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THUNDERSTORM FORMATION AND INTENSITY DETERMINED FROM A THREE-DIMENSIONAL SUBSYNOPTIC-SCALE TRAJECTORY MODEL

G. S. Wilson, *Marshall Space Flight Center, Alabama*

ABSTRACT

A diagnostic trajectory model has been used to provide a better understanding of the interrelationships between synoptic- and convective-scale systems. Results indicate that synoptic scale systems exert a strong controlling influence over the formation and intensity of small mesoscale convective circulations.

INTRODUCTION AND DATA

NASA's fourth Atmospheric Variability Experiment (AVE IV) was conducted from 0000 GMT 24 April to 1200 GMT 25 April 1975 primarily to further establish the variability and structure of the atmosphere in regions of convective storms, and to investigate the poorly understood interrelationships between these storms and their environment. AVE IV data provide a unique opportunity to evaluate these relationships and scale interactions since two severe lines of thunderstorms occurred during the experiment. Special rawinsonde soundings were taken at 3- or 6-h intervals in AVE IV over the U.S. east of 105°W longitude and all available surface, radar (from Manually Digitized Radar (MDR) data (Foster and Reap, 1973)), and satellite data were used in the diagnostic analyses.

This paper presents results aimed at providing a better understanding of the interrelationships between synoptic- and convective-scale systems obtained by following individual air parcels, embedded within the macro-scale flow pattern, as they traveled within the convective storm environment of AVE IV. A three-dimensional trajectory model was used to objectively calculate parcel paths while MDR data was used to locate convective activity of various intensities and to determine those trajectories that traversed the storm environment.

THE TRAJECTORY MODEL

To develop data for the trajectory model, the u, v, Θ, and ϕ variables of the AVE IV data were interpolated from randomly-spaced rawinsonde stations to equally-spaced grid points. Therefore, all input data for the model were contained on 18x18 grid arrays ($\Delta x=\Delta y=158$ km) at 18 pressure levels from the surface up to 100 mb for all times of the AVE IV Experiment and were stored on computer disk.

From these basic analyzed fields, vertical velocities were calculated for every grid point so that u, v, and ω components of the wind vectors were defined three-dimensionally over the experiment area. The method used in determining the vertical velocities follows exactly the technique used by Wilson and Scoggins (1976) and Wilson (1976). The technique is basically kinematic and extensive comparative research shows this method to be far superior to all other calculating techniques when results are compared to the observed weather.

All trajectories in AVE IV were computed backward in time to insure that air parcels would terminate their paths exactly at a given grid point on a given pressure surface. The mathematical procedure used to calculate trajectories from wind fields defined in Eulerian space is given by Collins (1970).

Figure 1 uses a specific plotting technique (after Reap, 1972) to show five air parcel trajectories passing over a severe squall line in AVE IV ending at the 300-mb level. Three-hour MDR composite charts, including data ± 1 h surrounding a given release time, were prepared for all nine periods of AVE IV. The 0600 GMT data is superimposed in the figure (maximum MDR value was chosen in each block for the composite chart and MDR values ≥ 4 are usually considered thunderstorms). The location of each parcel at the last four consecutive time periods (between 2100 GMT 24 April and 1200 GMT 25 April) is shown with tick marks and the vertical location is indicated in millibars (subsiding and rising parcels are shown in dashed and solid lines, respectively).

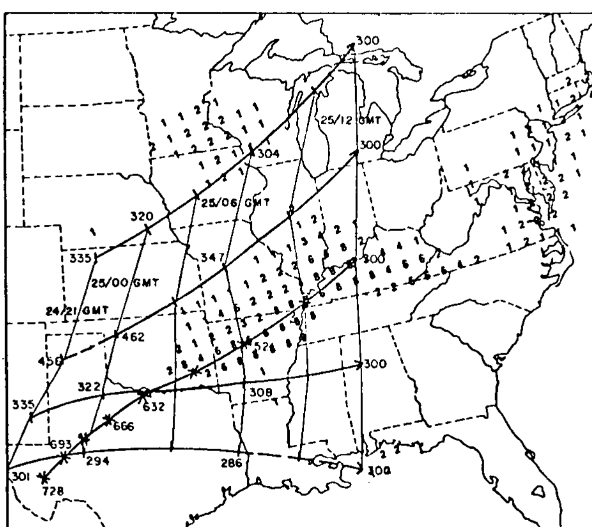


Fig. 1. Plotted trajectories for five air parcels passing over a severe squall line (MDR data superimposed) in AVE IV at 0600 GMT 25 April. All parcels terminate at 300 mb with the vertical location (mb) shown at each time period (tick marks).

