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# A DEMONSTRATION OF VORTEX CONFIGURATIONS IN AN INEXPENSIVE TORNADO SIMULATOR

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## 1. INTRODUCTION

Tornado simulation models were pioneered in the modern era of tornado research by the late Neil Ward (Ward 1972; Church and Snow 1993). The prototype that Ward developed became the standard for a number of other research programs based on such simulators; notable among these were simulators at the University of Oklahoma (Leslie 1977) and at Purdue University (Church et al. 1977; Snow and Lund 1988). The basic design of a Ward-type vortex chamber is illustrated in Fig. 1.

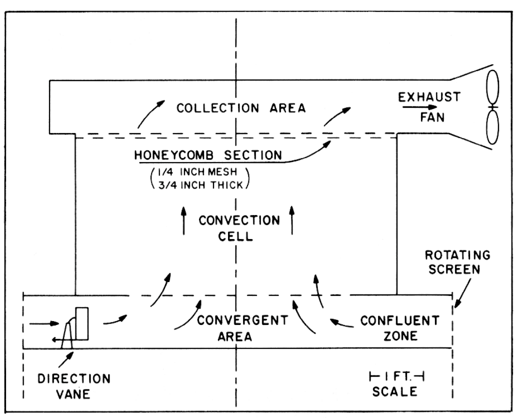


Fig. 1. Schematic diagram of a Ward-type vortex simulation chamber, showing the main components as first developed by Ward.

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Many variations on the basic design have been tried, typically to achieve greater resemblance to real tornadoes in some way (Davies-Jones 1976). Moreover, instrumentation for measurements has become more refined (e.g., Lund and Snow 1993).

For a time, Ward-type simulation models sparked a considerable amount of interest within the tornado research community. This interest was heightened when it was found that the multiple vortex phenomenon could be created within Ward-type vortex chambers. The use of the swirl ratio, $S$, defined as:

$$S = \frac{r_o \Gamma}{2Qh}$$

where $r_o$ is the updraft radius, $\Gamma$ is the circulation at $r_o$, $Q$ is the volumetric flow rate per axial length, and $h$ is the inflow depth, was shown by Davies-Jones (1973) to be an important factor in the simulated vortex dynamics. It was found that the existence of multiple vortices was related to the swirl ratio (e.g., Church et al. 1977). Numerical models were developed (e.g. Rotunno 1979) that in effect simulated the simulators! Apparently, it was felt at the time that the simulators were a valuable tool for exploring certain aspects of real tornadic vortices.

Eventually, however, the limitations of such simulations in doing research became apparent. All physical simulation models of tornadoes have some difficulty achieving complete dynamic similarity to atmospheric vortices. A major issue is the viscosity within the model versus that in the real atmosphere (Church and Snow 1993). A related issue is the behavior of the boundary layer in the model compared with that in a real tornado situation. The processes that produce the swirl in a real tornado are much more time-variable and are driven by physical processes that are difficult, if not impossible to achieve in these simulators. Within the basic Ward-type vortex chamber, it's difficult to create any vertical variation in the ambient wind, whereas it seems clear that real tornadoes may develop in situations with considerable vertical wind shear. Some efforts to modify the basic design were made (Rothfusz 1986; Ladue 1993) to produce horizontal vorticity in the inflow, but these have since been discontinued.

Although it isn't always possible to know why research decisions have been made, by the mid-1990s, the vortex chamber had ceased to be an important implement for serious research. As noted by Church and Snow (1993), it's easier and less costly to obtain information from numerical model simulations than from laboratory models. Programs using them have shut down and research-grade tornado simulators no longer exist as tools of tornado research. Simulators have continued, of course, as tools for entertainment, as school science fair projects, and for creating visual special effects for various media.

This paper describes a simple and inexpensive tornado simulator that was developed as a learning tool for stimulating students in both the subject of atmospheric vortices and the understanding of how to do controlled experiments. In the course of that development, however, it became apparent that certain aspects of the design could be used to examine the effects of vertical wind shear on the simulated vortex dynamics, in a special way.

In section 2, the simulator design is presented, and the key variables that the design can explore are discussed. Section 3 describes the results of some simple qualitative experiments and considers what they might imply about real tornadoes. Some final thoughts are given in section 4.

## 2. THE SIMULATOR DESIGN

The simulator is illustrated in Fig. 2, showing a view from the side. There are four fans (each rated 240 $ft^3$ $min^{-1}$) in the bottom plenum chamber, two on each side. The speed of these fans is controlled by a dimmer rheostat. The top fan is rated at about 2000 $ft^3$ $min^{-1}$ at its highest speed, also controlled by a separate rheostat. Looking down on the simulator from above gives the view shown in Fig. 3.

