THE RELATIONSHIP BETWEEN WATER VAPOR PLUMES AND EXTREME RAINFALL EVENTS DURING THE SUMMER SEASON

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Abstract

GOES 6.7 μm Water Vapor (WV) images were used to study the relationships between the WV plumes and the upper and lower level circulation patterns related to extreme heavy rainfall (125 mm or more in a 24-hour period) over the United States.

The study covers three summer periods (May through October, 1989–1991). One hundred and twenty nine cases were selected; 87% were associated with a well defined WV plume. These WV plumes originated essentially in tropical ocean areas, such as the Pacific Ocean, Gulf of Mexico or the Caribbean Sea. As the plumes move northeastward into the United States, they are often aligned with low-level equivalent potential temperature ridge axes and upper-level forcing mechanisms (i.e., jet streams, short waves, and vortices). Occasionally these plumes from the tropics interact with WV plumes originating from the polar regions or from the subtropics. These interactions often result in MCSs that produce flash floods.

WV plumes associated with extreme heavy rainfall, were classified into four categories. The categories were a function of the plume and jet stream structures.

The present study shows that the WV plume appears to be one connecting link between the global (climate) scale and the mesoscale/storm scale.

1. Introduction

GOES (Geostationary Operational Environmental Satellite) 6.7 μm Water Vapor (WV) imagery is an excellent tool for locating large scale features responsible for Mesoscale Convective Systems (MCSs) that produce extreme heavy rainfall (EHR) over the United States (U.S.) (Scofield and Robinson 1990, 1992). A discussion of Mesoscale Convective Complexes (MCCs) and other satellite convective cloud categories associated with heavy rainfall is presented by Maddox (1980) and Scofield (1985), respectively.

WV Plumes (WVPs) are observed in the animated WV imagery as northward surges of well defined boundaries of moisture from the Intertropical Convergence Zone (ITCZ). Northward moving plumes often become aligned with equivalent potential temperature (theta-e) ridge axes at low and mid-levels. These plumes and theta-e ridge axes have been shown to be a precursor for flash flood producing thunderstorms (Scofield and Robinson 1990). The authors developed a conceptual model that locates the flash flood and severe weather producing MCSs within the proximity of the WVP and the theta-e pattern at low and mid-levels.

Another key factor for generation and maintenance of conditions favorable for intense convective storms is the difluent configuration induced by the presence of polar and subtropical jet streams ahead of an advancing trough (Whitney 1976). Upper level divergence associated with the exit region of the southern jet and the entrance region of the northern jet creates a configuration of indirect and direct transverse vertical circulations in the exit and entrance regions of the two jets, respectively. This enhanced upper level divergence between the two jets results in intense vertical motions that favor the development of convective clouds and precipitation (Uccellini and Johnson 1979). In addition, the role of upper tropospheric jet streaks and low-level jet maxima in destabilizing the atmosphere and contributing to low-level heat and moisture transports has been widely documented (Uccellini and Johnson 1979; Kocin et al. 1986); these jet phenomena generate and maintain conditions favorable for intense convective storms. The advection of cool, dry air within the middle troposphere and the rapid northward transport of heat and moisture by the lower-level jet create a differential transport that increases low-level theta-e and the resulting convective instability.

The purpose of this study is to document the location of MCSs that produce EHR relative to the position of the: (1) WVP, (2) 300-mb jet streaks, and (3) low-level theta-e ridge axes. Another reason for this investigation is to test the conceptual model developed by Scofield and Robinson (1990, 1992) that heavy rainfall producing thunderstorms develop in the proximity of the tropical WVP and the low to mid-level (850 to 700-mb) theta-e ridge axis. It should be emphasized that there are also EHR events in the WV imagery that are not directly associated with tropical WVPs (Thiao et al. 1993). This study is part of a project to understand how each meteorological scale interacts and prepares the environment for convection that leads to flash floods. The scales involved range from the global to synoptic scale down to the mesoscale to storm scale and of course the feedback from the smaller scales to the larger scales.

In this paper, the 6.7 μm WV imagery, the 300-mb analyses and the theta-e analyses at 850 to 700 mb have been used to describe the global and synoptic scale features associated with the EHR events for three summer periods.

2. Selection of Extreme Heavy Rainfall Events

The National Weather Service River Forecast Centers' daily 24-hour rainfall charts for the period 1989 through 1991 were examined to identify and select the EHR events. These 24-hour rainfall charts are valid at 1200 GMT and contain data from the regular National Weather Service's rain gauge network as well as other data from cooperative observers.

An EHR event is defined as 125 mm (about 5 inches) of rainfall or more reported in a given state during a 24-hour period. The maximum 24-hour rainfall amount reported during that 3-year period was 390 mm (15.6 inches) over northwestern Florida on 9 June 1989. This EHR event resulted from heavy rain producing MCSs that developed over eastern Texas and moved slowly eastward resulting in flash floods over Mississippi, Alabama, and Florida between 8 and 9 June.

Most of the EHR events occurred between May and October. A mean monthly distribution of occurrence, displayed in Fig. 1, shows that the EHR events are more frequent in May–June with a maximum of 11.7 occurrences in June. Thus, for the purpose of this paper, the study will focus on EHR events that took place between May and October of 1989–1991.

A total of 181 events were selected (remember that at least 125 mm of rain had to occur to be considered as an event). The geographical distribution of the events in this study (Fig. 2) shows that the EHR events develop more frequently in the southern U.S. Most of the events (39%) occurred in Texas, Louisiana and Mississippi while no event was reported over the western U.S. However, tropical WVP events are associated with the southwest monsoon and are a major cause of the flash floods in the western U.S. during the summer season. It should be emphasized that a typical flash flood event in the western region is less than 125 mm of rain. Due to the soil type and structure and the presence of steeply sloped terrain, generally only 25 to 50 mm is needed to produce a flash flood in the western region. Of course the lack of validating rain gauge observations in the western region is also a major problem and could account for some of the rather low observed rainfall amounts that accompany many of the flash floods.

Note that "different" MCSs may produce EHR in "different" states during a 24-hour period. In such cases, the EHR reported in those states is considered as an individual event and is referred to as an Event Day. Thus, in this study, a total of 129 Event Days will be considered.

3. Global and Synoptic Scale Aspects of the Extreme Heavy Rainfall

a. Water vapor imagery characteristics

Characteristics of the Water Vapor (WV) imagery have been detailed by Weldon and Holmes (1991) and others, therefore, they will only be described briefly in this paper. The 6.7 μm WV channel measures and integrates the radiations emitted by WV between 700 and 200 mb, with a peak response in the middle to upper troposphere between 500 and 300 mb. The resultant image is representative of the middle-level moisture and cloudiness (see Figs. 3, 4, and 5). The common convention is that lighter (whiter) gray shades indicate lower energy measurements from areas of large amounts of moisture and give an indication that middle or high clouds are being detected or a deep layer of moist air is present above 500 mb. Very dark gray shades indicate dry areas where no clouds and little WV are present in the middle and upper troposphere. Medium gray shades represent atmospheric moisture somewhere between 700 and 200 mb; the precise location cannot be determined from the WV image, itself.

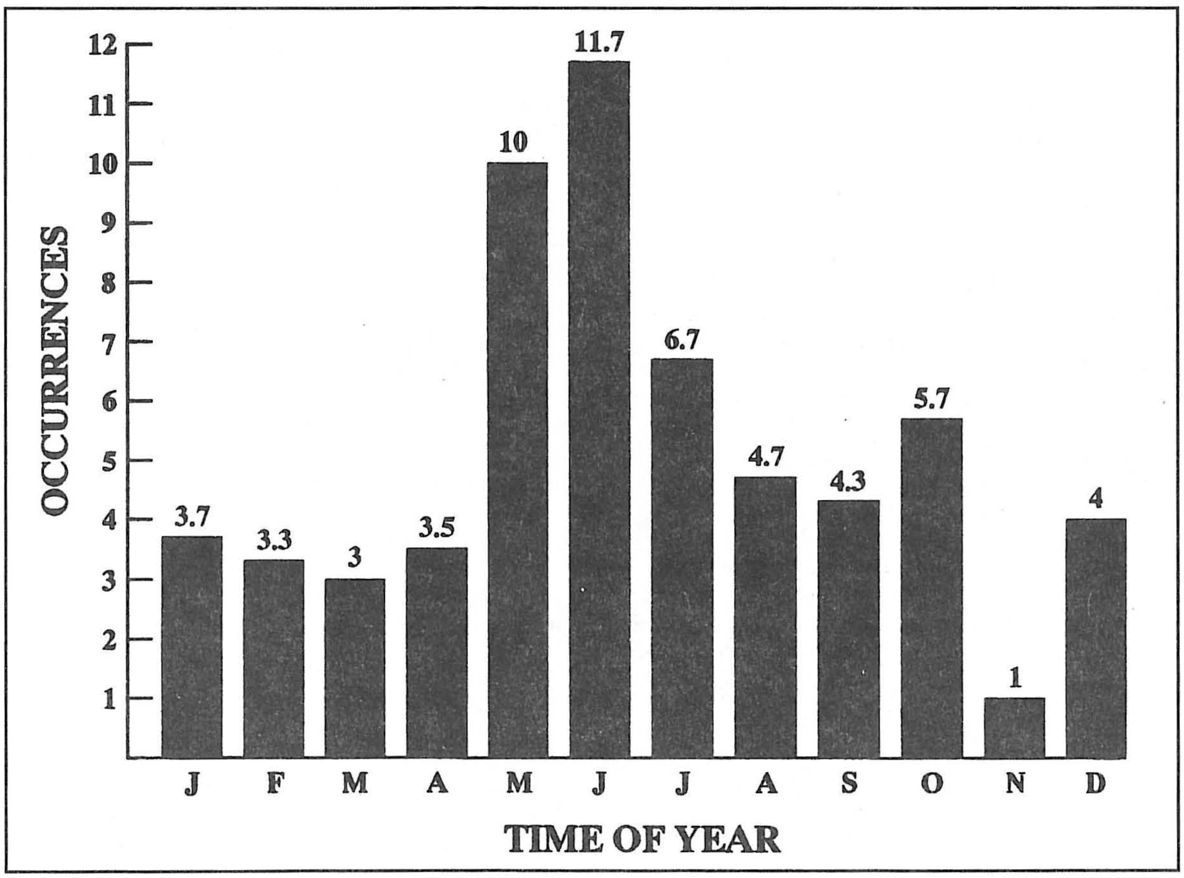

Fig. 1. Mean monthly distribution of extreme heavy rainfall event occurrences.

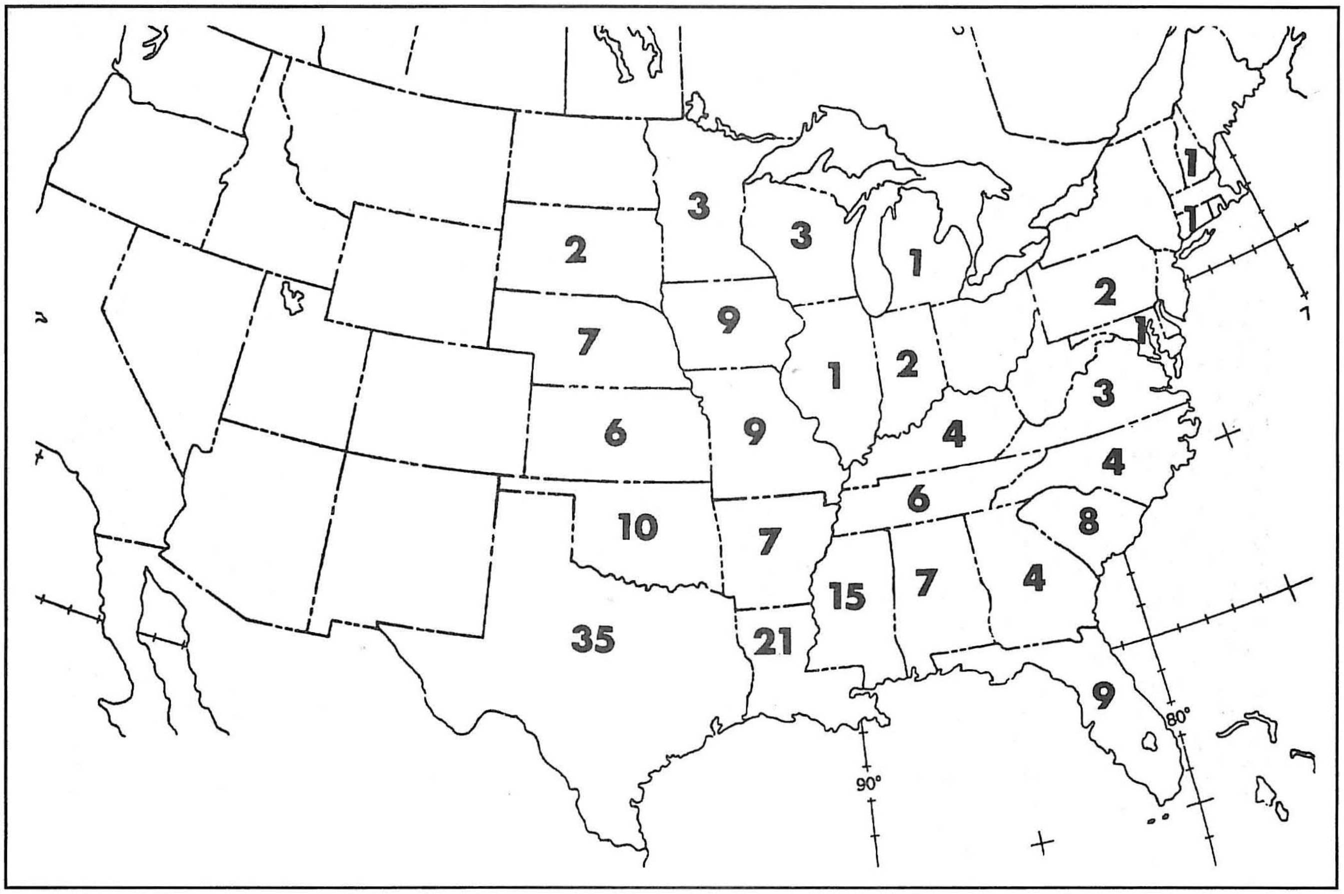

Fig. 2. Geographical distribution of extreme heavy rainfall events.

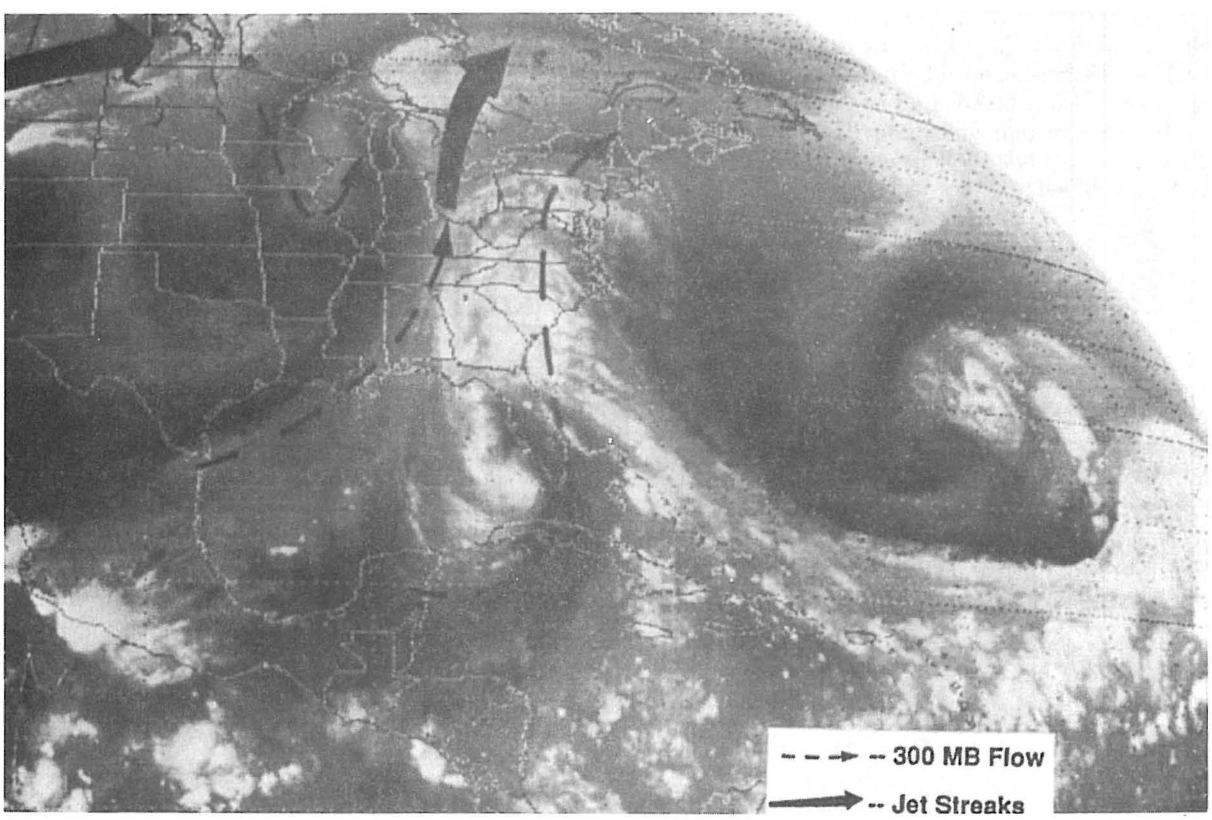

Fig. 3. Example of water vapor plumes in the Eastern and Southern Regions with 300-mb flow superimposed, 1701 GMT 10 October 1990; flash flooding occurred over S. Carolina and Georgia.

