Possibility of determining the cloudiness altitude and velocity using passive sounding methods

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A possibility of determining altitude and velocity of a cloudy field by passive sounding methods at observation from a single point is discussed. The potentialities of the implementation and errors of this method are estimated. The paper describes the results of comparative measurements of the cloudiness altitude and velocity obtained with a lidar and the proposed method.

On the average, about 60% of the sky are normally covered with clouds. For local regions the cloudiness is the most important climate and weather forming factor.[1] Prediction of cloudiness is the problem with a great number of input parameters, and when solving this problem it is necessary to consider first the interaction of clouds with pressure systems.[2] The pressure systems determine such characteristics of cloudiness as its altitude above the Earth's surface and velocity that are often measured by different methods. One of the most promising methods of sounding the cloudiness to determine its altitude and velocity is the lidar technique enabling one to obtain the prompt results with high spatial resolution.[3–5] However, the use of lidar techniques is connected with the use of complicated and expensive equipment as well as requires high-qualification staff that causes the increase in cost of lidar measurements and limits their applicability. The goal of this paper is to assess a possibility of determining the altitude and velocity of clouds based on passive sounding techniques.

Consider now two observation experiments while presenting schematically the cloudiness moving as a whole along a single direction. Figure 1 shows the first diagram for the plane surface model.

It is assumed that all the areas of a cloud field move parallel to each other and the vectors of their motion are coplanar to the Earth's surface. If linear and angular motions are normalized to the measurement time, the values of V, V_1, and ω can be considered as appropriate to describe the velocity. When observing one and the same cloud area from two spatially separated points, the altitude and the velocity of cloudiness can be determined on the basis of triangulation methods. We now can state the problem on determining the altitude and velocity of clouds based on the observation from a single point. If we consider the value ω to be small (short period of time), then for V_1 we can write the following expression:

$$V_1 = \omega H / \sin \beta.$$

It is seen from this equation that it contains two unknown terms (V_1 and H) and it is valid at $\beta \neq 0$. The increase in the number of equations owing to observations at different angles β does not solve the problem since the obtained set of equations has the only trivial solution at $H = 0$.

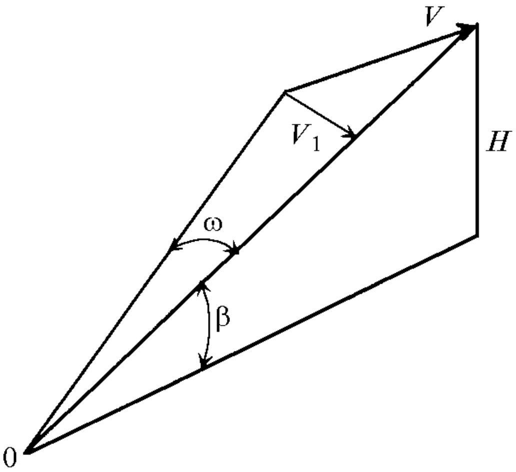

Fig. 1. Geometry of cloud observations for the plane surface model. 0 is the observation point; V is the linear motion of an observed cloud area during the observation time; V_1 is the cloud area projection on the perpendicular to the sight line; ω is the angular velocity of the cloud area motion during the observation time; H is the cloud height; β is the elevation angle of the observed cloud area.

However we can consider a different observation scheme taking into account the sphericity of the Earth's surface (Fig. 2). Within the framework of the same assumptions as in the model of plane surface, we can write the following expression:

$$\omega_1 H = \omega_2 L. \tag{1}$$

Here ω_1 and ω_2 are the angular velocities of the observed areas of cloudy field in the direction to zenith and near the horizon, respectively. If the direction of motion of clouds is known from visual observations, we can select an azimuth direction perpendicular to the vector of motion of the cloudy field, then $V_1 = V$. Within the observation geometry chosen, Eq. (1) can be solved relative to H and V:

