The concept of vortex convective storms

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Abstract. It is proposed a method of analyzing the effects of the environmental vertical wind shear on the structure and dynamics of convective storms, the conditions for the occurrence of vortex storms based on the hydrodynamic laws of flow around of solid body in the Lagrangian coordinate system. There is described an example of the evolution of a supercell based on radar observations with the updated information of 3 minutes. It is shown the unity of the complex structure and dynamics, which allows proposing a typical model of vortex storms. The method of analysis affords to explain the sequential continuity of the types of storms, the prevalence of the right-propagation (in the Northern Hemisphere). It is proposed a classification of convective storms based on the interaction of the internally associated ascending flow and rotation with the environmental dynamic factor of wind shear.

1. Introduction

Many authors, both in Russia [1] and especially in the West (many works are summarized in [2], [3]), attach great importance to the influence of the environmental wind and, in particular, wind shear when studying the structure and dynamics of Cb. The article considers the mechanism of formation and the model of vortex convective storms based on elementary hydrodynamic laws of flow around a solid body.

2. Methods and results of research

For the convenience and visibility, the analysis of the dynamic effect of the environmental wind on the Convective Object (CO) - the Convective Cell (CC) or a storm, all processes will be considered in the Lagrangian Coordinate System (LCS). The LSC moves with the CO placed in its center along the mainstream \( V \) (the average wind in the layer occupied by the CO, or the wind at the level of 600 hPa, along which the CC moves). For the transferring the usual hodograph (in the Euler Coordinate System - ECS) of the environmental wind into the Dynamic Hodograph (DH) in the LCS [4], [5], it is enough to connect by vectors \( C \) of hodograph points with the mainstream point (figure 1-I) , since \( C_{LCS} = C_{ECS} - V \). The obtained vectors - dynamic winds (CO-relative) - show from which direction and with what speed the horizontal streams flow to the CO. From the point of view of the physics phenomena associated to convection, on the vertical section of a linear DH (figure 1-II.1 and III b), the following tropospheric layers and the role of dynamic winds can be distinguished: the lower, sub-cloud, 0-2 km (G), containing the main share of the resource - humid, heated air - the source of mass of water vapor and energy of phases transitions; the feeder, 2-4 km (F), in which feeder clouds form and move; the average, 4-9 km (M), in which main formation of hydrometeors takes place; the upper, > 9 km (H), in which there is a flow around the CO from above and blowing off of passive cloud masses. There is
stand out two main layers - M and G (which are separated by an intermediate layer 3-4 km thick of relatively weak dynamic winds) according to the physical importance and dynamic strength of the winds: M separates the forming hydrometeors at the early stage of the CO development, flows around it in the mature stage with the possibility of the formation of the main stationary vortices and Stationary Convergent Zones (SCZ, figure 1-IVa,b and Va), dynamic pressure on the CO; G provides the rate of resource recovery in the area of the CO evolution and thereby its intensity and durability, the formation of stationary and Mobile Convergent Zones (MCZ) as a result of the collision of the flowing around CO flows with the counter flows of its rotation (figure 1-Vb), the formation behind the rotating main vortices of the vortex-satellites (figure 1-IVc and Vb), the dynamic pressure on the CO. By mutual orientation of the vectors M and G, 3 types of dynamic hodograph can be distinguished: linearly, with a left turn, with a right turn above the level of the mainstream (figure 1-II).

![Coordinate axis of hodograph and vectors in LCS](image)

**Figure 1.** The concepts put at the basis of the method of analysis of vortex convective storms. I. The transfer of the ordinary hodograph in ECS into a dynamic hodograph in LCS. II. Types of dynamic hodograph: 1-linear; 2, 3 - with a left turn; 4, 5 - with a right turn upper the level of the mainstream. III. Vertical section of the linear hodograph: a) in the ECS, b) in the LCS. IV. Dynamic effects of horizontal flow around the vertical obstacles: a) and c) - a stationary and rotating cylinder, b) and d) - a vertical plate. V. Dynamic scheme of a complete vortex storm: a) formation of a vortex couplet in the mean layer M with stationary convergent zones (SCZ) (light gray spots); b) the formation of opposite vortex satellites and additional mobile convergent zones (MCZ) (dark gray spots) after the couplet down into the flows of the surface layer G; 1-5 – SCZ numbers.