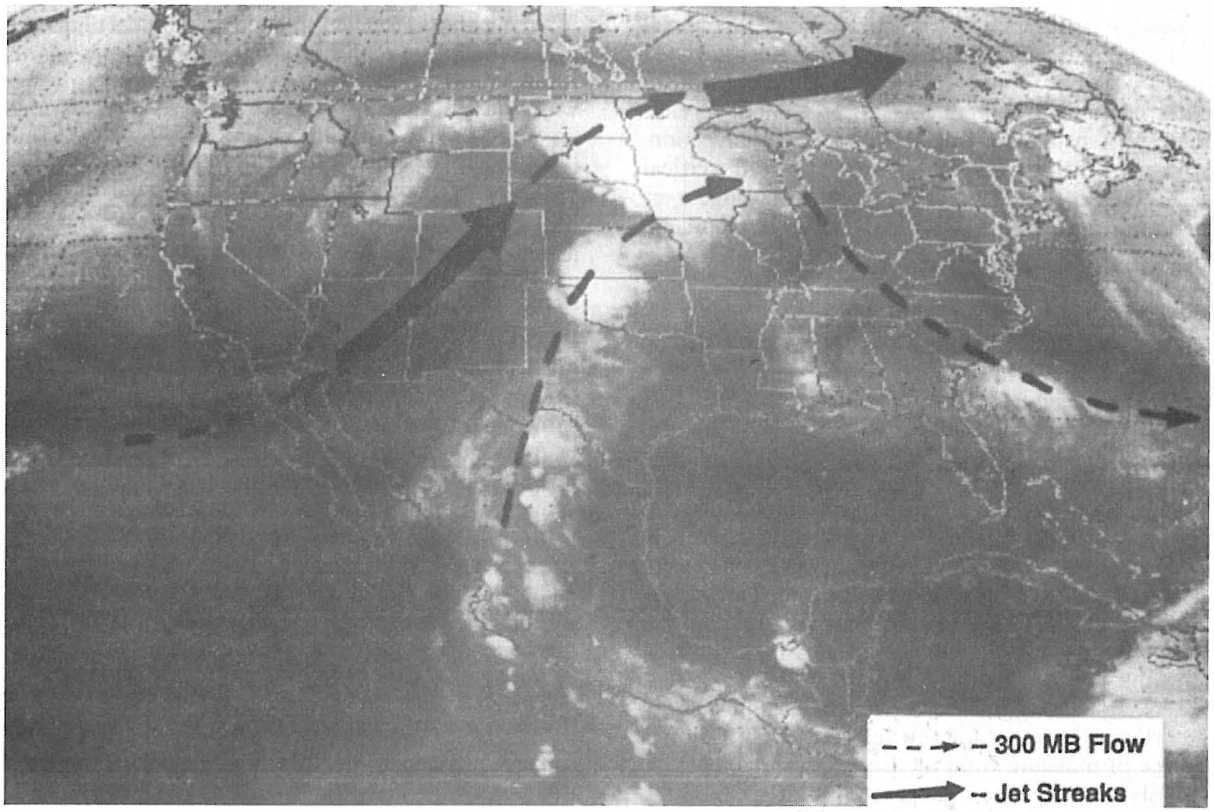

Fig. 4. Example of water vapor plume in the Central Region with 300-mb flow superimposed, 0601 GMT 16 June 1990; flash flooding occurred over Minnesota, Iowa and the Dakotas.

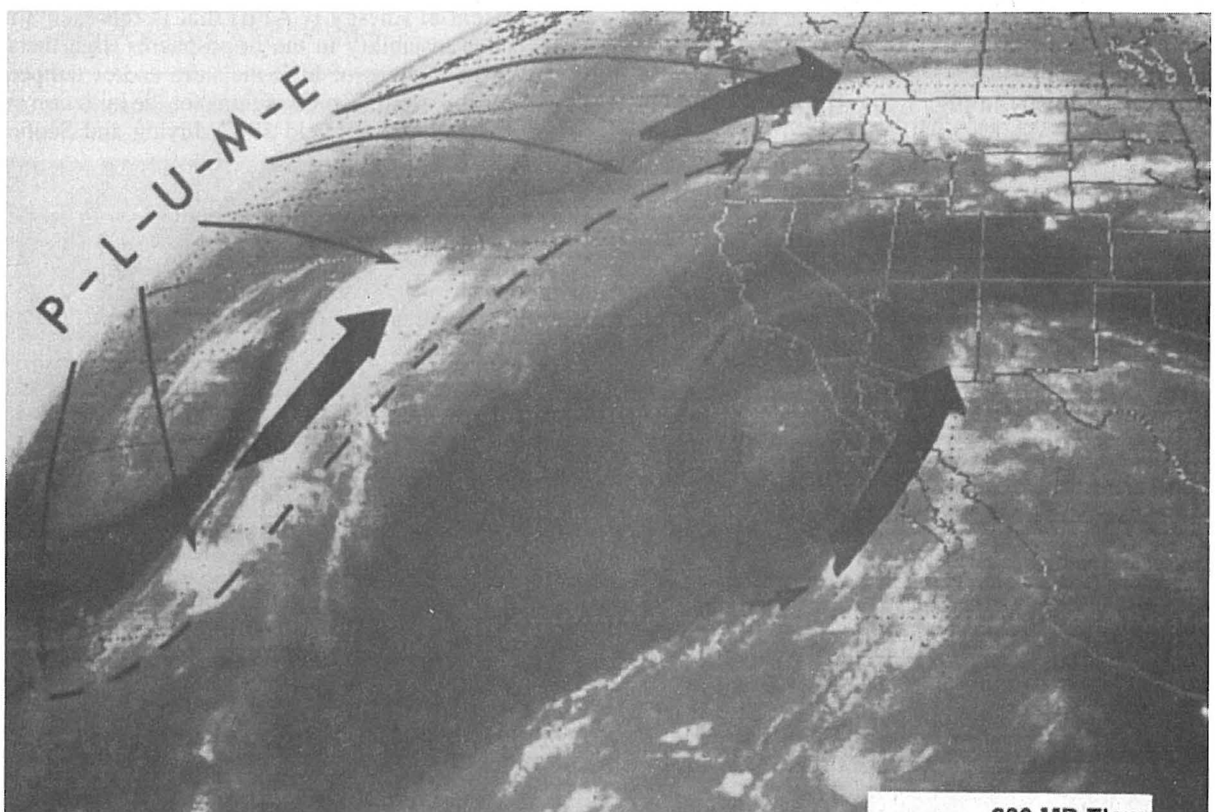

Fig. 5. Example of water vapor plume in the Western Region with 300-mb flow superimposed, 0701 GMT 25 November 1990; flash flooding occurred over Washington.

When viewed in time lapse, WV imagery shows the spatial and temporal continuity of the vertical motion field associated with mid-level systems (Scofield and Funk 1986; Funk 1990). However, use caution in making this interpretation because some of these WV patterns could be due to pure advection. Mid-level features that are associated with upward vertical motion can become coupled with low-level theta-e ridge axes and create favorable conditions for thunderstorm development.

b. Water vapor plumes

In this study, GOES 6.7 μm WV imagery described in the above section were used to characterize the WVPs related to the EHR events.

1) Definition

The WVP can be defined as movements or surges of well shaped global scale bands of mid to upper-level moisture. Generally, WVPs are associated with large scale circulations at mid to upper-levels, and take on a plume-like appearance in animated WV images (Scofield 1991, 1990). WVPs can easily be distinguished from other general areas of moisture as they are often associated with deepening troughs and building ridges. Northward moving WVPs are often associated with southward moving "digging" jets streams and troughs in the westerlies.

As time sequential images have been used in this study, a WVP was considered present for any selected Event Day if a stream or surge of moisture from the tropics seemed to move towards the EHR areas almost in parallel with the 300-mb flow. The WVP usually originates from the ITCZ and extends northward to the U.S. Examples of WVPs are shown in Figs. 3, 4, and 5; 300-mb flow is also indicated on the imagery. These are referred to as tropical WVPs or simply tropical plumes. In Fig. 3, flash floods occurred over South Carolina and Georgia, while in Fig. 4, flash floods were reported in Iowa, Minnesota and the Dakotas and finally in Fig. 5, floods took place in the state of Washington.

Adang and Gall (1989) related the tropical plume to the onset of the southwest monsoon during the summer season and the resulting flash flood producing thunderstorms over the southwestern U.S. An example of a plume associated with the southwest monsoon is depicted in Fig. 6 (at "S–W"). Another plume is observed in the eastern region (at "E–R"). Within the next 12 hours, flash floods occurred with these plumes over New Mexico and Arizona and from Georgia to Virginia. McGuirk and Ulsh (1990), have also investigated the evolution of tropical WVPs.

The WVP can also originate in the subtropics and middle latitudes in which case they are referred to as subtropical or polar plumes. These plumes are normally associated with the subtropical and polar jet streams, respectively. A schematic showing the configuration and relationship of a typical subtropical/polar plume and the tropical plume appears in Fig. 7a. A polar (P–P′) plume approaching a tropical (T–R) plume is shown in Fig. 7b. In this case, flash floods occurred with the large MCS over Nebraska where deep-layer moisture was present. Severe weather was noted with the MCSs over the Texas and Oklahoma Panhandles. However, no floods were reported. The occurrence of severe weather and lack of EHR was partially due to the close proximity of the dry air (dark area in Fig. 7b) to the west of the MCSs.

2) Relationship to equivalent potential temperature

The equivalent potential temperature (theta-e) is a conservative meteorological parameter that combines temperature and moisture into a single quantity whose vertical distribution is related to convective instability. As a result, theta-e gives an indication of the vertical distribution of the Convective Available Potential Energy (CAPE) that is representative of the convective instability in the troposphere. High theta-e values correspond to areas of high moisture and/or temperature and therefore represent favored regions for the initiation of thunderstorms (Jiang and Scofield 1987; Juying and Scofield 1989).

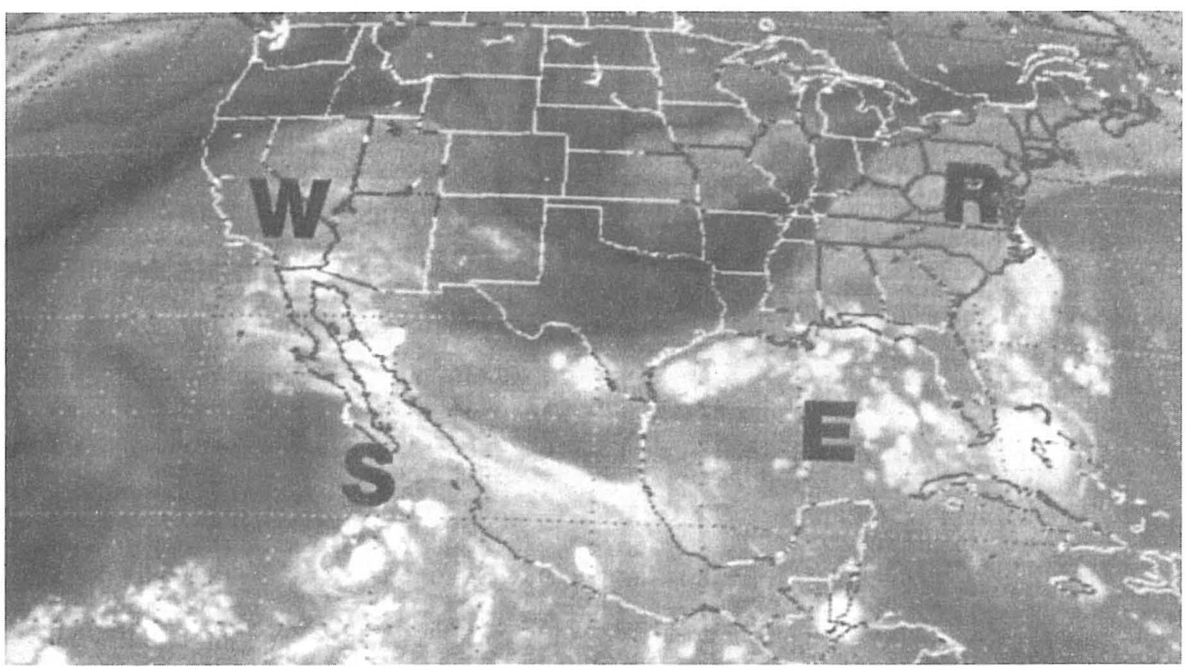

Fig. 6. Examples of 2 water vapor plumes: (1) associated with the Southwest Monsoon and (2) located in the Eastern Region, 1900 GMT 13 July 1990.

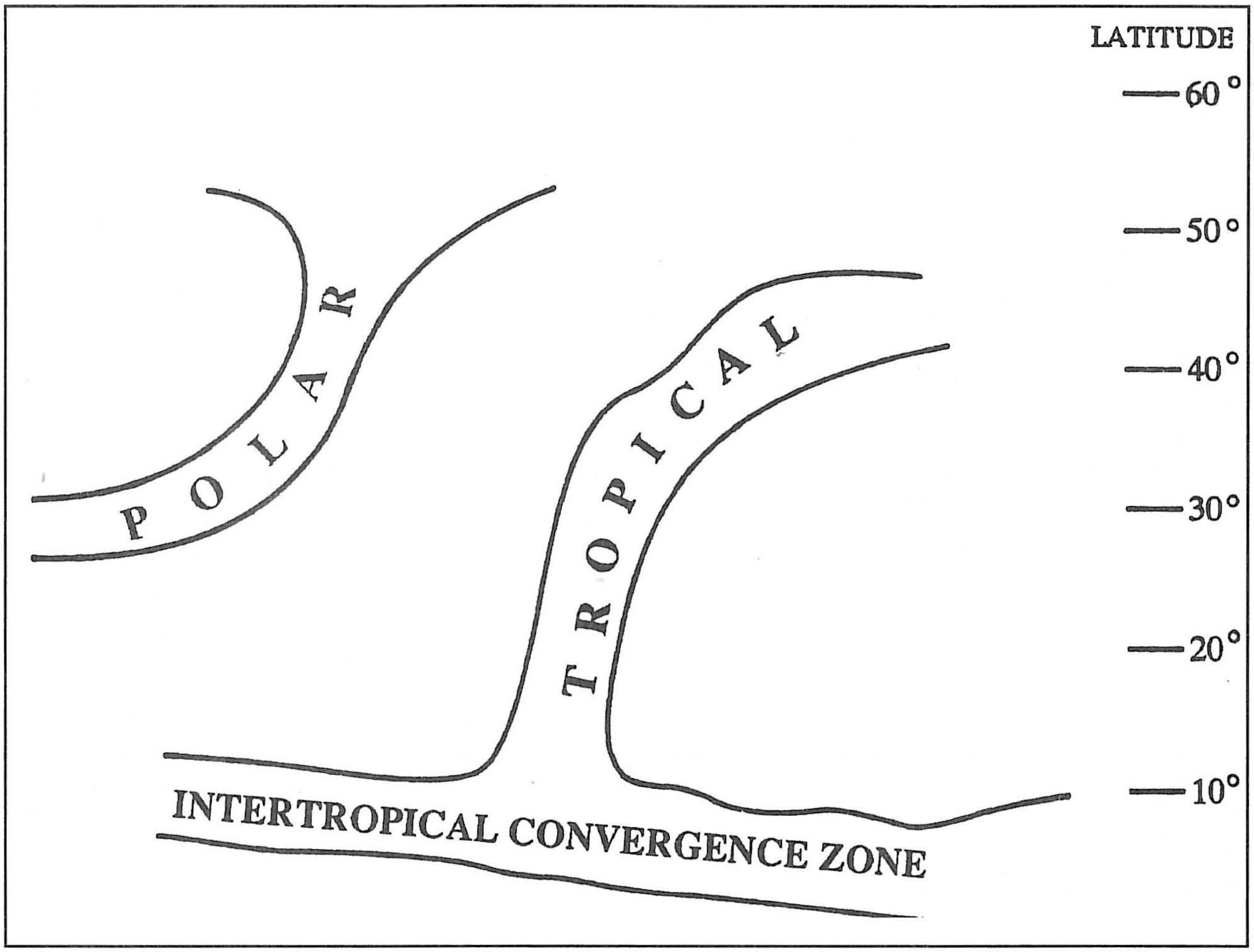

Fig. 7a. A conceptual model of the polar and tropical water vapor plumes.

