Why does the atmosphere produce deep columnar convective vortices?

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(Dated: 26 August 2011)

I. INTRODUCTION

It's important to understand that the ideas presented in this have *not* been thoroughly tested to the point where the material is ready for formal publication. Although some evidence on behalf of these ideas is offered, a rigorous evaluation of these hypotheses has not yet been done. The presentation of them is to stimulate thought and discussion about the topic, rather than to make a strong case.

The ideas herein are based on what I consider to be an important but unproven "principle" in atmospheric science: that atmospheric dynamic processes do not occur randomly as a result of chance juxtapositions, but rather these processes serve some purpose and occur when and where they become necessary. If this is a valid perspective, then a complete understanding the process necessarily requires knowing the purpose it serves. In many cases, dynamic processes seem to involve an instability of some sort, where an energy source can be identified that is converted to the kinetic energy of the process. Examples include: deep moist convection, extratropical cyclones, tropical cyclones, and so on. We can identify the reasons why the atmosphere needs them and we have some understanding of the instabilities that drive them as well as their energy sources.

So the essence of the idea is to seek an understanding of why the atmosphere requires the formation of deep columnar convective vortices, with the main emphasis on supercells and tornadoes. These vortices are *deep* (a depth on the same order as the depth of the troposphere), *columnar* (the width of the vortex is of the same order or smaller than its depth), and they involve *moist convection* (i.e., buoyancy associated with latent heat is necessary).

II. SUPERCELLS

Browning is recognized as the originator of the supercell conceptual model—the term was used first in Browning (1962). Browning and Landry (1963) and Barnes (1970) were among the first to suggest that tilting of horizontal vorticity associated with the ambient vertical wind shear could cause updrafts to rotate.

The developments of Doppler radar and numerical cloud models in the 1970s made that decade a watershed in understanding supercells. The radar presented an opportunity to observe the inner airflows of supercells, confirming many of Browning's early ideas that had been based only on the 4-dimensional behavior of radar reflectivity. The numerical model simulations permitted a quantitative investigation into simulated supercell storm dynamics and the relationship between storm structure and environmental conditions. Of particular importance was the ability to explore *quantitatively* the relationship between the ambient vertical wind shear and the perturbation pressure field produced by the storm (Rotunno and Klemp 1982). The significance of this relationship is that the simulations demonstrated how a significant contribution to vertical motion can occur with supercells from a nonbuoyant energy source: the perturbation pressure field. The contribution from perturbation pressure (associated with thermal buoyancy) to vertical motion in ordinary DMC typically is *opposed* to the contribution from thermal buoyancy itself (Yau 1979), whereas supercell updrafts can be enhanced substantially by the perturbation pressure contribution: specifically, the so-called "dynamic" perturbation pressure, due to the interaction between the updraft and the ambient airflow (Rotunno and Klemp 1982).

Because supercells are members of the broader class of deep, moist convective storms, the question naturally arises: What are supercells doing that can't be accomplished by non-supercellular deep, moist convention (DMC). Clearly, DMC mitigates the instability associated with convective available potential Energy (CAPE). I don't believe, however, that can be the whole story when it comes to explaining what supercells are doing in the atmosphere.

I propose that the kinetic energy increase within a supercell associated with the development of a mesocyclone is drawing upon a "reservoir" of energy represented by the helicity in the pre-storm environment, in conjunction with the CAPE reservoir. Of course, air flow by itself represents kinetic energy, but helicity is not about the kinetic energy of the airflow, per se, but rather is about the particular *distribution* of that airflow in space (in a storm-relative reference frame, so it is *storm-relative* helicity, or SRH). It is that airflow distribution that can be thought of as a potential energy source for vortex intensification, as first suggested by Carbone (1983), albeit in the context of tornadoes rather than supercells. The idea that the distribution of airflow can be an energy source for amplifying disturbances should not be so surprising, given its acceptance in the theory of shear instabilities. A supercell converts the SRH of the air flowing into its updraft from the horizontal to the vertical. Once the updraft becomes helical, stretching of that tilted streamwise vorticity within the accelerating part of the updraft amplifies the vertical vorticity to mesocyclonic proportions. Both buoyant and nonbuoyant sources of energy are present. From this perspective, supercells represent a synergistic interaction between environmental CAPE and environmental helicity.