The stable vortices can be formed in the middle troposphere for flow around modes within the limits of critical values of the Reynolds number Re: \(Re^* < Re < Re^{**}\), wherein \(Re = \frac{\rho v d}{\eta}\), \(\rho\) is the density of air in the middle layer; \(v\) – the wind speed in this layer; \(d\) - the size of the obstacle; \(\eta\) - the dynamic air viscosity. Considering the values of \(\rho\) and \(\eta\) are constants, the condition for the existence
of stable vortices is $K_1 < M \cdot d < K_2$. The presence of such conditions and processes in the lower troposphere has been proven, e.g. by the photographs of the Karman vortices formed with horizontal air flows around islands (size 5-6 km) in the ocean. The glider pilots discover stationary vortices and the specific circulation of flows around mountaneous arrays (of the same scale) on land. The air density in the middle troposphere is about 2 times less and to achieve the desired mode requires high speeds or the size of the obstacle ($\nu \cdot d$), which is quite possible.

As the result, represents the following mechanism for the formation of a vortex system, with which such concepts as «supercell» and «mesocyclone» are associated. It is considered the linear DH and quasi-perpendicularly orient to the vector $\mathbf{M}$ obstacle (dense elongated cloud masses of CO) on the middle layer. At the beginning of the next stage of development in the process of periodic self-oscillations of the CO intensity (which occur due to the fact that the CO assimilates the resource faster than it is restored [6], [7]), reaching of critical flow around mode, a vortex couplet is born: cyclone-anticyclone. When the elongated obstacle is located at an angle to $\mathbf{M}$, the birth of one vortex is possible - cyclone or anticyclone (figure 1-IVd). When the couplet is downing into the lower layer $G$ («dynamic tube effects»), it is flown around by counter flows of this layer with the formation of satellite vortices on the opposite side, rationalizing the flow around regime. Eventually, a system of four connected stationary vortices is formed (figure 1-Vb). In this system are formed the corridors – the sections of joint rotation of neighboring vortices: the main resource collection is between cyclonic and anticyclonic vortices, cyclonic propagation - between cyclonic vortex and its satellite, anticyclonic - between anticyclonic vortex and its satellite, satellite - between satellite vortices. The main and satellite corridors form the storm convergence line (frontal and rear inflows of air and cloud masses of developing cells) and cyclonic and anticyclonic - the storm divergence line (removal of cloud mass and precipitation of dissipating cells). In this case, the $SCZs$ with increased pressure forms (figure 1-Vb): basic (1), rear (2), propagation (3), anticyclonic (4) and central (5). It will be used the concept of the propagation of the CO - the increase in its mass (area) at $Z_m > 45\text{dBZ}$ in the middle layer. The propagation is manifested in varying degrees of contiguity of the feeder CC (the Footh coefficient - $K_b$), which reached the specific reflectivity in this layer - the signal CC (shows the storm propagation area), to the main mass (area) of the CO. On the ASU-MRL radar maps, this is referred in the form of radio-echo canopies or file-by-file increments in the LCS of the CO area. The direction of the propagation of the CO depends both on the development stage of the CO and on the dynamic vectors $G$, $\mathbf{M}$ and $W_m$ - the maximum speed of updraft.