$$H = 2\omega_2^2 R_3 / (\omega_1^2 - \omega_2^2); \tag{2}$$

$$V = \omega_1 H. \tag{3}$$

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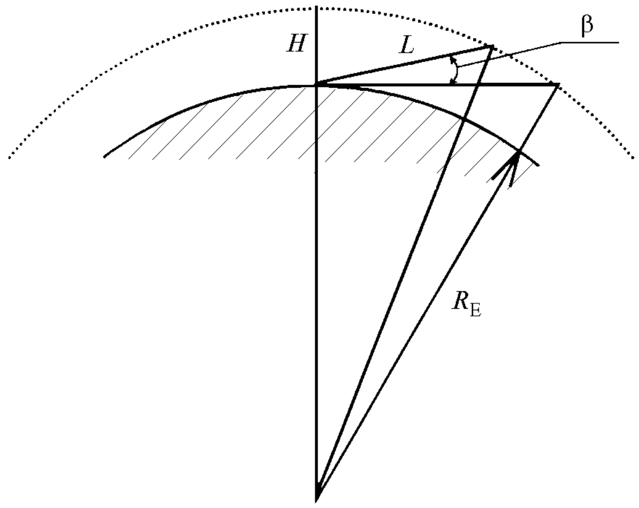

Fig. 2. Geometry of cloud observations taking into account sphericity of the Earth's surface. H is the altitude of cloudiness; L is the distance to the clouds observed along the near horizon direction; R_E is the Earth's radius.

In principle, Eqs. (2) and (3) enable us to calculate the motion velocities and the altitudes of cloudiness, however, a practical implementation of this method is difficult. This happens because of large optical depths corresponding to the observations along the near horizon direction that results in a decrease in the contrast of clouds against the sky background thus making the measurements difficult or even impossible.

Therefore it is worth considering the observation geometry at elevation angles not equal to zero. The equation for this case is assumed to have the form:

$$(H + R_E)^2 = R_E^2 + L^2 - 2R_E L\cos\alpha, \qquad (4)$$

where the angle $\alpha = \pi/2 + \beta$. As a result of simple but rather cumbersome calculations, this equation is solved relative to H. As a result we derive the following expression:

$$H = 2R_E(1 + \cos\alpha \sqrt{k})/(k - 1), \qquad (5)$$

where $k = \omega_1^2/\omega_2^2$. It can be easily checked that at $\beta = 0$, Eqs. (5) and (2) are equivalent. The velocity of cloudiness motion in this case is also determined by Eq. (3).

The analysis of formulas derived shows that the measurement accuracy based on the proposed methods is limited by the errors of measurements of angular velocities and directions as well by systematic errors due to the assumptions forming the basis of this method. Let us assess now the influence of every of these factors on the estimate of the total error. The measurement of angular velocities can be made based on theodolite observations. Since the measurement error of modern theodolites is very small (seconds of arc), in this case high precision can be achieved. The error in the obtained results depends also on the correct assessment of the direction of cloudiness motion. This parameter can be obtained both from visual observations or from analysis of the sequence of images of a cloud field recorded by the use of a TV camera directed along the zenith direction.

Figure 3 shows the calculated results on the measurement errors in the cloud altitude due to the errors in the determination of angular velocity ω at the angle β being equal to 1°, 2°, and 3° (curves *3*, *2*, and *1*, respectively). The analytical treatment of errors shows that the relationship between δH and $\delta\omega$ is linear. It is known that the angle of line inclination depends on the angle of observation β and does not depend on the altitude H. A rapid growth of the measurement error with the increasing angle β shows that there exists an optimal range of the measurement parameters. This range is determined by the required measurement accuracy and is limited by the optical characteristics of the atmosphere, on the one hand, and by the errors of determination of the angular velocity on the other hand.

