A WATER VAPOR IMAGE FEATURE RELATED TO SEVERE THUNDERSTORMS

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Abstract

A persistent "V" or "C"-shaped dark band sometimes observed in GOES water vapor imagery near the upstream edges of a thunderstorm's cirrus anvil may indicate the likelihood of severe weather. The subtle feature can also be oval or circular in appearance. One hundred and forty-seven (147) convective storms were observed to have this feature during the spring and early summer of 1989. Eighty-two percent (82%) of the storms were severe. The predominant type of severe weather observed was large (≥¾ inch diameter) hail.

1. Introduction

The 6.7μm channel water vapor (WV) images from GOES (Geostationary Operational Environmental Satellite) have been available since 1981. Thermal radiation in this portion of the spectrum is strongly affected by absorption from water vapor that may be present in the frozen, liquid or gaseous states. The image brightness is a complex function of the height, temperature, humidity, thickness and vertical distribution of moisture. Simulations of image brightness relating to various moisture conditions have been completed (e.g., Weldon and Steinmetz, 1984). In a region of high, thick, cold clouds (such as thunderstorms) the only thermal energy able to reach the satellite sensor is from near the cloud tops, which appear as light gray or white. Conversely, regions of low humidity aloft appear dark gray or black because observed thermal energy originates from warm lower levels of the troposphere and passes unhindered into space. Intermediate gray shades are more ambiguous, and a wide range of conditions may be present that are best assessed with the help of other types of satellite imagery and radiosonde data. In most situations, the amount of energy originating from a layer below 700 mb in a WV image is negligible.

Water vapor images have been generally used as a tool for synoptic scale weather analysis. Descriptions of these applications are provided in the literature (Weldon, 1991; Ramond, et. al, 1981). The basis for synoptic scale applications is that boundaries between moist and dry regions often relate to significant upper level flow features such as troughs and jet streams. These boundaries become oriented in the direction of the upper flow with slow moving weather systems. Decreases with time in the image brightness have been found to be related to a net loss of moisture in the atmospheric column caused by subsidence (Muller and Fuelberg, 1990).

Water vapor imagery has mesoscale applications as well. The availability of hourly WV images starting in late 1987 has permitted the monitoring of changes in mid and upper level moisture in the environment of convective storms. For example, increasing image brightness may be an indication of vertical motion due to an upper level trough or jet streak, resulting in enhanced potential for thunderstorm development (Rodgers and Griffith, 1989). Other mesoscale uses of WV imagery are summarized by Beckman (1987) and Ellrod (1990). This paper describes a convective-scale WV feature that suggests a high probability of severe thunderstorms.

2. Feature description and observation conditions

There are instances when a narrow dark zone is observed in WV images that envelopes the upstream edge of the cold cirrus anvil of a thunderstorm cell or cluster. This dark zone usually has a "C" or "V" shape, similar to a collar, but may also be observed as a small circular or oval pattern. An example is shown in Figure 1. A dark band, estimated to be at least 30 to 40 n mi wide, lies along the western edge of the white area denoting the thunderstorm system from 1200 UTC to 1700 UTC. In a high percentage of cases, including the case shown in Figure 1, severe weather (large hail, strong winds or tornadoes) occurs when this feature is present.

One of the environmental conditions required for the observation of the dark band feature is *near absence* of thick cirrostratus in the vicinity of the upstream portion of the thunderstorms. Because of its persistence and opacity, cirrostratus tends to obscure any darkening that may occur. Since there is less interference from merging anvil debris, the dark band is most often observed with isolated or widely scattered convective cells or systems. On the other hand, where extremely dry air aloft is present, the dark zones are rarely observed, probably due to the lack of sufficient contrast between the ambient air mass and the small scale feature surrounding the thunderstorm. Minor adjustments of contrast and brightness on video displays should improve the detection of subtle dark zones. Since the dark band is a small scale feature, it is best observed when the satellite images are enlarged. An example would be the sub-sector mode on the Satellite Weather Information System (SWIS) used at the National Weather Service Forecast Offices.

3. Examples

a. 25 May 1989 case

During the early morning hours of 25 May 1989, a thunderstorm developed rapidly just to the north of Kansas City, Missouri, then moved eastward across central Missouri. Hail up to two inch diameter and high winds occurred along its path, resulting in extensive damage (NOAA Storm Data). Figure 1 is a sequence of WV images from 1100 to 1700 UTC which shows the evolution of convective cells and the development of the dark zone. A strong cell developed by 1100 UTC (A) in northeast Kansas. By 1200 UTC, a pronounced dark zone appeared (A) that had grown in length and width by 1400 UTC. Just prior to 1200 UTC (1145) large hail began in northwest Missouri. Hail and locally damaging winds persisted as the storm system marched across the