It is examined an example of supercell data from 05/25/2008 based on archived materials of the radar ASU-MRL, Kornesti village, SSAI, RM. The DH (figure 2-C) can be considered linear, almost coinciding with the mainstream $V$, the dynamic winds $G \approx 9 \text{ m/s}$, $M \approx 7 \text{ m/s}$ are relatively small. The value of $Re$ is: $Re = 0.6\text{kg} \cdot \text{m}^{-3} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot 6000 \text{m} / 18000000 \text{Pa} \cdot \text{c} \approx 0.001$. In the time period from 15:00 to 16:10, the reflectivity in the layer of 6-8 km exceeded 55 dBZ (therefore, presumably as a condition for the occurrence of vortices can be taken $K_1 < M \cdot d < K_2$), and the CO was in the supercell, vortex state during which there are three stages of development with periods of about 20-25 minutes (figure 2-A). The first stage (15:05-15:25) is associated with the formation of a complete vortex storm, which appears at the beginning in the formation from (amplifying from 14:50 to 15:05) the main cell of the initial storm of the main corridor, as well as a rapidly developing a new «cell» - a cyclonic vortex of the south of the corridor on the leeward side of the obstacle relative to $\mathbf{M}$ (figure 2-D).

In the white isolines of radar reflectivity $Z_m = 55 \text{dBZ}$ of surface precipitations on the leeward side, the characteristic notches associated with the centers of the vortices of the couplet are visible. Then, the precipitations began to separate into two areas of maxima (“RFD” and “FFD” [2], [3]) due to the impact on them of two adjacent opposite vortices with the creation of two hail fallouts streaks (figure 2-B). Wherein, the largest hail, due to centrifugal forces, is concentrated on the outer side of the cyclonic vortex in the main corridor and is retrieved by the anticyclonic vortex (and then by the satellite of the cyclonic vortex). There is a gradual transformation of the horizontal field of the radar reflectivity $Z_m$ of the cyclonic vortex: from the maximum in the center of the circle to its distribution...
along the outer circumference with the formation of ascending and descending branches. The main storm is forming in SCZ-3 with the 1st CC in the canopy.

Figure 2. Supercell 05/25/2008. A - time course of radar parameters (top - heights of different reflectivity levels, down - Zm) and B - map of the kinetic energy of hail from 13:47 to 16:47; C - hodograph for 15:00 utc, Chisinau: the large circles - ground and 600 hPa, black - dynamic vectors G and M, gray - mainstream V; D - water content map at 15:04 (circumference - incipient cyclonic vortex, arrow - convergence line); E - the map of the horizontal section at the level of 4 km at 16:17; F - influence map at 16:35 (storm dissipation), 1 and 2 - vertical sections along with the arrows on this map.

The figure 3 shows the maps of the ASU-MRL at 15:18, 15:29 and 15:48. The obvious elements of structure on those or other maps allow drawing the outlines of all vortices. The vertical sections of Zm along the divergence line clearly show the separation of fallouts precipitation into two branches: along the propagation and anticyclonic corridors, as well as the development of the cells of the main storm. In the period 15: 25-15: 50, the 1st CC of the main storm, being in the mean layer with the reflectivity of more than 45 dBZ and being carried away by the flows around and the rotation in this layer, is partially drawn into the cyclonic vortex, and partially is carried away beyond its limits and dissipated. This is manifested in the rotation of the canopy and the increments in the LCS around the vortex circumference. At the same time, the 2nd CC of the main storm appears and grows. In the period 15:50-16: 15, a similar process of carrying away of the 2nd CC and the inception and growth of the 3rd CC takes place, which at 16:06 gave an absolute maximum reflectivity of 72.6 dBZ. At 15:18 on the A1 map in figure 3, a "trident" is visible at the exit of the propagation corridor, formed by two descending branches of diverging vortices and the main storm between them. On maps A6 and C6, hail-dangerous chains are visible (according to H_{15}) in the ascending branch of the anticyclonic vortex.

