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Methods of hydrodynamic modeling of the extreme atmospheric phenomena against theory and observational data*

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Extreme atmospheric phenomena include thunder-storms, heavy rains, hailstorms, and tornadoes. These events have much in common. They usually develop on the basis of a convective cloud of the vertical size exceeding 10 km. The width of strips of heavy rain, hailstorm, or tornado is approximately the same, seldom exceeding 1 km. In meteorology, such phenomena are called local. Tropical cyclones lasting several days and covering areas of about 100 thousand square kilometers are also considered as disastrous atmospheric phenomena. In meteorology, the phenomena of such a scale are called regional. In the present epoch, the extreme atmospheric phenomena fill a highly important place in damage to national economy. In addition to losses due to a strong wind and a hailstorm, there are forest fires, flooding, and mud flows caused by lightnings and heavy rains.

Let us begin the paper with presenting methods of simulation of local atmospheric phenomena, which were developed in the Institute of Computational Mathematics and Mathematical Geophysics, the Institute of Water and Ecological Problems, and the Institute of Computational Technologies of the Siberian Branch of the Russian Academy of Sciences. One of the most widespread methods is Large Eddy Simulation (LES) [1].

The LES is primarily designed for reproduction of the meso-scale turbulence occurring in the atmosphere vertical instability resolution. This is a convective instability, or instability induced by the vertical shear of wind speed and direction. The horizontal size of the calculation area is from 1 up to 30 km. When the convective turbulence is simulated, the LES should roughly describe the internal structure of convective cells (large thermics and convective clouds) and simultaneously reproduce sufficiently great (statistically significant) number of convective cells. The LES allows us to determine a spectrum of clouds and thermics, their mean size, moisture content, and other statistical characteristics of convective ensembles.

A distinctive feature of the LES is the independence of boundary conditions of the horizontal coordinates. For this purpose, the underlying surface (land or water) is given as flat, with a homogeneous landscape and temperature. Above it, the layer of several meters thickness is located, where

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heat, moisture, admixtures, and moment-of-momentum fluxes do not vary. A convective layer with thickness varying from several hundreds of meters up to several kilometers is located above it. Convection is described by the equations of "deep" or "shallow" convection with allowance for phase transformations within the "vapor-water-ice-aerosol" system. The free atmosphere layer is located above a convective one, where the meteorological fields are assigned. Various LES reported in the literature are mainly designed for investigation of different types of atmospheric convection. The LES models are of little avail for the prediction of disastrous local atmospheric phenomena.

For this purpose, models of the atmospheric boundary layer (BL) [2] are applied. Topography, landscape, temperature of the underlying surface for the ABL are taken from real data. Initial data are defined by processing atmosphere radar scanning data. The ABL models are, commonly, the main component of a very short-range weather forecast technological line. The ABL model structure and equations are the same as those of LES, while the boundary and the initial conditions are essentially different.

Our LES [3–5] and BL [2, 5] models contain more than 10 equations, among which seven equations take into account various fractions evolution with aerosol participation. Figure 1 shows a pattern of mutual transitions in the vapor-water-ice-aerosol system.

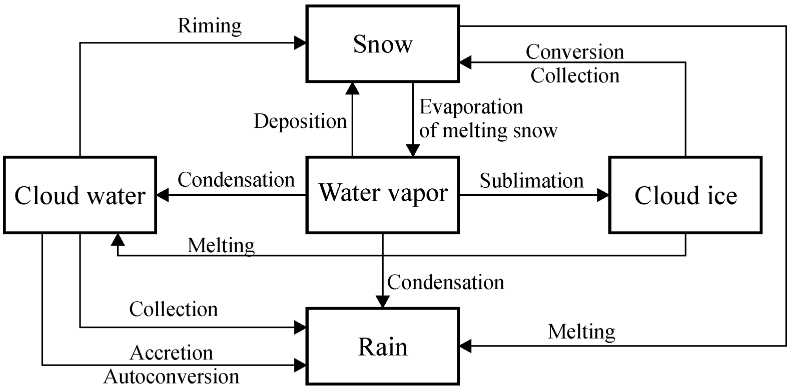

Figure 1. Scheme of interconversions in the vapor-water-ice system

The "western" models contain already up to 50 nonlinear equations. Therefore it is impossible to prove that calculation results are quite an exact solution to the initial system. In addition, the solutions found, similar to a real process, are sufficiently complex, thus making their interpretation difficult. Therefore we used simplified models to reveal a convection mechanism [3, 5–7]. They were used to study the following processes:

- convective cells destruction [3, 5–7];

- convective ensembles formation [3, 5–8];
- tornadoes [9–11];
- tropical cyclones [3, 7].