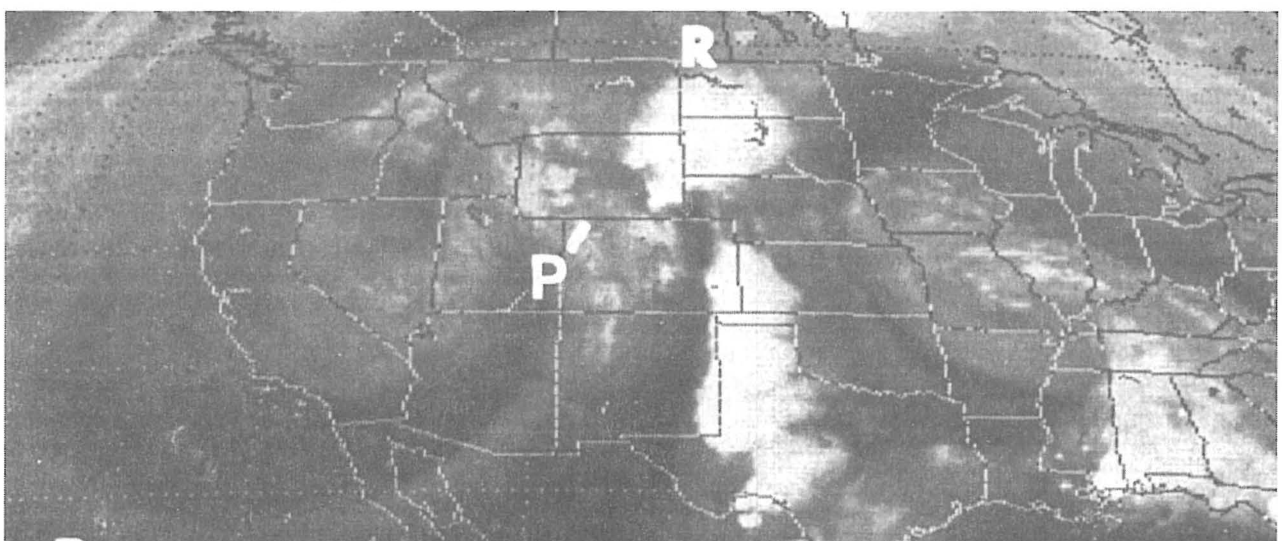

Fig. 7b. An example of a double water vapor plume, 0101 GMT 11 May 1991.

An analysis of theta-e at different levels often shows that mean theta-e ridge axes through a layer, for example surface to 700 mb, is indicative of a deeper layer of moist, warm air available to a convective system. Regions of maximum instability are often related to areas of maximum low-level theta-e (Funk 1989, 1991).

Scofield and Robinson (1990, 1992) developed a conceptual model of the tropical plume and theta-e connection (see Fig. 8). The conceptual model is dependent on the fact that the WVP usually occurs on the back side (western portion) of a subtropical high. Over the USA, the western portion of the subtropical high not only locates the WVP but also the return of low-level moist, unstable air from the subtropics (tropical Pacific, Gulf of Mexico, and tropical Atlantic). Therefore, the WVP and low-level moist, unstable air are often collocated. The schematic (Fig. 8) shows a tropical plume (depicted by solid lines) consists of mid to upper-level moisture that often extends northward from the subtropics and tropics. A theta-e ridge axis at 850 to 700 mb is depicted by dashed lines and the tongue of deep layer moisture is shaded. Notice in this conceptual model that typically the low-level theta-e ridge axis and tongue of deep layer moisture are located in the eastern portion of the plume. The water vapor plume, theta-e, and deep moisture relationships are not too surprising since the plume is often located on the backside of an upper-level ridge. In addition, the eastern portion is a favored location due to its proximity (as compared to the west side) to the low-level moisture from the Gulf of Mexico or Atlantic Ocean. The plume environment makes it rain more efficiently since dry air isn't being pulled into the storm. Cloud seeding from cirrus may also enhance the rainfall. Jet streaks, short waves, and other forcing mechanisms with their associated upward vertical motion fields are often observed near the back edge (western portion) of the tropical WVP. Sometimes vortices are embedded within the plume itself and produce enough lift that can result in flash flood producing MCSs. The northern part of the tropical plume is often where the low-level forcing (theta-e ridge axes and warm air advection) becomes coupled with upper-level forcing mechanisms (jet streaks) creating favorable conditions for development of MCSs. Of course the theta-e ridge axis or secondary theta-e ridge axes (Juying and Scofield 1989) can also be located just to the west of the WVP or collocated with the plume.

When the theta-e ridge axis is located in the western portion or just to the west of the plume, MCSs will develop within this drier air (area 1). These MCSs tend to produce severe weather (tornadoes, hail and strong winds). When the theta-e ridge axis is located in the eastern portion of the plume, as described by the model, MCSs will develop within the moist tropical plume environment (area 3) where deep layer moisture is often present. In this case, MCSs will tend to produce heavy rainfall and flash floods. Finally, when the theta-e ridge axis is collocated with the plume, MCSs may develop in the western portion of the plume near the dry air/moist plume interface (area 2). In this situation, both severe weather and flash floods can occur. Additional features in the WV imagery that are related to severe thunderstorms are presented by Ellrod (1990).

Figure 9a shows an example of a "connection" between a tropical plume and theta-e for an Event Day, 6 September 1990, over eastern Minnesota and western Wisconsin. A well defined tropical plume located at "P-L-U-M-E" in the WV image extends northward from the ITCZ. The 700-mb theta-e analysis at 0000 GMT (Fig. 9b) shows a sharp ridge axis (dashed line) oriented from northern Mexico into Nebraska and eastward into the Minnesota-Wisconsin area. This axis corresponds quite closely to the location of the tropical plume in the WV imagery (Fig. 9a) and represents a region of high convective potential juxtaposed with an area of less favorable convective conditions across western Texas and Oklahoma where theta-e values were lower. Another relative theta-e maximum was located over east Texas, Louisiana, Arkansas and Missouri. A MCS developed within the moist air and theta-e ridge axis in the northern part of the plume over Minnesota; this MCS moved eastward to Wisconsin. In addition to the presence of the plume and theta-e ridge axis, the surface and upper air composite (Fig. 9c) shows that a stationary front and relatively strong low-level southwesterly winds are present over Minnesota; a jet streak is located just to the north. The location of the MCS (from Fig. 9a) is depicted in Fig. 9c. EHR and flash flooding were reported in this part of Minnesota.

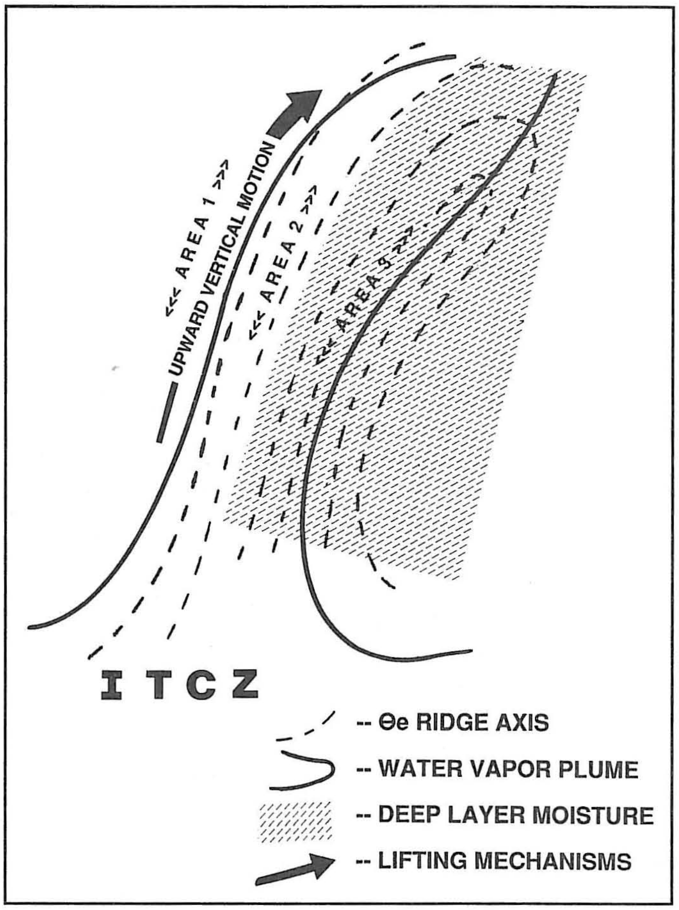

Fig. 8. A conceptual model of the tropical water vapor plume and theta-e connection.

c. 300-mb wind analyses

Every 12 hours, 300-mb wind analyses from the NWS National Meteorological Center (NMC) were used to study the interactions between the positions of the upper level jet maxima and the WVP. The procedure consisted of examining closely the upper level features as shown on the WV imagery and the 300-mb wind analyses. The jet streak positions were recorded on the WV imagery. This operation was repeated for the 129 Event Days and it was clear that for most of the cases, there was a WVP associated with a jet stream. The interactions between the WVP and the jet stream structure can be separated into two categories.

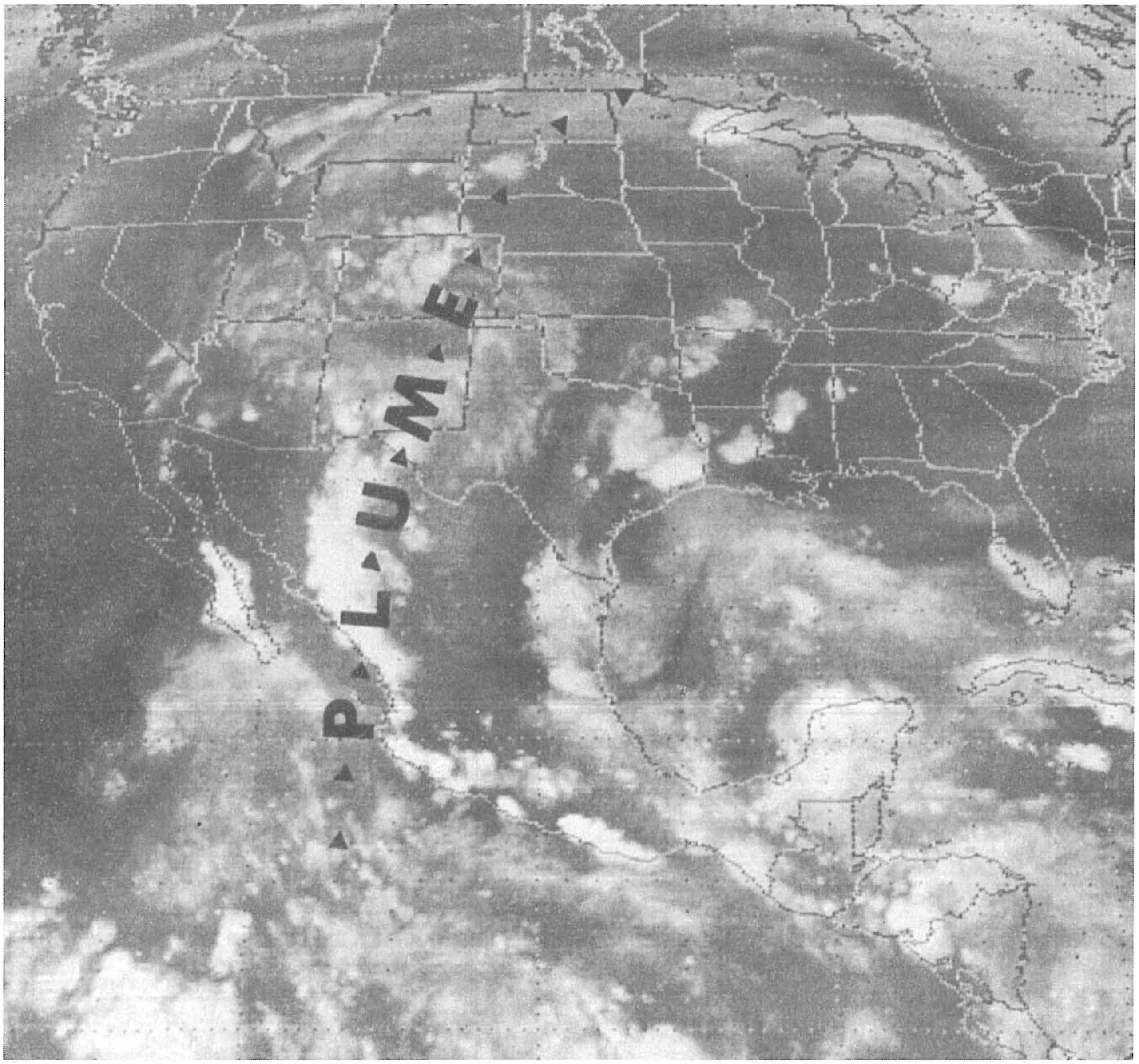

Fig. 9a. 6.7 μm water vapor imagery for 0000 GMT 6 September 1990.

1) WV plume associated with a dual jet streak

An example of a WVP associated with a double jet streak structure took place on 25 October 1991. This was an Event Day for Oklahoma and Iowa. It is displayed in Figs. 10a–10f. The 300-mb analysis (Fig. 10b) shows a deep meridional trough located over the western U.S. with two jet streaks. One is located over the southwestern U.S. (''J–S'' in Fig. 10a) at the base of the trough with a maximum wind of 115 kts. Another jet streak (maximum wind 95 kts) is observed on the forward side of the trough extending from western Iowa towards eastern Canada. An extreme 300-mb difluent pattern is located over southeast Oklahoma.

The WV imagery on 25 October 1991, at 0000 GMT (Fig. 10a) exhibits a tropical plume (T–P′) originating from the ITCZ in the Pacific Ocean moving northeastward and nearly parallel to the subtropical jet stream axis, especially from the southwest U.S. into the southern and central Plains. This type of configuration where the jet stream axis and plume are quasi-parallel is often associated with slow moving and flash flood producing MCSs, especially when other conditions are favorable. Weldon and Holmes (1991) described this ''parallel'' configuration as well as those cases where the jet stream axis is more nearly normal to the plume. In these more ''normal'' configurations, MCSs tend to move faster. It has also been noted that slow moving plumes and MCSs are associated with mid-level isotherms that are quasi-parallel to the mid-level height contours. Faster moving plumes and MCSs are associated with mid-level isotherms that are nearly normal to the contours. In this case, the low-level theta-e ridge axes (dashed in Fig. 10d) was also closely aligned to the eastern portion of the WVP.

