Study of correlations between a cloud structure and distributions of meteorological elements with the use of space images

O.A. Dubrovskaya,[1] V.V. Ivanov,[2] A.A. Lezhenin,[3] V.M. Mal'bakhov,[3] S.I. Mis'kiv,[2] and A.I. Sukhinin[4]

[1]*Institute of Computational Technologies, Siberian Branch of the Russian Academy of Sciences, Novosibirsk*
[2]*All-Russia Scientific Research Institute of Civil Defense and Emergency Affairs, Russian Ministry of Civil Defense and Emergency Response, Krasnoyarsk*
[3]*Institute of Computational Mathematics and Mathematical Geophysics, Siberian Branch of the Russian Academy of Sciences, Novosibirsk*
[4]*Sukachev Institute of Forest, Siberian Branch of the Russian Academy of Sciences, Krasnoyarsk*

Received January 15, 2007

Possibilities of constructing an information-analytical system for identification of clouds and cloud ensembles aiming at analysis of weather conditions in the low and middle troposphere are considered. A combined approach is proposed, which includes numerical simulation of cloud ensembles and obtaining of standards for comparison with actual cloud distributions.

Introduction

Visual observations, as well as images from spacecrafts and aircrafts, show that cloud fields usually have a quasiordered structure. Sometimes cumulus clouds form irregular hexagons referred to as cloud combs. Most often convective clouds line in ranks of several kilometers long, forming cloud bars and tracks. In cyclones, clouds form spiral structures hundreds of kilometers long. The air motion is directed along these spirals, and the wind velocity is proportional to their curvature.

Combs, bars, and tracks appear not only in the atmosphere of the Earth and other planets, but also upon convection in a viscous fluid moving in a cavity between two plane horizontal plates with different temperatures. The mean size of such formations is several centimeters. In fact this is a well studied Rayleigh–Benard convection.[1] Similar shape of convective structures is caused by similar mechanisms of their formation, while different scales are connected with the turbulent character of motions in the atmosphere and the laminar one in a viscous medium. In Refs. 2–4, the experimental and theoretical results obtained for the Rayleigh–Benard convection were used to explain peculiarities in the structure of the convective atmospheric boundary layer. The presence of a shift in the vertical wind profile disturbs the Kolmogorov cascade of the spectrum of convective pulsations. In investigation of convection in a flow with a wind shift, it was shown that a part of energy of the mean flow and a part of energy of convective pulsations are transferred into two-dimensional turbulence characterized by the inverse energy cascade toward long waves.[3,4] Just these mechanism leads to formation of cloud combs, bars, and tracks (Fig. 1).

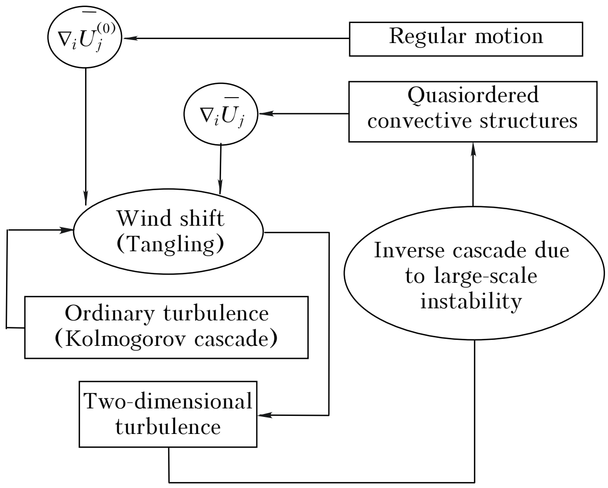

Fig. 1. Diagram of energy cascade for convection in a flow with vertical shift of the background wind velocity.[4]

In the atmosphere, as in a viscous fluid, any set of external parameters corresponds to a certain type of convection. In a laboratory experiment, these parameters are specified, but in the atmosphere the conditions, at which convection takes place, are determined by environmental factors. Visual observations and images from spacecrafts and aircrafts provide information about the character of atmospheric convection under actual conditions.