The conceptual model presented herein focuses on the helicity of the storm-relative flow that enters the updraft. Storm motion is manifestly important for this conceptual model, but an accurate forecast of storm motion is not always easy to obtain from the available information (Ramsay and Doswell 2005) and involves more than the processes going on within storms. That is, storm motion can modified substantially by storm *propagation*, which can be influenced strongly by processes independent of the DMC storm, such as pre-existing boundaries, topography, and so forth (Zeitler and Bunkers 2005). An extensive theoretical treatment of supercell motion was done by Davies-Jones (2002), who concluded, among other things that "In all cases, tilting of storm-relative environmental streamwise vorticity explains the origins of rotation."

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This process is illustrated schematically in Fig. 1. The inflow to the storm is essentially horizontal and if its vorticity is streamwise (the vorticity vector is parallel to the airflow) then that inflow can be said to have SRH. As that inflow approaches the updraft, the streamwise vorticity is tilted into the vertical and amplified by the rapidly accelerating upward motion. Note that as the mesocyclone

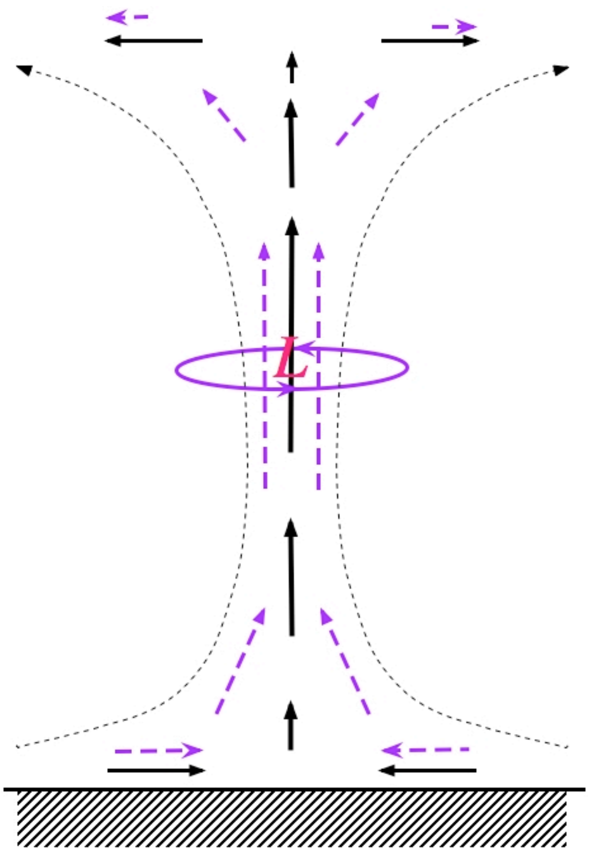

FIG 1. Supercell conceptual model, showing the vertical circulation (black solid arrows and short dashed streamlines) and the vorticity vectors (dashed purple arrows). The magnitude of the vorticity vector is indicated by its length,. The red “L” shows the mesocyclone aloft where the predominantly vertical helicity (solid purple horizontal streamline) of the airflow is large,

intensifies aloft, this increases the nonhydrostatic perturbation pressure gradient force contributing to vertical motion and so the updraft intensifies, in turn. This is a positive feedback mechanism that results in what I call "helicity instability". A helical flow can be amplified by accelerations in the airflow parallel to the vorticity vector — via the stretching term in the vorticity equation—and those very accelerations are amplified by nonbuoyant contributions to the vertical airflow resulting from the increasing vorticity aloft. Above the level of nondivergence, the acceleration of the vertical motion changes sign and the vorticity (and helicity) decreases rapidly with height in the strongly divergent airflow near the anvil level. The streamwise vorticity vector is tilted away from the vertical in the outflow above the level of nondivergence. If the spin down in the upper portions of the storm is such that the resulting outflow has less SRH than when it entered the supercell, the overall result is to reduce the SRH, as postulated in the conceptual model.

III. TORNADOES

Much of the modern, pioneering research about tornadoes has its roots in the needs of operational forecasters (see Doswell 2007). This includes the observation that tornadic storms tend to occur in environments characterized by strong vertical shear of the horizontal wind. That is, such storms are mostly supercells.

For tornadoes, despite their association with supercells, it is not at all evident what the energy source for tornadoes really is. What is the instability associated with tornadoes? It has been recognized for years that tornadoes can develop rapidly—on times scales on the order of a few minutes. This seems to suggest an exponentially-growing “disturbance” associated with the stretching term in the vorticity equation.