A feature often observed with slow moving and back-building MCSs was thickness difluence (Jiang Shi and Scofield 1987; Juying and Scofield 1989). As discussed by Funk (1991), thickness difluence implies that a pattern of low-level conver-

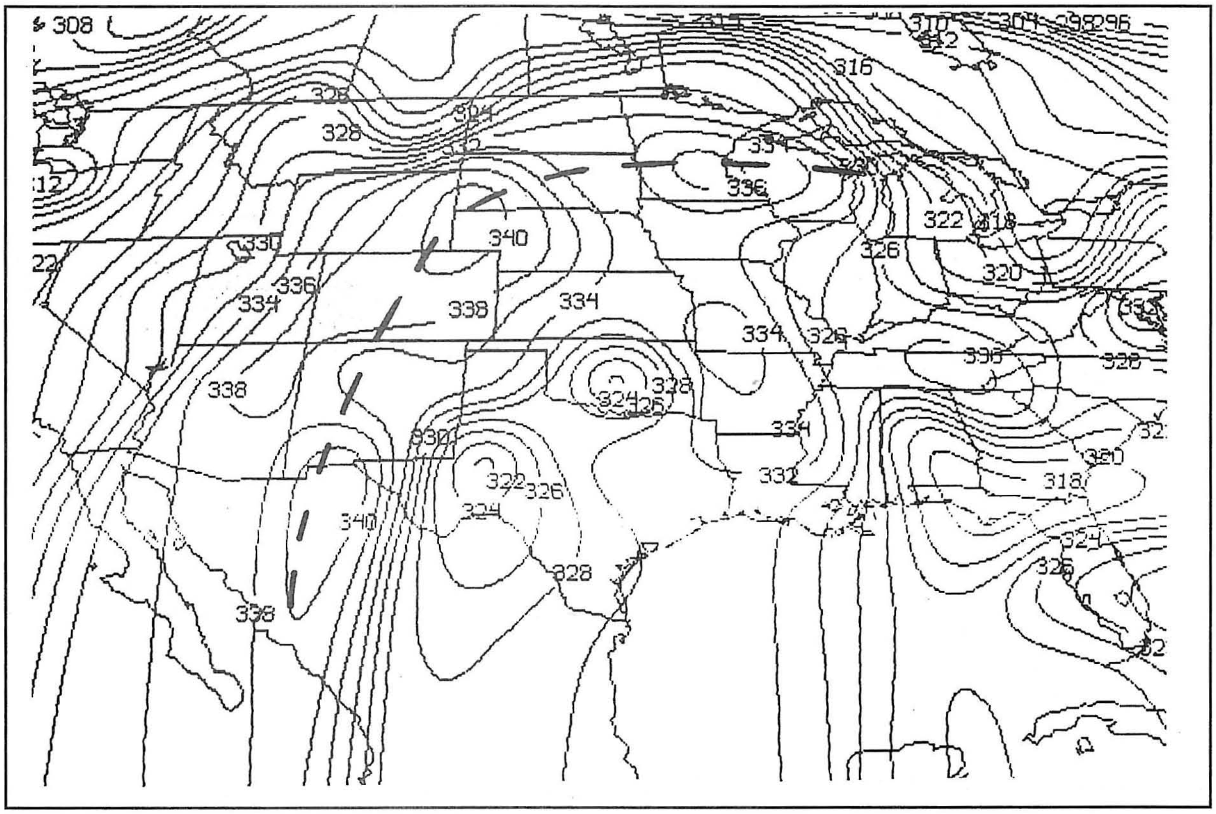

Fig. 9b. 700-mb theta-e analysis (°K) for 0000 GMT 6 September 1990.

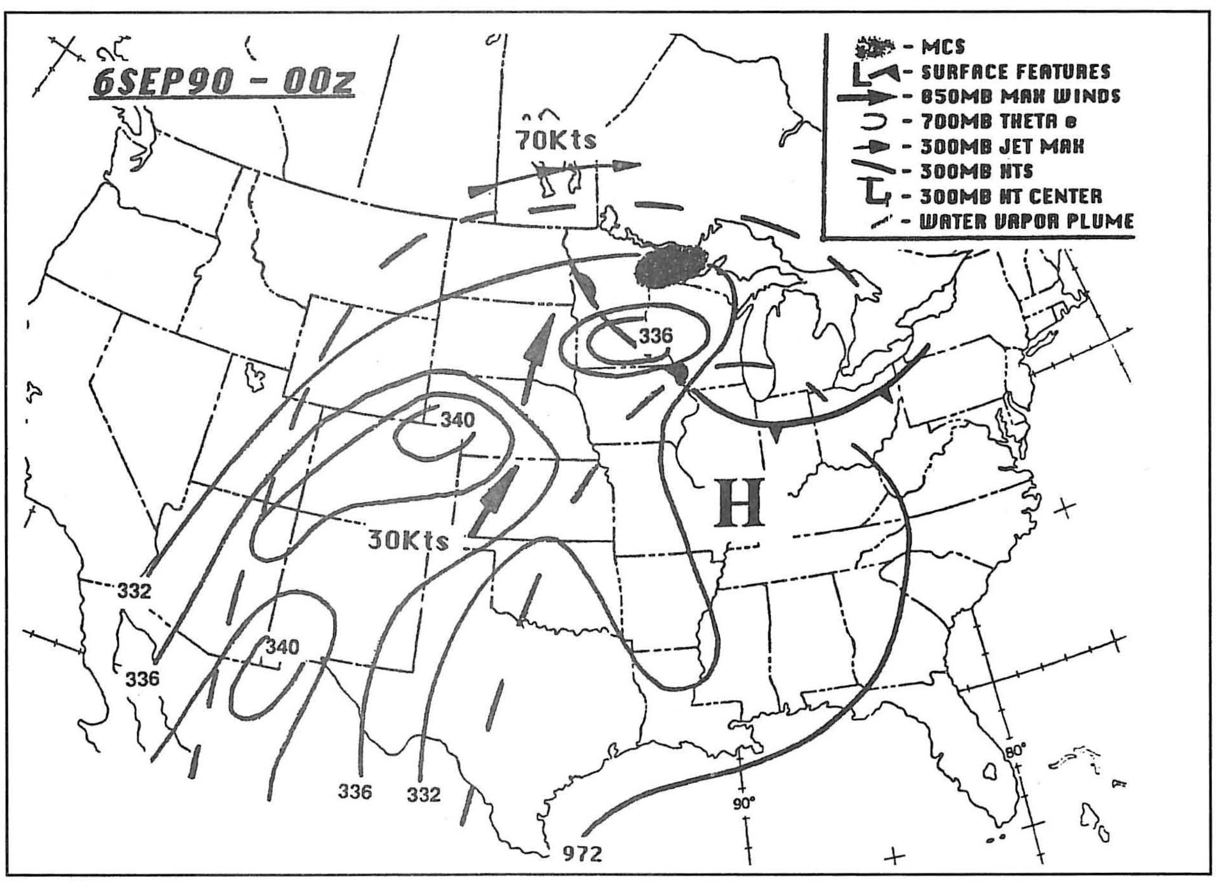

Fig. 9c. Surface and upper-air composite of meteorological features associated with extreme heavy rainfall producing MCSs, for 0000 GMT 6 September 1990.

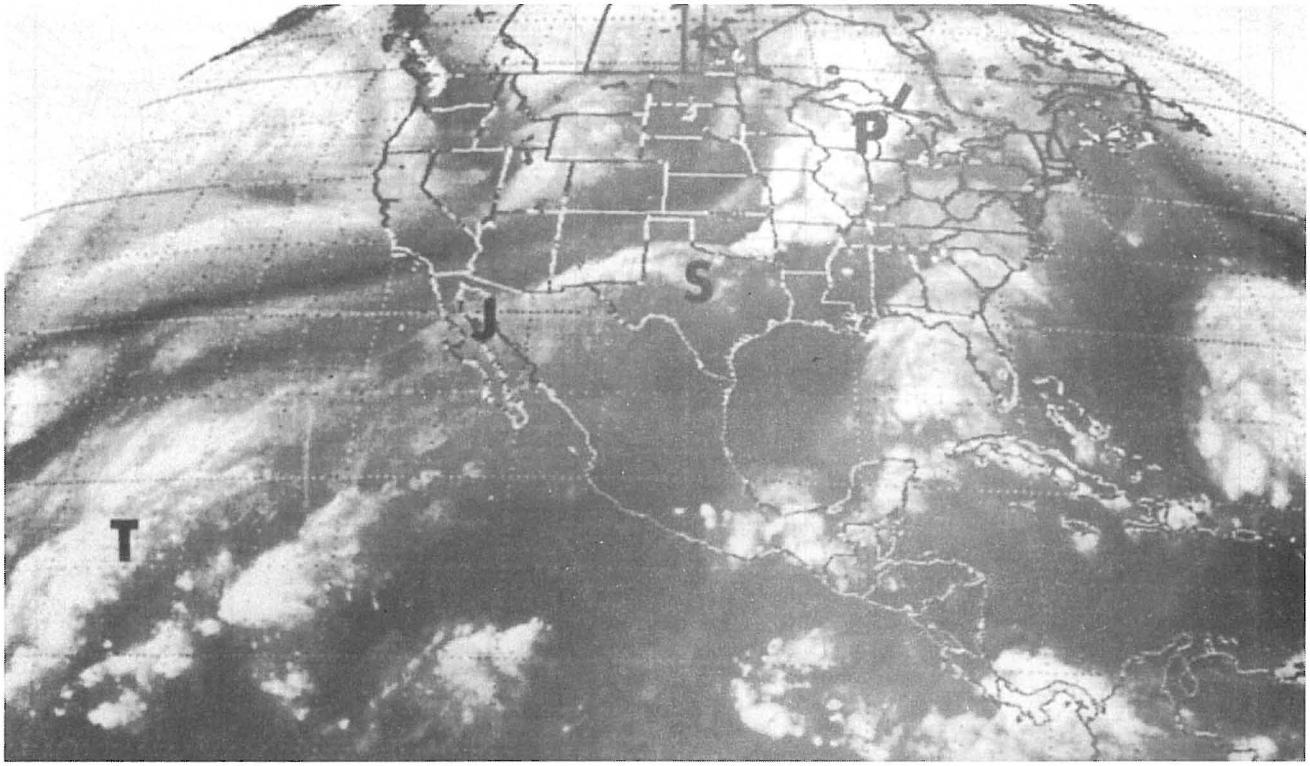

Fig. 10a. 6.7 μm water vapor imagery for 0000 GMT 25 October 1991.

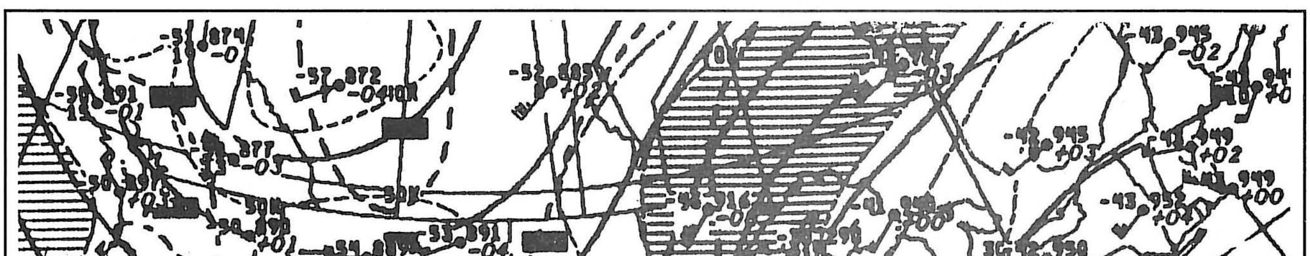

Fig. 10b. 300-mb analysis for 0000 GMT 25 October 1991.

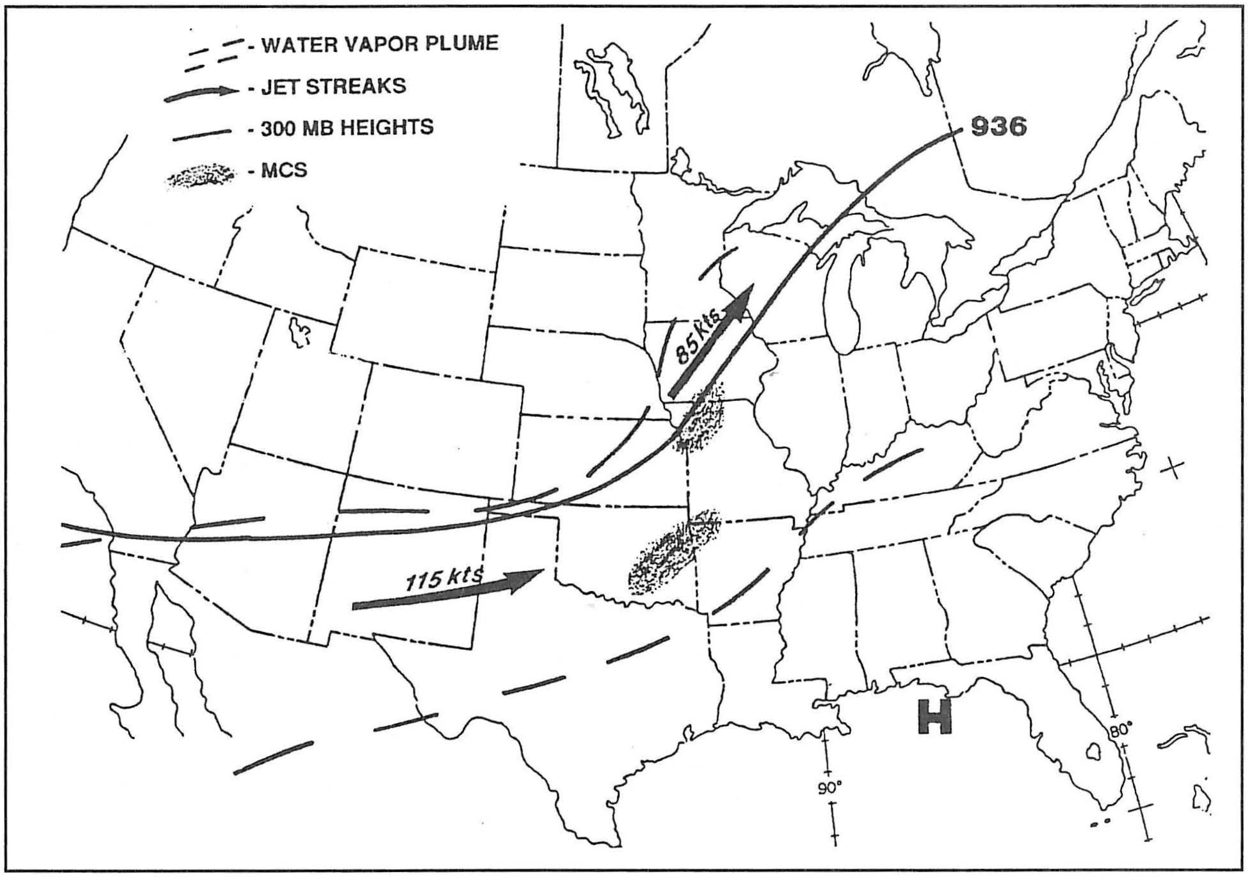

Fig. 10c. 300-mb jet streaks and water vapor plume composite for extreme heavy rainfall events of 25 October 1991.