There are no walls on the sides of the simulator, and the experiments can be sensitive to flow disturbances from activity in the simulator room. As with other Ward-type simulators, a flow-straightener is inserted between the fan

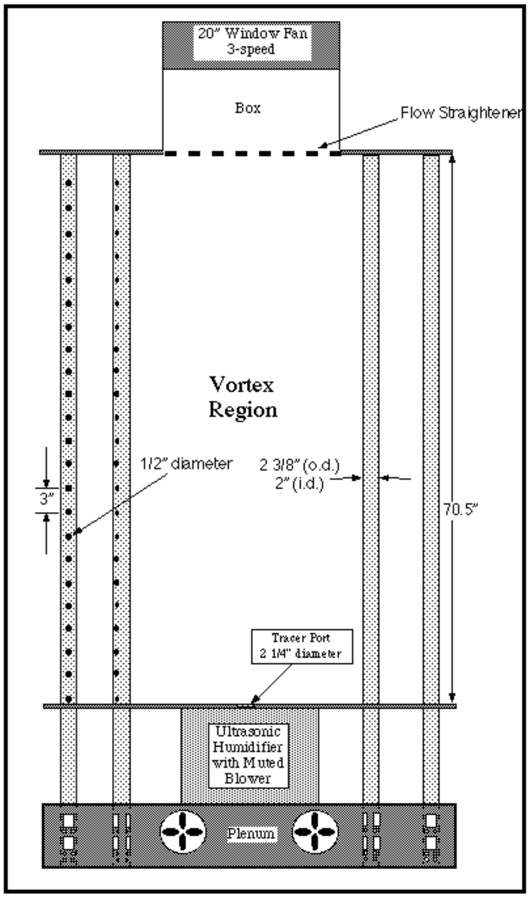


Fig. 2. Schematic view of simulator, with the vertical tubes at the front omitted for clarity (see Fig. 3). Horizontal airflow exits from the vertical tubes; this flow comes from fans (at the bottom) pushing air into a box, so that air is forced upward through the tubes. The ultrasonic humidifier produces a fine mist for flow visualization. The large fan at the top produces inflow within the vortex chamber.

and the chamber in order to decouple the vorticity produced by the fan from the vortex experimental area beneath.

The tangential flow produced by the airflow from the tubes creates vertical vorticity for the inflowing air. By blocking the holes in the tubes, it becomes possible to control the vertical distribution of vertical vorticity. As we will describe below, this permits the exploration of three distinctly different vertical distributions of vertical vorticity.

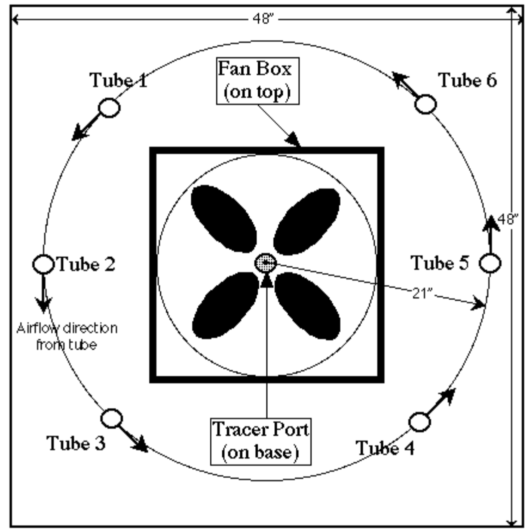


Fig. 3. View of the simulator from above, showing all six of the vertical tube locations and the tangential flow produced by the tubes.

It turns out that flow visualization was a challenge. A commonly-used method, that of putting dry ice in water, produces a mist that is notably heavier than air. The relatively high density of such a mist supplied from below inhibits the vertical advection induced by the fan at the top, making the vortex less stable. This made the use of a mist-generating humidifier a better choice to provide flow visualization.

## 3. SOME SIMPLE EXPERIMENTAL RESULTS

With none of the holes blocked, the experiment produces a single-celled vortex that is quite stable and persistent. This is the baseline from which we begin the experiments. For the baseline vortex, the fans in the bottom plenum are operating at about half their capacity via the rheostat; the fan at the top is on its low speed, and the rheostat is used to produce a speed roughly half of that.

3a. Reduction of low-level vorticity

When the holes are blocked starting at the bottom, the vortex tends quickly to become less stable. By the time the 3rd hole up from the bottom is blocked, it becomes quite difficult to produce a steady vortex, and minor disturbances of the airflow in the simulator room can either help or hurt vortex formation. This suggests that the vertical advection of vorticity from low levels is of critical importance in the maintenance of a deep, steady vortex. At least in the simulator, it turns out to be relatively difficult for vorticity aloft to create an intense vortex at the surface when near-surface vorticity is absent.

