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A SINK-FLOW THEORY OF TORNADOS

I. I. Smul'skii

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A sink-flow model of a tornado is proposed. The mechanisms of the formation of circulation and reasons for the sink flow are considered. Relations that are necessary to describe the processes in tornados and to predict them are obtained. The way of preventing tornados is outlined.

1. Introduction. Depending on the scale, it is common practice to classify the vortices that form in the atmosphere as cyclones with a diameter of thousands of kilometers, tropical storms with a diameter of hundreds of kilometers, tornados of about 1 km, and dust vortices with a diameter of tens of meters.

Of greatest interest are tornados. In some regions, they are a real disaster. In the USA, for example, there form up to 1000 tornados a year, 10% of which lead to destruction and casualties. On June 9, 1984, in the Ivanovo region, a tornado left a destruction zone with a width of up to 500 mm and a length of about 100 km [1]. The tornado was a "trunk" released from a dark funnel cloud which rocked from side to side, rotated rapidly, drew objects in and threw them at height. The tornado tore a tank from a water tower, and threw it 200 m to the side. Whistle and hum were heard as if from a jet aeroplane. The funnel inside was shining.

When tornados pass, sharp pressure decreases (up to 90 kPa) are recorded [2]. The rotational velocity in tornados attain 50–150 m/sec, their height is up to 10 km, and ascending flows in tornados have a velocity of up to 20 m/sec, sometimes of up to 100 m/sec. The directions of rotation are different.

Because of the complexity and poor study of the tornado phenomenon there are many hypotheses and models of formation. Thus, E. V. Shcherbinin [3] proposes an electromagnetic mechanism for the occurrence of tornados. A number of researchers, including I. N. Yanitskii, link the process of tornado generation to fractures in the earth's crust. V. V. Nikulin [4] considers a thermal mechanism of tornado formation, according to which intensification of the rotation of a liquid over a heated surface can model atmospheric vortices. In [5], a hypothesis of tornado formation due to vertical air oscillations is proposed. The authors of [6] come up with the idea of tornado formation due to the concentration of turbulent pulsation energy. J. Simpson [7] and other authors believe that tornados occur when intense horizontal vortex tubes in the lower part of the boundary layer suddenly become vertical.

Many authors [7, 8], on the basis of the data of meteorological observations and results of radar and aerospace observations, have analyzed different mechanisms of atmospheric vortices. We think that these investigations lack a central idea that could tie up the observed phenomena into one integral picture. On the other hand, vortex chambers that were created in the 50s to study tornados in a laboratory have found wide application in technology. However the results of these investigations are not used when analyzing atmospheric vortexes though they permit explanation of many properties of tornados. High tangential velocities near the vortex axis can exist when the velocities at the periphery are low, for example, the maximum tangential velocity V_{max} in the chamber is capable of exceeding the peripheral velocity by a factor of 45 [9]. The high rarefaction in the center of the tornado which suddenly occurs outside buildings creates large loads on the structures that destroy them. Thus, for an external pressure of 90 kPa per square meter of a building's wall, a force of one ton will be applied from the inside. The large pressure gradients in the vortex chamber explain why objects adjacent to destroyed buildings can be unaffected by a tornado. The effect of the tornado's "foot" (compacted straw, pressed-in branches along the tornado's path) finds its explanation in the counterflow which, as in a vortex chamber, can take place in the center of the tornado. The high velocity of motion in it in combination with the natural fall of objects in the gravity field

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Institute of the Cryosphere of the Earth, Siberian Branch of the Russian Academy of Sciences, Tyumen'.
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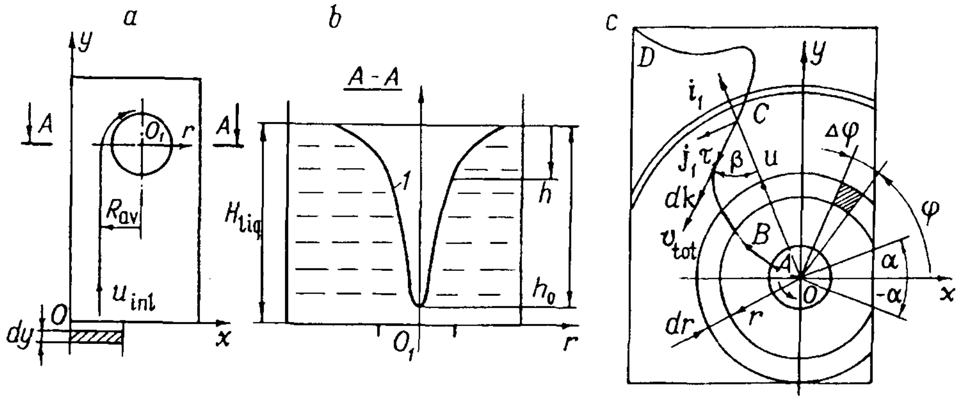

Fig. 1. Funnel formation in drain flow of a liquid from a tank: a and b) for liquid drain flow with feed (b is the funnel profile); c) without feed.

will lead to their pressing into the ground's surface. The observed strong electrification of the rotating layer of particles in the vortex chamber and electric discharges in it are identical to electric phenomena (flashes of lightning along the tornado channel, radiowave emissions) occurring in tornados, which also form the rotating layer of the underlying surface material entrained by the tornado. All this enables us to consider a tornado as a powerful manifestation of a vortex which is modeled in vortex chambers.

