток на ниво 500 *hPa*. На базата на сравнение с реални синоптични ситуации е показано, че използваната параметризационна схема на ПГС значимо подобрява резултатите.