Simplified and complete models should certainly yield similar results thus ensuring their correctness.

The basic conclusions from the analysis of calculation results of complete and simplified models are presented below:

1. Molecular viscosity induces founding a convective ensemble consisting of cells several centimeters in size. This type of convection is observed as a haze above plough land or asphalt [3, 5–7].
2. A well-developed convective ensemble serves as turbulence for an ensemble consisting of larger cells [3, 5–7].
3. Under favorable conditions the process can recur, and cells of 10 km and greater size are the dangerous phenomena [3, 5-7].
4. Change in speed and direction of the background wind with height results in grouping the convective cells into the ordered structures: pouch-like clouds, cloud streets, and cloud billows which can also be different in size [6, 12].
5. The presence of rotary moment in the atmosphere can result in the formation of tornadoes [3, 7, 9, 10].

Figures 2–6 illustrate a comparison of the theory with the results of measurements of the cloud ensembles structure.

Figure 2 shows a function of clouds distribution according to their size. The agreement of theoretical and observed data is satisfactory.

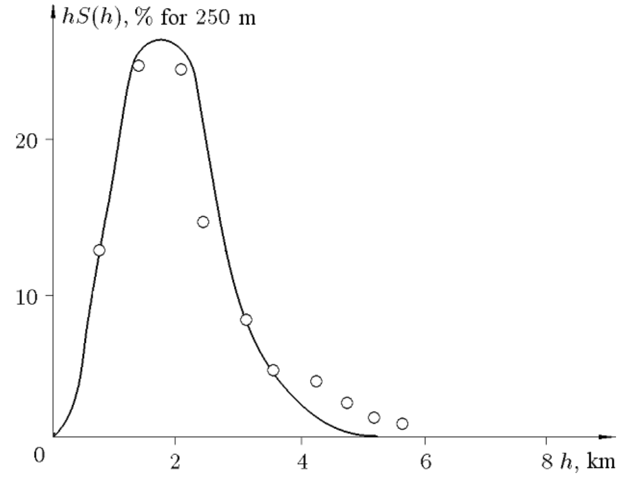

Figure 2. Comparison of theoretical and measured functions of cloud distribution: the theoretical curve is drawn with solid line, circles are observed data

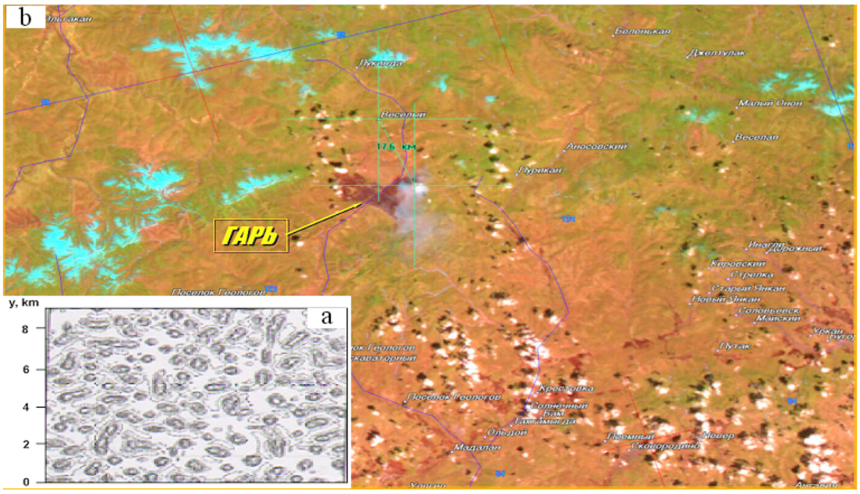

Figure 3. Chaotic distribution of clouds: a) the isolines for positive values of vertical speed component are shown with solid lines and isolines for negative values are shown with dashed lines; b) satellite imagery of cloudiness