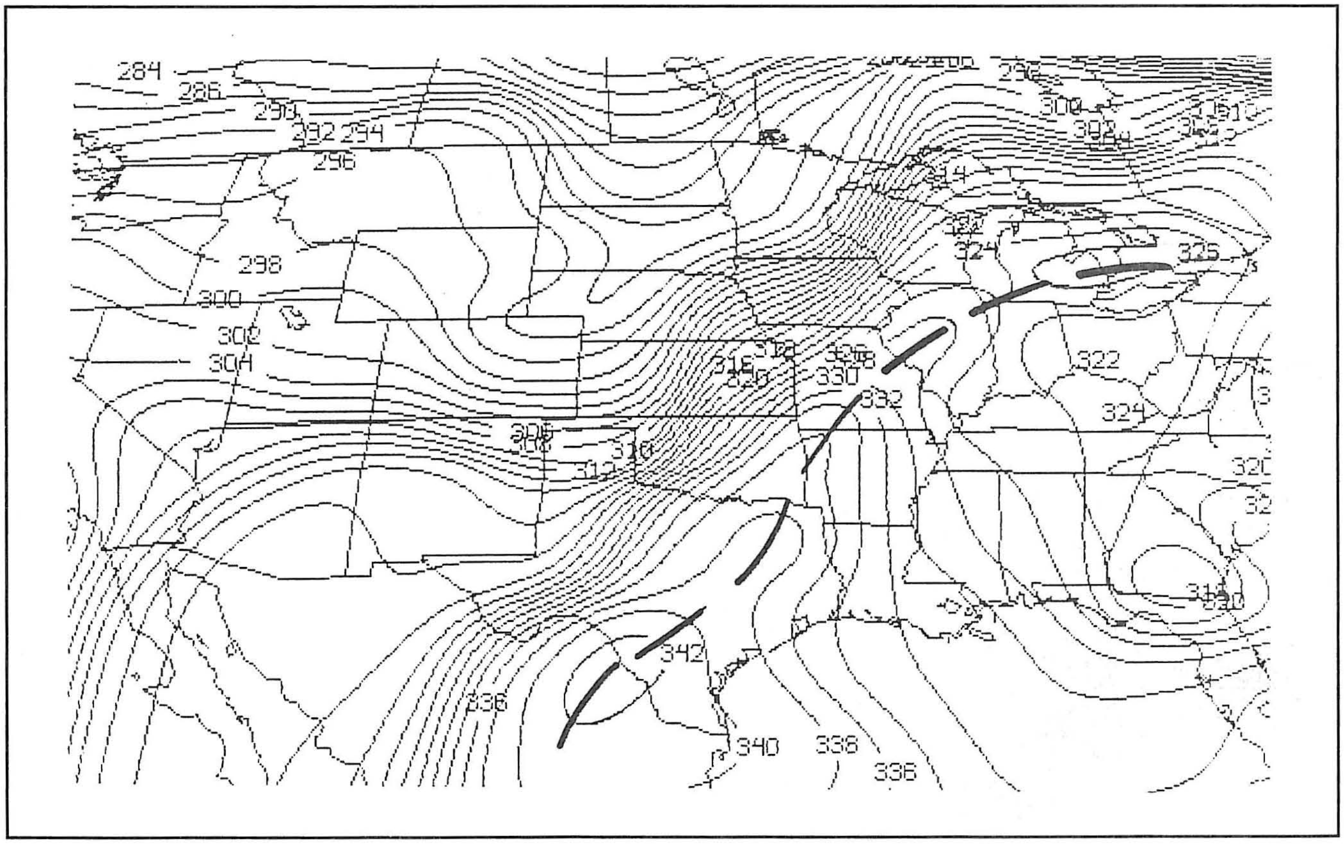

Fig. 10d. 850-mb theta-e analysis (°K) for 0000 GMT 25 October 1991.

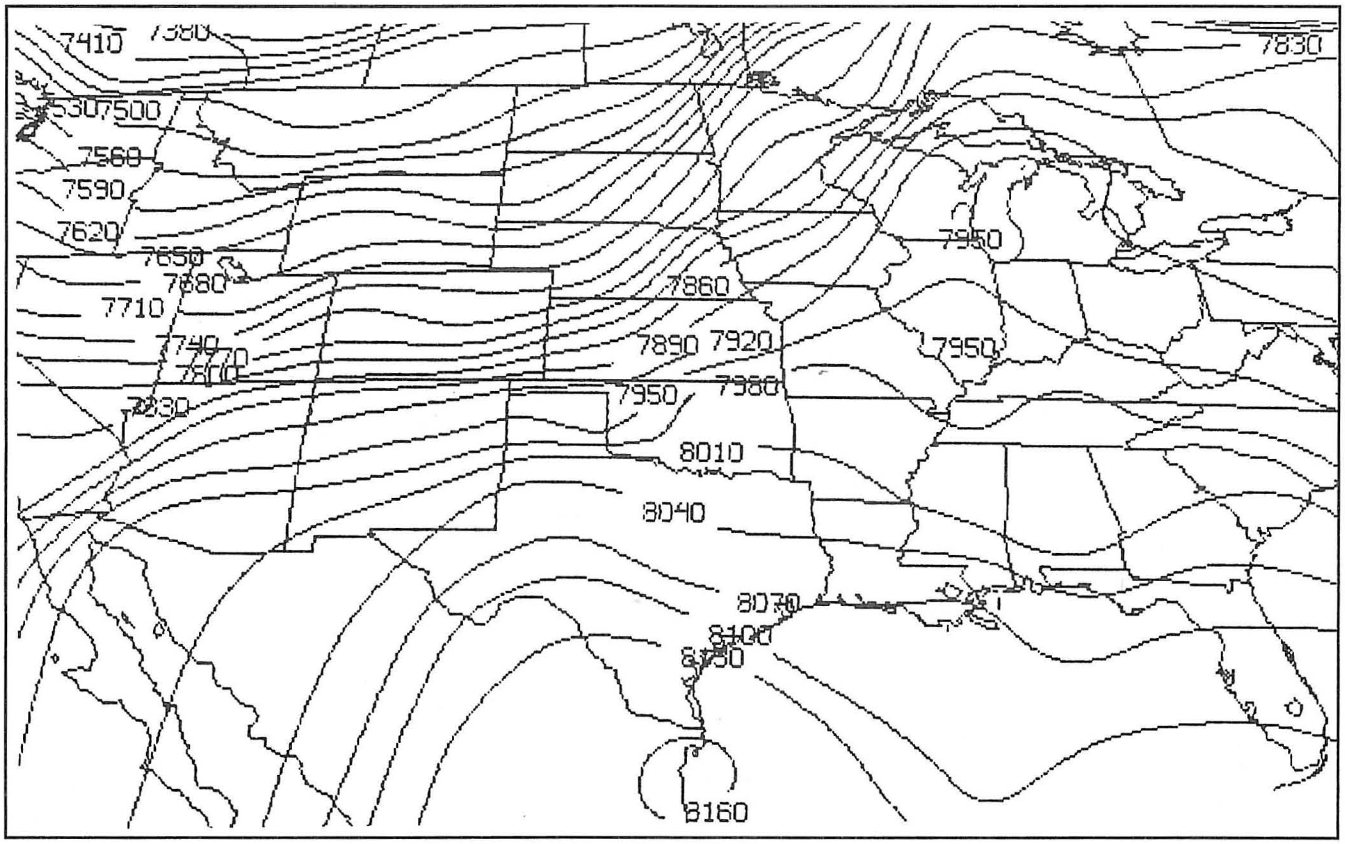

Fig. 10e. 850-300 mb thickness isopleths (gpm) for 0000 GMT 25 October 1991.

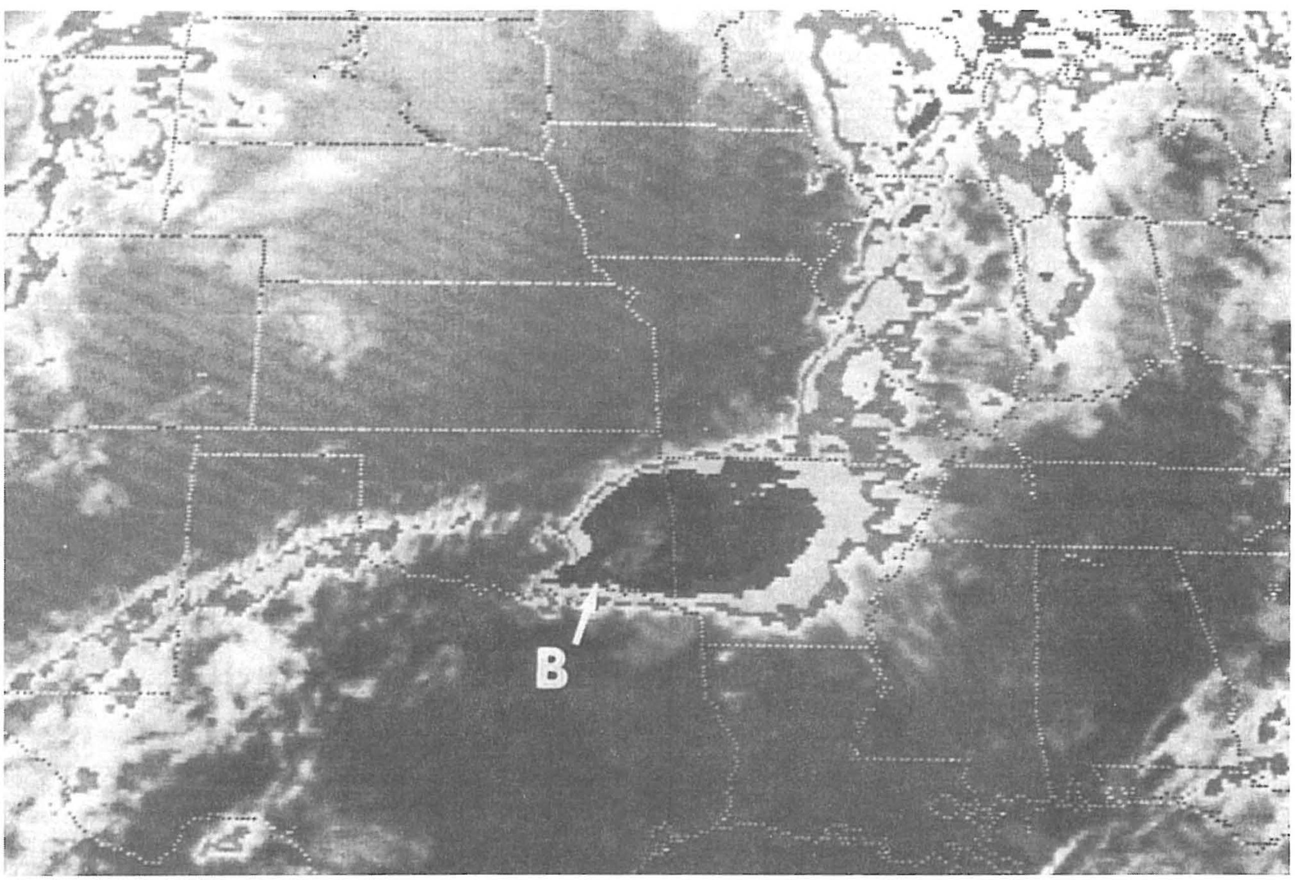

Fig. 10f. Enhanced infrared imagery (MB curve) for 0600 GMT 25 October 1991.

gence and upper-level divergence exists in conjunction with an upper-level jet streak. Such was the case in this event, where the 850–300-mb thickness isopleths (Fig. 10e) were difluent over the southern and central plains and a back-building MCS was observed in Fig. 10f at (B) over Oklahoma. Furthermore, the location of two jet streaks north and south of the EHR area respectively, created a transverse vertical circulation (Junker et al. 1990; Corfidi et al. 1990) in the exit and entrance regions of the two jet streaks. These transverse vertical circulations enhanced the vertical motion that resulted in the development of the MCS (over Oklahoma) with EHR. Transverse vertical circulations also helped to maintain the northward moisture transport from the ITCZ to the central U.S. Uccellini and Johnson (1979) have discussed in detail the importance of transverse vertical circulations produced by jet streaks for the development of severe weather. NMC forecasters extended this relationship to include EHR events. This double jet streak relationship is presented as a conceptual model in Fig. 11.

2) WV plume associated with a single jet streak

Although the double jet streak configuration discussed previously has been thought to be a significant mechanism for initiating intense convection, a single jet streak structure was also noted in this study. Figures 12a, 12b, and 12c illustrate a tropical WVP associated with a single jet streak structure on the Event Day over Texas, Arkansas and southern Kansas on 28 July 1991.

The WV imagery (Fig. 12a) on 2100 GMT 27 July shows a well defined tropical plume originating from the tropics and extending into the central U.S. (T–P′); a dark narrow band is located on its western side over the Texas and Oklahoma Panhandles. The 300-mb analysis on 0000 GMT 28 July (Fig. 12b) shows an anticyclone located over the southwestern and

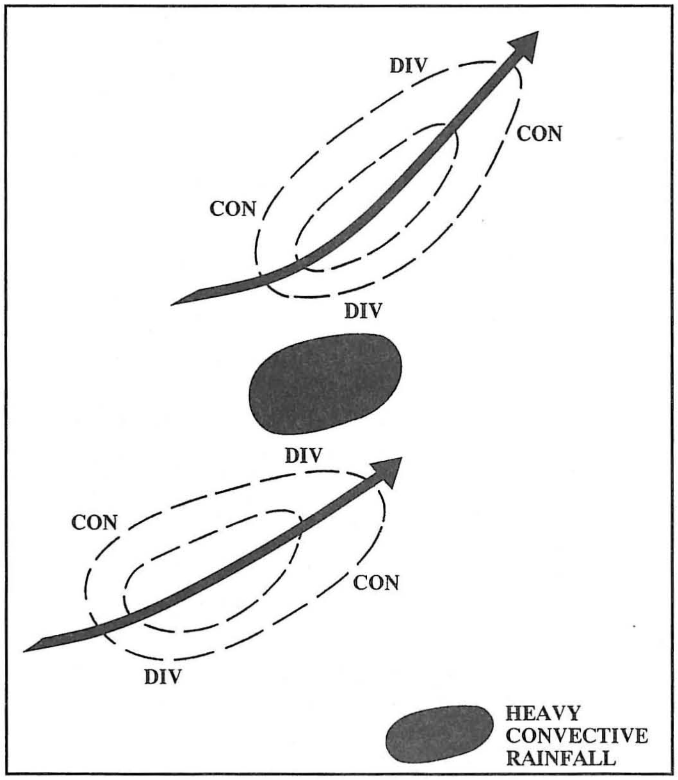

Fig. 11. Conceptual model of a double jet streak structure.

southeastern U.S. and an axis of maximum winds between 55 and 65 kts that is coincident with the dark back edge ("D–B") of the tropical plume on the WV imagery. This axis of maximum wind is located from the Texas and Oklahoma panhandles and extends northeast to northern Missouri. Much of the EHR appears to be near the entrance region of the jet streak. Intense convection resulting in EHR took place within the tropical plume just south of the jet entrance region in Oklahoma (Fig. 12c). This formation of MCSs that produced EHR from a single jet streak structure demonstrates that high-level divergence creates favorable conditions for moisture transport into the region. The heavy rainfall does not have to be the result of transverse vertical circulations associated with two jet streaks. The entrance region of a single jet streak and its associated transverse vertical circulation may induce sufficient divergence aloft that is favorable for lifting any capping inversions and releasing convective instability. Such was the case in this event when flash flood producing MCSs were the result.

4. Statistical Results

A total of 129 Event Days were selected for the period May through October of 1989–1991. An event day is defined as a day where 5 or more inches of rain occurred in a 24-hour period. Table 1 shows the WVP categories and the associated jet streak structures at 300 mb; 109 of the 129 Event Days (84%) were associated with a single WV plume. Ninety four of the 109 single plume types (86%) were tropical plumes and 15 of the single plume types (14%) were subtropical or polar plumes.

An analysis of the jet maxima associated with the single WVP shows that 84 of the 109 cases (77%) were connected with a double jet streak structure; 18 out of 109 (17%) were associated with a single jet streak structure and only for 7 cases (6%), a jet stream was not observed. On a few occasions, five of the 129 Event Days (4%), there was an interaction between a tropical and a polar or subtropical plume. These interactions referred to as the double plume structure were usually associated with a double jet stream structure. Fifteen of the 129 Event Days (12%) were not connected with a well defined WVP.