In a vortex chamber, a medium with an initial swirl arrives from the periphery, and in motion toward the center due to conservation of the moment of momentum its tangential velocity increases. Then, via the central orifice in one end cover, it flows out of the chamber. A similar mechanism of funnel formation takes place in water drainage from a sink. Atmospheric vortices form in the same manner: the air layers of high buoyancy which are superheated at the surface tend to move upward. This flow continues until the entire superheated air layer runs out. Unlike in a sink, here the drain point and hence the atmospheric vortex can move with respect to the earth's surface.

In a vortex chamber, the initial swirl is imparted to the flow at its periphery due to the tangential inlet. When a fluid drains from the atmosphere the initial swirl is formed by different conditions, which will be considered below. In a vortex chamber, the medium is drained due to the pressure difference between the inlet and outlet; in a tank, due to the gravitational forces; and in the atmosphere, due to buoyancy. The study of the processes of the formation of the initial swirl and the drain driving force will enable us to represent the sink-flow mechanism of tornado formation completely. Some cases of the formation of circulation are also characteristic of liquids: therefore, they will be considered as applied to it.

2. Occurrence of Rotation in Liquid Drain Flow. The observation of funnel formation enables us to distinguish two cases of liquid drain flow: with additional feed (Fig. 1a) and without feed (Fig. 1c). For nonaxisymmetric feed, an inflowing volume element of liquid $dm = \rho H b dy$ with respect to the center of the drain has the moment of momentum

$$dM = dm u_{\text{inl}} R_{\text{av}} . \tag{1}$$

Then the moment of momentum for a unit mass of the liquid will be

$$\Gamma = dM/dm = u_{\text{inl}} R_{\text{av}} . \tag{2}$$

In accordance with this circulation, there forms a funnel above the drain. By varying the perimeter R_{av} we can produce a funnel of varying intensity which rotates in any direction.

The drain of the rotating liquid via an orifice is identical to the motion of the medium in a vortex chamber [9], in accordance with which a variation of the tangential velocity and pressure along the funnel radius can be approximately described in the following manner:

$$v = \frac{2 v_{\max} r / R_v}{1 + (r/R_v)^2} ; \tag{3}$$

$$p = 2\rho v_{max}^2 \left(0.5 - \frac{1}{1 + r^2/R_v^2}\right) + C. \quad (4)$$

Expressing the constant C in terms of the pressure at the center p_0, which is determined from (4) for $r = 0$, we rewrite the latter as

$$p - p_0 = 2\rho v_{max}^2 \left(1 - \frac{1}{1 + r^2/R_v^2}\right). \quad (5)$$

Replacing p by the hydrostatic pressure ρgh, where h is the funnel surface depth, we obtain the funnel profile in the form

$$h = h_0 - \frac{2v_{max}^2}{g} \left(1 - \frac{1}{1 + r^2/R_v^2}\right). \quad (6)$$

Since $h \to 0$ as $r \to \infty$, then from (6) the funnel depth at the center will be

$$h_0 = \frac{2v_{max}^2}{g}. \quad (7)$$

The parameters for $8.2 > v_1/w_{av} > 0.36$ in relations (6) and (7), according to [9], are equal to

$$v_{max} = \frac{v_1 \left[1 + (R_1/R_v)^2\right]}{2R_1/R_v}; \quad v_1 = \frac{\Gamma}{R_1}; \quad w_{av} = \frac{Q}{\pi R_1^2}; \quad R_v = 0.35 R_1 \sqrt{\left(\frac{v_1}{w_{av}}\right)}. \quad (8)$$

The obtained expressions determine the depth and profile of the funnel as functions of the feed parameters u_{inl} and R_{av}. From (6) and (7) it follows at the middepth of the funnel its radius will be equal to R_v, where, according to (3), the liquid rotates with velocity v_{max}. Above and below, the rotational velocity for the funnel will be lower. Expressions (6) and (7) also apply to natural vortices that form in rivers and oceans.

Liquid drainage from a tank without a supply is possible for the settled and unsettled liquids. If M is the total moment of momentum for the settled liquid with respect to the center of the drain, then once the orifice is opened, the outflow will rotate with circulation

$$\Gamma = M/m. \quad (9)$$

From this Γ value, in accordance with (6)-(8), we can determine funnel parameters.

Let us consider the escape of a settled liquid by the example of a rectangular tank (Fig. 1c). Once the orifice is opened the liquid falls freely through it. As a consequence of the continuity of the medium, an annular layer of radius r with average radial velocity

$$u = \frac{Q}{2(\pi - \alpha) rH}. \quad (10)$$

begins to move to the drain orifice.

