Investigation of the effect of quasi-flat relief on the local inhomogeneous structure of the atmospheric boundary layer based on the modeling and the long-term experiment

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Results of numerical simulation of perturbations of atmospheric flows by an actual quasi-flat relief are presented. A comparison is given with long-term minutely measurements of wind velocity and aerosol concentration conducted at atmospheric monitoring stations, which are spaced from 0.8 to 5.2 km apart. The comparison of results points to a qualitative adequacy of the model (relief effect) and measurements in the range of local scales and mesoscales between 0.8 and 5.2 km.

Introduction

One of the factors, affecting the processes in the atmospheric boundary layer, is the ground relief,[1] which affects first of all the field of wind velocities. As a consequence, the relief effect can be detected via the field of aerosol concentrations and other atmospheric parameters. It is naturally to expect manifestations of such effect in mountains.[4] However, a series of papers[2,3] point to a possibility of such effect significance for quasi-flat terrains, where it can be detected both in mesoscale wave processes and in stable continuous perturbations. Of interest is the study of the effect peculiarities for actual quasi-flat terrain of the eastern Central Russian Hills based on many-year measurements at the network of atmospheric monitoring stations on scales of 0.8–5.2 km.

To detect the relief effect, it is desirable to exclude other disturbing factors (anthropogenic, seasonal dependences, and so on). One of the ways to solve the problem is a three-dimensional computer simulation,[1,4,5] which allows one to clarify effects of individual factors and make prognoses. The model adequacy is of importance as well.

Statement of the problem

We have investigated the relief effect on the atmospheric flows for an area of 25×25 km in the region of Almetyevsk town (53°N, 51°E). Such local scales, along with mesoscales, attract a growing interest in modeling.[5] In the framework of the stated problem we studied a model of an air flow. As a whole, the terrain is characterized by rough hills and a hollow extended from northwest to southeast. The relief has a pronounced anisotropy in directions. Against the background of air mass general motion in a certain chosen direction the only perturbing factor is the terrain relief. We investigated eight directions of the mean wind (north, north-east, east, and so on) on the area under study. In each case we simulated a stabilized flow of the lower layer (up to 2000 m) above a quasiflat relief of the actual geographic terrain (Fig. 1).

For calculations, we have chosen one of the simulation methods of general hydrodynamics, namely, the method of final volumes,[7] which corresponds to equations of conservation and continuity.

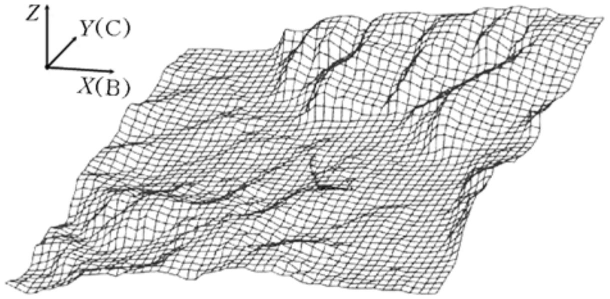

Fig. 1. The relief in the Almetyevsk region (the town is in the center) of 25 km×25 km. The height difference is about 250 m (quasiflat relief) at a height scale of 10:1.

We have at our disposal a unique series of data of long-term (1995–1999) minutely synchronous measurements of atmospheric parameters (temperature, wind velocity, aerosol concentration, etc.) for the region.[6] Synchronous measurements cover a period of 38 months. The monitoring stations are located in the town at a height of 2.4 m above the ground level.

Experiment

Long arrays of measurements allow averaging over the entire observation period and eliminating many irregular perturbations, as well as seasonal and daily variations. As a result, we obtain a pattern of stable flows in the region under study. Although there exist other perturbations (macroturbulence, the

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influence of buildings, etc.), which can be only partly removed by averaging, the relief remains a regular time-constant disturbing factor. Therefore, the pattern of air flows obtained after averaging is determined mainly by the relief, especially close to the surface.