The paper is devoted to development of a technique for reconstruction of the convective boundary layer

0235-6880/07/10 800-05 $02.00

parameters in the atmosphere with cumulus clouds. For this purpose, information from space images of clouds is compared with theoretical results.[5] The wind field corresponding to actual conditions is evaluated qualitatively from smoke plumes of forest fires seen in the images. The heat and humidity fluxes are estimated from intensity of cloud convection. The main goal is to study possibilities of constructing an information-analytical system for identification of clouds and cloud clusters in order to analyze weather conditions in the low and middle troposphere. A similar approach is used for short-term weather forecasts and very short-range forecasts of hazardous hydrometeorological phenomena. The space information about clouds serves as a synoptic map of a region.

Simplified model of mesoscale ensembles of convective cells

The mechanism of formation of ordered structures in cloud fields was studied in Ref. 5. Let us dwell on main assumptions laid in the basis of the corresponding model. We believe that in the atmosphere at rest every cloud has a cylindrical shape with the upward flow W_+ at the center and the compensating downward motion W_- at the cell periphery.

Such an idealized cloud in the stable atmosphere is shown in Figs. 2*a* and *b*.

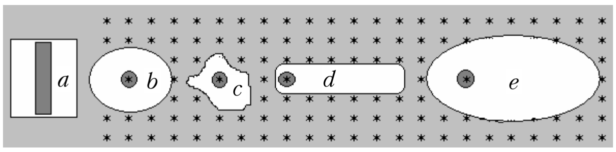

Fig. 2. Structure and interaction of convective cells: in the atmosphere at rest (*a*, *b*); in the “turbulized” atmosphere (*c*); in the atmosphere with the vertical shift of the main flow (*d*); in the Eckman boundary layer (*e*); side view (*a*); top view (*b*–*e*).

The region of upward motions is shown by dark color. The region of the compensating downward air motion is marked by white color. The cloud vertical dimension is proportional to the convective flux of the heat and humidity. Downward motions suppress the development of convection in the intercloud space. Equal cells initiate identical downward flows. The action of this flow can cover no more than 8 neighboring cells (including 4 nearest convective cells, laying to the left and to the right along two principal diagonals from the parental cell).

The scenario of a convective ensemble evolution can be specified as follows. As in Ref. 5, we believe that at the initial time the growth of the statistically significant number of convective cells starts in the lowest layer $z = 0$ at nodes of a regular grid with $\Delta x = \Delta y =$ const under the effect of the continuous flux of heat and humidity. In Fig. 2, these cells are shown as asterisks against the light-gray background. The growth rate of all convective cells is chosen so that for the time $\Delta t =$ const each cell increases its size by $\Delta z =$ const. As a cell grows, the region of downward motions increases in width. As one or several neighboring cells fall within this region, the cell having the larger size continues to develop, while other cells disappear. In this case, the nearest remained cells become neighboring, and the evolution of the ensemble can continue.

To avoid formation of identical cells, the generator of random numbers sends pulsations in the values of upward (w'_+) and downward motions (w'_-) at every node of the grid with the interval equal to one time step. The amplitude of these pulsations is assumed proportional to the degree of the convective layer turbulence. Every cell is unstable and collapses under the effect of external perturbations. In the model from Ref. 5, the larger is the cell, the higher is the probability of its collapse (disappearance). Cells collapse under the effect of w'_-. If these values are much smaller than the values of W_+ and W_-, then the convective ensemble is realized, in which cells lie at an equal distance from each other. The wider is the region of downward motions, the longer is this distance. If the values of w'_- are comparable with the values of W_+ and W_- (this case corresponds to Fig. 2*c*), then the ensemble with the chaotic arrangement of convective cells is realized.

Observations show that clouds slope toward the shift of the background wind and, as a rule, a downward flow W_- is formed near this side of a cloud. The influence of the constant (in height) vertical gradient of the background flow, characteristic of the thermal wind, is modeled by specifying W_- (Fig. 2*d*). This case corresponds to the convective ensemble with the comb arrangement of cloud cells. Convection in the Eckman boundary layer is modeled by specifying the deformation field with a maximum in the direction of the geostrophic wind (Fig. 2*e*). In this case, convective cells line in tracks along this direction. Similar conclusions on the cloud structure were obtained theoretically[4] and were confirmed by a laboratory experiment.

The results of calculation by the model from Ref. 5 and the data of space images are shown in Figs. 3–5.