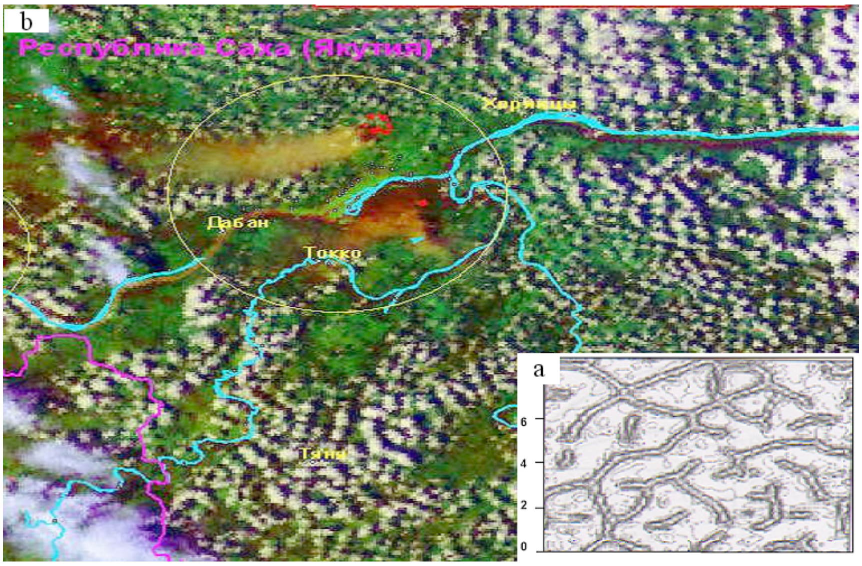

Figure 4. Pouch-like clouds. Notations are the same as in Figure 3

Figure 3 shows convective ensembles corresponding to a light wind and shallow convection. The right part of the figure contains the LES calculations [12], the left part — a satellite image of the cloud ensemble. The length and shape of a fanning plume from the forest fires distinguished in the figure give a representation of wind speed. The wider and shorter the fanning plume, the lighter the wind. Both the theory and observations show that