First, the measurements were pre-sorted for different events of the mean wind direction. Every synchronous measurement of mean wind velocity was assigned to one of 8 directions (north wind, northeastern wind, etc.) at a tolerance of ± 10 degrees. Measurements, which did not correspond to any of directions within the tolerance limit were excluded from consideration. The time-averaging of data was made for each of the above-mentioned 8 cases individually. Thus, we have obtained the characteristic pattern of stable flows for each of 8 mean wind directions.

In the data analysis we used the following function:

$$B_K(m, n) = |<(K(\mathbf{r}_m) - K(\mathbf{r}_n))>_t| =$$
$$= |<K(\mathbf{r}_m)>_t - <K(\boldsymbol{r}_n)>_t|, \qquad (1)$$

where | | means the absolute value, $\langle\ \rangle_1$ is the averaging over observation times, K is the parameter, for which the function is calculated, r_m, r_n are coordinates of monitoring stations ($m, n = 1...4$). Further, this function is called pseudostructural function. This difference function enables one to decrease the effect of atmospheric inhomogeneities with a characteristic size greater than the distance between stations, as well as possible errors connected with the direction-sorting procedure (in particular, as the experience has shown, better results can be obtained for the confidence interval). The obtained results almost coincide for the direction sorting at a tolerances of 5° and 10°. This argues for high stability and validity of the obtained pattern of flow disturbances.

The values of pseudostructural function for a non-disturbed flow are zero. For disturbed one, the order of magnitude of pseudostructural function values and their variations is the same as that of disturbances.

The first important result. As is seen in Fig. 2, the pseudostructural function reveals disturbances in the experimental pattern of a stable flow. That is, stable inhomogeneities conditioned by the relief are observed in the experiment. Below we study this effect by computer simulation.

Note that for cases of head wind direction (north and south), the pseudostructural functions of wind velocity behave differently; the flow pattern, when inversing the wind direction, changes significantly and is not reduced to a simple inversion of all wind velocities (otherwise, pseudostructural functions were the same).

The second important result. For north and south winds, an evident correlation is observed between the experimental aerosol concentration and projection of wind velocity vector on the basic flow direction. Such a correlation was detected also for directions of northeastern and southeastern winds.

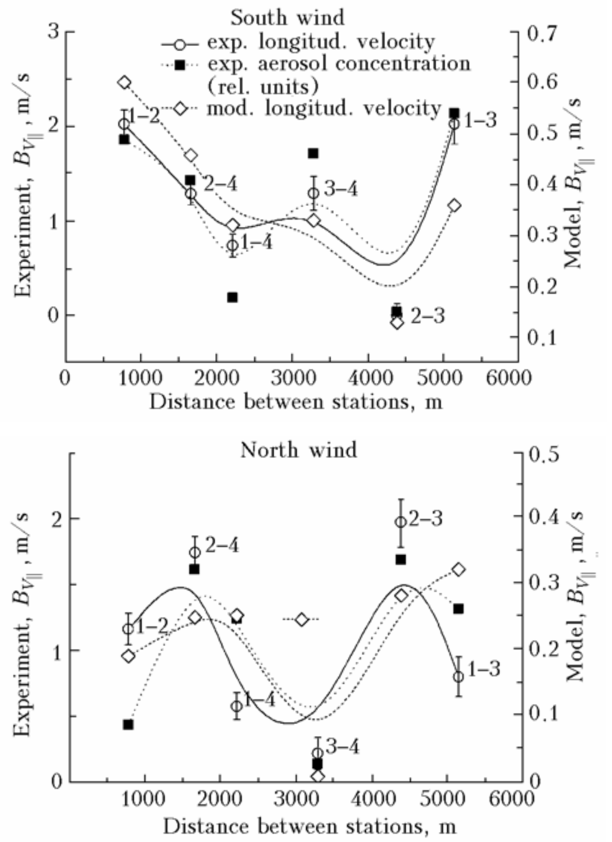


Fig. 2. Comparison of experimental and modeled results. Inter-station distances are pointed on the horizontal axis (the station numbers are marked by figures). Aerosol concentrations are given in relative units. The confidence intervals are shown at a level of 0.997.

