Rotation effects explain the energy source of tornado, hoping to increase the warning time

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Tornadoes and hurricanes are deadly rotating storms. Early knowledge of which cloud will spawn a tornado will save the lives of hundreds of victims every year, but the present warning time is only 13 minutes. This short time is insufficient for too many citizens to take shelter. Many models tried to explain the tornado's behavior. See detailed reviews [1], [2], [3], [4] of models and references therein. Bluestein concluded that trying to control a tornado without understanding it, ”is like shooting in the dark [5],” and that ”Tornado formation... is not well understood [6].” He also said that it is not known which cloud will spawn a tornado [7]. The rotational destructive winds of tornadoes are similar to those of hurricanes. Consequently, some researchers explain that a tornado is similar to a hurricane-like flow [2]. For some researchers it is difficult to understand why humid air outside the funnel of the tornado cannot go inside the funnel; this is why the humid air in the funnel is supplied only from the cloud above the tornado. For the few researchers who understood, it was difficult to understand that at the same time, water droplets inside the funnel are expelled outside the funnel; this is why there is no rain inside the funnel. Without understanding these two points, the mechanism of the tornado cannot be explained. Here we explain the main differences between a tornado and a hurricane, in addition to the difference in size, and suggest how to use this knowledge to increase the warning time. A hurricane always originates above an ocean, but a tornado always takes place beneath a cloud. Hurricanes receive their energy from water vapor from the ocean below, but tornadoes and waterspouts receive their energy from water vapor from the cloud above. The flow in the vertical eye is upwards in hurricanes, but downwards in the funnels of tornadoes and waterspouts. A simulation of a hurricane-like flow cannot give results applicable to a tornado. We rely on the rules of conservation of angular momentum and energy and on understanding the rotation effects [3] and their implications on the warning time and which cloud may spawn a tornado.

In this article, we will explain the mechanism of a tornado.

The pressure in the pipe of the tornado is lower, down to about 0.9 of the regular atmospheric pressure. A tornado funnel sucks water vapor only from the cloud above (see figure) because of the rules of conservation of angular momentum and energy that prevent moisture and air encircling the pipe from entering it (see below).

This water vapor condenses to droplets that are instantly driven out of the pipe by the centrifugal forces caused by the rapid rotation (see figure).

Out of the pipe, the droplets transfer their latent heat to the surrounding air, giving it buoyancy. The warmed air rises up, causing a reduction of pressure. Air from regions farther away attempts to move closer to the pipe instead of the ascending air (see figure).

The law of conservation of angular momentum determines that the circumferential velocity is higher when the distance to the axis of rotation is smaller, like a ballet skater who pulls in his or her hands to increase his or her rotation speed.

Denoting L as the angular momentum, v as the circumferential velocity, r as the distance from the axis of rotation, and m as the mass of a particle, we have the law of conservation of angular momentum:

$$L = mvr \quad (1)$$

where L is constant. From (1) we obtain the circumferential velocity:

$$v = L/(mr) \quad (2)$$

which is larger for a smaller r. This also shows how the fast, destructive winds that characterize the tornado or hurricane are produced when the circumferential winds come closer to the axis of rotation of the tornado or hurricane. This conclusion is valid here, although the air is compressible because the velocities are less than the speed of sound.

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The well-known formula for kinetic energy is

$E = (m/2) v^2$ (3)

When *v* from (2) is substituted in (3), one obtains for the energy *E*:

$E = (m/2) (L/mr)^2 = [(L^2)/2m] (1/r^2)$ (4)

This means that air that approaches the funnel needs additional energy, again like the ballet skater who has to forcefully pull his or her hands inward in order to increase his or her rotation velocity.

Because the available energy is limited, the air outside the pipe cannot reach closer to the central funnel than a certain limit radius

$R_{limit} = L/\sqrt{2mE}$ (5)

This way, the pipe of a tornado has no other alternative but to suck only whatever is in the cloud above because it cannot suck water vapor or air from the ground below. The eye of a hurricane sucks water vapor from the ocean water below.