Of particular interest is the extreme diverging of the air parcels between 2100 GMT (over the Southern Plains) and 1200 GMT (over the Eastern U.S.) as they traveled over the squall line, indicating the large magnitude of the upper-level divergence. In response to this divergence, the air parcel traveling from southwest Texas northeastward across Arkansas and Kentucky rises from 728 to 300 mb (a-372-mb net vertical displacement (NVD) in 15 h) while the other three air parcels change their pressure less than 50 mb during the same time period.

Reap (1972) has developed a technique for translating results from a trajectory model into an Eulerian framework. A quantity called net vertical displacement (NVD) was developed by Reap which, when translated into the Eulerian grid, resulted in a spatial distribution of dp/dt for all air parcels ending their trajectories at all grid points in the grid array. The rate of pressure change along the parcel's path is actually calculated from $\Delta p/\Delta t$ where Δp represents the pressure change observed by the parcel as it moved three-dimensionally in space over a time period of 12 h (Δt). Using the 3- and 6-h data available in the AVE IV experiment, NVD's were computed in a similar manner as was previously described except Δt was 3 or 6 h. The increased temporal resolution of the data produced a NVD distribution that related well to the location and intensity of convective activity.

NET VERTICAL DISPLACEMENTS, PARCEL ENERGY INDICES, AND CONVECTIVE STORM DELINEATION

Figure 2 shows the average vertical profiles of NVD (mb/3h) as a function of precipitation intensity (from MDR data) from all nine time periods of AVE IV. "No precipitation" areas had small positive NVD's at most levels while negative values occurred in

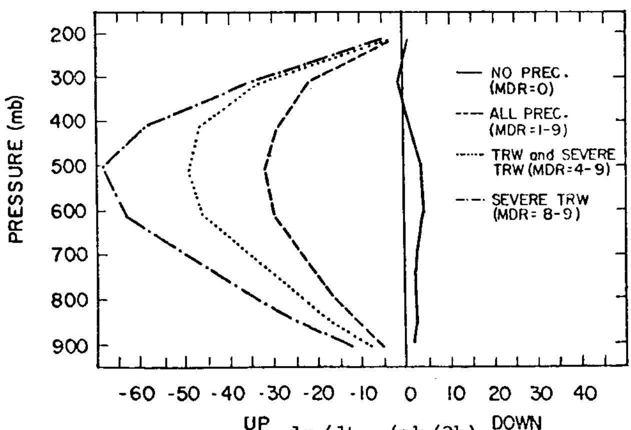


Fig. 2. Average profiles of dp/dt or NVD as a function of pressure and MDR coded precipitation intensity. (Maximum MDR value was assigned to a grid point within 1/2 grid distance (≈80 km) in MDR 3-h composite charts).

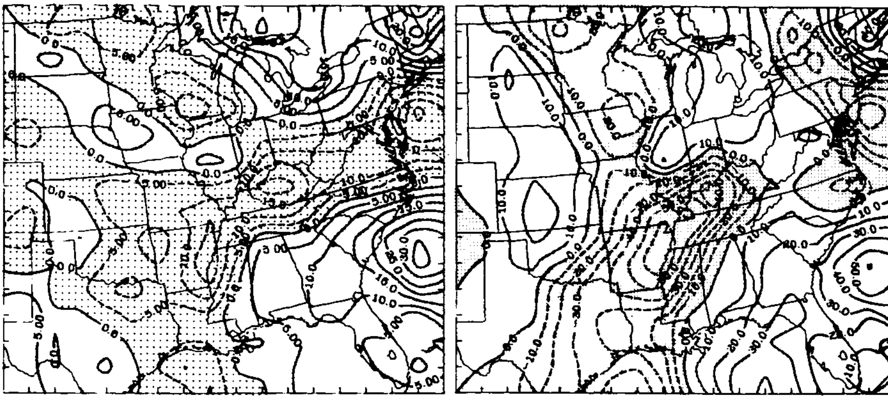
precipitation areas with the maximum upward values located around 500 mb. The magnitudes of the average values of NVD's were larger at all pressure levels in areas containing more intense convective activity so that a value of -70 mb/3h was associated with severe TRW in AVE IV.

Figure 3a shows examples of the gridded trajectory data (NVD's at 850 and 500 mb) for 0600 GMT April 25 when a severe squall line was located in the middle of the network. The NVD fields of AVE IV not only exhibited good spatial and temporal continuity but correlated highly with both the location and intensity of precipitation as revealed by the radar observed convection for Fig. 3a (see Fig. 1 for MDR composite chart) and Fig. 2. Negative (rising air parcels) NVD centers were associated with all major precipitation areas and subsidence (positive NVD's) usually separated these systems.