The presence of distortions and the absence of the above regularity for other directions of the mean wind can be explained by a closeness of significant local disturbing factors (near-by buildings and sources of pollution) and by a complexity of actual atmospheric processes. From case to case the role of different atmospheric processes in formation of aerosol concentration perturbations may be greater or lower comparative to the role of the relief. The abovementioned evident anisotropy of the relief, probably, also somehow influences the flow, depending on the direction of the mean wind.

Modeling

General atmospheric parameters: wind velocity, pressure, temperature, etc., were under modeling. The relief was the only perturbing factor that corresponds to the assumption on a stable inhomogeneity in the experimentally averaged pattern of atmospheric flows. Eight cases of flow direction (north wind, northeastern wind, and so on) were set by the corresponding boundary conditions.

The method of finite volumes[7] was used in the numerical approximation and solving. To do this, some separated volume above the area under study was covered by a regular three-dimensional grid. The relief was set by a complex shape of the region lower bound. The adhesion condition was used as a boundary one for a given bound.

The atmospheric flow was meant initially unperturbed, that is, at lateral surfaces of the three-dimensional modeling region its velocity had a certain direction, and the flow itself changed with height according to some chosen typical profile (between 0 m/s close to surface and 20 m/s at a 2000 m height). Typical vertical profiles for other parameters at boundaries (turbulence intensity and so on) were respectively specified.[8]

The following physical approximations were used in calculations. The air flow of an ideal gas meeting the averaged Havier–Stokes equations was modeled.[6] To close the equations, the turbulence model of one equation was used.[9] A stationary three-dimensional pattern of the air flow was calculated taking into account the process nonlinearity, molecular and turbulent viscosity in the approximation of gas compressibility, the process adiabaticity (a stagnation temperature of 300 K). A 10 cm height of surface roughness[10] was assumed.

Final modeling was performed for a region of 25 km × 25 km area and 2000 m height at a model horizontal resolution of about 100 m (a grid of 240 × 240 nodes). The vertical step of grid was variable: from 0.2 m near surface to 200 m at the top bound.

The model calculation was carried out using the cluster of the Physical Faculty of the Kazan State University.

Modeling results

In the course of modeling, we have obtained the detailed three-dimensional patterns of the air flow in the region for every direction of mean wind, where a distinct manifestation of the relief effect was observed.

To analyze the disturbance pattern at a certain height over the surface, we used the structural functions:

$$D_K(\Delta x, \Delta y, h) = \\ = \langle [K(x, y, h) - K(x + \Delta x, y + \Delta y, h)]^2 \rangle_{x,y}, \quad (2)$$

where $\langle\ \rangle_{x,y}$ is the averaging over the modeling region, x, y are the horizontal coordinates (OX, OY, OZ are, respectively, east, north, and vertical axes). As h we used the reduced height over the ground surface, which is similar to standard sigma coordinates in its behavior ($h = 0$ m is the complex ground surface, $h = 2000$ m is the plane top boundary).

$$h/(z_\text{t} - \langle z_\text{b} \rangle_{x,y}) = h_\text{r}/(z_\text{t} - z_\text{b}), \quad (3)$$

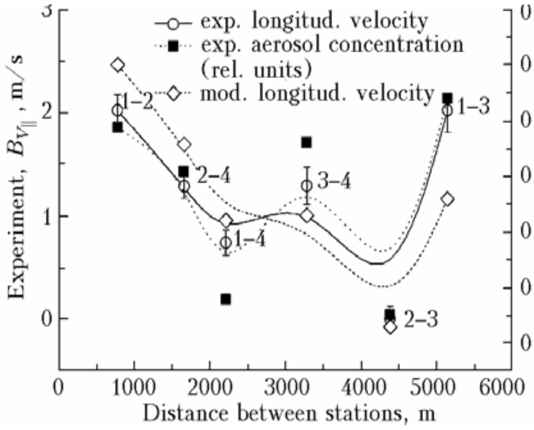
where $z_\text{t} = const$ is z-coordinate of the top boundary, z_b is z-coordinate of the ground surface, h_r is the actual height at the point under consideration. In our case $(z_\text{t} - \langle z_\text{b} \rangle_{x,y}) = 2000$ m. Further the reduced height is meant, unless otherwise stated. Figure 3 exemplifies a structural function of the wind velocity vertical component as most typical.