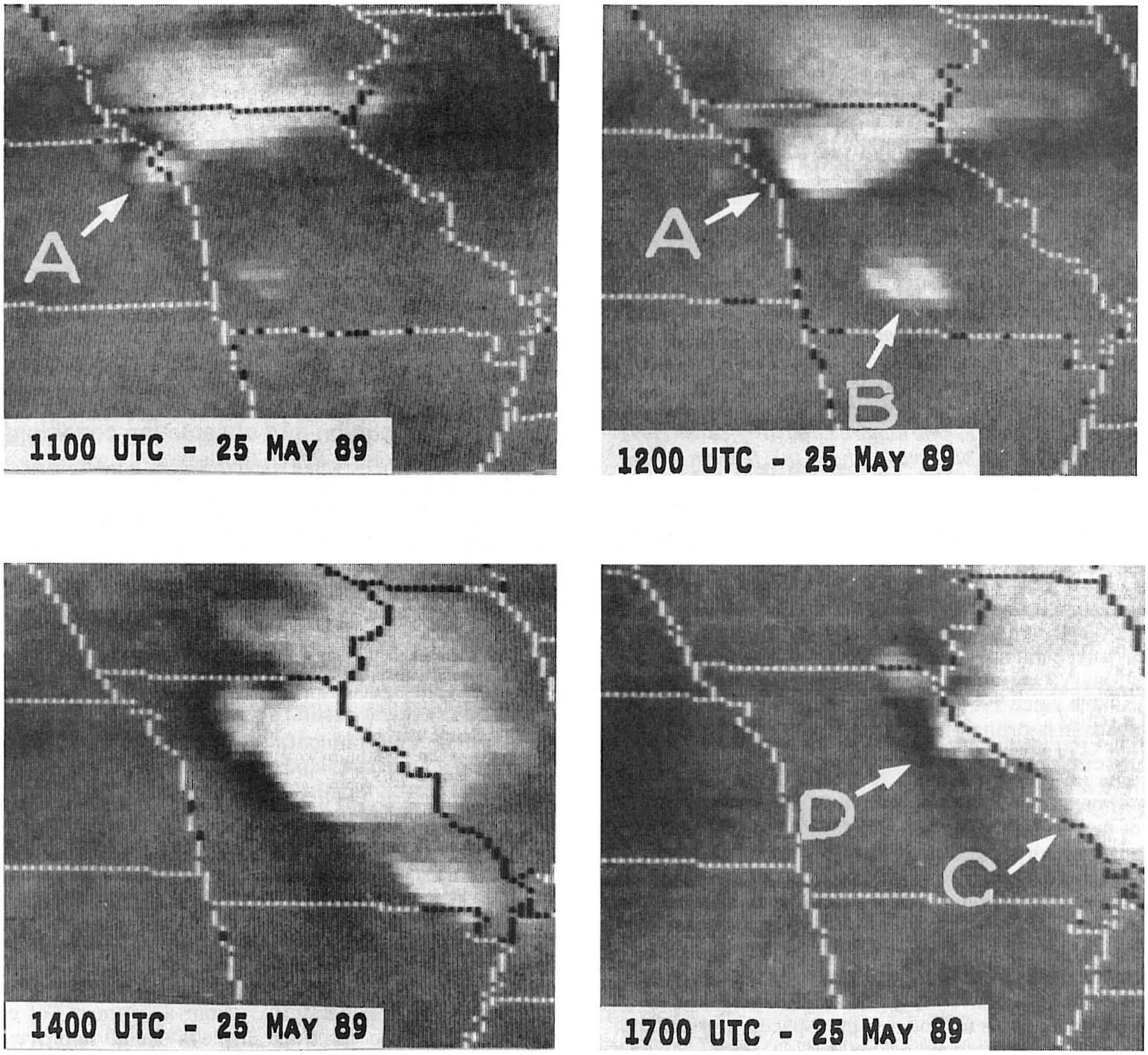

Fig. 1. Water vapor images from GOES-7 at (a) 1100 UTC, (b) 1200 UTC, (c) 1400 UTC and (d) 1700 UTC on 25 May 1989. Letters refer to thunderstorm areas described in text.

state. By 1700 UTC, the dark zone dissipated along the southern end (C) as the storm weakened, with no further hail reported. Farther north, a dark band maintained its clarity near the convection at "D." The cell at "D" also produced large hail and high winds as it moved into west central Illinois. It should be noted that a cell in southwest Missouri that was first evident in the 1200 UTC image (B) also generated large hail (up to 2¾ inch diameter) but did not exhibit the WV dark collar. The hail occurred shortly after 1300 UTC and was relatively short-lived.

National Weather Service (NWS) radar composites for the period from 1035 UTC to 1535 UTC are shown in Figure 2. The development of the dark zone in the WV images coincided with an intensification of the primary cell (A in Fig. 1) to a radar top of 52,000 ft (15.9 km) by 1235 UTC and the observation of hail. By 1535 UTC, another strong convective storm (tops 52,000 ft) developed in northeast Missouri (D in Fig. 1).

A sequence of enhanced GOES infrared (IR) images (Fig. 3) shows the three separate thunderstorm areas clearly. At 1401 UTC, coldest cloud top temperatures (CTT) were less than −60°C in north central Missouri (E) with a new cell intensifying rapidly just to the northwest (F). An enhanced-V signature, often associated with severe storms (McCann, 1983), appeared to exist in the anvil cirrus (E). A high percentage of storms that exhibit the enhanced-V (up to 70%) are accompanied by severe weather. The enhanced-V did not become clearly evident until 1300 UTC, however. By

