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ANALYTIC STUDIES ON SATELLITE DETECTION OF SEVERE, TWO-CELL TORNADOES

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ABSTRACT

It is argued that a two-cell structure is likely to be the unique property, and potentially satellite-accessible observable, of the exceptionally severe tornado. Analysis elucidating the dynamic, thermodynamic, and geometric properties of this two-cell structure is described. The analysis ultimately will furnish instrumentation requirements.

INTRODUCTION

The goal of this research is to identify and to characterize a unique property of the exceptionally severe tornado that might permit its detection by future passively instrumented geosynchronous meteorological satellites with highly refined resolution. Such a tornado tends to have long path length ($\sim$100 km) and long life span ($\sim$1 hr), such that early detection makes possible worthwhile warning. Since the exceptionally severe 2% or so of tornadoes effect about 98% of tornado-associated destruction (Darkow 1977), these special cases deserve emphasis. Of course, the inability of passive satellite detectors to penetrate the highest-level cloud layer is a serious restriction in achieving the goal.

One would prefer to forecast the onset of tornadoes. Current satellite indicators [midtropospheric minimum in the vertical profile of the total static enthalpy (Darkow 1967, Negri 1977), or low cloud-top temperature with rapid cloud-area increase (Adler 1977)] cannot specify whether, when, or in what form, severe weather will arise. In fact, despite Adler's success for one specific event, Negri finds for another event that the minimum cloud-top temperature occurred hours after an intense hailstorm, and that explosive cloud-top growth was absent for a concomitant devastating tornado. Intuitively, inferring the existence of significant convective activity is distinct from detecting a specific unerring indicator of severe-tornado occurrence (see Darrah 1978). Thus, here attention is confined to satellite use for severe-tornado detection, as opposed to forecasting.

IDENTIFICATION OF AN OBSERVABLE ACCESSIBLE TO A SATELLITE

Funnel-cloud-length interpretation (Dergarabedian and Fendell 1973) permits one to establish instantaneously and accurately the peak swirl speed, relative to the axis of rotation, of any sighted tornado; in practice, these speeds are found to reach, but never to exceed, about 110 m/s. Examination of a very large number of atmospheric soundings taken in close spatial and temporal proximity to tornadoes (Dergarabedian and Fendell 1977) readily establishes that the ground-level horizontal pressure deficits from ambient achievable by moist-adiabatic ascent are at most about 1-2 kPa (10-20 mb). By the cyclostrophic balance, such deficits are equivalent to peak swirls on the order of 50 m/s. The 10-kPa (100-mb) pressure deficits consistent with 100-m/s peak swirl are achievable thermohydrostatically only by having a central dry-adiabatically compressed downdraft of nonrotating, originally tropopause-level air. In short, the same evolution from one-cell to two-cell structure that marks the evolution of a tropical storm to a very dangerous typhoon (Fendell 1974), also marks the evolution of a mesocyclone to a dangerous-tornado-bearing supercell (Dergarabedian and Fendell 1977), although vastly different horizontal scales characterize the two types of vortical storms. There must exist a well-developed "eye" (nonrotating, descending core) within an "eye wall" (annulus of swirling updraft), with the "eye"/"eye wall" interface sloping appreciably away from the axis of rotation with height, from simple conservation-of-angular-momentum considerations in an atmosphere with density decreasing with altitude. Otherwise, peak swirl speeds, relative to the axis of rotation, of 110 m/s are thermohydrostatically inexplicable, and no plausible alternative mechanisms have been identified.

Thus, the "eye" furnishes a unique characteristic of the severe tornado and an observable possibly accessible to passively instrumented meteorological satellites. Elucidation of the typical geometric dimensions, dynamic properties, and thermodynamic states of the "eye"/"eye wall" interface becomes the goal of this research.

INPUT FROM OVERFLIGHTS OF THUNDERSTORMS

Descriptions from aircraft overflights of anvil clouds (Anonymous 1977) report observations of "cumulonimbus collapse" and "hole formation" in the cirrus shield of thunderstorms one-quarter to one-half hour before onset of a destructive tornado. The inference drawn here is that compressional heating associated with "eye" insertion is being observed; of course, the nascent "eye" may not extend the depth of the troposphere, so "hole formation" does not imply a severe tornado inevitably follows. Incidentally, it is probably a misconception that cumulonimbi "overshoot" (Fujita et al. 1975) their level of neutral stability; such momentum build-up in so subsonic an atmospheric flow as buoyancy-driven ascent of a cumulonimbus (typified by speeds of 10 m/s, with gusts of 25 m/s) is unlikely. As a rotating thunderstorm spins up, entrainment into cumulonimbi decreases (Emmons and Ying 1967), especially in the lower troposphere, such that later cumulonimbi transcend the neutral stability level (i.e., the tropopause) established by earlier, more diluted cumulonimbi.