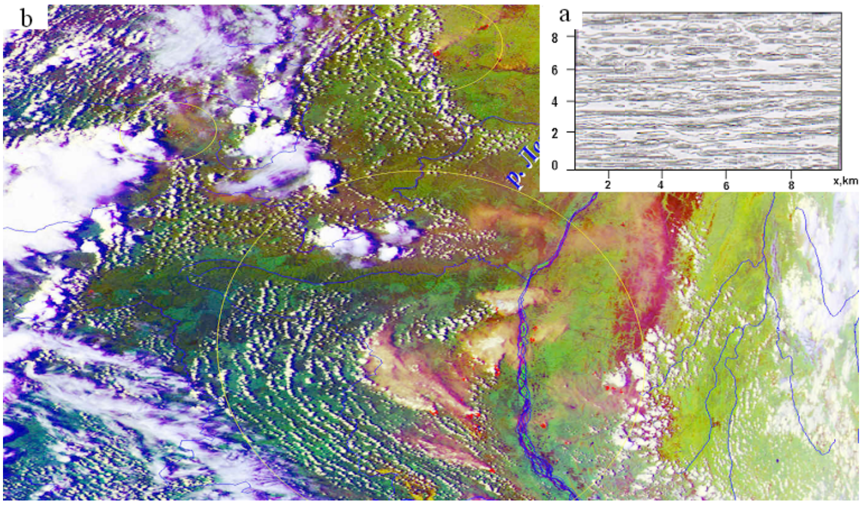

Figure 5. Cloud streets. Notations are the same as in Figure 3

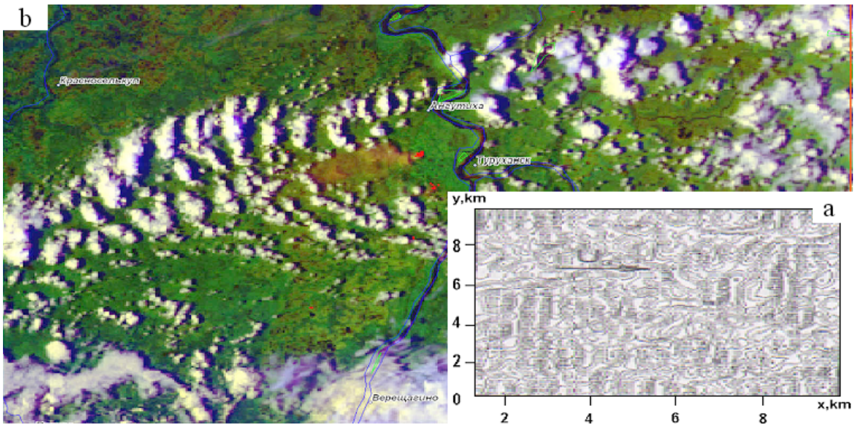

Figure 6. Cloud billows. Notations are the same as in Figure 3

there is a correspondence between a light wind and chaotic distribution of small clouds in the convective ensemble. Such a distribution of clouds is typical of the summer morning calm weather. These are the so-called fair-weather-clouds. As the sun rises the convection intensity and the number of clouds and their size increase. Sometimes, in the afternoon time clouds form ordered pouch-like structures, as Figure 4 shows. If a cloud ensemble begins to form in the windy weather conditions, then clouds are grouping along a speed vector. It is the most commonly observed structure of convective ensembles called the cloud streets (Figure 5).

The most thick clouds are observed in cyclonic conditions with a strong wind whose speed increases with height. Figure 6 shows that the intensive

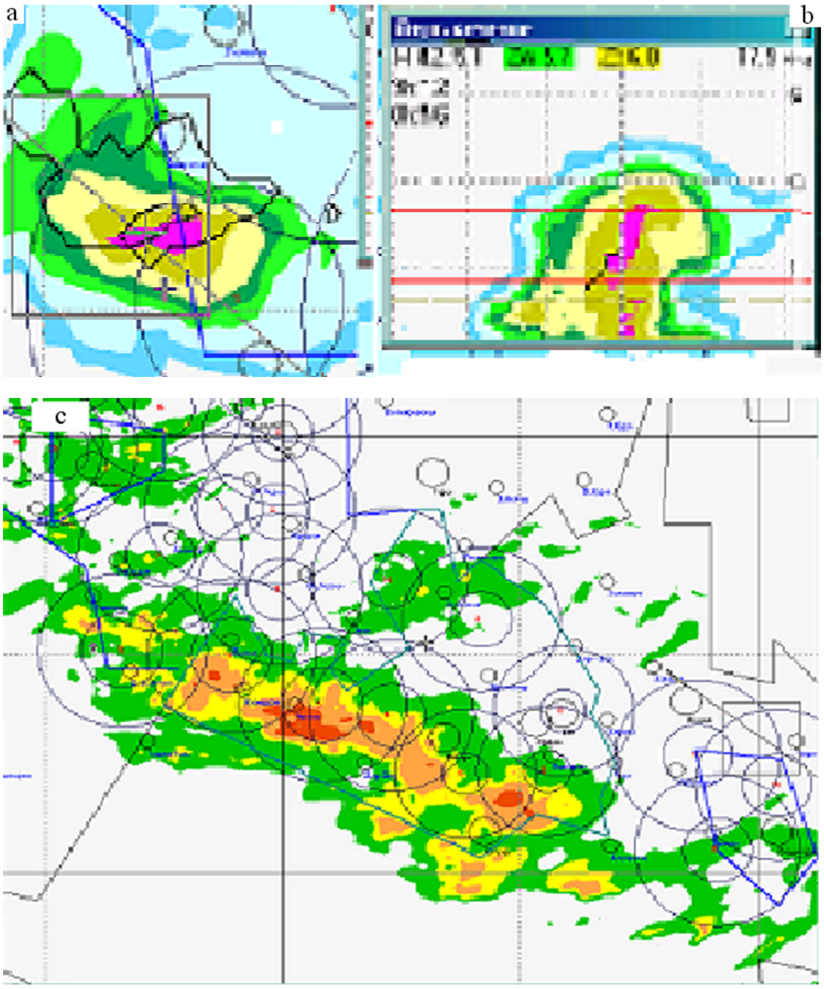

Figure 7. Cloud super-cell: a) horizontal section of the cloud at the height of 8 km; b) vertical section of the cloud through its most active part; c) zones of hail fallout at the territory of Kabardino–Balkaria and North Ossetia

convection both in nature and in theory is related to cloud billows (clouds are located transversely to a speed vector). The thickest billows which are several kilometers in width and several hundreds kilometers in length are associated with passing the atmospheric fronts. These are squall lines whose passage is often preceded by the storm warning.