Figure 4 shows the vertical sections of the radio-echo on the influences map at 15:18 along the three indicated contours.
In the first two, they manifest the natural cycle of gradual development of cells rotating around the circumference of a cyclonic vortex, as well as carried away from the MCZ. It can be seen that having dropped precipitation in the main and propagation corridors, rather dense residual cloud masses continue to rotate in the circumference and rising in the ascending branch of the vortex. The pool of cold air from dropouts spreading at high speed along the propagation corridor stimulates the main storm. Figure 5 shows CCs at different stages of development, rotating in a circumference 6 km in diameter around the axis of the cyclonic vortex (exact correspondence [2] [3]; the diameter of the vortices should probably be equal to half the length of the obstacle, i.e., \( \approx \frac{d}{2} \)).
It can be seen that the region of maximum ascending flows is located not in center of vortex, but in the ascending branches of the main vortices in the SCZ-1. The dissipation of a vortex storm begins when the conditions for its occurrence disappear: the value of Re of the flow around regime in the middle layer M becomes less than the critical Re* with a decrease in the size/density of the obstacle d in this layer due to the weakening of the convection intensity. The anticyclonic vortex begins to weaken and blur, its satellite disappears. The cyclonic vortex, decreasing in size, shifts to the driving edge of the storm, strengthening, together with its satellite, as a result of which Zm even reaches its maximum. After the collapse of the cyclonic vortex, its satellite remains the leader: figure 2-E shows that the last chain of the CCs drowns into it from the cyclonic vortex. In the final stage of storm dissipation, after the destruction of all vortices, the storm is elongated similar to the starting line. The remnants of three storms/CCs are visible in it (respectively, three former SCZ on the storm divergence).
line, figure 2-F), more powerful in SCZ-3. During the entire evolution period, the presented full vortex storm did not divide into right- and left-propagation halves. During the stage of development of a vortex storm, there is a gradual increase of the velocity of the updraft and, accordingly, the speed of rotation of the vortex, then a decrease. It looks like turning the entire vortex system counterclockwise, then back (row C versus row A, figure 3). This corresponds to the deflection of the upper hail fall band and the approach of the lower band with it in the period up to 15:40 (figure 2-B), followed by a return to the previous position. This phenomenon determines the zigzag direction of the storm propagation in the LCS (figure 4-E, [4]).

Figure 6, based on the results of the presented analysis, as well as the analysis of other vortex storms, presents the generalized structural-dynamic model of the vortex storm (for the Northern Hemisphere, with a more active cyclonic vortex), on which can be seen its main structural elements (features).

![Figure 6](image_url)

**Figure 6.** Structural-dynamic model of vortex storms. A - full tetra vortex storm ("mesocyclone", "HP-supercell") and B - double vortex storm at the separation of the full storm [2], [3] or independent formation ("RM CL-supercell" or RP CL supercell in LCS, right-propagation) at linear dynamic hodograph. C and D - the variant of the analysis of vortex storms with the right (C) and left (D) rotation of the dynamic hodograph (Figure 1-II, 5 and 3, respectively). Light (dark) arcs - ascending (descending) branches of the trajectories of cloud streams along with the circumference of the maximum tangential speed of rotation of the vortices; curved black thick arrows - trajectories of hail precipitation in the mean and lower layers in the process of their sinking and falling to the ground; the black point line limits the area of precipitation falling out and carried by vortexes on the surface layer; the black thick solid line delimits the area with a reflectivity of more than 45 dBZ in the mean layer; black thin solid arrows - surface G flux lines, and dashed - opposite outer lines of currents of vortices of the couplet; light gray spots - stationary convergent zones; dark gray spots on the sides - mobile convergent zones of feeder origination (circles); contour vector - main storm; black spots - areas of the most intensive precipitation and hail (in A: on the right - "FFD" and on the left - "RFD"). Lines with arrows of the end inside – convergent line, outside – divergent line.