An important question is the energy source for tornadoes. The notion has been advanced (e.g., Lilly 1982) that tornadoes ultimately derive their energy from CAPE, which leads to the idea of a so-called *thermodynamic speed limit* for tornadoes based on CAPE (see Fiedler and Rotunno 1986). If tornadoes are drawing their energy exclusively from CAPE, they have the same source of energy as the DMC that gives them birth. In this view, a tornado is a process within DMC that is competing with the DMC itself for the CAPE reservoir. The growth of one process would seem to inhibit the growth of the other (as implied by Lilly 1982, p. 157), who states “... the effect is to reduce the updraft, essentially transforming some of its energy into that of rotary motion.” If this concept is correct, a tornado would be a parasitic process, drawing its energy from the same source as the DMC. Further, it is evidently equivalent to the concept enunciated by Lemon (1976), known as the “vortex valve” hypothesis.

An understanding of tornadoes has been elusive, in part because of their small spatiotemporal scale, and also owing to their relative rarity—tornadoes are difficult to observe and document in detail. They are the most intense form of DCCV and are thought to represent, in the most extreme examples, the strongest windstorms of all, with windspeeds near the surface arguably as high as 150 m s^{-1}. Tornadoes are observed most commonly with supercells, and it appears that the most intense examples are associated virtually exclusively with supercells.

Interestingly, in a classic review paper, Ludlam (1963, p. 24) speculated that the rotation of tornadoes might have its origin on the interface between updraft and downdraft: "It is tempting to look for the spin of the tornado in the vorticity present in the general air stream as shear and tilted appropriately in the vicinity of the interface between the drafts as a consequence of the up- and down-motions." This also was considered a central idea by Lemon and Doswell (1979), who speculated further about the role played by solenoidal generation of vorticity. Ludlam (op. cit.) made another prescient comment in his review: "It may be particularly important for the intensification and persistence of a tornado that some of the downdraft air may be derived from potentially warm air … ." Ludlam somehow had anticipated the recent observations that the RFD air in *tornadic* supercells is unlikely to be strongly negatively buoyant (Markowski et al. 2002). The notion that tornadoes develop from the process of stretching vorticity in the vertical generally has been accepted for some time.

IV. DISCUSSION

In summary, the proposed conceptual models are based on the notion that the presence of storm-relative environmental helicity represents an energy source for exponential growth of vertical vorticity in the updraft of a DMC storm. In the case of a supercell, the helicity and buoyancy provided by CAPE combine to amplify both the vertical vorticity and the updraft's vertical velocity. That is, the updraft is driven both by CAPE and by nonbuoyant processes associated with perturbation pressure gradients arising because of vertical wind shear in the environment. A supercell storm ceases if it consumes, or is cut off from, its supply of inflow with CAPE. If the supply of helicity in the inflow is exhausted, the storm may continue so long as a CAPE reservoir can be tapped, but it will lose its supercell characteristics. A nonsupercell storm can become supercellular if it encounters enhanced environmental helicity (see Burgess and Curran 1985). In any case, some or all of the pre-existing helicity will have been used to develop the mesocyclonic vorticity and is exported to upper levels in the storm, where it is dissipated.

It has been proposed herein that a tornado taps the energy of the low-level SRH, in particular, and the air parcels within the tornadic circulation contribute only trivial buoyant energy for amplifying the vorticity through release of latent heat in the vortex airflow. Thus, the tornado is not necessarily a parasitic process that diminishes CAPE that would otherwise power the updraft. Instead, the tornado uses an existing storm updraft to amplify the streamwise vorticity associated with helicity near the surface. If there is some theoretical energy-based limit to the speed of winds in a tornado, it likely is not the thermodynamic parameter, CAPE. An important thermodynamic constraint, however, is that the air flowing into the vortex should not be strongly stable to ascent, which would inhibit the stretching process necessary for the instability. All that is needed to produce an intense vortex is helical inflow combined with intense stretching along the streamwise direction. DMC storms provide the intense stretching, but the storm environment provides the helicity in the inflow to the DMC storm (or the potential helicity, in the case of nonsupercell storms

For additional details, the reader is directed to: http://www.flame.org/~cdoswell/SuptorRoles/SuptorRoles.html.

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