If a convective attains the heights exceeding 10 km, then there are cloud super-cells with the vertical speeds exceeding 10 m/s. Intensive processes of the precipitation formation occur in these large and fast cells that can cause extreme rainfalls and hailstorms. Such a cell passed over the territory of Kabardino–Balkaria and the North Ossetia in August, 20, 2005. Figure 7 shows the results of computer-aided processing of the cloudiness scan radar data obtained by the system, consisting of several radars located at a sufficient distance from each other. The system is used by the Kabardino–Balkarian group for a very short-range hailstorm forecast and for the choice of the rocket volley parameters for seeding an agent application to the hail formation zone. Figure 7a is a horizontal section of the cloud at a height of 8 km. Figure 7b is a vertical section of the cloud through its most active part. The zones indicated in black are the areas bearing a large-size hail whose possible fallout threatens gardens and vineyards. The vertical and horizontal scales of a cell are approximately identical, i.e., about 15 km. The lower figure shows areas of the hail fallout resulted from this super-cell passage over the territory of Kabardino–Balkaria and the North Ossetia. Zones indicated in black are the areas of a large-size hail fall out which has essentially damaged the protected territory. Zones indicated in light gray are the areas of sleet fallout which has not damaged agriculture. Zones indicated in intermediate colors are the areas of a finer hail fallout which has partially damaged the protected territory. Thus, in this case the active influence on cloud has not prevented the large-size hail fallout.

Let us consider in detail the results of numerical modeling of tornados and windspouts. The great number of such models are reported in the literature, however [9] presents the results which are closest to the observational data. The main results are the following:

1. An eddy occurs on the basis of a thermic and above a convective cloud at the rotary moment.
2. The rotary moment at the external boundary of a cloud converges to the axis, the rotation speed of the cloud central part increases.
3. The rotary moment is transferred to the thermic until rotation reaches the land surface.
4. The vertical velocity component increases almost by an order.
5. The eddy horizontal size is insignificant.

Figure 8 compares the model calculation results [9] to the measurements in the Dallas tornado. The theory explains intensive rotation and the vertical velocities in tornado and a fast sharp pressure drop occurring during several seconds of the tornado passage. Due to this factor, the pressure inside buildings turns to be higher than that outside, and constructions blow up from the surplus pressure.

Figure 9 shows a snapshot of a real tornado which illustrates the model validity [9]. Indeed, there is a slowly rotating cloud in the upper part of the picture and a quickly rotating eddy wind in the lower one. The theory differs from reality by a common vertical rotation axis for an eddy and a cloud which is located in the center. The fact is, the theory does not explain