Space information was received by the Department of Reception and Processing of Space Information of the All-Russia Scientific Research Institute of Civil Defense and Emergency Affairs (Krasnoyarsk) from the NOAA and TERRA satellites. Actual clouds in all images are shown as white spots against the dark background corresponding to the surface. The wind speed and direction can be judged from smoke plumes from forest fires seen in all images. The wider and the shorter is the plume, the weaker is the wind. The size and height of clouds can be estimated from images of their shadows (see Fig. 3). The results of calculation by the model from Ref. 5 are shown in the insets. Asterisks denote convective cells. The gentle wind and weak convection correspond to the ensemble with asterisks arranged chequer-wise (asterisks against the gray background in Fig. 2).

At the strongly turbulent atmosphere corresponding to the scenario shown in Fig. 2*c*, cells are arranged chaotically (see Fig. 3). The both cases take place in the nature. They are the so-called fine-weather clouds (*Cum hum, Cum med*) observed in summer in the morning hours in the absence of strong wind.

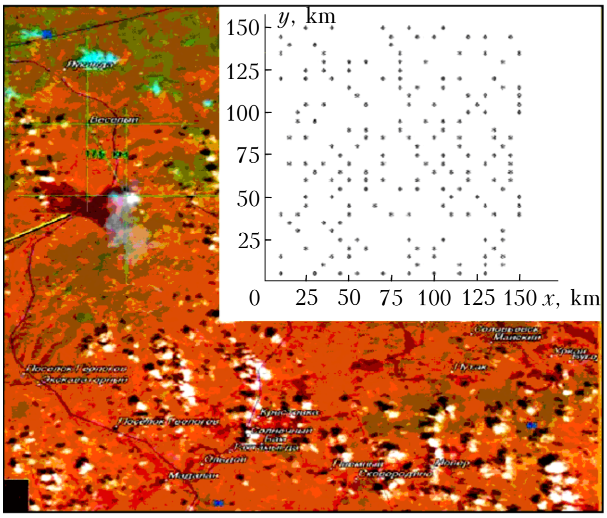

Fig. 3. Comparison of theory with observations. Fine-weather clouds.

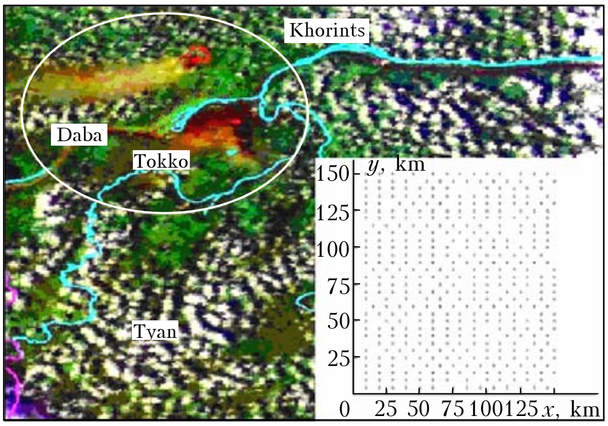

Fig. 4. Comparison of theory with observations. Cloud combs.

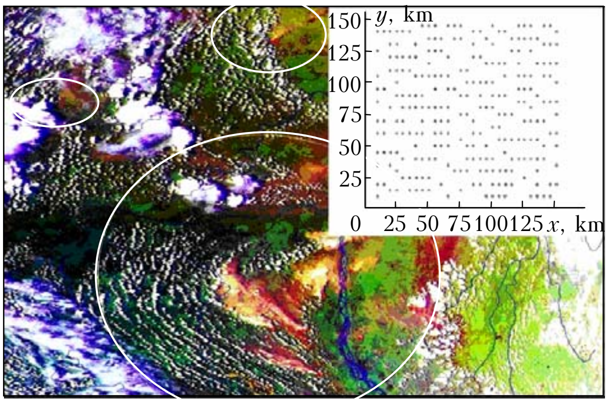

Fig. 5. Comparison of theory with observations. Cloud tracks.

As the surface heats, the convection intensity increases, and the cloud number and size increase too. Sometimes in the middle of a day or in its second half, cloud form ordered honeycomb structures. This case corresponds to the scenario in Figs. 2*d* and 4.

It should be noted that the honeycomb structure of clouds is more typical of cyclone conditions, under which the thermal wind is often observed.

If a cloud ensemble is formed at windy weather typical of cyclonal conditions, then clouds group in the wind vector direction. This case corresponds to the scenario in Figs. 2*e* and 5.