Let us consider an element of the layer with angular sector $d\varphi$ and height dz. Its mass $dm = \rho r d\varphi dr dz$. If β is the angle between the total velocity v_{tot} and the radius, it will be written as

$$v_{tot} = u/\cos\beta. \quad (11)$$

Then the momentum of the element dm will be

$$d(d\,\mathrm{K}) = dm v_{tot} = \rho r v_{tot}\, dr dz d\varphi. \quad (12)$$

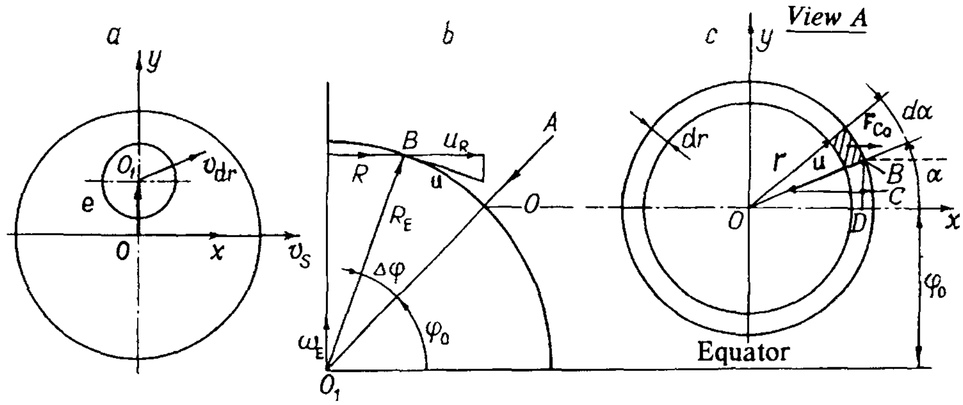

Fig. 2. Formation of circulation in atmospheric drain flow: a) for relative motion of atmosphere and drain flow; b and c) for drain flow on the rotating Earth (b is the Earth cross-section along the meridian through the center of the drain O, c is the view of the center of the drain O along arrowed line A).

Upon integrating (12) with respect to φ we obtain the momentum for the annular sector with the angle $2(\pi-\alpha)$ as

$$d\,\mathbf{K} = \frac{2\rho ru \sin\alpha\, dz}{\cos\beta}\,(\mathbf{i}\cos\beta + \mathbf{j}\sin\beta)\,dr\,, \tag{13}$$

where $\mathbf{i}$ and $\mathbf{j}$ are unit vectors in the directions of the x and y axes. The mass of this sector is $dm_{\text{lay}} = 2(\pi - \alpha)\rho r dr dz$ and its center of mass is found from the radius

$$r_{\text{cent}} = r\frac{\sin\alpha}{\pi - \alpha}\,.$$

For each equidistant layer of radius r, according to this relation, the distance r_{cent} to the center of mass will be determined, it being located on the center line of discontinuity. The points of the centers of mass for all equidistant layers form the line of the centers of mass, and since they depend on the position of discontinuity this line will be a function of the angle φ, i.e., $r_{\text{cent}} = r_{\text{cent}}(\varphi)$. This function is determined by the position of the orifice and the configuration of the tank. The vector of the momentum of the equidistant layer (13) is directed at the tangent to this line. With allowance made for this, let us write formula (13) as

$$d\,\mathbf{K} = dm_{\text{lay}}\frac{ur_{\text{cent}}}{r\cos\beta}\boldsymbol{\tau}\,. \tag{14}$$

The vector $d\mathbf{K}$ with respect to the center of the drain produces the moment of momentum $d\mathbf{M} = d\mathbf{K}r_{\text{cent}}\sin\beta$, integrating which over all equidistant layers of the tank and the height z, we obtain the expression for the total moment of momentum

$$M = GS_{\text{as}}\,, \tag{15}$$

where

$$S_{\text{as}} = \frac{1}{H}\int_0^h\int_{\varphi_1}^{\varphi_2} r_{\text{cent}}^2\, d\varphi dz\,. \tag{16}$$

The quantity S_{as} will be referred to as the asymmetry cross section. As can be seen from (16) it is governed by the configuration of the tank and the position of the drain orifice.

Thus, in a settled liquid due to drain asymmetry moment of momentum (15) can occur. In this case, circulation is determined by relation (9), and all funnel parameters, by (6)-(8). For many tanks, the lines of the centers of mass and S_{as} can be estimated without calculations, which indicates the possibility of funnel formation and its rotation direction. The obtained results are confirmed by the known [10] and our experiments [9].

3. Formation of Circulation for the Relative Motion of the Atmosphere and Drain. Let us consider the drainage of an air mass which is restricted by surface S and moves with the velocity v_S (Fig. 2a) through an orifice with the center at point O_1 displaced from the center of the region by the distance e. If the velocity of motion for the center of the drain is $\mathbf{v}_{dr} = v_{dr\,x}\mathbf{i} + v_{dr\,y}\mathbf{j}$, then an air-mass element $dm = \rho h dx dy$ with respect to the center of the discharge will produce the moment of momentum

$$dM = dm\,(v_S - v_{dr\,x})\,(e - y) - v_{dr\,y}\,x dm\,. \tag{17}$$

Upon integrating over the entire volume S of the air mass, we obtain the moment of momentum in the form

$$\mathbf{M} = m\,[(\mathbf{v}_S - \mathbf{v}_{dr}) \times \mathbf{e}]\,. \tag{18}$$

The circulation which occurs with drain flow is determined by relation (9), and we find the parameters and profiles of the tangential velocity and pressure in the vortex by formulas (3), (4), and (8) when $C = 0$.