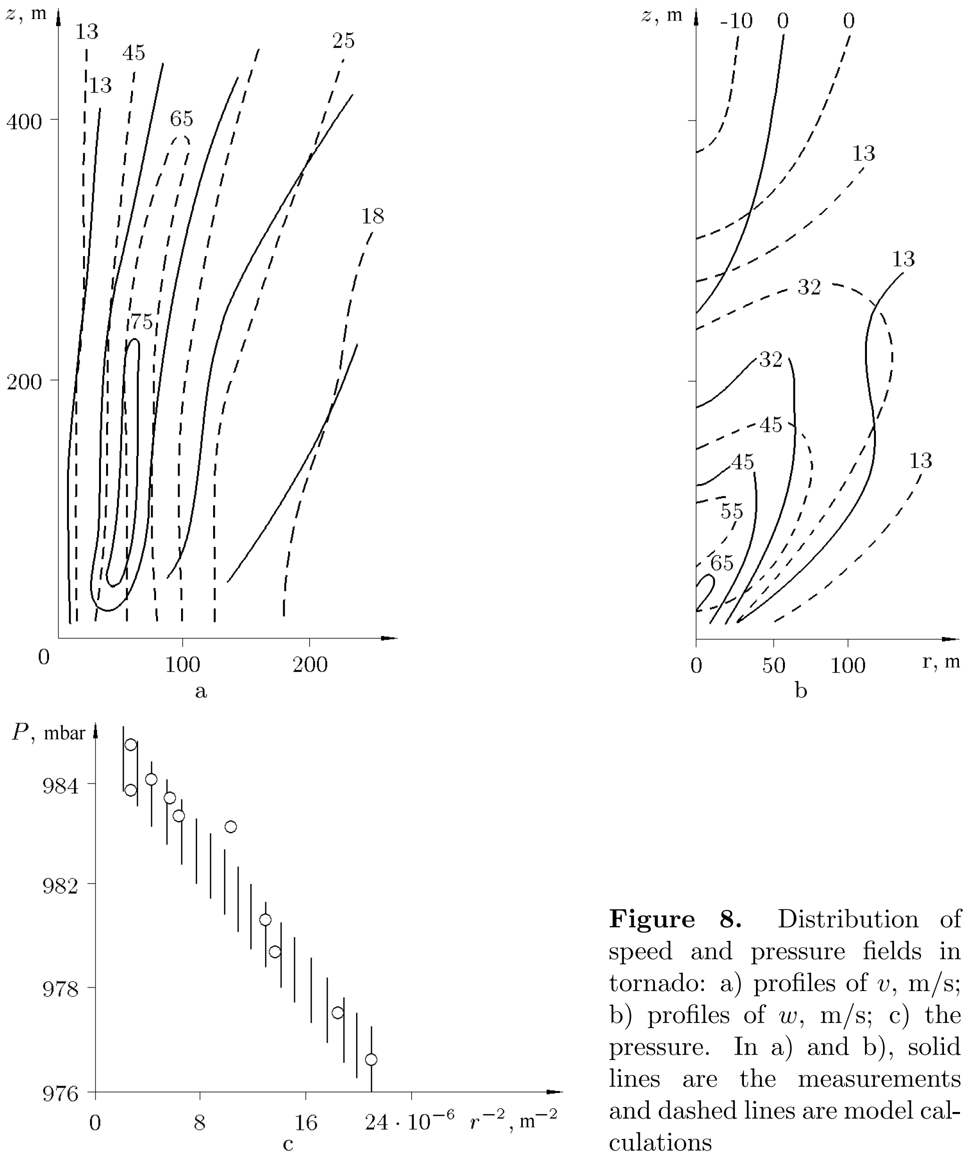

Figure 8. Distribution of speed and pressure fields in tornado: a) profiles of v, m/s; b) profiles of w, m/s; c) the pressure. In a) and b), solid lines are the measurements and dashed lines are model calculations

why the cloud rotates, in the model this rotation is assigned via boundary conditions.

In many models including ours [7], there were attempts to obtain a rotation assigning wind and other factors of the pre-tornado environment. Such models have not still given velocities typical of a well-developed tornado. Both strong tornadoes and rather light windspouts transfer a solid and a liquid aerosol, as Figure 9 shows. We attempted to estimate this aerosol mass using simplified models [7]. The results of these estimations show that

Figure 9. Photography of real tornado

the strong tornado-scale wind eddy lifts up to 10,000,000 tons of aerosol. It consists mainly of rather large objects up to several tons in weight. If a wind eddy passes above a water surface, there are many liquid droplets in the air. The wind eddy can entirely "suck dry" a retention pond of a nuclear power station, or other toxic waste products that really took place. Another real case which speaks well for this estimation took place in May, 2005. Two strong tornadoes have emerged from the sea to the Sochi coast and ceased several km from the coast line. This time some groups have rafted from the Krasnaja Poljana to the Black Sea coast. The powerful rainstorm and flooding in mountain conditions have caused the loss of 17 persons.

