Modeling of near-surface flows over an aeolian relief

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Abstract. As a result of interaction of an air flow with the elements of an aeolian relief, the character of the flow changes. It affects both the conditions of dust blowing from the surface and the surface shape itself. A model is developed for the formation of the windward slope under the influence of wind. It makes it possible to estimate the dynamic speed when moving up the windward slope on the basis of data on height and movement of the dunes. The coefficient of linear change in the dynamic velocity and its decrease with increasing structure are obtained. This property is probably due to a change in the nature of the flow and circulation at the surface. To study such problems, dome methods are applied to simulate the air flow near a complex 3D surface using the open OpenFOAM package with a 4-level spatial grid. A technology is also proposed for converting the digital terrain data into a format understandable to mathematical packages for modelling of air flow around a 3D object. Based on the simulation results, the coefficient of linear change in the dynamic velocity for aeolian structures with a height of about 100 m has been calculated, which generally corresponds to values obtained from theoretical estimates and real data on changes in height and movement of dunes.

1. Introduction

Modern changes in the ecological situation and global warming [1] lead to increase in desertification and soil degradation [2]. Remote sensing data, such as near-surface temperature, albedo, and vegetation indices, are intensively used in the analysis and forecasts of desertification [3, 4] and dust storms modeling [4, 5, 6]. It is well-known that for moving sands involved in the formation and movement of the dune-type aeolian structures wind removal is more intensive [5]. There is a clear relationship between the ripple motion velocity and the wind speed [7]. The relief on a small scale [8], [9] affects the regimes of wind removal [10] and the circulation in the boundary layer over desert territories [11]. The structure of the wind-sand flow has an impact on the formation of the aeolian relief [9, 12].

In this regard, the study of air circulations and motions in the vicinity of a heated surface in conjunction with the transformations of aeolian relief forms is an especially important problem. The influence of changes in the shape of dunes on the features of their flow is of interest when refining paleogeographic scenarios. The relief data obtained on the basis of geoinformation models and software tools for constructing 3D surface models are used after conversion as a flow object in a numerical experiment [13].
In contrast to the consideration of mesoscale atmospheric dynamics with the relief [13], the analyses of aeolian processes must include the study of the relationship between two media: air and sand. In our study, the relief data were used to solve two problems: 1) estimation of the air flow deceleration when moving up the windward slope based on the analysis of the principle of formation of the windward slope and the dynamic processes on the leeward side; 2) numerical simulation of the airflow around a complex 3D surface.

2. Estimation of air flow deceleration when moving up the windward slope based on SRTM data

Evaluation of the air flow deceleration over aeolian structures is possible using SRTM data [14]. The SRTM (Shuttle Radar Topographic Mission) is a radar topographic survey of most of the globe, which is used, in particular, in Google Earth [13].

To assess the air flow deceleration when moving up the windward slope, we used a model of the windward slope formation under the assumption of a layered ripple structure [10]. The ripple structure is characterized by the arrangement of particles in layers at different horizontal levels. A certain fraction of the particles of the upper layer is blown out by the air flow. The remaining sand grains roll along the surface of the lower layer to an obstacle in the form of a platform formed from stationary particles. This formation is an extended element of the layer. Considering the linear approximation for \( k = k_0 + \mu \zeta \), we can obtain the equation for the length of the elements layer \( x \):

\[
\frac{\partial x}{\partial t} = -\left( k_0 + \mu \zeta \right) \left( \frac{r}{t_p} \right) \frac{\partial x}{\partial \zeta}.
\]

Here \( \left\{ r \right\} \) is the average particle radius, and \( t_p \) is the average value of the detachment time.

The displacement of the leeward slope can be estimated from [10] as

\[
\Delta x = \frac{1}{2} \frac{\Delta z^2 \Delta k^2}{h_{str}} \cos \beta.
\]

Here \( \Delta k = k_L - k > 0 \) is the difference between \( k \) and \( k_L \), \( k, k_L \) are the fractions of detached particles at a given point and at a point at a distance equal to the saltation length \( L \), \( \beta \) is the critical angle of the leeward to the horizon, \( \Delta z \) is the increase in the aeolian structure height, and \( h_{str} \) is the structure height. Since the fraction of detached particles at each point on the windward slope is determined as a relative value, taking into account the fraction of the delivered particles. Thus, \( \Delta k = k_0 - k \). Here \( k_0 \) is the fraction of detached particles at the base of the windward slope.