Using (18) in a number of cases we can easily determine situations of the occurrence of vortices and the direction of air rotation in them. As the drain flow moves and its position varies circulation can occur and become stronger or weaker, while the air rotation can even change to the opposite direction. These variations take place in tornado formation. For example, on June 9, 1984, [1] in the regions of Central Russia tornados suddenly occurred and disappeared, and the rotation direction was different. On November 23, 1985, in northern Wales, 105 tornados were recorded in a period of about 5 h.

4. Formation of Circulation due to the Rotation of the Earth. Let us consider a drain flow of the atmosphere with the center at point O whose width is φ_0 (see Fig. 2b and c). The average radial drain velocity at points on a circle of radius r will be

$$u = (-1)^c \frac{Q}{2\pi r H}\,. \tag{19}$$

An element $dm = \rho H r dr d\alpha$, due to the rotation of the Earth with angular velocity ω_E, is acted upon by the Coriolis force

$$d\,\mathbf{F}_{Co} = 2dm\,[\boldsymbol{\omega}_E \times \mathbf{u}] = 2dm_E\,u_R\,\boldsymbol{\tau}\,. \tag{20}$$

Here $\boldsymbol{\tau}$ is a unit vector tangent to the rotation of the Earth and $u_R = CB \sin\varphi = u \sin\alpha \sin\varphi$ is the projection of the velocity u onto the distance $R = R_E \cos\varphi$ to the axis of the Earth's rotation (see Figs. 2b and 2c). The width φ of an element dm at point B (see Fig. 2b) can be expressed in the following form:

$$\varphi = \varphi_0 + \Delta\varphi \simeq \varphi_0 + CB/R_E = \varphi_0 + r\,(\sin\alpha)/R_E\,.$$

Since $\Delta\varphi << 1$ the expression for u_R can be simplified:

$$u_R \approx u\left(\sin\alpha \sin\varphi_0 + \frac{r}{R}\sin^2\alpha \cos\varphi_0\right). \tag{21}$$

The force (20) with respect to the center of the drain flow O produces the moment $d\Omega = -dF_{Co} r \sin\alpha$, which, for the entire circle, will be written as

$$d\Omega = -2\rho\omega_E H u r^2\,dr \int_0^{2\pi}\left(\sin^2\alpha \sin\varphi_0 + \frac{r}{R_E}\sin^3\alpha \cos\varphi_0\right) d\alpha = -2\pi\rho\omega_E\,u r^2 \sin\varphi_0\,dr\,. \tag{22}$$

By integrating (22) over the entire region of drain flow from the peripheral radius R_2 to the drain radius R_1, in view of (19), we obtain the total moment of forces which act on the draining medium

$$\Omega = -(-1)^c 0.5G\omega_E \sin\varphi_0 (R_2^2 - R_1^2). \tag{23}$$

The moment of forces Ω produces a flux of the moment of momentum for the medium $G\Gamma$, i.e., $\Omega = G\Gamma$. Then the time-and space-averaged circulation in the draining medium will be

$$\Gamma = -(-1)^c 0.5 (R_2^2 - R_1^2) \omega_E \sin\varphi_0. \tag{24}$$

From this expression, it can be seen that, for cyclonic motion ($c = 1$), circulation in the northern hemisphere ($\varphi_0 > 0$) will be positive, i.e., the rotation direction is counterclockwise, while in the southern hemisphere ($\varphi_0 < 0$), it has the opposite direction. For an anticyclone ($c = 2$), the rotation directions will be opposite. It also follows from (24) that at the equator circulation is equal to zero, while in cyclones which move away from the equator circulation will increase and therefore winds will become stronger. These phenomena do occur in nature [10]. For example, tropical cyclones become stronger with distance from the equator [11], and out of 832 cases of the generation of tropical cyclones in 10 years [12], none formed at the equator or near it.

The circulation (24) which is due to the rotation of the Earth becomes substantial for large regions of drain-flow; for example, at latitude $\varphi_0 = 45^\circ$, vortices with radius R_2 will have the circulations

R_2,	km	1	10	100	1000
Γ,	m^2/sec	26	$2.6 \cdot 10^3$	$2.6 \cdot 10^5$	$2.6 \cdot 10^7$

Dust vortices and tornados with the drain-flow region of $R_2 < 1$ km have a circulation of the order of $\Gamma = 600-2000$ m^2/sec [13], while $\Gamma = 6.6 \cdot 10^6$ m^2/sec for a typhoon with $R_2 \approx 500$ km, from which it follows that the circulation which is due to the Earth's rotation becomes the basic mechanism of formation for such large atmospheric vortices as cyclones, anticyclones, tropical cyclones (typhoons), and large tornados.