The disastrous atmospheric phenomena also include tropical cyclones lasting several days and the covering areas about 100 thousand square kilometers. In meteorological parlance the events of such a scale are called regional. Tropical cyclone models appeared in the late 60s and the early 70s. They have shown that a well-developed tropical cyclone in distinction from a middy latitude cyclone is a self-induced system drawing energy from heat release in the precipitation formation. The regional models of a tropical cyclone are not being developed any more, but are used for validation of various schemes of convection parametrical account. We have offered a similar model of a tropical cyclone [3, 7]. The results of simulation and their comparison with real data are presented in Figure 10. The upper part of the figure shows the calculation results of the wind speed module in different parametrization modes of cloud and precipitation formation processes.

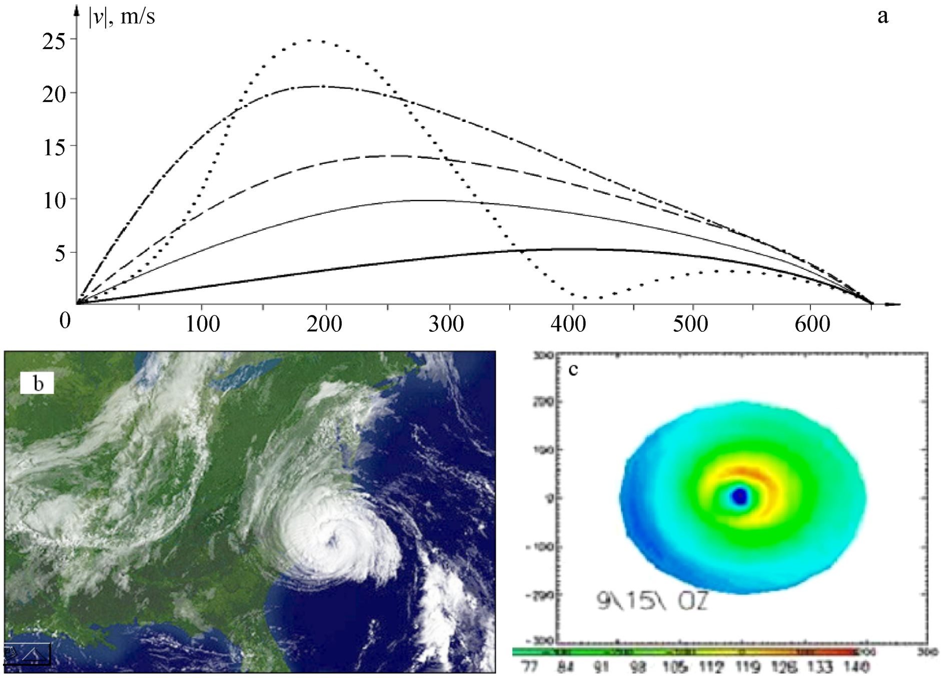

Figure 10. Comparison of theory with observation data in tropical cyclones: a) values of speed module at different distances from cyclone axis in different ways of parameterization of processes of cloud and precipitation formation; b) satellite image of real tornado; c) data of speed measurements in this tornado

The left lower part of the figure presents a tropical cyclone satellite image. The tropical cyclone observation data are plotted in the right lower part of Figure 10. This is a typical tropical cyclone emerged from an area south of Cuba and coming to the USA coast in the area north of Florida. The cyclone diameter is about 400 km. The diameter of the most active part is half the size. The greatest speeds are 140 km/hour or 40 m/s. There is a calm in the center of the cyclone, or the so-called eye of a storm, obligatory attribute of all tropical cyclones. As we can see in the upper part of the figure, our model with any way of cloud parametrization gives underestimated speed values and overestimated values of the cyclone size. Such results cannot be considered satisfactory according to the present standards, thus our model is outdated. The modern schemes of the short-range and intermediate-range forecast are so perfect, that allow one to predict a tropical cyclone a week in advance.

It is to see that there are cloud walls before a cyclone front. These are squall lines which almost always precede cyclones. In addition, the eye of a storm is wind- and cloud-free, whence the name of “eye”. The right lower snapshot presents cyclones typical of the territory of Siberia.

The general conclusion that should be done is the following: Apparently the orderliness is one of obligatory conditions of an intensity phenomenon. Orderliness is induced by a change in the background wind speed and its direction with height, as well as by its rotation. An other obligatory condition of the phenomenon intensity is a sufficient atmospheric heat and moisture supply. It is proved by convective processes almost always associated with natural atmospheric disasters.

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