To accurately parameterize the static stability of the atmosphere in AVE IV, a method was developed to objectively calculate both the amount of buoyant energy (ergs/g) necessary to be added to a parcel to make it hydrostatically unstable (negative buoyant energy or NBE) and the amount available to be converted into kinetic energy of the upward vertical velocity (positive buoyant energy or PBE) or "updraft" if the parcel were to become unstable. For each time period, the basic gridded temperature and moisture fields were used to produce spatial fields of NBE and PBE. NBE was calculated by summing all negative buoyant energy up to 500 mb over each grid point. PBE resulted from summing all positive energy up to 100 mb. Smaller NBE values should correlate with the increasing occurrence of TRW while larger PBE should relate to the increasing intensity of convective activity.

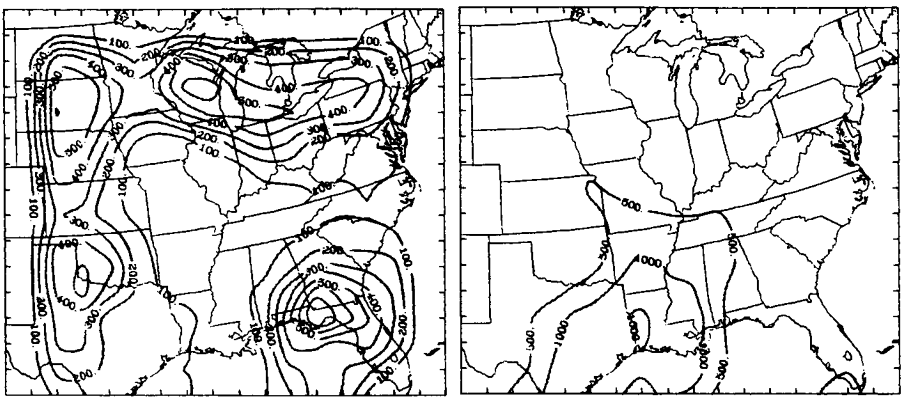
Figure 3b presents the NBE and PBE spatial fields (10^4 ergs/g) for the same period as Fig. 3a. Convective precipitation (MDR≥2) usually occurred where NBE values were <200. x 10^4 ergs/g, while thunderstorms and severe convection were associated with values <100. x 10^4 ergs/g. While the location of the convective activity was accurately delineated with the NBE fields, the PBE fields related well to the intensity where most MDR≤4 were associated with PBE values <500. x 10^4 ergs/g. In contrast, heavy and severe TRW (MDR≥6) occurred with higher PBE values (>500. x 10^4 ergs/g).

Since both a dynamic lifting mechanism and weak static stability are both usually needed for convective storm development, NVD's (at 9 pressure levels from 900 mb to 100 mb) and the NBE and PBE stability measurements were combined, using multiple linear regression, in an attempt to spatially delineate the location and intensity of convection for all AVE IV time periods. Correlations were computed with grid point data where the predictand was the MDR intensity categories (MDR<2, 2≤MDR<4, 4≤MDR<8, MDR≥8) calculated in the manner explained in Fig. 2. A linear correlation coefficient of 0.6 was obtained for these increasing intensity categories of convection with the most important parameters (in order) being NVD (500 mb), NVD (850 mb), NBE, and PBE (these parameters accounted for 98% of the total explained variance). This linear regression delineates (with 80% accuracy) between non-convective (MDR<2) and convective areas (MDR≥2) but it only determines the correct intensity category 50% of the time.



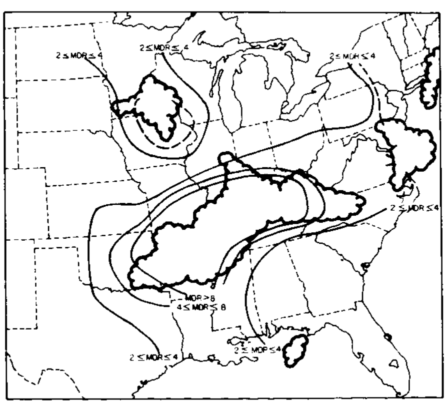
850 mb 500 mb

a. Net vertical displacements (mb/3h)



NBE PBE

b. Parcel energy indices (10^4 ergs g^{-1})



c. Diagnostic delineation of convective storm location and intensity

Fig. 3. Analyses of a) net vertical displacements, b) parcel energy indices, and c) diagnostically determined intensity categories of convection (scalloped areas are MDR≥2) for 0600 GMT April 25, 1975.

Figure 3c is an example of the diagnostic delineation of convective storm location and intensity for 0600 GMT 25 April. These results demonstrate the remarkably high degree of scale interaction between synoptic- and convective-scale systems which are separated (in scale length) by approximately three orders of magnitude.

CONCLUSIONS

A three-dimensional trajectory model has been used to both parameterize and dynamically explain the interactions between convective storms and their environment using data from NASA's AVE IV Experiment. By combining NVD's with an advanced measure of static stability (PBE and NBE), using multiple linear regression, convective activity of various intensities can be spatially determined. Convective and non-convective areas can therefore be delineated with 80% accuracy, which demonstrates the high degree of scale interaction between synoptic- and convective-scale systems.

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