The occurrence of powerful tornados is often accompanied by significant winds. For example, on June 2, 1980, in Ukraine tornados were accompanied by the motion of a cloudiness zone with a velocity of 50 km/h [14]. These vortices were moving. Therefore, the basic mechanism of formation for their circulation was due to the relative motion of eccentric drain flow (18). For example, a tornado with circulation $\Gamma = 30{,}100$ m^2/sec [15] can form for relative velocity $v_S - v_{dr} = 15$ m/sec and eccentricity $e = 2$ km.

For some features of terrain, vortices can form which are due to the drain flow with feed. Small vortices, visualized by dust, sometimes form in sunny, windless weather. Their circulation can be due to the mechanism of drain flow without feed (15), where the medium which drains upward is a region of a superheated air layer.

5. Potential Pressure of Drain Flow. Let an air volume with pressure P_1 and temperature T_1 for some reason (vertical velocity pulsations Δv, local superheating ΔT, interaction of the warm and cold fronts, etc.) ascend from height H_1 to height $H_2 > H_1$, where the pressure of the atmosphere is $P_2 < P_1$ and its temperature is $T_2 < T_1$. As a result of adiabatic expansion (dry air is considered) the volume temperature T_1 will decrease to T_{12}

$$T_{12} = T_1 \left(\frac{P_2}{P_1}\right)^{(k-1)/k}. \tag{25}$$

If $T_{12} > T_2$, the volume density will be lower than the density of the ambient air and the volume will continue to ascend; this stratification of the atmosphere is unstable. Conversely, if $T_{12} < T_2$, the colder ascended volume will descend again. This will be a stable atmosphere. The stability condition in view of (25) can be written as

$$\frac{P_1^{(k-1)/k}}{T_1} > \frac{P_2^{(k-1)/k}}{T_2},$$

from which for a stable atmosphere we obtain

$$\Phi(H_1) > \Phi(H_2), \tag{26}$$

where

$$\Phi(H) = \frac{(P/P_E)^{(k-1)/k}}{T/T_E}; \tag{27}$$

$P_E = 1.013 \cdot 10^5$ Pa and $T_E = 288.15$ K are the pressure and temperature on the Earth surface under standard conditions. We note that the similar reciprocal of $\Phi(H)$ is called the potential temperature in meteorology. From (26), it follows that the stable atmosphere corresponds to the function $\Phi(H)$, which decreases monotonically with height. If $\Phi(H)$ is nonmonotonic, there can be a height $H_2 > H_1$ at which the ascended air will be warmer than the ambient air and its ascent will continue.

Conditions for the upward drain flow of a lower atmospheric layer can occur if the potential $\Phi(H)$ at height H exceeds the value of Φ in the ground layer. Then a small disturbance will transfer a small ground volume to a height with a larger value of Φ, and this volume will continue to move upward. By virtue of the continuity of the medium the layers which are adjacent to this volume will be actuated, and then the entire ground layer will begin to move into the channel formed. This floating up of warm air bubbles is well known in atmospheric physics. It is in this manner that fair-weather cumulus clouds form in the second half of a summer day. Unlike clouds in vortex formation the entire superheated-air region does not float up simultaneously but flows continuously through a channel of a smaller size than the region size. Let us imagine that this flow occurs under the action of an external force which is expressed in terms of pressure, which is equivalent to the pressure in a vortex chamber and forces the air to move in it.

If the function $\Phi(H)$ has a maximum Φ_{max} at height H_Φ (see Fig. 3a), an air volume $dV = fdH$ that has ascended from height H_1 to H_Φ will be acted upon by the buoyancy force

$$dF = gf(\rho_\Phi - \rho_{H\Phi})\, dH. \tag{28}$$

Let us consider that a force dF which exceeds the weight force is applied to volume dV potentially when it is at height H_1. Therefore, summing up all the forces along the channel height H_Φ, we obtain the total force F that acts on the entire air column H_Φ. Then, expressing the density in terms of P and T using adiabatic relations, in view of (27) for the potential pressure that contributes to the air column flow upward we will have

$$\Delta P_{pot} = \frac{F}{f} = \alpha' \frac{gP_\Phi (P_E/P_\Phi)^{(k-1)/k}}{RT_E} \int_0^{H_\Phi} (\Phi_{max} - \Phi)\, dH. \tag{29}$$

Here the coefficient α' is introduced to allow for off-design conditions. From (29), it can be seen that the flow's driving force is apparently equivalent to the potential difference; therefore, we will call $\Phi(H)$ the atmospheric potential.

From the dependence $\Phi(H)$, the integral in (29) can be determined graphically. For example, for situation 2 in Fig. 3a, it is equal to 93 m. Then the drain-flow pressure $\Delta P_{pot} = 678$ Pa. Had an air volume of the radius R_1 taken an upward impulse near the Earth's surface, pressure would have been realized and ensured the upward flow of the ground layer. If the flow to the drain site has circulation Γ, this drain flow will occur with rotation, i.e., an atmospheric vortex forms. In this case, flow in the atmosphere can be compared with flow in a vortex chamber of radius R_2 with the outlet radius R_1 in which the excess pressure $p_{inl} = \Delta P_{pot}$ and circulation is Γ. With these parameters using the procedure of [9] we can calculate the velocity and pressure profiles in the vortex.