The linear dependence in (1) for \( k = k_0 + \mu \zeta \) was obtained by estimating the fraction of lifting particles taking into account the peculiarities of the particle size distribution and critical wind friction velocities:

\[
1 - k(u_s) = \begin{cases} A_1 \cdot u_s + B_1 & \text{at } u_s \in (0.26 - 0.28), \\ A_2 \cdot u_s + B_2 & \text{at } u_s \in (0.28 - 0.3). \end{cases}
\]

Here \( A_1 = 46.0, \ A_2 = 7.85, \ B_1 = -12.0, \ B_2 = -1.35 \) obtained from estimates of the fraction of separated particles taking into account their characteristic sizes when exceeding the critical wind speed [15]. These values correspond to a linear approximation for the friction velocity \( u_s = u_{s0} + \zeta \). The fraction of detached particles in a given area, \( 1 - k \), depends on the fraction of particles deposited and transferred from another one for an extended surface \( 1 - k_L \). For a fixed value of the particle saltation length, we obtain \( \Delta k = 1 - k - \left( 1 - k_L \right) = k_L - k \). For successive areas related to long saltation, we obtain values \( k_0, k_1, k_2 \ldots k \). Then on top \( \Delta k = k_0 - k \). For \( \Delta k \) we have
\[ \Delta k = A_i \left( u_0 - u_r \right) = A_i \gamma \left( z_0 - z \right) = A_i \gamma h_{str}. \]  

(3)

Here

\[ \gamma = \frac{\Delta k}{A_i h_{str}}. \]  

(4)

We used images of the Earth's surface included in Google Earth (https://www.google.com/earth/ https://www.google.com/intl/ru_ALL/earth/) to estimate the numerical values of the coefficients used in formulas (1)-(4). These data also allow one

1) to obtain historical photographs of the relief of the territories for a period of time up to 30 years,
2) to save broken lines that determine the position of the dune ridges in different years,
3) to measure the distances and the angles on the relief under consideration.

We find that according to the data taken for the four above-listed regions using the geometric characteristics of the aeolian forms from (3), the changes of the friction velocity when moving up the windward slope correspond to 0.015 m s\(^{-1}\) for aeolian structures 10 m high, 0.02 m s\(^{-1}\) for 70 m, 0.17 m s\(^{-1}\) if above 80 m [15]. The change depends on the structure height. The estimated linear friction velocity deceleration coefficient \( \gamma \) in (4) matches the values 0.0005 s\(^{-1}\) for \( h_{str} = 10 \) m, 0.0002 s\(^{-1}\) for \( h_{str} = 20 \) m, about 0.0001 s\(^{-1}\) for \( h_{str} > 40 \) m (Figure 1).

![Figure 1. Results of calculating the coefficient \( \gamma \) for structures of different heights from 10 to 80 m. Here ter1, ter2, ter3, and ter4 are data obtained for several structures of different heights for each of the four selected territories.](image)

The velocities on the ridge become higher with an increase in the aeolian structure height. This property leads to an increase in the coefficient of linear change. Moreover, for structures with different heights, almost equal increments in the values of the friction velocity between the lower and upper points above the windward slope are observed. A decrease in the coefficient of linear friction velocity change with increasing dune height may be a result of the arising vertical convective flows from a heated surface.
Later we used the capabilities of numerical simulation of the flow around the aeolian structure using the OpenFoam free software to find out the reasons for the change in the air flow velocity. An important point in this approach is the ability to integrate geographic digital data, 3D modeling programs, and a package for mathematical calculations. Therefore, further we will consider the process of preparing relief data in the required format.

3. The use of terrain data in the design of 3D surfaces for numerical modeling in flow problems

The technology for preparing a 3D surface for numerical modeling of the flow processes taking into account terrain features includes several stages: selecting a territory, converting the source file with elevation data for the terrain to the required format, and presenting the data in the STL file format. The next step is to prepare the surface to obtain a sustainable solution and start solving the problem.