The high wind velocity can be judged from the narrow and long smoke plume from forest fires. In cloud images corresponding to the cyclonal circulation, two types of cloud clusters are often seen. In the middle atmosphere, large spiral cloud structures are clearly seen, which allow the wind speed and direction in this layer to be estimated. Beneath, in the Eckman layer, cloud tracks can be often seen, which allow the wind speed and direction, as well as fluxes of heat and humidity in lower layers be estimated (Fig. 5). In the bottom left angle, a small part of a large spiral cloud structure is seen, as well as several cloud tracks under it. The orientations of the tracks and this structure not always coincide, especially, in the left part of the figure. This indicates that the wind direction at different heights can be different, that can be estimated from the analysis of space images.

In the top part of Fig. 5, an ellipse encloses the area, where cloud combs are seen, which is indicative of the thermal wind. The analysis of smoke plumes from forest fires shows that at the center of this area the wind changes its direction from southwestern to southern. This sector is encompassed with a large ellipse. Identical changes occur in the orientation of cloud tracks.

Thus, in the plane-parallel flow with the wind shift and rotation, the appearance of mesoscale quasiordered cloud clusters is possible with height. Another type of large-scale cloud structures is connected with peculiarities of atmospheric cyclones.

Cloud convection in atmospheric cyclones

To compare calculated and actual data in the case of cyclonic circulation, the program of reception of cloud images from NOAA space vehicles in the Analog Picture Transmission (APT) format with the following thematic processing was used. This program allows reconstruction of actual and prognostic values of some meteorological parameters from the brightness characteristics of the cloud cover. These parameters include the temperature and the height of the cloud top, the wind speed and direction at different isobaric heights, the precipitation amount, as well as the type of cloudiness and possible meteorological phenomena associated with this cloudiness. The method of wind field reconstruction is applied to cloud clusters having a vortical structure. We used the results of Ref. 6, in which the statistical correlation between cloud fields and air flows was determined (Fig. 6).

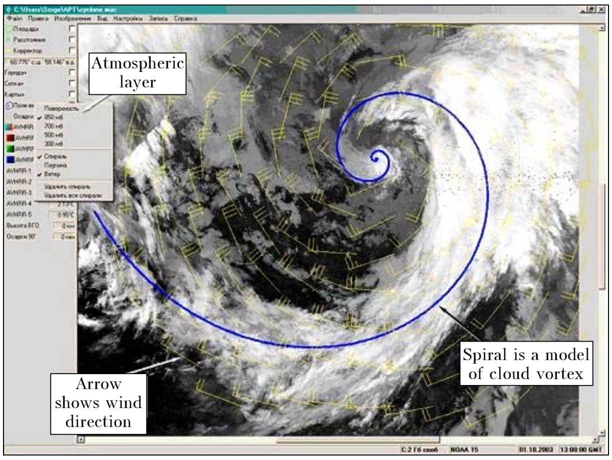

Fig. 6. Reconstruction of the wind field from the cloud field of a vortical structure.

Sizes of the synoptic vortices, seen in space images, are between 350 and 3500 km in diameter. The geographical orientation of cloud spirals can be different. To find statistical correlation between directions of cloud bands and the wind, a local coordinate system with the origin at the center of a cloud vortex is introduced. Only those cloud vortices were under analysis, in which cloud bands had shapes of elliptical spirals, because they occurred most frequently.

The principle of determination of the wind direction and speed at standard isobaric surfaces is the following:

1. In the initial cloud image, a cloud vortex with cloud bands of an elliptic shape is revealed.

2. The local coordinate system with the origin at the cloud vortex center is introduced; the abscissa (x) is directed in parallel to the asymptote of the hyperbolic spiral, while the ordinate (y) – perpendicular to it for to obtain the right-hand coordinate system.

3. The space, occupied by the vortical cloudiness, is divided into eight sectors with the central angle of 45° and into five equal parts along the radius. The maximal length along the axis y from the vortex center to intersection with the external edge of the cloud spiral is taken as the unit length. Thus, the cloud vortex is divided into 40 parts. For each part, at five standard atmospheric layers (ground surface, 850, 700, 500, and 300 mbar), the most probable values of the direction difference

$$\Delta\varphi = \varphi_w - \varphi_{cl}$$

and wind velocities have been determined by statistical methods. Here, φ_w is the wind direction; φ_{cl} is the direction of the cloud band. These values were obtained with the use of an extended statistical material.