In deriving (29) we considered the upward displacement of the air volume. For an unstable atmosphere with Φ_{max} at height H downward displacement of the volume will lead to its adiabatic heating. The temperature of the volume will be lower than the temperature of the ambient air and it will continue to descend. Therefore, movement of the air layer from height H_Φ to ground heights is possible. A large-scale descending flow mechanism forms an anticyclone. The descending dry and colder air in the anticyclone has a higher density as compared to

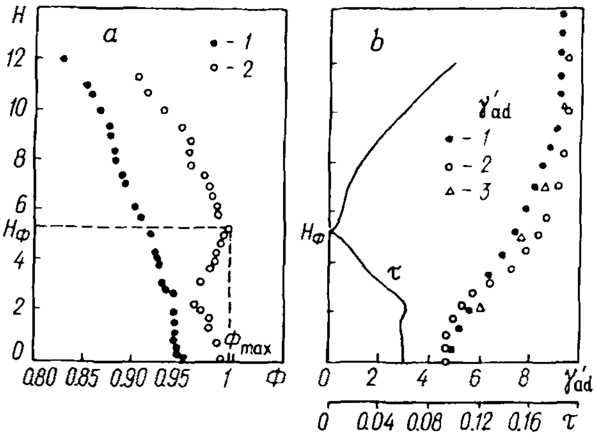

Fig. 3. Variation in characteristics of atmosphere along its height: a) profiles of the potentials of the drain flow Φ (1) Barnaul, July 7, 1980, 5.05 p.m. (local time); 2) Moscow, June 9, 1984, 10 a.m.; b) profiles of moist-adiabatic gradient γ'_{ad} and function τ (1) standard atmosphere, 2) Moscow, June 9, 1984, 10 a.m., 3) extrapolation (35)). H, km; γ'_{ad}, deg/km.

the ambient air. Therefore, the pressure at the center of the anticyclone is higher than at the periphery. Apparently, in some cases descending motion can form small-scale vortices, including tornados. These tornados could also produce the effects of a "tornado's foot" by their downward flow. In many properties, they must differ from cyclonic tornados. At the center of an anticyclonic tornado, due to the predominance of centrifugal forces, rarefaction can exist, however flow in the ground layer must be diverging. Therefore, this tornado cannot lift objects high and disperses them near the Earth's surface. If a cyclonic tornado is visualized by dust, water vapors, lifted objects, and ends in a cloud, an anticyclonic tornado, conversely, must be transparent and without an accompanying cloud.

6. Drain Flow of Humid Atmosphere. In vertical motions of humid air, there are phase transitions of water vapor, water, and ice in it, due to which the vertical temperature variation differs from that for dry air. Thus, with allowance made only for the water vapor-water phase transitions, the moist-adiabatic gradient [11] for air in the saturation state has the form

$$\gamma'_{ad} = \frac{dT}{dH} = -\frac{g + r_q \dfrac{dc_{sat}}{dH}}{C_p}. \tag{30}$$

According to the Dalton law, for a gas mixture, the concentration c_{sat} depends on the saturated vapor pressure P_{sat} as

$$c_{sat} \approx 0.622\,\frac{P_{sat}}{P}, \tag{31}$$

and with allowance made for the Clapeyron–Clausius equation for an ideal gas we have

$$\frac{dP_{sat}}{dT} = \frac{r_q P_{sat}}{R' T^2}. \tag{32}$$

Equation (32) can be integrated provided that at the dew point $T = T_d$ the saturated-vapor pressure will be $P_{sat.d}$. Then we obtain

$$P_{sat} = P_{sat.d} \exp\left[\frac{0.622 r_q}{R_{at}}\left(\frac{1}{T_d} - \frac{1}{T}\right)\right], \tag{33}$$

where $R_{at} = 0.622R'$ is the gas constant for atmospheric air. In view of (31)-(33) the moist-adiabatic temperature gradient (30) will take the form

$$\gamma_{ad}' = -\frac{g}{c_p}\frac{P + \dfrac{0.622r_q P_{sat.d}}{R_{at}T}\exp\dfrac{0.622r_q}{R_{at}T}\left(\dfrac{T}{T_d}-1\right)}{P + \left(\dfrac{0.622r_q}{R_{at}T}\right)^2\dfrac{k-1}{k}P_{sat.d}\exp\dfrac{0.622r_q}{R_{at}T}\left(\dfrac{T}{T_d}-1\right)}. \tag{34}$$

As examples Fig. 3b presents the values of γ_{ad}' calculated under the saturation condition for a standard atmosphere and a real situation. Here, their extrapolating dependence is

$$\gamma_{ad}' = -9.52 + 2.85\cdot 10^{-2}(13 - H)^2, \tag{35}$$

where H is measured in kilometers.