Table 2 shows that the origin of the tropical plumes exhibits a preference for the ITCZ located in the Pacific Ocean. If one considers the tropical plume in the single plume categories and the tropical plume in the double plume categories, 75 of the 99 cases (76%) originated from the Pacific Ocean. To distinguish the origin of the tropical plumes over this area, the Pacific Ocean was divided into 3 areas: area "A" extending from 90°

Table 1. WV plume categories

Categories	Number of cases
1. Single WV plume associated with:	109
a) double jet streaks	84
b) single jet streak	18
c) no jet	7
2. Double WV plume structure	5

Table 2. Origins of the tropical plumes

Origins	Number of trop. plumes
Pacific Ocean	75
Gulf of Mexico	22
Caribbean Sea	2

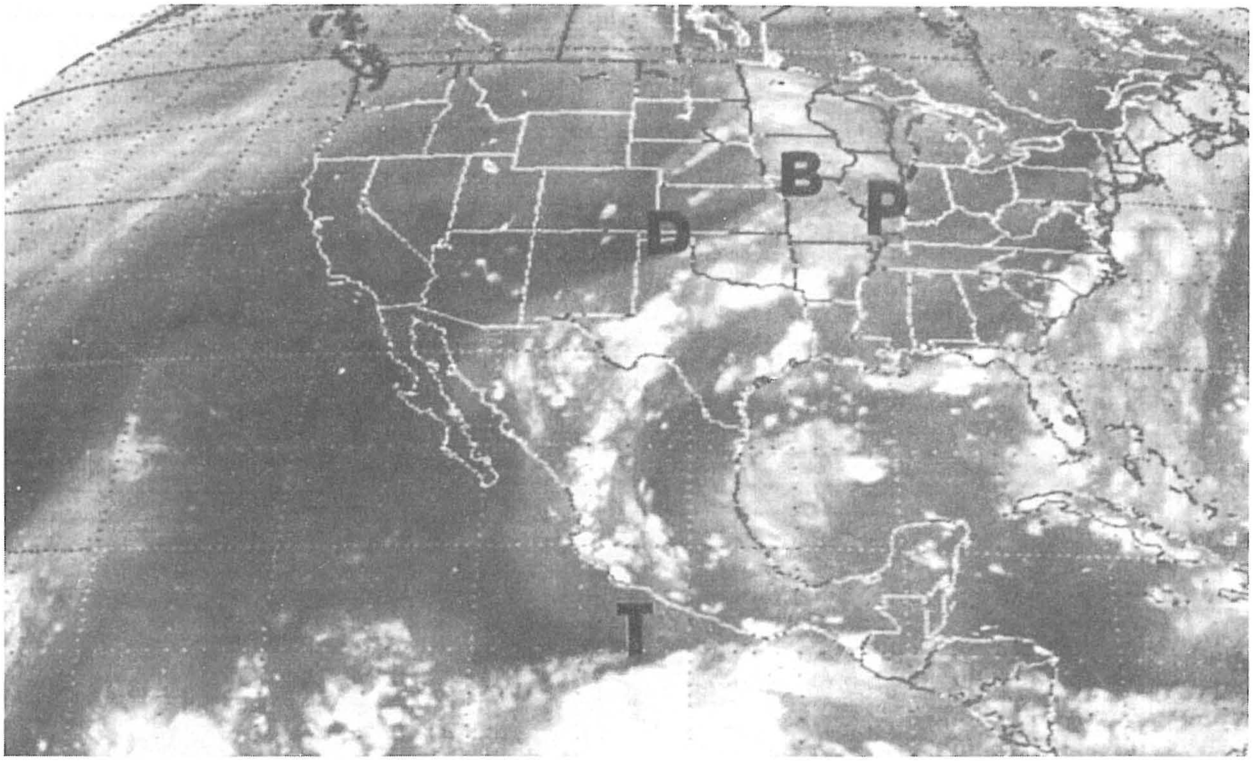

Fig. 12a. 6.7 μm water vapor imagery for 2100 GMT 27 July 1991.

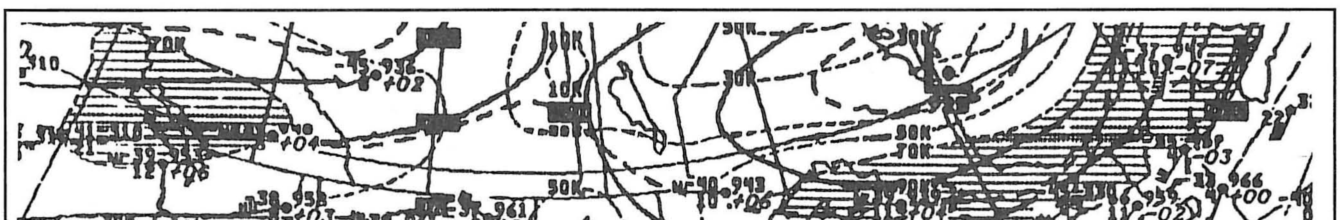

Fig. 12b. 300-mb analysis for 0000 GMT 28 July 1991.

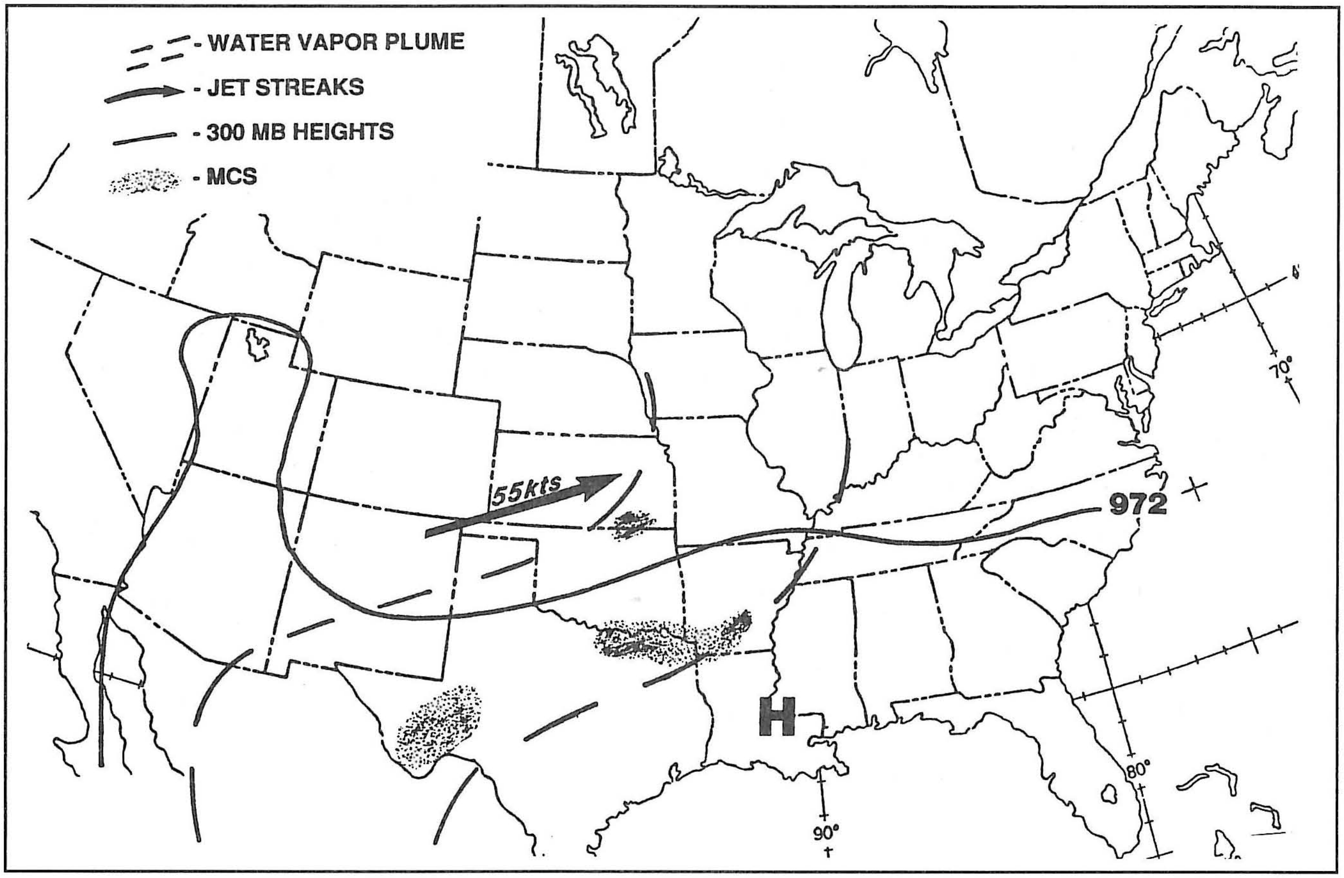

Fig. 12c. 300-mb jet streak and water vapor plume composite for the extreme heavy rainfall event of 28 July 1991.

to 120° W, area "B" extending from 120° to 150° W, and area "C" between 150° and 180° W.

Forty six cases (61%) originated in area "A", 25 cases (33%) originated in area "B", and 4 cases (6%) in area "C". Twenty two of the 99 cases (22%) originated from the Gulf of Mexico and only 2 cases (2%) originated from the Caribbean Sea. An examination of the 300-mb pattern and the surface location of the EHR areas showed that 112 of the 129 cases (87%) were located from the midtropospheric trough to ridge positions (southwesterly flow) while 17 of the 129 cases (13%) were located from the ridge to trough positions (north-westerly flow).

Statistics on WVP and theta-e ridge axis relationships were based upon 95 Event Days as the theta-e analyses were not available for 19 Event Days. Additionally, there were no WVPs observed for 15 cases. Thus, 80 of the 95 cases (84%) exhibited a connection between the WVP and the theta-e ridge axes while 15 of the 95 Event Days (16%) were not associated with a well defined WVP - theta-e ridge axis.

5. Examples of Extreme Heavy Rainfall Events

a. Event day of 16 June 1989

EHR occurred over southern Alabama where two stations reported 9.0 inches (225 mm) and 7.3 inches (182.5 mm), respectively, and over Kentucky where one station reported 9.6 inches (240 mm). If the report is correct, the event over Kentucky could be the result of a stationary, orographic-induced, "warm infrared (IR) top" MCS (Scofield et al. 1980) located under the tropical WVP. Eastern Kentucky is located in a mountainous area where orographic produced convection can occur with this type of synoptic pattern. Figure 13 shows the location of the EHR. Note that during the 24-hour period ending on 16 June 1989 at 1200 GMT, heavy rainfall occurred over Alabama, Georgia, Tennessee and Kentucky. The following discussion will focus on the EHR that fell over Alabama. WV imagery for 15 June 0000 and 1200 GMT, displayed in Figs. 14a and 14b, respectively, indicates a double plume structure was pres-

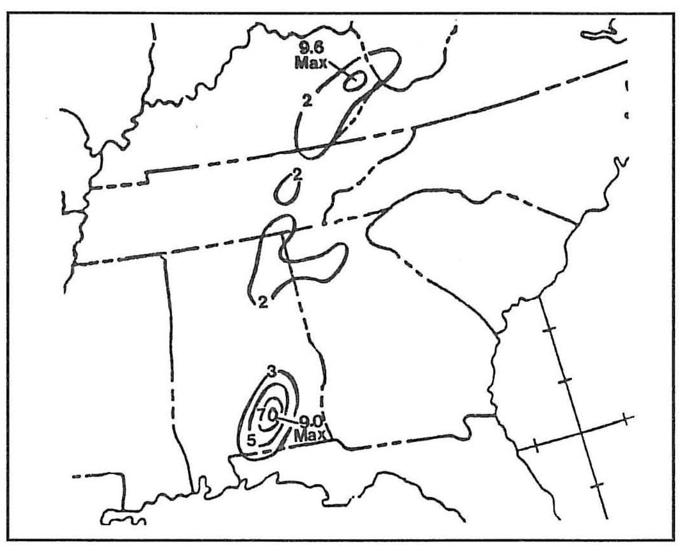

Fig. 13. 24-hour rainfall analysis (inches) ending at 1200 GMT 16 June 1989.

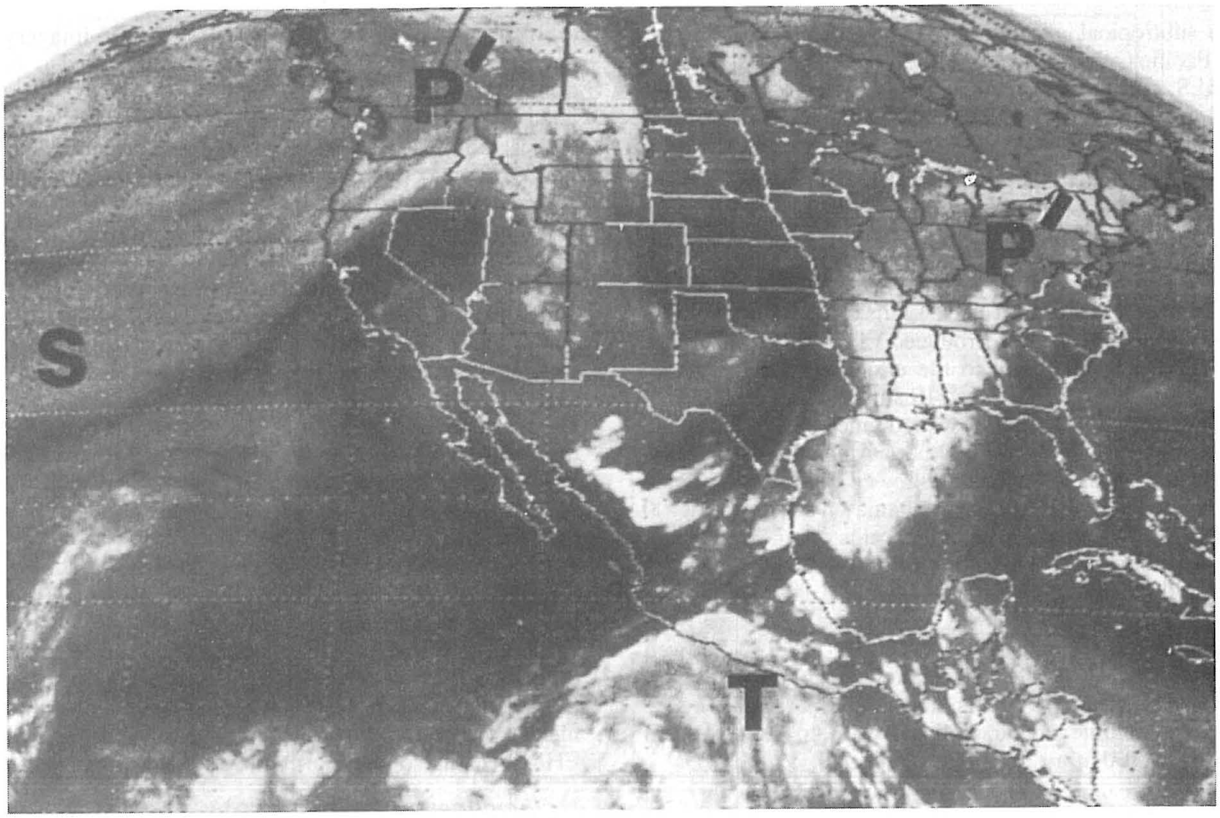

Fig. 14a. 6.7 μm water vapor imagery for 0000 GMT 15 June 1989.