If the base of the cloud is rich with warm water vapor, the vapor will flow down into the funnel where the pressure is lower. This way, the funnel will have a supply of water vapor, which will condense in the cool funnel. The condensed water droplets are warm because they keep the latent heat released during condensation, but as described above, the water droplets are immediately driven out of the fast-rotating pipe by the centrifugal forces before they can transmit their latent heat inside the pipe.

Outside the funnel, the water droplets give their latent heat to the surrounding ascending air as mentioned above, increasing its buoyancy, and thus giving the driving force to the destructive flow of winds outside the pipe.

Remote infrared observations of tornadoes [8] found an increase of temperature at the left and right edges of the pipe. There, according to our description, the warm condensed droplets transmit their heat to the ascending flow outside of the column of the tornado. Future remote spectral measurements at the left and right edges of the funnel may show that the warm edges consist of warm water droplets and confirm our model.

The shape of the funnel of the tornado (see figure) is solved by substituting $v(r) = L/mr$ of (2) with constant L and for variable r in the energy as the integral of the centrifugal force $F = m[v^2(r)/r]$:

$$\int (F\, dr) = \int m[v^2 /r]dr \quad (6)$$

which gives

$$\int(F\, dr) = m \int\{[L/(mr)]^2 /r\}dr =$$

$$= -[L^2/(2m)]/r^2+Constant \quad (7)$$

Addition of gravitational potential *mgh* where h is the height and *g* is the gravitational acceleration on Earth, yields

$$mgh = [L^2 /2m]/r^2 + Constant \quad (8)$$

that has a funnel shape *r(h)* (see figure) similar to the actual funnel of a tornado.

For height and power calculations and a more detailed description, explanations, and calculations, see Ben-Amots [3].

The quantity of the descending water vapor in the funnel appears to be too small to sustain or even have some bearing on the powerful tornado vortex. If the water vapor could mix with a significant quantity of comparatively dry air that surrounds the pipe no condensation would happen. However, we already proved *by angular momentum considerations that air around the pipe* *is not able to enter the pipe at all*. Rather, *the pipe continuously sucks water vapor and moist air from the cloud above*. Only when the cloud can provide enough water vapor, it is able to spawn and sustain a tornado. In some cases, too much condensed water vapor that was driven outside the pipe as water droplets are removed by opaque rain *outside the pipe*.

Condensation of water vapor discharges heat. Generally, the discharge of heat raises the pressure further. In numerous weather conditions, this rise of pressure is much larger than the reduction of pressure induced by the reduction of the volume of water vapor throughout the condensation. It appears strange. Why does condensation inside the pipe decrease the pressure in the pipe, although condensation also discharges heat that raises the pressure? Also, rain cannot take this heat away from the pipe, since it is known that ”it does not rain inside a tornado.” Nevertheless, condensation inside the pipe of a tornado acts differently: Because of the rotation, the dynamic ”barrier” that does not allow moisture and air around the pipe to enter inward into the pipe is a *one-way "barrier." It permits crossing the "barrier" outward* as explained below:

The latent heat of condensation of water vapor in the pipe heats up the water droplets that were produced by the condensation. *But during a few seconds, the strong centrifugal force caused by the rapid rotation of the pipe drives most of the droplets out of the pipe before they can discharge their heat or evaporate in the pipe.* This happens since the droplets are heavier from the rotating air in the pipe, and straightforwardly cross the "barrier" outward.

We approximate as explained below:

The radial acceleration *a* is:

$a = \omega^r$ (9)

where ω is a constant typical to every tornado since in the pipe of tornado $v = \omega r$ (Tanamachi et al. [9]):

$\omega = v_{Circumference}/R_{Funnel}$ (10)

Thus the radius *r(t)* is:

$r(t) = \iint a\, dt^2 = \omega^2 \iint r(t) dt^2$ (11);

Solving for *r(t):*

$$r(t) = A \exp(\omega t) + B \exp(-\omega t) \quad (12)$$

The second part of the solution $B \exp(-\omega t)$ converges rapidly, so it is small. It reduces the time necessary for a drop of water to be driven out of the pipe of the tornado. Disregarding it, one obtains a little longer time necessary for a drop of water to be driven out of the pipe of the tornado. Consequently, in the following calculation the actual time will be smaller than what the calculation will give.