If the density in (28) is expressed in terms of temperature using the equation of state, the potential pressure of drain flow in a humid atmosphere as a result of integrating (28) with respect to the entire air column is obtained in the following form:

$$\Delta P_{pot}' = \frac{gP_\Phi}{RT_\Phi}\int_0^{H_\Phi}\left(1 - \frac{T_\Phi}{T_{H\Phi}}\right)dH. \tag{36}$$

The integrand $\tau = 1 - T_\Phi/T_{H\Phi}$ for real situation 2 is presented in Fig. 3b, $T_{H\Phi}$ being calculated using (35). Graphical integration to height H_Φ gives an integral of 234 m. Then, according to (36), the potential pressure of drain flow is $\Delta P_{pot}' = 1750$ Pa. The excess pressure $\Delta P_{pot}'$ over the potential drain pressure for a dry atmosphere will be $\alpha' = \Delta P_{pot}'/\Delta P_{pot} = 2.57$. This result is obtained using the moist-adiabatic gradient (35), which, as Fig. 3b shows, differs to the same extent both from a standard atmosphere and from the accurate value in this situation. Therefore, we can use α' to estimate the influence of humidity on the potential pressure of drain flow.

7. Mechanics, Prediction, and Prevention of Tornados. As a result of superheating of the lower atmospheric layer or the interaction of cold and warm fronts, temperature stratification with potential maximum Φ_{max} at height H is produced. The potential pressure of the drain flow, according to (29), can be calculated for each point of the territory under study. At the maximum ΔP_{pot} as superheating increases further, there can be a breakthrough, and the lower layer will begin to move upward. If the flow has eccentricity e with respect to the center of the region and the upper layer velocity v_{dr} differs from the lower layer velocity v_S, then, according to (18), the flow will occur with circulation Γ. Other mechanisms of the formation of circulation, as has been already mentioned, are possible, too. A tornado will exist until the entire lower layer has moved upward.

Calculations by the procedure of [9] show that, in situation 2 (see Fig. 3a for $\Delta P_{pot} = 1750$ Pa), there could occur a tornado with maximum tangential velocity $v_{max} = 38.8$ m/sec on the radius $R_v = 390$ m and rarefaction at the center $p_0 = -2051$ Pa. However, on that day superheating of the lower layer continued, and at 4 p.m. a series of destructive tornados began to form in the Yaroslavl', Kostroma, Kalinin, and Moscow regions. According to the US tornado scale, tornados of this group destroy heavy buildings, turn over railroad cars, and lift large objects into the air for velocities of 93–116 m/sec. The calculations by our procedure of this tornado for $v_{max} = 100$ m/sec show that it could occur when $\Delta P_{pot} = 1.16\cdot 10^4$ Pa, and the absolute pressure in the center could decrease to $P_0 = 0.795\cdot 10^5$ Pa. A building which is found to be at the center of the tornado is under atmospheric pressure $P_{at} = 1.013\cdot 10^5$ Pa on the inside, and from the outside, it is acted upon by pressure P_0, which in the latter example will produce a load $\sigma = P_{at} - P_0$ of more than 2 tons per square meter of its surface.

In a number of cases, it is necessary to estimate the destructive factors of a tornado. According to (4), the excess pressure for $(C = 0)$ at the periphery of a tornado as $r \to \infty$ will be $p_2 = \rho v_{max}^2$. This pressure ensures medium motion in a vortex; therefore, $p_2 = \Delta P_{pot}$. Then we obtain the estimate for the maximum velocity in the tornado

$$v_{max} = \sqrt{\Delta P_{pot}/\rho}\ . \tag{37}$$

From (4), as $r \to 0$, the rarefaction at the center will be $p_0 = -\rho v_{max}^2$, and in view of (37)

$$p_0 = -\Delta P_{pot}\ . \tag{38}$$

Then the load on the building's walls will be

$$\sigma = p_2 - p_0 = 2\Delta P_{pot}\ . \tag{39}$$

To predict a tornado, we must find the distributions of the potential drain pressure over the territory. In the step of prediction investigation and development, it is necessary to probe the atmosphere in tornado-hazardous situations, to study the forms of the profiles $\Phi(H)$ and classify them, and to find the limiting values of ΔP_{max} and Φ_{max}. In this case, from the ΔP_{pot} fields, we can determine the maximum values of $\Delta P_{pot.max}$ for which tornado formation is the most probable. Time variations of $\Delta P_{pot.max}$ and Φ_{max} and their comparison with the limiting values enable us to establish the time and site of tornado formation.

The destruction and casualties which are produced by tropical cyclones and tornados force people to look for methods of their prevention. For example, the authors of [16] recommend that hurricanes be tempered with explosions. They also propose a method for decreasing the destructive action of tornados using a screw-shaped swirler which must swirl the entrained air jet and keep it from moving to the center of the tornado [17].