3b. Reduction of upper-level vorticity

When the holes are blocked from the top down, vorticity is progressively confined to lower and lower levels in the simulator. This is roughly comparable to the conceptual model of nonsupercell tornado formation, proposed by Brady and Szoke (1988) and discussed in detail by Lee and Wilhelmson (1997).

When this is done, the vortex shows relatively little change until the blocked holes reach roughly halfway down. With effort, it becomes possible to force the blockage below halfway down, but the vortex becomes quite sensitive to room disturbances. Although vertical advection can produce a deep vortex in a situation where the vertical vorticity is confined to low levels, such a development is apparently more likely when the near-surface vertical vorticity is not too shallow.

3c. Reduction of middle-level vorticity

Perhaps a logical experiment, given the first two, is to see to what extent a layer with little or no vertical vorticity exists between layer having significant vertical vorticity. This might be considered roughly comparable to a situation where mesocyclones are present in mid-troposphere and near the surface, with a layer in between having little or no vertical vorticity initially.

The effect is negligible when the layer is thin and near the middle of the chamber, but the development of a deep vortex is inhibited when the layer of weak vertical vorticity is comparable to about half the depth of the vortex zone. As with the other experiments, as the layer increases in depth, deep vortex formation becomes sensitive to room disturbances.

From the earlier experiments, it was expected that the location of the layer is important, as well as its depth. It's most important to have a reasonably deep layer of surface-based vorticity; when the surface-based vorticity layer becomes too shallow, the presence of more vorticity aloft can't seem to overcome the inability to produce a deep, intense vortex.

4. DISCUSSION

The results of these simple experiments are certainly indicative that the creation of a deep, intense vortex is dependent on the vertical distribution of the vertical vorticity. This conclusion is consistent with the paper by Trapp and Davies-Jones (1997). Nonsupercell tornado formation by the process first proposed by Brady and Szoke (1988) and described in Trapp and Davies-Jones (1997) as "mode II" can be demonstrated, but the low-level vorticity needs to be surface-based and not overly shallow. Although something like the "dynamic pipe effect" (or DPE; Trapp and Davies-Jones 1997) probably occurs in nature, our results suggest that the DPE might only be able to produce a deep vortex under certain special conditions. It's more difficult for a vortex to build downward in our simulator than it is for the vortex to build upward. We should be careful to point out that there could be reasons for this that are not directly related to tornado development in the real atmosphere.

The inhibiting effect of a layer of little or no vertical vorticity in between vortices near the surface and aloft is crudely comparable to mesocyclones within a convective storm and near the surface. In such cases, tornadoes seem to either develop upward from low levels or downward (and upward) from middle levels in the thunderstorm. Our results indicate that increasing the depth of this weak vorticity layer has a definite inhibiting effect on the creation of a deep, intense vortex within a mesocyclone. The creation of a deep, intense vortex within a mesocyclone is easiest if the low-level vorticity is not too shallow, indicating an important role for vertical advection of vorticity in building the vortex upward.

This paper has described an inexpensive simulator that can be employed to perform some potentially useful scientific experiments. These experiments may shed some light on real tornado behavior; that is, it's possible even within a simple vortex chamber to exercise control over several key variables in the development of the vortex, and contribute to scientific understanding in spite of a lack of precise quantitative measurements. In view of the results of this simple experimentation, to be shown as part of the "poster" display, the authors are advocating the reconsideration of the role of vortex chambers in tornado research.

Given their tutorial value, it is quite likely that vortex chambers would be an asset for any educational program, as well as a potential tool for tornado research. The creativity and enthusiasm of young people always exceeds the vision of their mentors; new variations on the vortex chamber may be developed by new scientists whose vision is not hindered by limitations of past work and who become excited about the laboratory simulations. In atmospheric science, it is generally possible to do controlled experiments only in numerical simulation models. Laboratory models offer the opportunity to learn about controlled experiments without the difficulties of software development and the intricacies of numerical simulations. Whereas the research community generally has abandoned the vortex chamber, apparently because it was widely felt that its research potential had been exhausted and its limitations too restricting, we believe that having access to such chambers in educational institutions may permit them to be stimulating and, therefore, valuable in research indefinitely.

Our simple experiments certainly do not provide us with definitive results. A more carefully-controlled research version of the simulator would be required to give more stable, reproducible, and quantitative findings than this inexpensive model can provide. What we believe we have shown, however, is that the laboratory vortex simulator's capacity to contribute has not been exhausted. If nothing else, experience with laboratory vortex simulators can help to guide numerical model simulations where dynamic similarity with real atmospheric flows can be controlled more carefully than with laboratory models.

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