Structural functions show a similar behavior and values up to heights of 10–15 m; then they decrease with the height, falling at 400 m height by a factor of 4–5 (in this case the structural functions are "smoothed"). The same behavior can be expected also from inhomogeneities of the atmospheric flow.

The variation of the boundary wind direction with height has shown the lower height layer of about 100 m to be a determining factor of the air flow qualitative pattern for heights of 2.4 m. A change of wind direction at a greater height up to 40° of the basic direction has an insignificant effect and does not change the flow pattern close to the surface.

Analysis of the dependence of results on the model horizontal resolution has shown that their stabilization begins at a resolution of 80 × 80 nodes. In the final modeling the calculations were conducted at a resolution of 240 × 240 nodes.

Structural function V_z. West wind. $h = 2.4$ m



Structural function V_z. West wind. $h = 400$ m

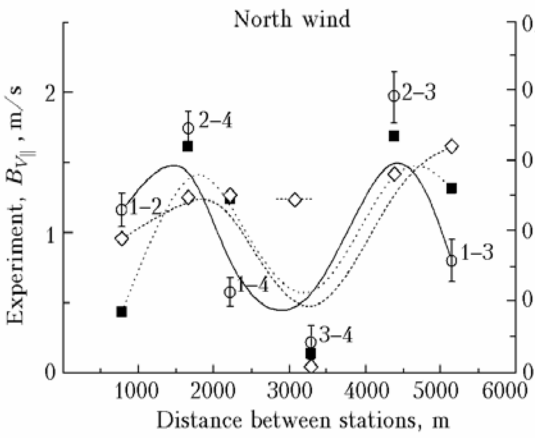


Fig. 3. Structural function for speed vertical component of the west mean wind.

A comparison of modeling results with the experiment

We can construct pseudostructural functions based on modeling results corresponding to pseudostructural functions of experimental data. The degree of agreement between model and experimental pseudostructural functions will made it possible to draw conclusions about the adequacy of the model and the degree of the relief effect.

Figure 2 presents an example of such a comparison for the north and south mean winds in the region. Pseudostructural functions are given for projection of wind velocity vector to the mean wind direction (model and experiment). The data for aerosol concentration (experiment) are also presented.

A qualitative similarity in behavior of experimental and model data is observed. As a whole, the model gives smaller values of disturbance as compared to actual ones (the difference is 4–5 times). However, the character of behavior of disturbances is predicted correctly, which argues for conclusion that the observed stable inhomogeneities are relief-conditioned.

A similar resemblance for the longitudinal wind velocity was found in case of the northwestern and southwest mean winds. As for other directions, it is assumed that the observed divergences can be explained by underestimated effect of urban constructions (all the experimental data were obtained within town limits), which is an anisotropic factor. The effect of the relief anisotropy is also possible when the degree of its influence becomes greater or lesser than other direction-dependent factors. Neglecting the inhomogeneity of the underlying surface albedo and the heating should not affect the results, because their effect becomes small at averaging experimental data over long-term observations and seasons.

On the whole, the model is to be improved, however, taking into account the foregoing, tests have shown its good qualitative adequacy. The conclusions drawn for a height of 2.4 m and their comparison with the experiment allow us to expect their correctness for lower heights.

Conclusion

The influence of a quasiflat terrain on the inhomogeneous structure of the atmospheric boundary layer is shown to be significant when considering the forecast of local variations of meteoparameters and impurities. The model has been built, showing in some cases a qualitative adequacy with experimental observations.

Acknowledgments

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