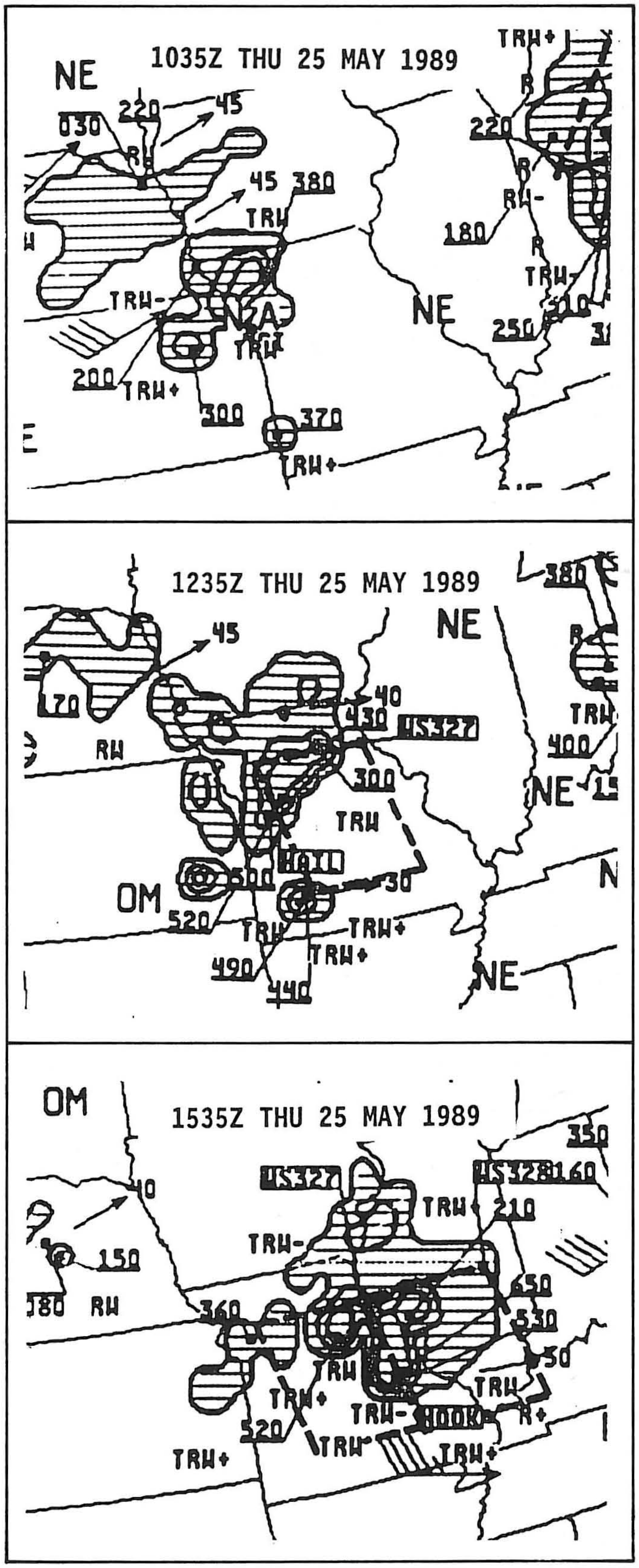

Fig. 2. NWS radar composites at 1035 UTC, 1235 UTC, and 1535 UTC, 25 May 1989. Arrows and wind barbs refer to cell movements and area movements (knots), respectively. Contours represent VIP levels 1, 3 and 5. Dashed boxes show areas where severe weather watches are in effect. Radar echo top heights (hundreds of feet) are underlined.

1701 UTC, the primary convective system had moved into southern Illinois and weakened.

b. 28 April 1989 case

Another example occurred on the afternoon and evening of 28 April 1989. The WV image at 2301 UTC (Fig. 4) showed that two areas of convection were present, one in eastern Oklahoma and Arkansas, the second in east Texas. The enhanced infrared image at the same time (Fig. 5) indicated that the minimum CTTs were $\leq -55°C$ (dark gray to black shading). By 0001 UTC, the WV image (Fig. 4) showed that dark zones had developed on the western edge of cells in north central Texas and south and west of the cell in Oklahoma (arrows). Starting at 0020 UTC, a tremendous hailstorm occurred near Ft. Worth, Texas (FTW). Hailstones ranged from 1 inch diameter to near softball size (4½ inch). At about the same time, hail of more modest size (1 inch) occurred in eastern Oklahoma.

NWS radar composites at 2135 and 0035 UTC (Fig. 6) show the development and intensification of thunderstorm cells over north central Texas during this period.

In this instance, some lead time (20 min) was present between the detection of the WV feature and the severe weather. In other cases where it was possible to determine lead time, it was usually less than 30 min. The delayed transmission of WV images on the GOES-Tap system reduces the timeliness of this technique in providing warnings. However, for situations where the severe weather persists over rather long periods (say, an hour or more), or is recurrent during the life of a convective system, some lead time would be provided for the latter portion of the event.

4. Statistical Results

The main type of imagery used in this study was fascimile prints of the CC3 standard sector, an operational product on the GOES-Tap transmission system. The CC3 sector covers most of North America with a resolution of no better than 14 km (8 n mi). Hourly animated imagery was also viewed on the VAS Data Utilization Center (VDUC) display system located at Camp Springs, Maryland. This type of display was found to be superior in identifying the dark bands because of an enhancement scheme that highlights subtle features much better than the CC3 prints. An important requirement was to determine that the dark zone did not exist prior to the formation of convection, and thus occurred as a direct result of the convection. Figures 1 and 4 clearly show this process.

A study of WV images during the spring and early summer of 1989 (29 March to 30 June) revealed 147 cases of this signature on 43 days. Based on NOAA Storm Data reports, 121 of the 147 cases (82%) were associated with severe thunderstorms. An analysis of the observed severe weather type (Fig. 7) shows that large hail ($\geq$ ¾ inch) was predominant by far, occurring in 87 of the 121 severe cases (83%). Nearly a third (31%) were accompanied by winds $\geq$ 50 kt (and/or wind damage), while more than one fourth (26%) were accompanied by tornadoes. Forty-two (35%) of the 121 cases had multiple types of severe weather observed.