The actual development of the considered processes and the particularities of the structure and dynamics of the vortex system depend on the mutual ratio of the modules and orientation of the vectors M and G, as well as the size and orientation of the obstacle relative to them. The degree of visibility of the structure of the storm and its transformation in time on radar maps strongly depends on the orientation of the storm relative to the radar. Taking the main thing in the CO (its inner essence) is the presence of coupled updraft W and rotation R, which are realized in environmental shear circumstances (G and M), and the other qualities are external manifestations of this process, it is possible to propose a classification of convective storms on the example of a linear DH (figure 7).
It can be noted an exceptional role in the couplet of the anticyclonic vortex, which together with the cyclonic vortex provides a vast area of inflow of resource-saturated flows $G$. This allows maximum precipitation productivity by a complete vortex storm. It can be seen that as the values of $R_m$ and $G$ increase, the elementary storm chain of convective cells (ESC) of non-dynamic storms is increasingly drawn into the rotational motion of a dynamic storm and is bent by rotation. This drives to a gradual reduction in the size of the canopies and increments, i.e. propagation to the vector $G$, up to disappearance. At the same time, the right-propagation is gradually developing due to the development of the MCZ and then the vortex satellite. The satellite contributes to the rotation of the dissipating branch of the ESC into a propagation corridor and the formation of the main storm, which provides the right-propagation of the dynamic storm (it is right relative to the mainstream $V$, as is customary, but more precisely, it is left relative to the vector $G$, and relative to the vector $V$ in the 90-180 degrees sector in depending on the wind turn in the lower 4 km layer, i.e. depending on the orientation of $G$.

\[ \text{Figure 7.} \text{ Classification and some particularities of the structure and dynamics of convective storms with a linear dynamic hodograph. Circumferences with arrows limit the area of the updrafts with rotation, the dashed circumference without rotation, circles with a contour of different shades - CCs of different stages of development (the third in shade gradation feeder CC - signal); a thick curved arrow shows the drifting of this cell from the main storm (white circle with a cross); the dashed contour vector - resource inflow strip with surface layer $G$ flows; solid contour vector - direction, strip and (conditionally) speed of storm propagation; light and dark gray spots - stationary and mobile convergence zones; small arrows - the inlet of feeder chains; 1 - separate formation of new CCs; 2 - alternate change in the dominance of successive CCs - ESC; 3 - "single" dominant CC with separate updraft and downdraft; 4 - the beginning development of significant rotation of the updraft of convective origin; 5 - the inception of the right-propagation; 7 - a full set of four vortices formed by the flow around in the mean and lower layers; 6 - half from division of full set (or a continuation of the 4-5 lines); } \]

\[ K_r = \text{Footh coefficient of propagation.} \]
relative to \( V \). It is evidently, that a dynamic storm can have several sources for the production of precipitation and hail in the form of ESC. In the full vortex storm, their number can reach five: two are involved in the rotation of cyclonic and anticyclonic vortices from the MCZ, two are drawn into the storm along the main and satellite corridors, and one directly feeds the main storm.

The values of the control parameters both within each category and in the sections between them are changing smoothly, forming a continuous spectrum of storms in terms of external manifestations. The possibilities of amplification rotation in storms of a convective nature are apparently limited. And for the formation of the flow around vortex storms, it is necessary to achieve some critical values of the parameter \( M \cdot d \). Noting that the physical meaning and dimension of all control parameters are the same: this is the speed of horizontal (flow around and rotation) and vertical flows in \( \text{ms}^{-1} \).

The created circumstance can help in developing indexes of the possibility of forming and intension of dynamic storms and, in particular, vortex storms. The extent to which the influence of mesoscale convective structures (MCS, \[8\]) on the direction of propagation of convective storms goes beyond the region of insignificant dynamic R-M-G factors is still unclear.

3. Conclusion

It is proposed a method of analyzing the effects of the environmental vertical wind shear on the structure and dynamics of convective storms, the conditions for the occurrence of vortex storms based on the hydrodynamic laws of flow around of solid body in the Lagrangian coordinate system. The method of analysis affords to explain the sequential continuity of the types of storms, the prevalence of the right-propagation (in the Northern Hemisphere). It is proposed a classification of convective storms based on the interaction of the internally associated ascending flow and rotation with the environmental dynamic factor of wind shear.

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