4. From the direction of the cloud band at each part of the coordinate system, we can determine the wind direction and speed in the area of interest.

5. Discrepancies of the r.m.s. deviation of the wind vector obtained by the above technique from those calculated from radiosounding data are small and range from 20 to 30°. This allows the method to be used to evaluate the wind field as a cyclonal system with the developed spiral cloud structure. In addition, determination of wind field characteristics is interesting just in cyclonal areas, since they are associated with most variable speeds and directions of air flows.

Images in the APT format allow the cloud cover structure to be studied from the character of the pattern of the image and the brightness of cloud elements in order to classify the cloudiness. However, for more accurate determination of the character of atmospheric processes and their activity on the territory under study, the information about the vertical dimension of clouds is necessary in some cases. This is especially important for thick clouds of vertical development, which are associated with the majority of dangerous meteorological phenomena: thunderstorms, squalls, hail, heavy showers, etc.

Application of this technique allows the height of the cloud top boundary (CTB) (in kilometers) to be determined from space APT images in the IR region by placing the mouse pointer at any point of the cloud cover.[7]

The method of visualization of the CTB height is based on the dependence of the height of the emitting surface on the value of the brightness temperature. Such dependence was calculated from the comparison of the emitting surface temperature on the image with the data of the atmosphere aerological sensing by the network of stations of the Russian State Hydrology and Meteorology Center. Comparisons were carried out for different seasons, latitudes, and times of a day. As a result, the empiric dependence of the CTB height on the brightness temperature was obtained:

$$H_{\text{CTB}} = -KT_{\text{br}},$$

where H_{CTB} is the CTB height; K is an empirical coefficient of the dependence varying with the use of a receiving module of a station at different sites and in different seasons; T_{br} is the brightness temperature. The CTB height can be measured by this method accurate to 1 km, which is close to the measurement accuracy of a radar station. The CTB height is measured most reliably in the presence of dense cirrus clouds, thick clouds of vertical development, or dense middle-layer clouds. In the case of semitransparent, optically thin clouds, the CTB interpretation becomes difficult.

Conclusions

1. According to the theory[5] and observations, cloud clusters can be divided into mesoscale and cyclonic.

2. Fine-weather clouds, cloud tracks, and cloud combs fall in the category of mesoscale structures. The presence of *Cum hum, Cum med*, and *Cum cong* in images is indicative of the air-mass character of convection at a gentle wind.

3. Cloud tracks in images are indicative of the strong wind and significant stores of heat and humidity in the Eckman boundary layer.

4. Cloud tracks are main elements of cyclonic circulation.

5. Other main elements of cyclones are vortical cloud structures having the size of several hundreds of kilometers and lying in the second convective layer.

6. The shape and orientation of cloud tracks and cloud spirals allow the wind speed and direction in the low and middle troposphere to be estimated.

7. The presence of cloud combs is indicative of the thermal wind in this region.

The regularities revealed will serve a basis for development of an information-analytical software system intended for the use of space information in the problem of diagnostics of meteorological parameters in the low and middle troposphere. For this purpose, the relation between the orientation of cloud combs and the speed and direction of the thermal wind should be examined thoroughly.

References

1. G.Z. Gershuni and E.M. Zhukhovitskii, *Convective Stability of Uncompressible Fluid* (Nauka, Moscow, 1972), 392 pp.
2. N.F. Vel'tishchev and T.Kh. Geokhlanyan, Tr. Gidromettsentra SSSR, No. 132, 71–87 (1974).
3. T. Elperin, N. Kleeorin, I. Rogachevskii, and S. Zilitinkevich, Phys. Rev. E **66**, 066305 15 (2002).
4. T. Elperin, N. Kleeorin, I. Rogachevskii, and S. Zilitinkevich, Boundary-Layer Meteorol. **119**, 449–472 (2006).
5. V.M. Mal'bakhov, Meteorol. Gidrol., No. 11, 33–40 (1997).
6. M.A. German, *Space Methods of Meteorological Investigations* (Gidrometeoizdat, Leningrad, 1985), 286 pp.
7. G.A. Boldyrev et al., Tr. GMTs SSSR, No. 1973 (1971).