The diurnal variation of the *initial* observation of the WV feature (Fig. 8) indicates that it may be observed at any time of the day, with a preference for the late afternoon and evening period. Previous studies of the diurnal distribution of thunderstorms (Wallace, 1975; Easterling and Robinson, 1985), tornado occurrences (Kelly et al., 1978) and non-tornadic severe thunderstorms (Kelly et al., 1985) all show a

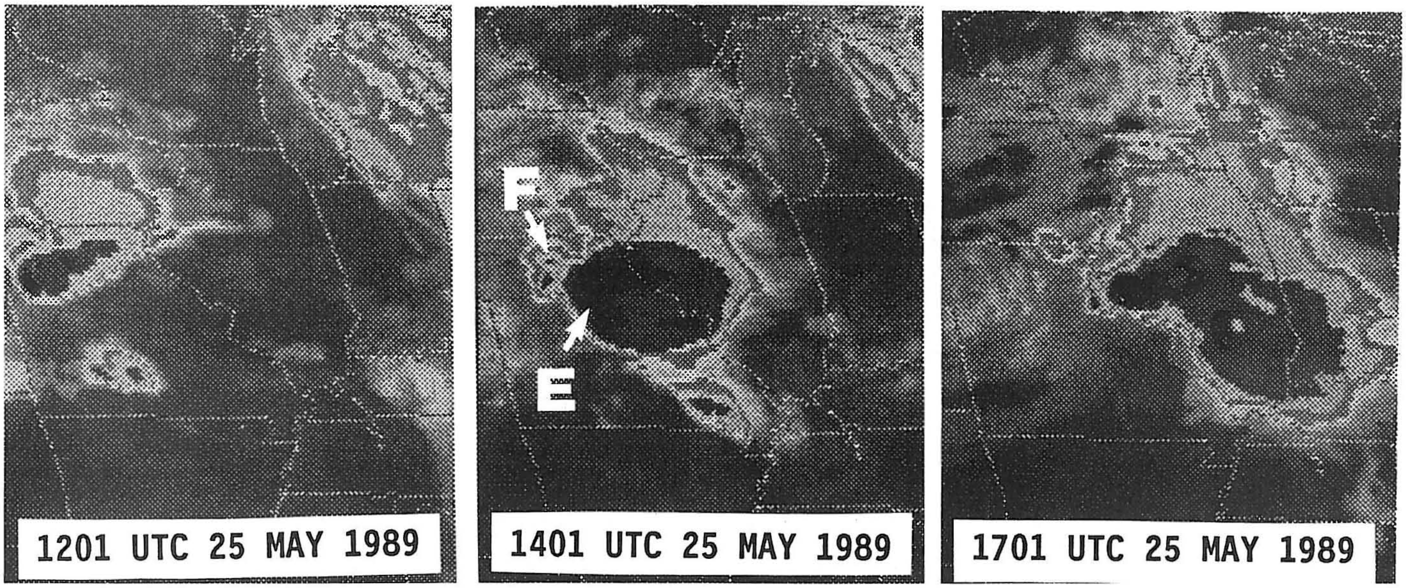

Fig. 3. GOES infrared images at 1201 UTC, 1401 UTC, and 1701 UTC, 25 May 1989, enhanced with "MB curve." Black areas show cloud top temperatures colder than −60°C.

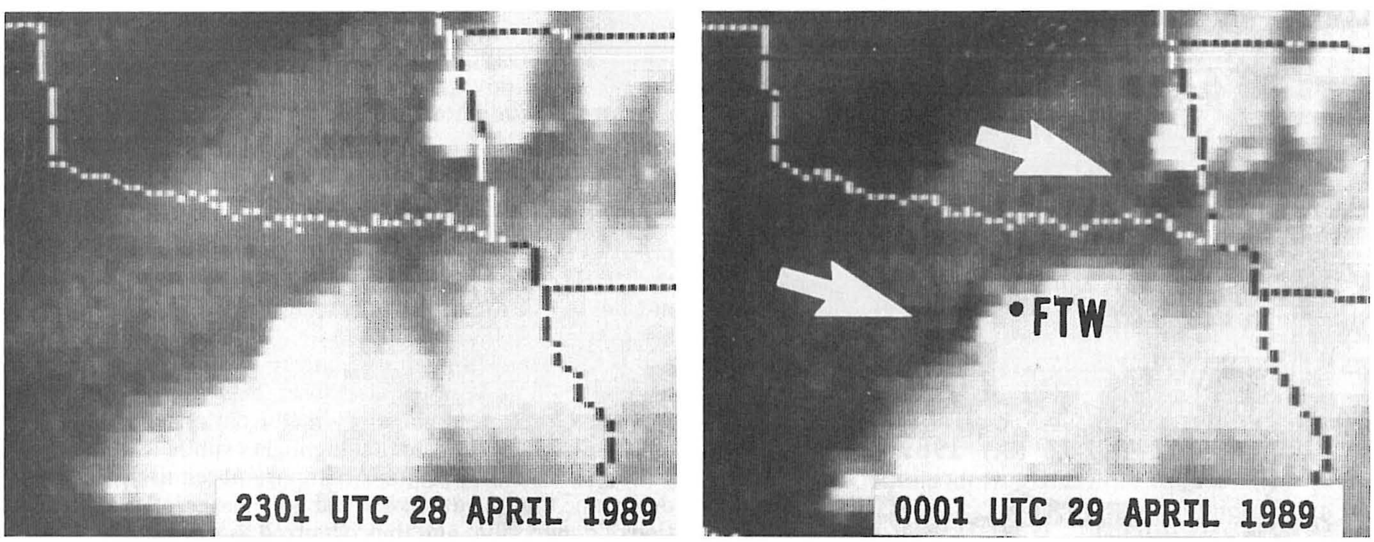

Fig. 4. GOES WV images at 2301 UTC, 28 April 1989 and 0001 UTC, 29 April 1989.

preference for the afternoon and evening hours, consistent with the results shown in Figure 8.