The drag on the drops makes longer the time necessary for a drop of water to be driven out of the pipe of the tornado, yet the drag is not the same for small and large drops, causing the drops to travel at different velocities and in somewhat different directions. This causes collisions that cause the little drops to merge into the bigger ones. The increase in time for large drops (radius>1mm) is comparatively little since these large drops do not reach their final velocities.

For simplicity, in the following approximate calculation, we disregarded the second solution B and the drag on the drops, which are small, as we explained above. The following simplified formula allows a fast calculation for any tornado.

We approximate the main branch for $B=0$ and $A = r_0$:

$r(t)/r_0 = \exp(\omega t)$ (13)

and solve for t:

$t = \{\ln[r)/r_0]\}/\omega$ (14)

for $r > r_0$.

Substituting ω of (10) and $r(t)$ as the radius of the pipe R_{Funnel}, we obtain the approximate time that a drop condensed in radius r_0 is driven out of the pipe:

$t = R_{Funnel} \ln(R_{Funnel}/r_0)/v_{Circumference}$ (15)

that for most tornadoes is a few seconds from 95% of the pipe volume where $r_0 > R_{Funnel}/4.5$

Out of the pipe, the warm droplets join the rising part of the flow (Figure 30). There, they transmit their heat to the ascending air surrounding the pipe, thus strengthening the buoyancy at region *B* and accordingly strengthening the inward flow at region *E*, which by *angular momentum conservation* develops into a rotational tangential rapid flow, thus *providing energy to the destructive tornado winds surrounding the pipe*. Depending on the moisture and temperature of the air that flows inward (see figure), the water droplets that were driven out of the pipe may precipitate as rain around the pipe of the tornado or evaporate. The heat transported *outside* the pipe of the tornado was already observed and measured by Tanamachi et al. [8], who assumed that it was caused by the temperature of dust.

Driving the condensed water drops out of the pipe by the centrifugal force explains in addition why there is no rain in the pipe.

The combination of *all the relevant dynamical and thermodynamical processes* should be understood so that numerical analysis will describe what actually happens.

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The various structures and shapes of tornadoes obscure their common mechanism. Each tornado is initiated by a cloud, yet clouds have many different influencing features that, in their turn, determine various features of the tornado. Furthermore, the turbulent flow caused by the very high gradient of velocities of wind around the tornadoes causes a chaotic flow superimposed on the main phenomena explained in this chapter, and on the combination of the various relevant features of the cloud above the tornado.

Tornadoes share a few features with hurricanes, such as the high speed of destructive rotational winds, and the source of energy, which is the condensation of water vapor. But other significant features are not similar. The energy of the hurricane comes from warm ocean water below, but the tornado’s energy is provided by water vapor from the cloud above.

The theory presented here and in Ben-Amots [3] also explains why *tornadoes are always under clouds*, and why *there is no rain inside the pipe*.

A better understanding of the rotation effects on the dynamics of a tornado as explained here and in more detail in Ben-Amots [3], may increase the warning time (just 13 minutes at present), and, later perhaps help gain some control over tornadoes.

One useful conclusion is that a cloud that spawns a tornado has to be at least somewhat warmer than neighboring clouds because we have seen above that such a cloud should supply energy to the tornado in the form of warm water vapor. Therefore, developing appropriate, precise instruments that can remotely measure the temperature of cloud base with a precision of 0.2-0.3oC, and the richness of the cloud base in water vapor may help determine earlier whether a certain cloud is going to spawn a tornado.

The explanation given in this chapter is supported by the well-known fact that *a tornado or a waterspout always occurs beneath a cloud.*

Without understanding the mechanism described in this chapter, one may be misled to miss the mild *downflow inside the funnel,* and derive only the legitimate upward flow of a hurricane or a dust-devil, which are upward, and ”confirm” by measuring the *upward flow out of the funnel*.

Without prior understanding as described in this chapter, the results of numerical simulations and observational measurements may ”confirm” misleading conceptions, either because of *misinterpretations* of measurements or because of simulating a *wrong model*.