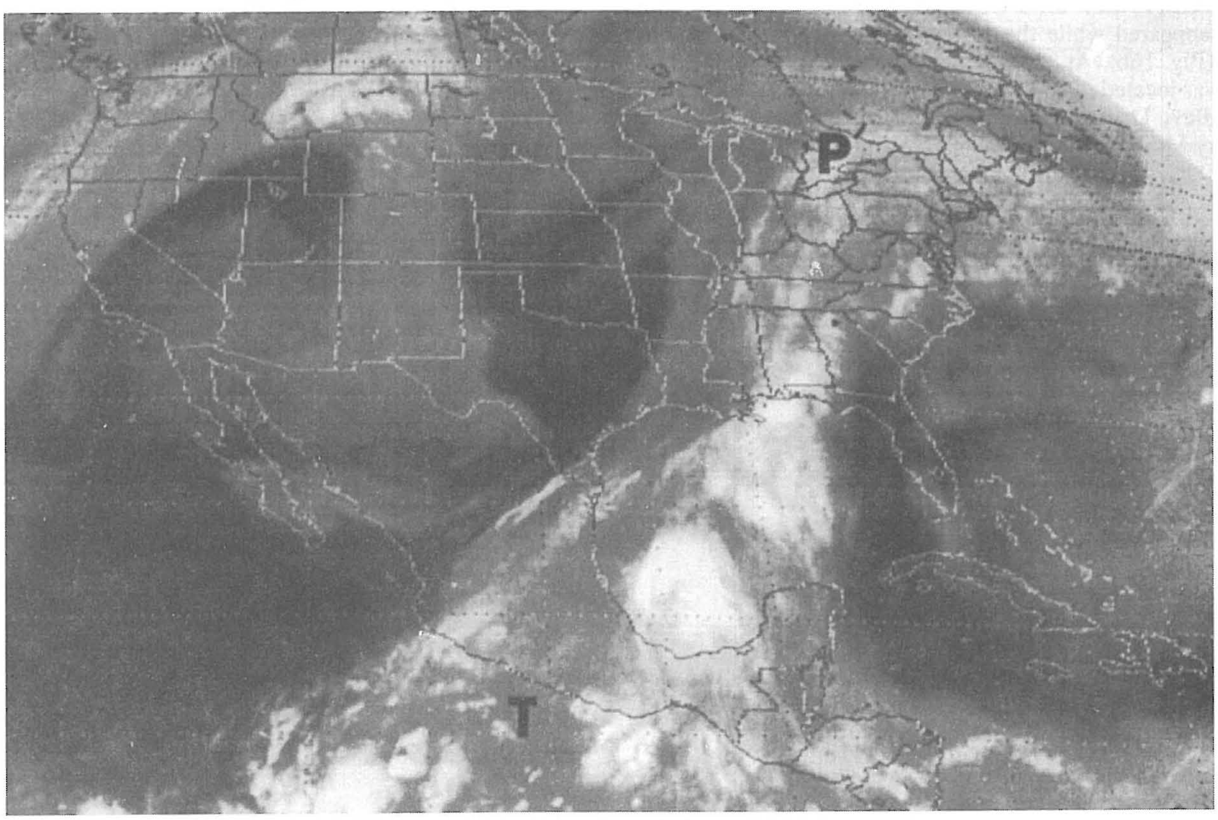

Fig. 14b. 6.7 μm water vapor imagery for 1200 GMT 15 June 1989.

ent: (1) a subtropical plume indicated by (S–P′), originating from the Pacific Ocean, that moved northeastward to the northwestern U.S. and then southward to northern Mexico; it then stretched east-northeastward and approaches; (2) a tropical plume indicated by (T–P′), extending from the ITCZ north-northeastward to the Ohio Valley. During this 12-hour period (0000 to 1200 GMT), the subtropical and tropical plumes became connected. Several embedded MCSs developed within the tropical plume.

An observation of earlier IR images (not shown here) showed that MCSs developed over Texas, Louisiana and Mississippi on 14 and 15 June 1989, and produced EHR over these areas. As the MCSs moved slowly to the east, EHR was reported over southern Alabama. Enhanced IR imagery (at 1200 GMT) displayed in Fig. 15a revealed well defined MCSs over the Gulf of Mexico (at "M") and southern Alabama (at "S"). A sequential view of the IR imagery showed that newly formed clusters developed over southern Alabama on 15 June at 0900 GMT. During the next six hours, these clusters merged into a MCS that exhibited slow moving, backbuilding characteristics as the MCS over southern Alabama (at "S") built southwestward and in turn merged with MCSs moving northward from the Gulf of Mexico. IR imagery at 1400 GMT (Fig. 15b) showed that backbuilding MCSs (at "S") tended to be quasi-stationary and produced EHR. These MCSs developed in the eastern side of the tropical plume and moved eastward to southwestern Georgia where 100 mm of rain were reported.

Composites of meteorological features are shown in Figs. 16a and 16b. On 15 June at 0000 GMT, two surface fronts extended from Texas to a low located over northern Indiana and from Mississippi to another low located over Maryland. By 1200 GMT, both lows weakened and the western surface front disappeared while the eastern front advanced slowly to the east (Fig. 16b). At 300 mb, a jet stream with associated jet streaks was located over the northwestern U.S. and the northern Ohio Valley. The jet stream was connected with a ridge over the Rocky Mountains and a rather deep meridional trough over the central U.S. A time lapse view of WV imagery showed that the movement of the plumes was well related to the circulation field at 300 mb. The 300-mb jet stream axis nearly paralleled the tropical plume in the southeastern U.S. As mentioned earlier in Section 3c(1), slow moving and flash flood producing MCSs often occurred with this "parallel" type of configuration between the jet stream axes and the plumes; this of course assumes that other conditions were favorable. Some of these other conditions are now discussed. The location of the 850-mb maximum winds and theta-e ridge axis in Figs. 16a and 16b showed that low-level warm and moist air advection (theta-e advection) was occurring over Alabama, Tennessee and Kentucky. A theta-e ridge axis at 850 mb was located from the Gulf of Mexico northward into Kentucky. The orientation of the potential energy axes (i.e., axes of the theta-e ridge and the low-level maximum wind) as described by Scofield and Robinson (1990, 1992) were closely aligned with the tropical plume. Thickness difluence (not shown) was also present over the southeastern United States.

In summary, the above features showed: (1) the presence of a tropical WVP; (2) a continuous replenishment of moist unstable air to the southeastern U.S.; and (3) the presence of upward vertical motion since the southeast was located in the front-entrance region of the jet streak positioned over the northern Ohio Valley. All of these features contributed to the development of slow moving MCSs that produced flash floods and EHR over the southeastern United States.

b. Event day of 29 August 1989

During the 24-hour period ending on 29 August 1989 at 1200 GMT, an EHR event was reported over northwestern Missouri and over western Indiana. Heavy rainfall was also reported over parts of Iowa and Illinois. Figure 17 depicts the observed rainfall for that period. A time sequential view of the enhanced IR imagery from 0000 GMT 28 August to 1200 GMT 29 August showed that the EHR over Missouri/southwest Iowa and Indiana were produced by two different MCSs. Both of

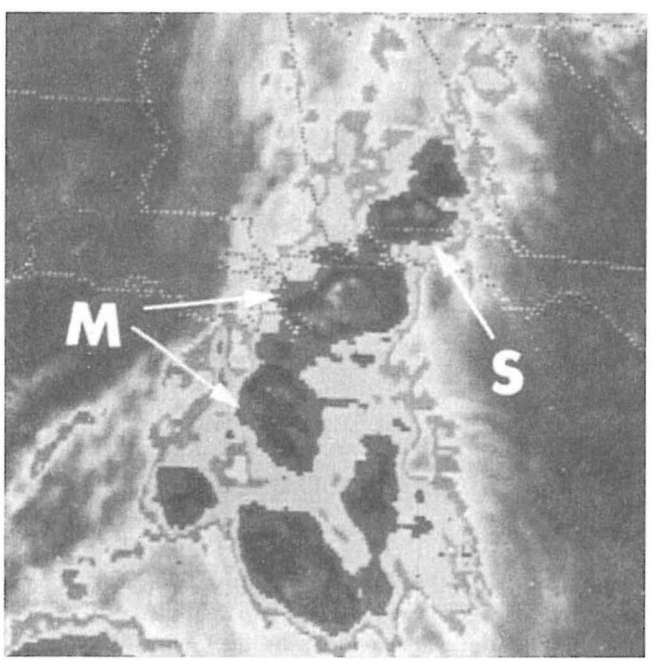

Fig. 15a. Enhanced infrared imagery (MB Curve) for 1200 GMT 15 June 1989.

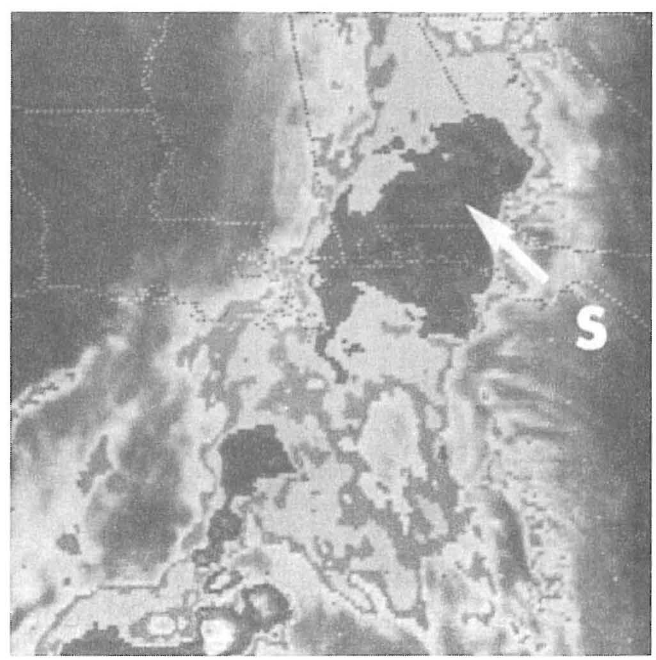

Fig. 15b. Enhanced infrared imagery (MB Curve) for 1400 GMT 15 June 1989.

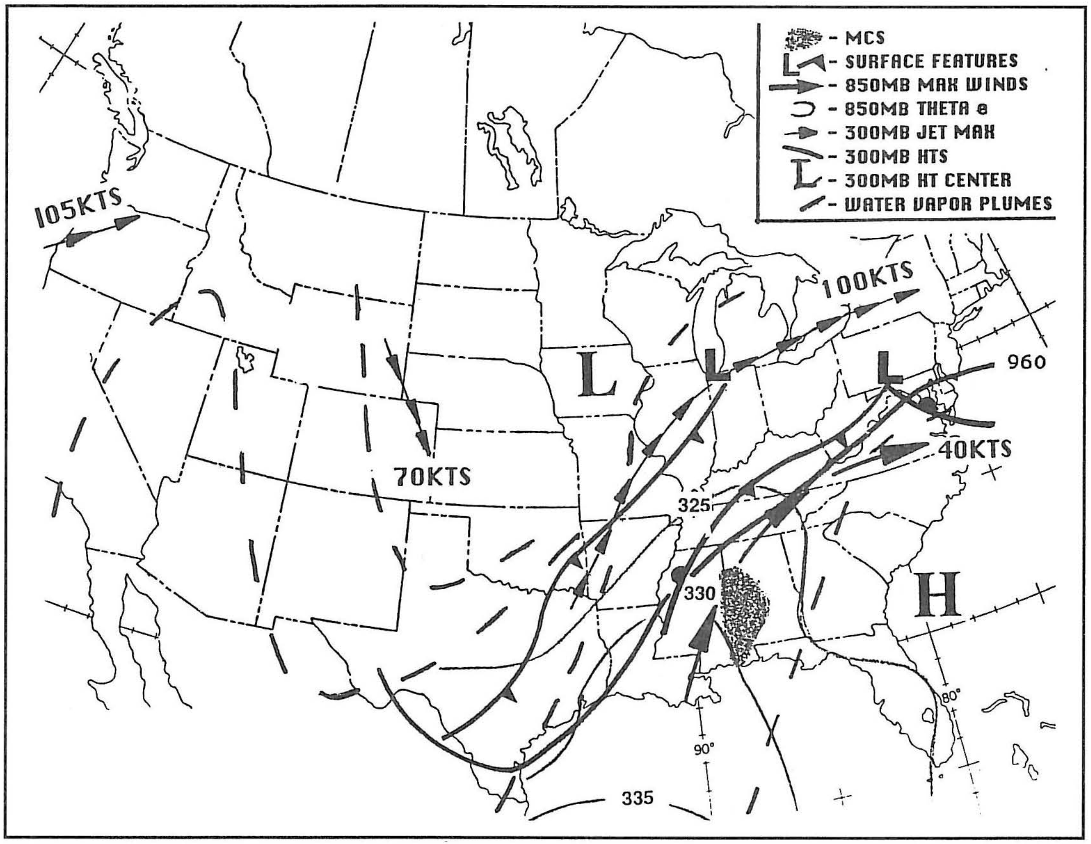

Fig. 16a. Surface and upper air composite of meteorological features associated with extreme heavy rainfall MCSs for 0000 GMT 15 June 1989.

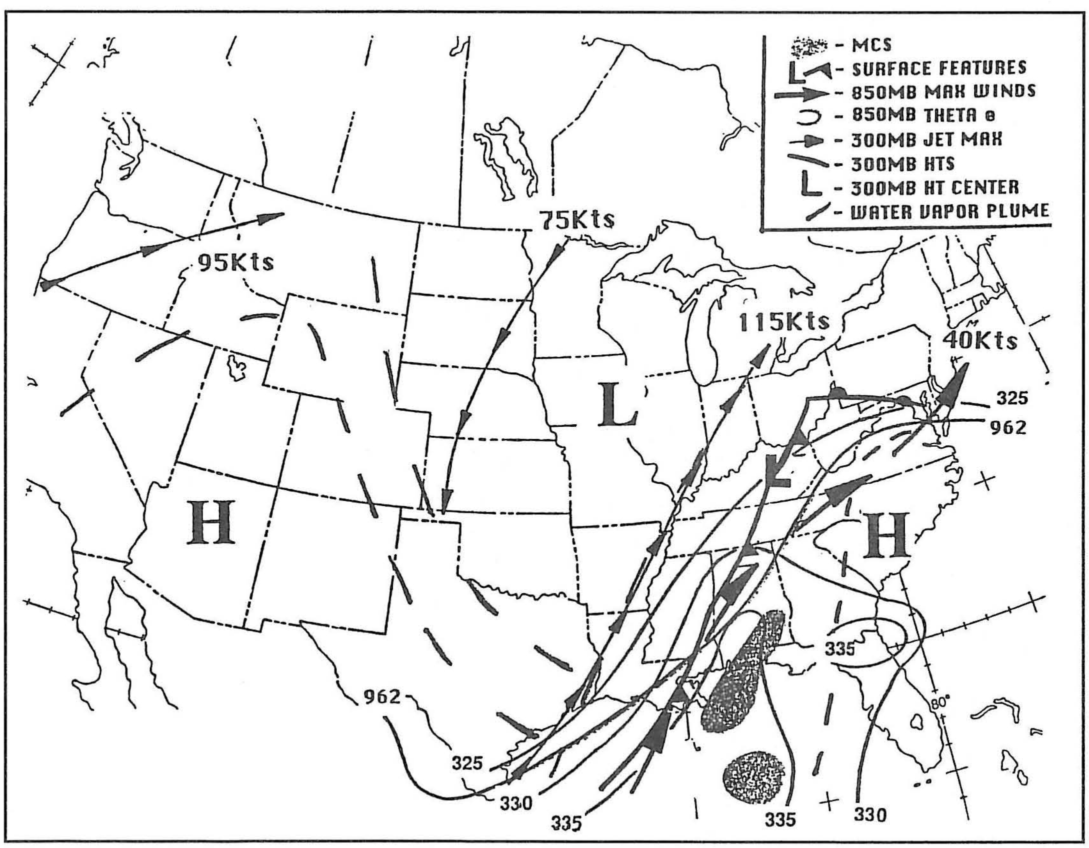

Fig. 16b. Surface and upper-air composite of meteorological features associated with extreme heavy rainfall MCSs for 1200 GMT 15 June 1989.

these EHR areas were located near the extreme eastern portion of the tropical WVP (T–P′) at 1200 GMT 28 August (Fig. 18). The theta-e ridge axis (Fig. 19) was positioned along and just to the east of the plume. Maximum winds at 850 mb were situated from southern Iowa to western Illinois. A jet streak was located over the Minnesota/Wisconsin area. EHR fell between 0000–1200 GMT 29 August over northwest Missouri and between 1200 GMT 28 August and 0000 GMT 29 August over Indiana and Illinois.

This case concentrated on a rather large MCS that produced the EHR over Indiana and Illinois. The enhanced IR at 1200 GMT (Fig. 20) shows the initial stage of the thunderstorm over western Indiana (at "S"); a dissipating MCS is observed over southwestern Iowa (at "M"). This dissipating MCS produced an outflow boundary that moved eastward toward Illinois (Fig. 21). A front was located in extreme northern Illinois. Additionally, an area of differential heating between cloudy skies and cooler temperatures to the north and clear skies with warm and unstable air to the south was situated over central Illinois. As illustrated in Fig. 22, it was along this differential heating boundary (B–Y) that thunderstorms developed westward across central Illinois. With the additional uplift due to the intersection of the outflow boundary (O–B) from the west, these thunderstorms merged into a rather large MCS (Fig. 23) that remained quasi-stationary and built backwards slowly toward St. Louis, Missouri. Notice that the very cold tops embedded within the MCS (at "H") were associated with extremely heavy rainfall. The surface and upper composites for 0000 GMT 29 August depicted that the MCS over the Illinois/Indiana area modified the environment with its rain cooled air and created a rather pronounced theta-e minimum over the same area (Fig. 24). However, a key feature is revealed by the fact that high theta-e air was being replenished in western Illinois by relatively strong low-level winds. This instability advection along with thickness difluence (not shown) helped to produce the backbuilding MCS observed over western Illinois. A jet streak continued to be present over the Minnesota/Wisconsin area.