The geographical distribution of the WV signature (Fig. 9) showed a maximum in the central United States, predominantly in the southern plains. Only 20 cases (19%) in the 1989 sample were observed east of the Mississippi. This is not surprising, in light of the normally higher frequency of severe weather in the Great Plains (i.e., Baldwin, 1973). It has also been found that large hail is the primary severe weather event in this portion of the country (Kelly et al., 1985), consistent with the predominance of hail observed with the WV signature (Fig. 7). While no occurrences were observed over parts of the southeast and northeast United States in 1989, some cases were seen in those areas during 1990.

5. Discussion

The cause of the thunderstorm dark zones, while still open to conjecture, is believed to be sinking along the upstream edge of the anvil cirrus. This effect should be most pronounced with a combination of: (1) moderate to strong upper level flow and (2) a strong, sustained thunderstorm updraft which tends to block the environmental flow. Since the stable tropopause presents an obstacle to rising motion, the approaching air sinks as it converges with the anvil outflow. Some warm, dry stratospheric air is possibly forced to sink also. The result is both warming and a net loss of moisture in the air column, leading to darkening in the WV images. In the 25 May 1989 case, for example, winds in excess of 100

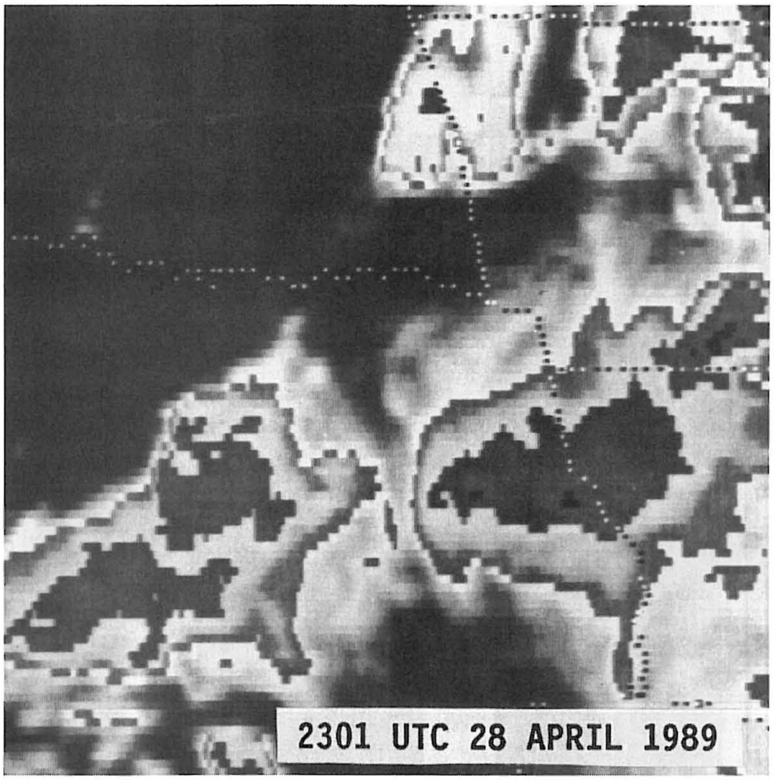

Fig. 5. GOES enhanced IR at 2301 UTC, 28 April 1989.

Fig. 6. NWS radar composites at 2135 UTC, 28 April 1989 and 0035 UTC, 29 April 1989.