The preparation of the relief data as a file in text format for meshing and applying iterative solution methods in a computational experiment involves the following steps:

Stage 1: work with altitude data for the selected area for combining 3D modeling file formats with programs for the numerical solution of the flow problem:

1) receive a file with a map element of the studied area in geotif format using USGS GIS data (US Geological Survey) from the EarthExplorer service (https://earthexplorer.usgs.gov, Google Maps);
2) trim using the 3DEM program to the required size in connection with the task;
3) create a height file in dew format (Autodesk Civil 3D), since the height file obtained by unloading from 3DEM is not accepted by mathematical packages;

Stage 2: preparation for the numerical solution of the flow problem:

4) to export the drawing (Autodesk Civil 3D, 2013), import the drawing file in Multiphysics or Salome programs in the 3D geometry section, set the correct orientation (rotation) and scale (by transforming the surface mesh);
5) use the tools of geometry in the Multiphysics or Salome programs to build a volume bounded above by the exported surface shape, below and on the sides by planes, defining it as a streamlined element with the relief upper part;
6) perform flattening, that is, reduce the level of heights at the edges of the volume to level 0 in the volume under consideration where the flow is simulated, to speed up and improve the quality of calculations;
7) by means of an open package OpenFoam, perform grid construction and numerical simulation of the flow.

Exporting real data on the earth’s surface relief makes it possible to simplify the process of constructing a 3D-model of the surface, which is used in detailed numerical modeling of the boundary layer flow. Such data give a realistic picture of the surface structure and can be taken, including for other planets, where geodetic measurements are not possible.

Let us dwell on point 7 in more detail.

4. Surface preparation for solving flow problems

At this stage, it is important to use a good version of the spatial grid for calculations. The result is a multi-level grid using snappyHexMesh, which has a smaller scale of elements near the surface with a minimum grid pitch of 0.2 m, which allows us to study the effect of the surface topography on the features of the air flow circulation. Since the surface has a complex shape, the VTK format was used to represent the grid data; this allows us to improve its quality and reduce the number of defects (Figure 2).

An object is created for a streamlined surface where boundary conditions and a surface grid are specified. Patches for each surface element are registered separately:

"cone_patch.+
{ type calculated;
  value uniform 0;}

Figure 2. Structure of a multi-level grid using the utility snappyHexMesh and FoamToVTK.

As a result, a flow object is placed in the cube region, for which boundary conditions are set as for the surface. The adapted multi-level grid allows one to detail small-scale processes at the surface and abstract from them at some distance. The grid parameters can be configured and refined.

At the next step, we configure the selected solver.

5. Steady flow

In the numerical experiment, an airflow with neutral stratification around a hill is simulated not taking into account the effect of saltating particles. The region of the flowing medium is represented by the volume of a parallelepiped with a height of 500 m and a length of the faces of the base of 1000 m. The transverse and vertical dimensions of the computational domain are chosen so as to exclude the influence of the boundary conditions. The hill length corresponds to 350 m. We assume that the air flow generally moves horizontally, at the upper boundary a flow is set with a velocity of 7 m/s characteristic of this height. On the left and right walls there is a free flow with a zero gradient. On the bottom wall and for the surface modeling the shape of the hill, the adhesion conditions are used.

The solver SimpleFoam with $k-\varepsilon$ model for a stationary incompressible RANS flow from the OpenFoam open-source was used to evaluate the effects of changes in the friction velocity. The pressure-correction scheme is associated with employing the contravariant velocity. Semi-explicit calculation methods use nonorthogonal, bodyfined coordinates, which is better for irregular geometry [16, 17]. In [18], a number of issues are discussed regarding the use of turbulent models in OpenFoam in considering the air flow above a single dune. As initial parameters we used:

$$E = \frac{3}{2} (u_{ref} T_i)^2,$$

$E$ is the kinetic energy of turbulent mixing, $u_{ref}$ is the velocity at the upper boundary, and $T_i$ is the turbulence intensity,

$$\varepsilon = 0.09^{3/4} \frac{E^{3/2}}{l} \text{ m}^2 \text{s}^{-3}, \quad l = 0.07L.$$