We think that effictive control measures for intense atmospheric vortices can only be undertaken when allowance is made for their real mechanisms. Apparently, the statement of the problem of controlling small vortices and tornados is quite realistic at present. It is possible to prevent a tornado by ensuring drainage of the ground air layer with small velocities. For this purpose, it is necessary to produce a vertical pulse such that a channel of one large diameter could occur or several drain flows could form simultaneously. If drain flow is produced beforehand, a superheated layer will not accumulate and will move upward with small velocities. Therefore, unlike the proposals considered above, drain flow and ascending motion are not suppressed but, conversely, are initiated so that no ground-layer energy is accumulated and there is no a subsequent disastrous manifestation of it. To produce a vertical pulse, it is necessary to deliver to a certain height a fuel packet and to atomize and fire it. We need to organize combustion in such a manner that the lower boundary of the heated volume will have a minimum velocity directed downward. This can be ensured by combining the delivery rate and direction of fuel atomization. Our estimates show that, to prevent a tornado which is similar to the tornado of June 9, 1984, we must produce several sources for ascent of the heated ground air mass, each requiring 8.3 tons of liquid fuel.

The considered mechanisms of the formation of atmospheric vortices are based to a great extent on experimental material for vortex chambers. It seems of interest to perform investigations of atmospheric flows which could significantly extend the understanding of processes in the atmosphere. Visualization of atmospheric vortex formations using markers probes with controlled effective density can be one method [18]. These markers enable us to see the moment of the generation of an atmospheric vortex and its dynamics, to imagine the paths of air-mass motion, and to observe the global processes of atmosphere dynamics.

NOTATION

C_p, heat capacity of atmospheric air at constant pressure; e, eccentricity between center of region S and center of drain; F_{Co}, Coriolis force; M, moment of momentum; m, volume mass or the mass of liquid in tank; dm_{lay}, mass of equidistant layer; u_{inl}, inlet feed rate, average over the cross section $H \times b$; b, feed channel width; H, thickness layer for liquid or air; H_{liq}, thickness of liquid layer in tank; h, funnel surface depth; h_0, funnel depth at center; v, tangential velocity; v_1, tangential velocity on radius equal to outlet radius R_1; R_2, radius of drain region; v_S, velocity of region S; v_{dr}, velocity of center of drain; u, radial velocity; w_{av}, vertical velocity, average over cross-section of the drain orifice; v_{tot}, total velocity; P, absolute pressure; p, excess pressure over atmospheric pressure; P_{at}, atmospheric pressure; P_0 and p_0, absolute and excess pressures at center of vortex; p_{inl}, pressure at inlet to vortex chamber; ΔP_{pot}, potential pressure of drain flow; $\Delta P'_{pot}$, potential pressure of drain flow in humid atmosphere; $\Delta P_{pot.max}$, limiting value of the potential pressure of drain flow; R_v, radius of the position of the maximum tangential velocity v_{max}; Q, volumetric rate of the liquid that drains from orifice; $G = Q\rho$, mass flow rate of liquid through orifice; g, free fall acceleration; Γ, circulation; α, half-angle of discontinuity for equidistant annular layer of thickness dr; dK, momentum; r_{cent}, distance from the center of drain to center of mass of equidistant cross-section; $\boldsymbol{\tau}$, unit vector of tangent to line $r_{cent}(\varphi)$; i_1 and j_1, unit vectors of local coordinate system; φ_1 and φ_2, initial and final polar angles of lines of centers of mass for equidistant cross sections; φ_0, latitude of center of drain; S_{as}, asymmetry cross section; R_E and ω_E, Earth's radius and angular velocity; u_R, velocity in direction of radius R; O, B, C, and D, points in Fig. 2c; CB, segment; k, adiabatic coefficient for air; T, absolute temperature; ρ, density; Φ, atmospheric drain potential; H_Φ, height at which Φ attains its maximum, i.e., $\Phi = \Phi_{max}$; $\rho_{H\Phi}$ and $T_{H\Phi}$, density and temperature of air volume ascended from height H to height H_Φ; ρ_Φ and T_Φ, density and temperature of ambient air at height H_Φ; T_{12}, temperature of the air volume displaced from height H_1 to height H_2; f, area of horizontal section of volume; α', coefficient to allow for the humidity of the atmosphere; γ'_{ad}, moist-adiabatic temperature gradient; r_q, specific heat of condensation; c_{sat}, specific concentration of saturated vapor, kg/kg of atmospheric air; P_{sat}, saturated-vapor pressure; $P_{sat.d}$, saturated-vapor pressure at dew point; T_d, temperature of dew point; R_{at} and R', gas constants for dry atmospheric air and water vapor; τ, relative temperature variation for ascent of air volume to height H_Φ; dΩ, moment of force dF_{Co}; σ, load on building walls. Subscripts: 0, zero; H, refers to height H; max, maximum; P, refers to pressure P; q, refers to heat of condensation; R, refers to radius R; S, region S; v, refers to velocity v_{max}; Φ, potential Φ; ad, adiabatic; as, asymmetry; inl, inlet; E, Earth; Co, Coriolis; sat, saturated; sat.d, saturated at dew point; pot, potential; tot, total velocity; d, dew; lay, layer; av, average; dr, drain; cent, center of mass; ', humid-medium parameters; c, index in (19), for the sink, $c = 1$ (cyclone), for the source, $c = 2$ (anticyclone).

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