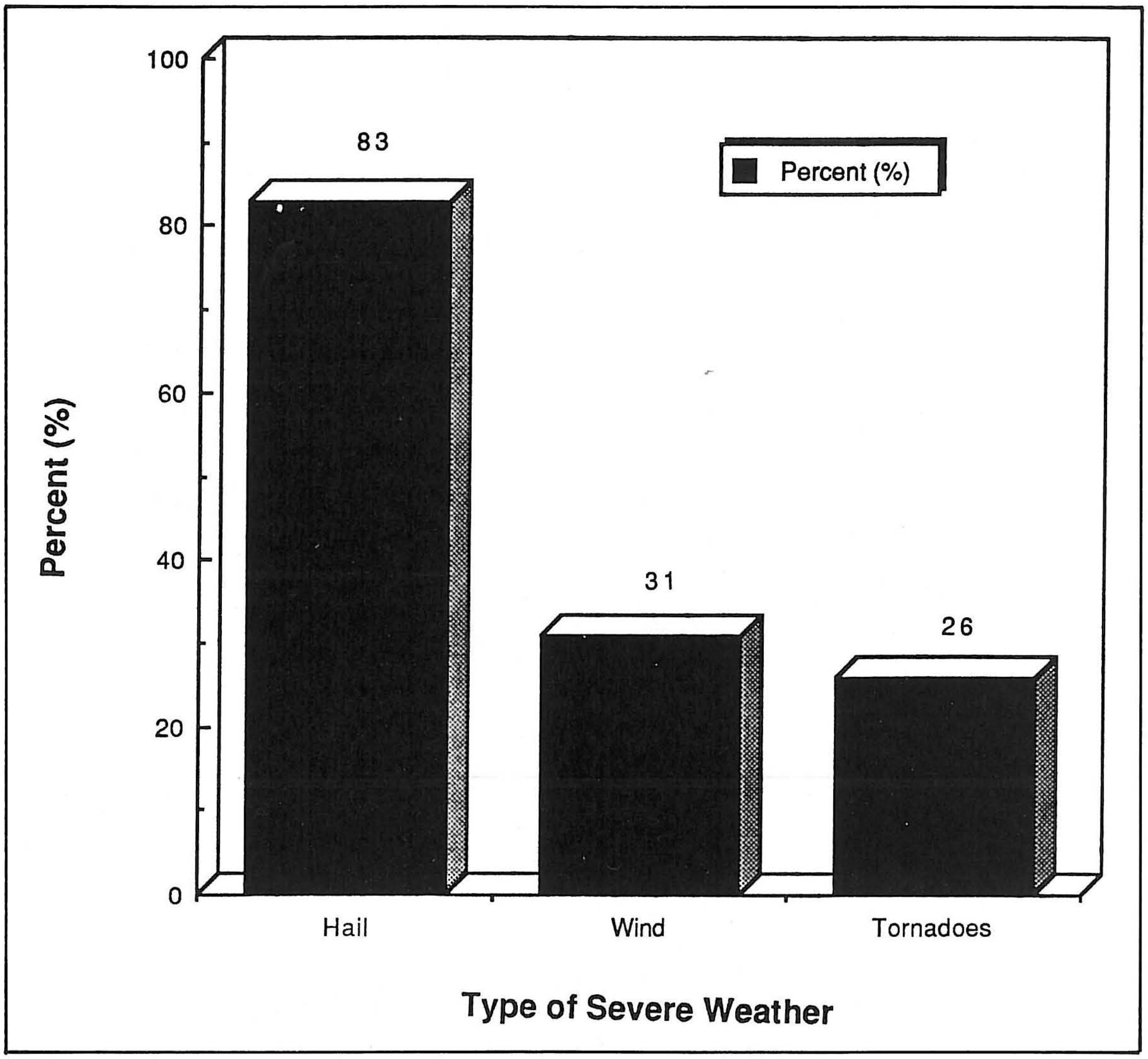

Fig. 7. Distribution of severe weather types observed for cases of the observed WV signature, expressed as percent of the total number of severe storms. Hail is ≥ ¾″ diameter. Wind refers to straight-line winds ≥ 50 kt and/or thunderstorm wind damage.

kt (50 m sec^{-1}) were present at 250 mb on the upstream side of the convection (Fig. 10). Conceptual models of airflow in the environment of supercell thunderstorms (e.g., Lemon and Doswell, 1979) suggest that mid to high-level sinking on the upwind side of the anvil may initiate the "rear-flank downdraft" (Fig. 11). Three-dimensional numerical studies of thunderstorm structure (i.e., Schlesinger, 1986) also suggest the presence of subsidence on the upstream side of the anvil, particularly in strongly-sheared environments.

6. Summary and concluding remarks

A dark zone observed in GOES water vapor imagery on the upstream edge of strong convective storms identifies that particular convective system as likely to contain severe weather. Of a sample of 147 cases, 82% were severe. The severe weather observed was predominantly large hail (83%), although tornadoes occurred in one-fourth (26%) of the cases. The feature was usually first observed near the time of the initial reports of severe weather, but lack of timeliness in satellite data transmission reduces its utility as a warning indicator.

Our ability to monitor the environment of severe thunderstorms is expected to improve with the higher resolution and greater frequency of WV imagery from GOES I-M satellites in the 1990's. In the meantime, the hourly GOES WV imagery may serve as another analytical tool in the detection of severe storm activity.

Author

Gary Ellrod has been a meteorologist with the Satellite Applications Laboratory of NESDIS since 1982. His primary responsibility is in applications of satellite data to aviation forecasting, and is also interested in severe thunderstorms and tropical storms. He received a B. S. in meteorology from Penn State in 1965 and the M. S. from the University of Wisconsin in 1972.

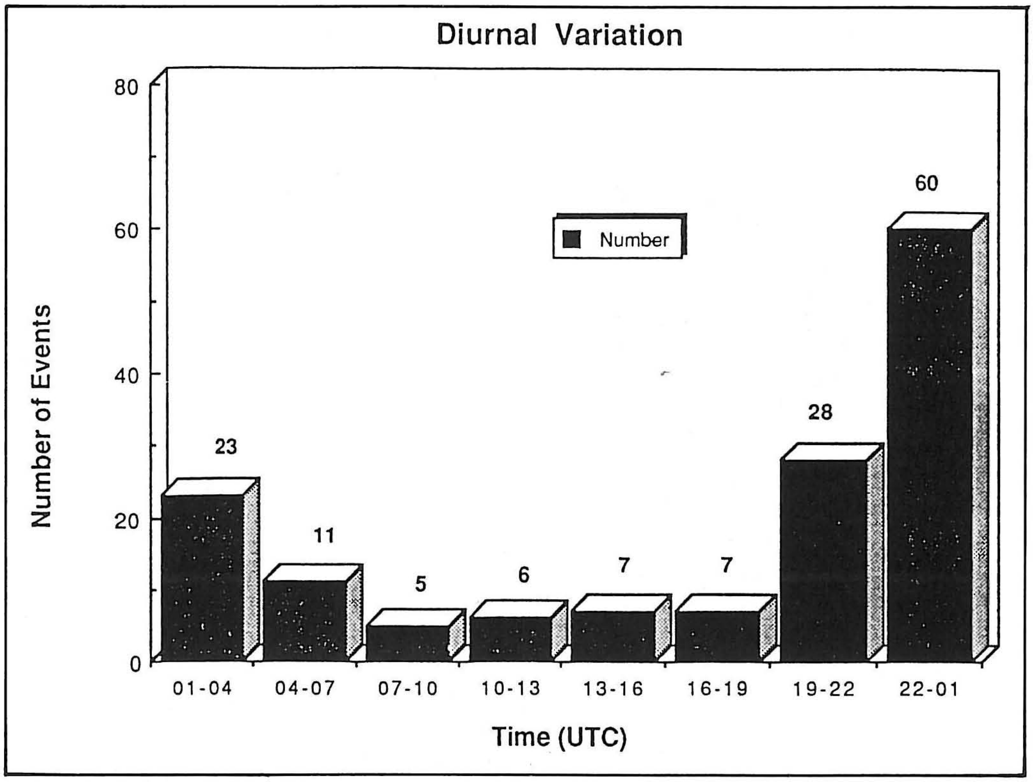

Fig. 8. Diurnal variation of the *initial* observation of the WV signature for combined severe and non-severe cases.