The streamlined surface is a hill about 100-120 m high. The length of the windward slope is about 150-190 m. The size of the modeling area is 760 m x 1000 m x 1300 m. Since the height of the streamlined object is, on average, 110 m, we can use this value as an estimate for $L$ ($L=110$ m). Depending on the conditions, the turbulence intensity $T_i$ values vary from 0.05 to 0.25. For a given scale the turbulence model used provides stable solutions with the ratio $\frac{E}{\varepsilon} \approx 43$ (s).
Figure 3. Wind velocity field above a hill on the windward slope for $u_{\text{ref}} = 7 \text{ m s}^{-1}$, $k = 1.22 \text{ m}^2\text{s}^{-2}$, $\varepsilon = 0.029 \text{ m}^2\text{s}^{-3}$.
In Table 1 we present the values of $T_i$ approximately corresponding to this value of $\frac{E}{\varepsilon}$. The minimal number of iterations for obtaining a stable solution has been reached at $u_{ref} = 7$ m·s$^{-1}$ (Figure 3).

**Table 1.** Selection of $T_i$ values with a stable solution.

| $L$ (m) | $u_{ref}$ (m·s$^{-1}$) | $E$ (m$^2$·s$^{-2}$) | $\varepsilon$ (m$^2$·s$^{-3}$) | $\frac{E}{\varepsilon}$ (s) | $T_i$ |
|---------|-------------------------|----------------------|-----------------------------|-----------------|--------|
| 110     | 9                       | 1.22                 | 0.029                       | 42.51           | 0.1    |
| 110     | 8                       | 1.16                 | 0.027                       | 43.48           | 0.11   |
| 110     | 7                       | 1.24                 | 0.030                       | 42.05           | 0.13   |
| 110     | 5                       | 1.22                 | 0.029                       | 42.51           | 0.18   |

Since the linear variation of the friction velocity with height was estimated in Section 1, the difference derivative along the contour line repeating the surface profile at a certain height was determined for the results of a numerical experiment,

$$\Delta u = \frac{u(z, x_2) - u(z, x_1)}{x_2 - x_1}.$$  

Here $x_1$ and $x_2$ are on the contour.

Along the lines of the surface contours at heights of 2 and 8 m, the velocity varies along the slope by 1 m·s$^{-1}$ and 1.5 m·s$^{-1}$. The differential derivative $\gamma$ has values of 0.01 s$^{-1}$ and 0.016 s$^{-1}$, respectively.

The wind velocity profile $u(z)$ over a sand surface can be represented as [1-3]

$$u(z) = \frac{u_*}{\chi} \ln \left( \frac{9u_*z}{\nu} \right).$$  

(5)

Here $\chi = 0.4$ is the Karman constant, $u_*$ is the friction velocity, and $\nu$ is the kinematic viscosity.

From Equation (5) we obtain the velocity change along the slope according to the data of a numerical experiment: $\gamma = 0.0001$ s$^{-1}$ for $h_{str} = 100$ m. This value of $\gamma$ corresponds to the estimates using the relief data and the computational model given in Section 1. The coefficients of the velocity change along the surface at various heights are determined by the shift of the slope line to a given height (Figure 4).

6. **Conclusions**

The use of SRTM images taking into account the flow processes can combine the results of studies of dynamic processes on different time scales.

A technology was proposed for converting digital terrain data into a format applicable to mathematical packages for numerically solving the problem of flow around an object with a 3D surface.

The technology for the preparation of digital terrain data includes the creation of a 3D surface, its extension, cropping, orientation, flattening, file preparation in the required format for calculations in numerical modeling on high-performance computers.

A test of turbulent flow modeling implemented using the OpenFOAM open-source package and snappyHexMesh utility, as well as estimates based on changes in the geometric characteristics of aeolian landforms, have shown close results for changing friction velocity when moving up the windward slope.
This study was supported by a major project of the Presidium of the Russian Academy of Sciences, P12/KP19-270, and by a joint project of the Russian Foundation for Basic Research and the Russian Geographical Society (No. 17-05-41121).

Figure 4. Change in the air flow velocity above the slope. The orange line is at 2 m. The blue line is at 6 m.

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