The explanation of tornado in this chapter appears with other words in two previous papers: BenAmots [3] with more details, and Tao et al. [4] with more concise explanation based on Ben-Amots [3].

For many experts it is difficult to understand why humid air outside the funnel of the tornado cannot go inside the funnel. This is why the humid air in the funnel is supplied *only from the cloud above the tornado*. For the few experts who understood, it was difficult to understand that at the same time water droplets inside the funnel are expelled outside the funnel. This is why there is no rain inside the funnel. Without understanding these two points, the mechanism of the tornado cannot be explained. However, a ballet dancer understands this easily. Alyssa from the U.S.A., with 19 years of ballet experience, understood this easily, as well as 9-year-old Mika after one year in ballet class.

While the existence of tornadoes depends on slow top-down flow in the funnel, radar observations showed that tornado funnels originated at low height above the ground [10], and then climbed up fast. Its arrival at a large height was also observed by the radar [10], [11]. If so, when the ascending funnel meets an appropriate humid warm cloud, the low pressure at the funnel attracts the warm water vapor into the funnel and uses it as the source of energy for the tornado as described above. The radar precision was not sufficiently sensitive to detect the slow top-down flow in the funnel [10]. Summarizing, even a humid warm cloud capable of spawning a tornado, will spawn it only if the cloud is hit from below by an ascending vortex funnel. Further research is necessary to determine whether cutting a tornado high near the base of the cloud may stop the tornado without regeneration.

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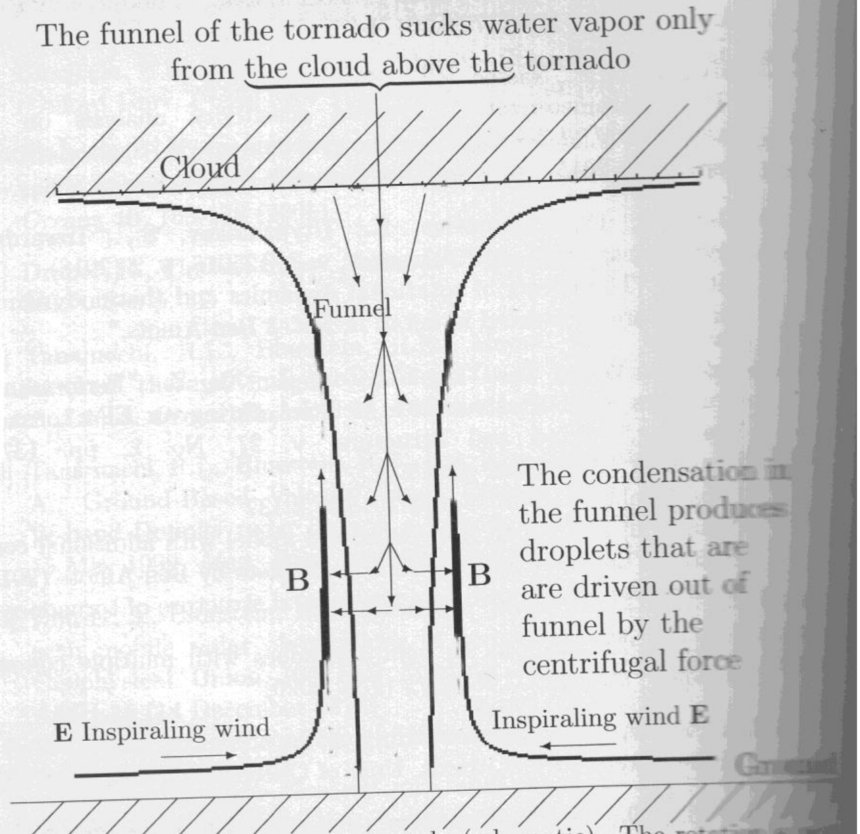

Figure 30: Section of a rotating tornado (schematic). The rotat
shown. The thick vertical lines are the regions **B** where the
ply the latent heat to the ascending wind, thus contributing
supplying the driving energy to the tornado. No rain in the funnel

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