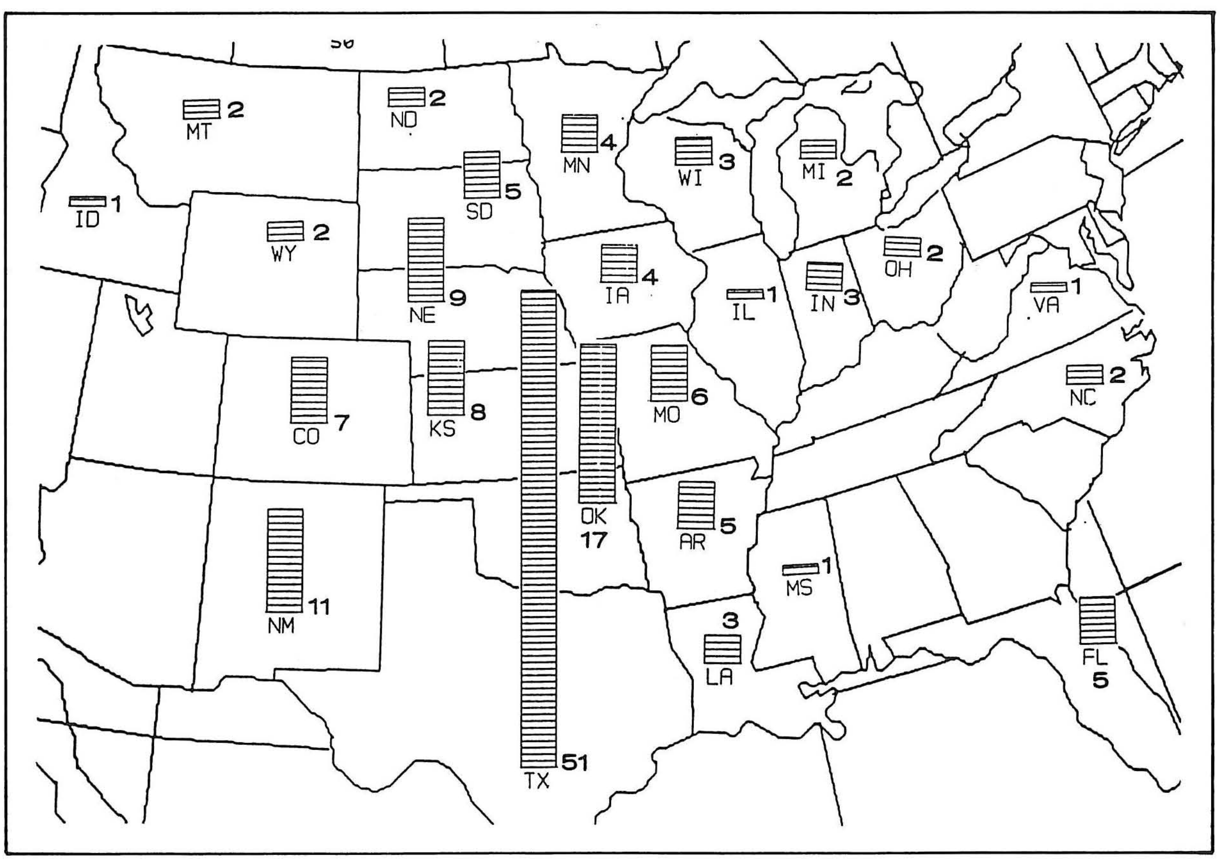

Fig. 9. Geographical distribution of the observed WV feature expressed as the number of events per state.