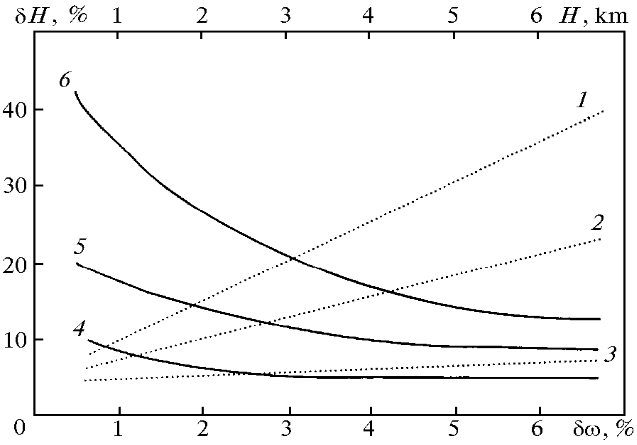

Fig. 3. The relationship between the measurement error of the cloud altitude δH and the error in determination of the angular velocity $\delta\omega$ and the altitude H.

Curves *4*, *5*, and *6* show the dependence of δH at a fixed accuracy of ω measurements, being equal to 1%, for the cloud altitude H at the observation angles β of the order of 1°, 2°, and 3°, respectively. It is evident from the diagrams that measurement error rapidly decreases with the altitude increase. This clearly shows the need for higher measurement accuracy when observing higher cloudiness. The assumption on the equality of altitudes and velocities of motion of clouds spaced at large distances can result in systematic errors. To decrease these errors observations, it is necessary to select the largest forms of cloud fields whose lifetime is much greater than the measurement time.

Experimental check of this method was carried out at the Institute of Atmospheric Optics in summer 1997 during a week. The measurements were made under conditions of a fine sunny weather. The visibility was more than 20 km. The clouds under investigation refer to the cumulus type with the cloud amount of 10–20%, the velocity of motion varied within the limits of 7–20 m/s, the altitude range of the lower cloud limit was 0.8–1.7 km. Test measurements of the cloud field altitude were made using a LISA–1 wind correlation lidar accurate to 10–15 m, the angular motions were recorded using a theodolite.

A comparison of the results obtained by two different methods has shown that in some cases (65–75%) the results of measurements are in a good agreement. The mean error of determination of cloud altitude over the whole period of measurements was 18% that is sufficient for some applications. Further decrease of the measurement error based on the use of the described method is possible when employing special optical systems, effective computer technology and improved data processing algorithms.

In particular, the above method can be best used if the instrumentation is of the type of an "All sky" optical systems. Using these systems we can observe the entire sky hemisphere.[6] " esides, by means of such systems the pictures of the sky can be taken with a digital TV camera and stored in a computer, where a qualitative processing of the obtained images can be performed based on the modern algorithms. This would have made it possible to make the process of extracting the necessary information in a fully automated mode except for the attainment of the required accuracy.

Thus the analytical expression has been obtained, which enables one to measure the altitude and the velocity of clouds using passive methods. The experiment was carried out supporting the applicability of these methods. However the limitations typical of the above methods should be noted. A serious limiting factor is the cloudiness structure itself, as well as blurring of its boundaries and its transformation during the period of measurements. It should be noted that for observations along slightly elevated paths the time of measurements increases due to the distance increase and, hence, for obtaining necessary accuracy the proportionally larger scales of the structures under study are needed. In addition, if the measurements are made at different distances, the automatic scaling is used, i.e., with the increase of the distance the larger cloud are better observed.

Besides, the necessary operating condition for this measurement scheme is the interrelation between the observed objects and the cloud field, for which the equality of altitudes and linear velocities in two spaced areas must hold The estimates show that the distance between these points may be tens of kilometers, therefore we use the above methods for investigating the cloud formations belonging to the large-scale synoptic objects. The presence of multilevel cloudiness, small spatial scale of its homogeneity, as well as low atmospheric transmittance make the application of these methods difficult.

Acknowledgments

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