INPUT FROM MODELING

One would prefer to concentrate immediately on the upper-tropospheric flow in a severe tornado, because this portion of the flow is accessible to passive satellites. However, there are crucial constraints on mass, momentum, and heat flux, into and out of the upper-tropospheric flow, posed by the lower-tropospheric flow. In fact, a logical analytic procedure is to follow the flow through the same sequential "path" as air is "processed" in the tornado.

The severe tornado is here modeled as a closed vertical quasisteady axisymmetric system of four subregions (Dergarabedian and Fendell 1970); in each of the four subdivisions significantly distinct physical processes enter. The bulk of the system is a potential vortex, in which little axial variation occurs in the dynamics and in which radial flow is negligible. Air slowly sinks from the potential vortex, in cyclostrophic equilibrium, into a near-ground inflow layer, in which angular-momentum-dissipating frictional forces upset the cyclostrophic balance to permit radial influx ("teacup effect"). A critically important, but rarely appreciated, characteristic of the high-swirl portion of the inflow layer is that it is inviscidly controlled, such that the role of friction is confined to a very-near-ground sublayer (Carrier 1971; Burggraf et al. 1971; Carrier and Fendell 1978). The swirling radial influx erupts into an annulus of swirling updraft, that conveys lower-tropospheric fluid to the upper troposphere; the annulus consists of three components: a turnaround or corner flow, an "eye wall", and an upper-tropospheric outflow -- these three regions together are considered the third subdivision of the tornado. The fourth subdivision, unique to the severe tornado, is the "eye" (see Figure 1).

RECENT RESULTS FROM MODELING

In the past, solution for the potential vortex and for the near-ground inflow layer has been available. However, the turnaround flow, which tends to be an elliptical domain bounded by two streamsurfaces of initially unknown position, has proved an intractable free-boundary problem for analysts. Here solution for the turnaround flow has been furnished by method-of-lines integration of a turnaround-flow formulation, which is rendered of parabolic-like character by transformation of variables (Carrier, Dergarabedian and Fendell 1978). Results show that accelerations from streamline curvature during separation of the inflow give but a 10% augmentation in swirl in the turnaround over peak swirl speeds in the potential vortex. More importantly, displacement of the annular swirling updraft from the axis of rotation is now characterized for the lower troposphere.

CONCLUDING REMARKS: DIRECTIONS FOR FURTHER WORK

In view of results just enumerated, it now seems possible to proceed logically to the characterization of the thermodynamic, dynamic, and geometric properties of mid- and upper-tropospheric "eye"/"eye wall" configurations. This information will furnish the resolution and sensitivity required for meteorological-satellite instrumentation dedicated to detection of severe tornadoes. The only alternative to pursuing and exploiting this knowledge is to grasp at correlations without established meteorological bases.

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THE FOUR-PART STRUCTURE OF A MATURE QUASISTEADY AXISYMMETRIC VORTEX (CLOSED SYSTEM)

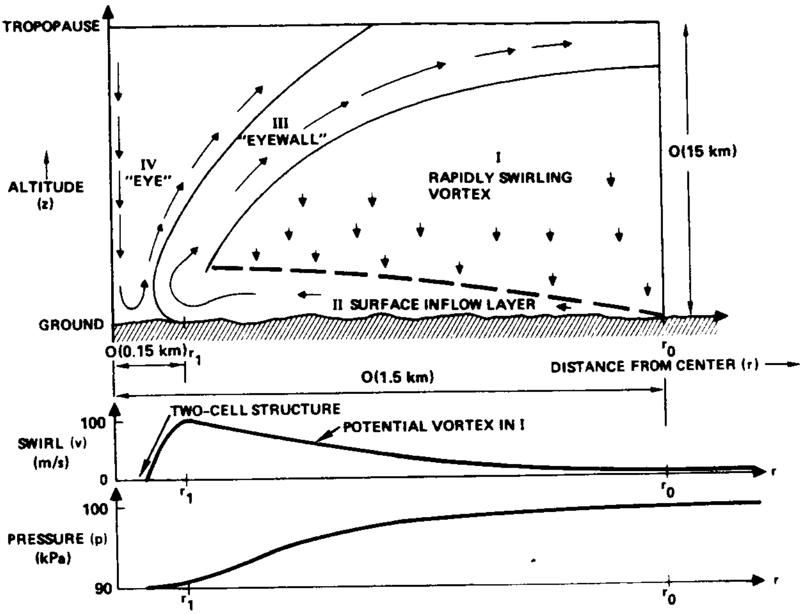

Fig. 1. A schematic, not to scale, of the structure of a tornado, with 100-m/s peak swirl relative to the axis of symmetry. The radial profile of the swirl, at midtropospheric altitude, reveals a nonrotating central "eye" joined to a nearly potential vortex. The pressure deficit from ambient, at ground level, may reach about 10 kPa; the outwardly sloped "eye"/"eye wall" interface permits fluid in the potential-vortex portion of the tornado to achieve swirl speeds consistent with this pressure deficit.