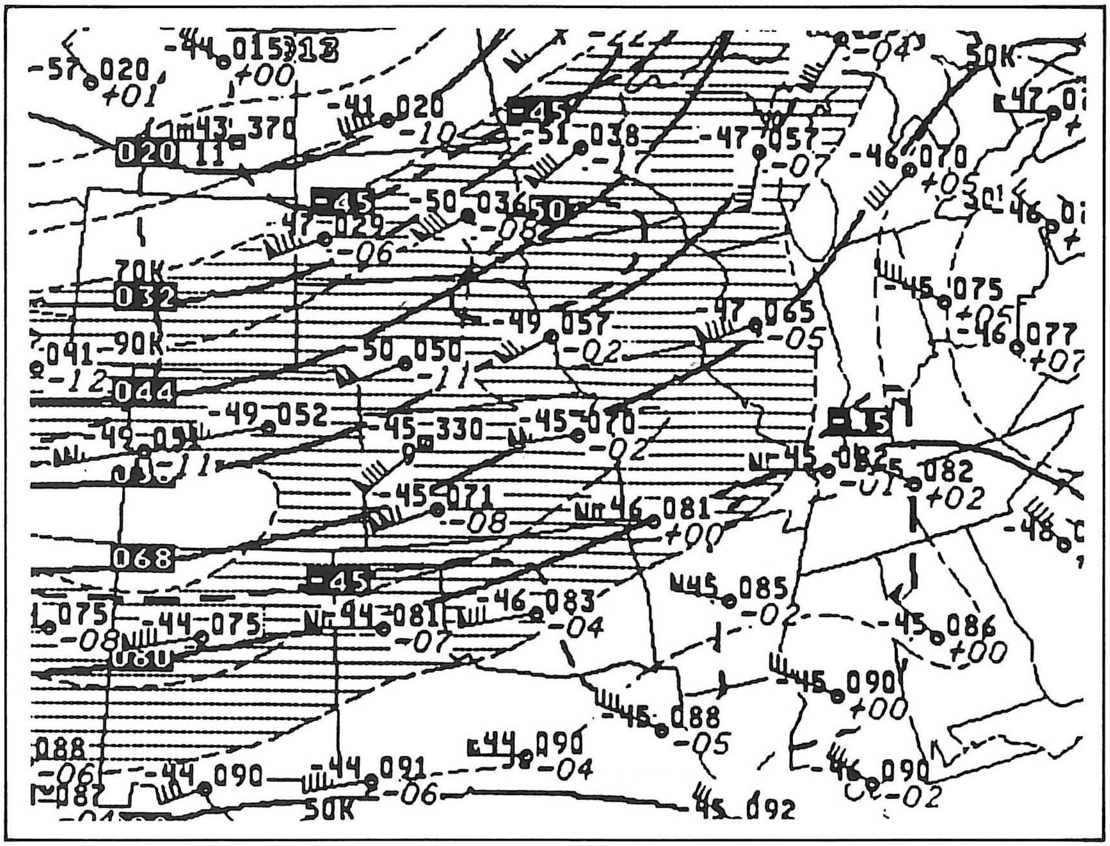

Fig. 10. NMC 250mb analysis for 1200 UTC, 25 May 1989.

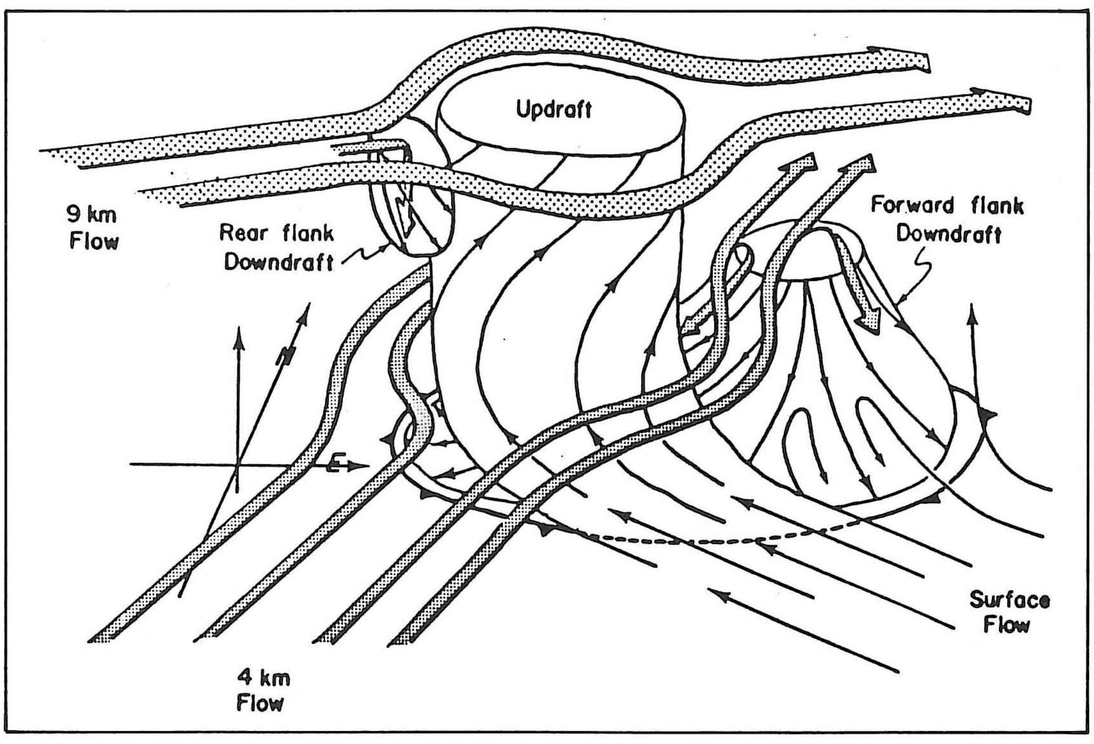

Fig. 11. Three-dimensional model of airflow during the early stages of a supercell thunderstorm (from Lemon and Doswell, 1979).

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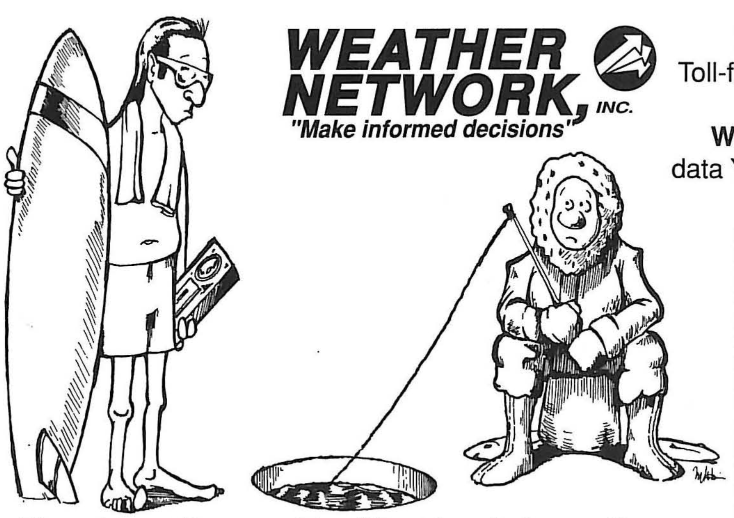

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