The WV imagery ending on 0000 GMT 29 August (Fig. 25) showed that the tropical plume was nearly stationary during this 12-hour period (1200 GMT - Fig. 18 to 0000 GMT - Fig. 25). Notice how the MCSs developed in the eastern portion of the plume from west Texas north-northeastward to Illinois and Indiana. As mentioned before, the theta-e ridge axis was also located in the eastern portion of this plume. In fact, a time sequential view of the WV imagery showed that the tropical plume was indeed quasi-stationary and that the inside boundary on its western edge was becoming more distinct. Formation of this inside boundary is usually associated with deformation and upper air anticyclogenesis (Weldon and Holmes 1991). As a result, the location of upper air features, such as the tropical plume, will be slow to change. Thus a synoptic scale pattern that favors heavy rainfall and flash floods should persist.

6. Summary and Conclusions

The WVP characteristics associated with EHR over the U.S. during a 3-year summer season were presented in this paper. The WVP appeared to be an important component for intense convection and the development of MCSs that produced EHR; 114 of the 129 Event Days (88%) were associated with a well defined WVP. Two different configurations were depicted: the single WVP structure was found most frequently on 84% of the total Event Days while the double WVP structure represented only 4% of the cases. Of the WVPs documented, 99 of the 119 (83%) originated mainly from the tropics and were referred to as tropical plumes. The tropical plumes originated mainly from the Pacific Ocean (76%) while 22% and 2% of the cases originated from the Gulf of Mexico and the Caribbean Sea, respectively. Although WVPs were usually tropical plumes, 20 of the 119 (17%) were subtropical or polar plumes.

We are just beginning to use Special Sensor Microwave/Imager (SSM/I)-derived Total Precipitable Water (TPW) fields for analyzing the depth of the moisture under the WVP over the ocean areas. GOES-derived TPW is being used over land areas. In addition, model-derived and SSM/I-derived sea surface winds in conjuction with the above TPW fields are being used to compute moisture transport, advection and convergence—key ingredients for heavy precipitation. SSM/I data is received from the Defense Meteorological Satellite Program (DMSP). The use of sea surface temperatures for representing low-level theta-e will also be explored. Such a possibility may be an effective way of quantifying the "energized" return flow from the warm waters of the Gulf of Mexico.

An examination of analyses of theta-e at 850 to 700 mb revealed that for 84% of the Event Days, the WVP was closely aligned with the theta-e ridge axis. Additionally, the 850-mb wind analyses documented in the two examples, 16 June 1989 and 29 August 1989, possessed wind maxima from a southerly direction. Such a wind direction was associated with a transport of warm, moist, unstable air from the subtropics. The 300-mb jet maxima "played" a major role in initiating storms that produced heavy precipitation. Seventy seven percent of the cases were associated with a double jet streak structure configuration that if coupled with lower-tropospheric jet maxima was shown (Junker et al. 1990; Corfidi et al. 1990) to destabilize the atmosphere. This also contributed to low-level heat and moisture transports that acted to initiate heavy precipitation producing MCSs. Some of these double jet streak structures were the result of the MCS modifying the environment to produce a mesoscale-induced jet streak to the north of the MCS.

Four categories of WVPs were formulated: the single WVP associated with 1) a double jet streak structure; 2) a single jet streak structure; 3) no jet; and 4) the double WVP structure that is often associated with a double jet stream configuration.

On many occasions, the WVP moved northeastward on the backside of a 300-mb anticyclone or on the forward side of a trough. The plumes were nearly parallel to the 300-mb flow. As mentioned previously, this type of synoptic pattern (the western portion of an upper-level ridge) favors plumes and the return flow of low-level moist, unstable air. MCSs usually developed within the moist, unstable (theta-e ridge axis) air on the eastern side of the WVP. In addition to this eastern portion, the northern part of the tropical plume was often where the low-level forcing (theta-e ridge axes and warm air advection) became coupled with upper-level forcing mechanisms (jet streaks) creating favorable conditions for development of MCSs. The southerly upper-level flow on the backside of the ridge seemed to maintain the northward transport of the WVPs.

Although the WVPs and the upper tropospheric jet streaks appeared to be related to the EHR events documented in this study, 12% of the Event Days did not present a well defined WVP. On a few occasions, there was not an obvious jet stream detected at 300 mb at the time of the EHR event. Thus, differential temperature advection and/or low-level advection of warm, moist, unstable air were additional contributing factors for destabilizing the atmosphere and creating conditions favorable for the development of MCSs that produced EHR.

In closing, flash flood producing MCSs are a multiscale and concatenating event. Therefore, in the future as we merge the WSR-88D radar data with the various GOES 8 and 9 multi-

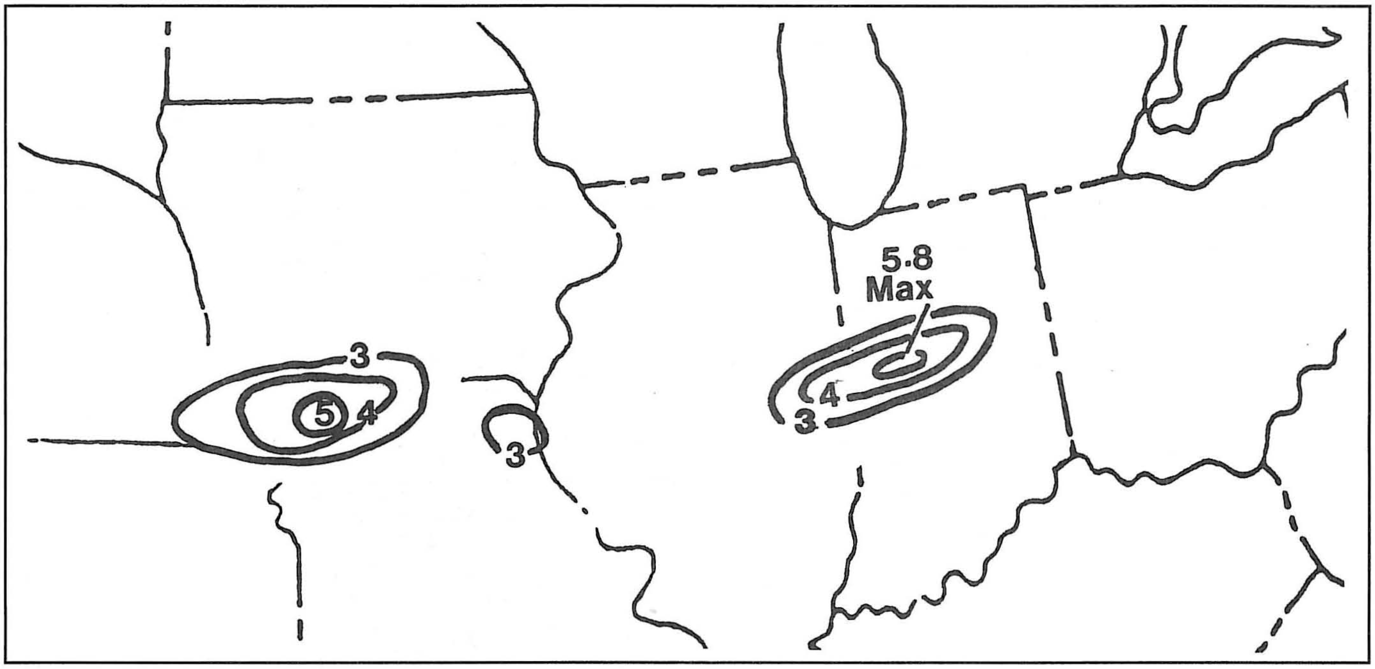

Fig. 17. 24-hour rainfall analysis (inches) ending at 1200 GMT 29 August 1989.

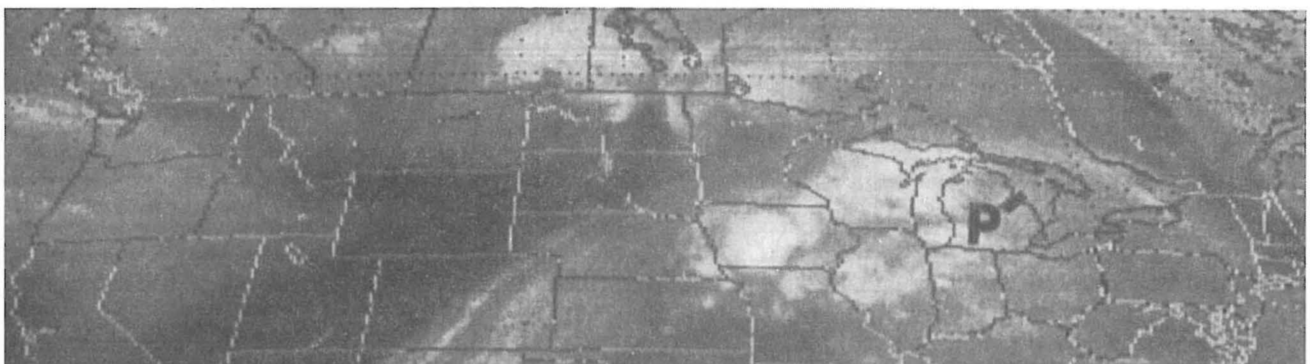

Fig. 18. 6.7 μm water vapor imagery for 1200 GMT 28 August 1989.

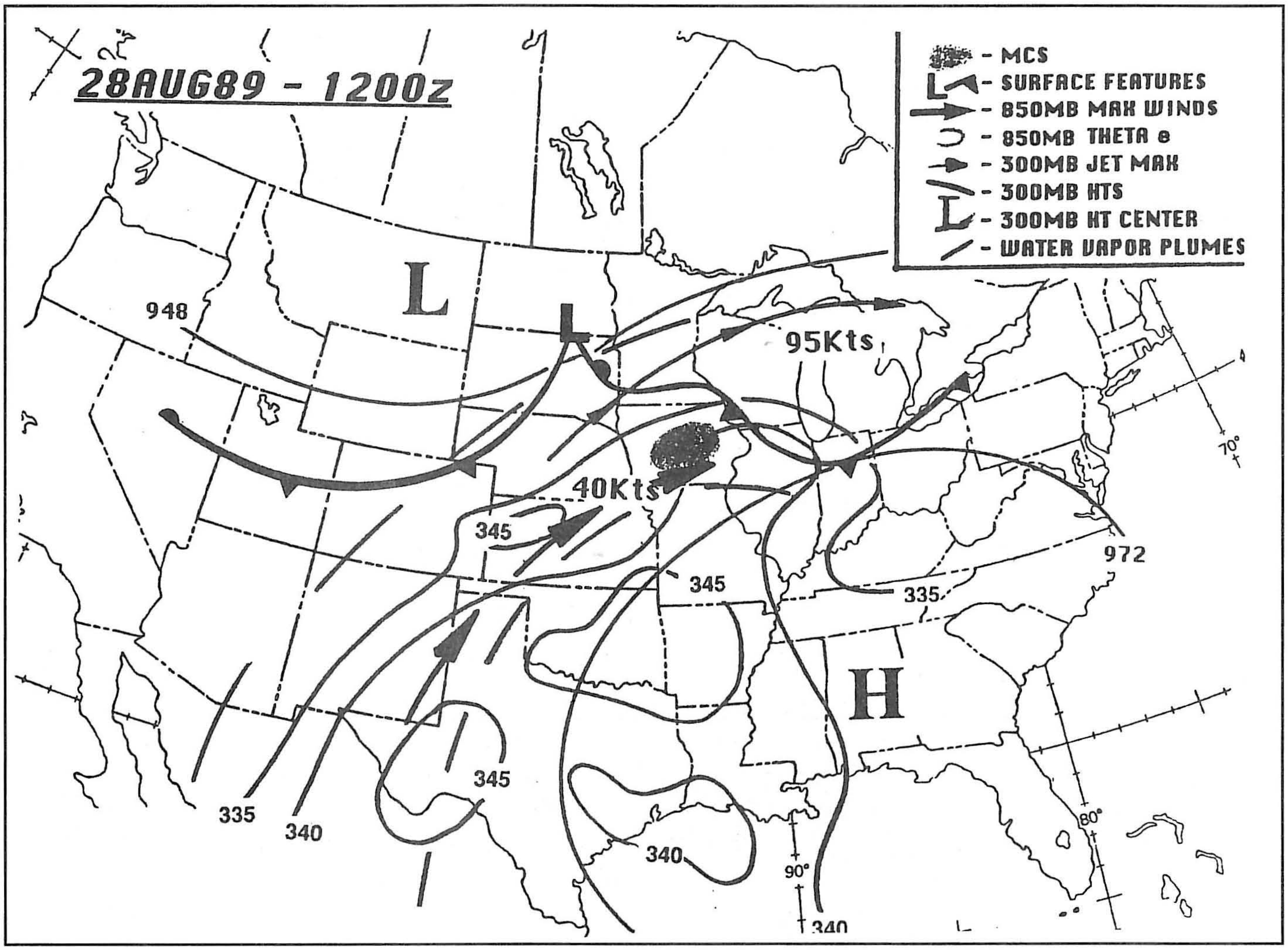

Fig. 19. Surface and upper air composite of meteorological features associated with extreme heavy rainfall MCSs for 1200 GMT 28 August 1989.

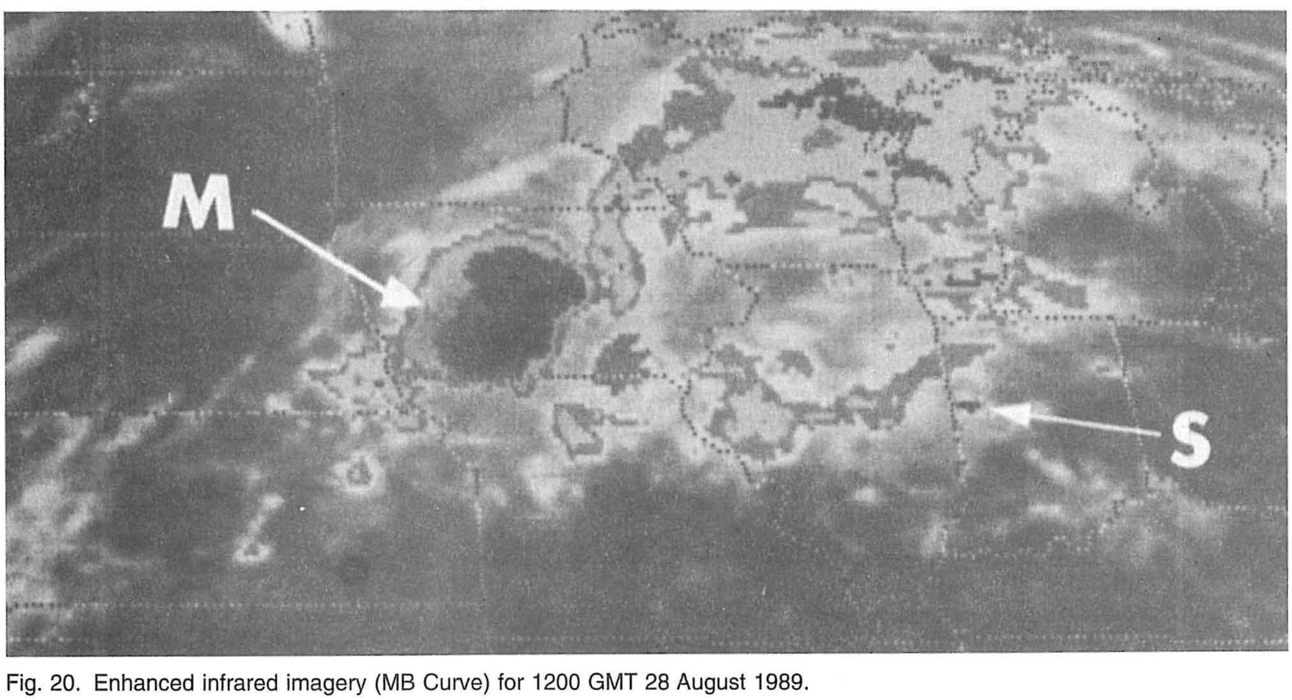

Fig. 20. Enhanced infrared imagery (MB Curve) for 1200 GMT 28 August 1989.

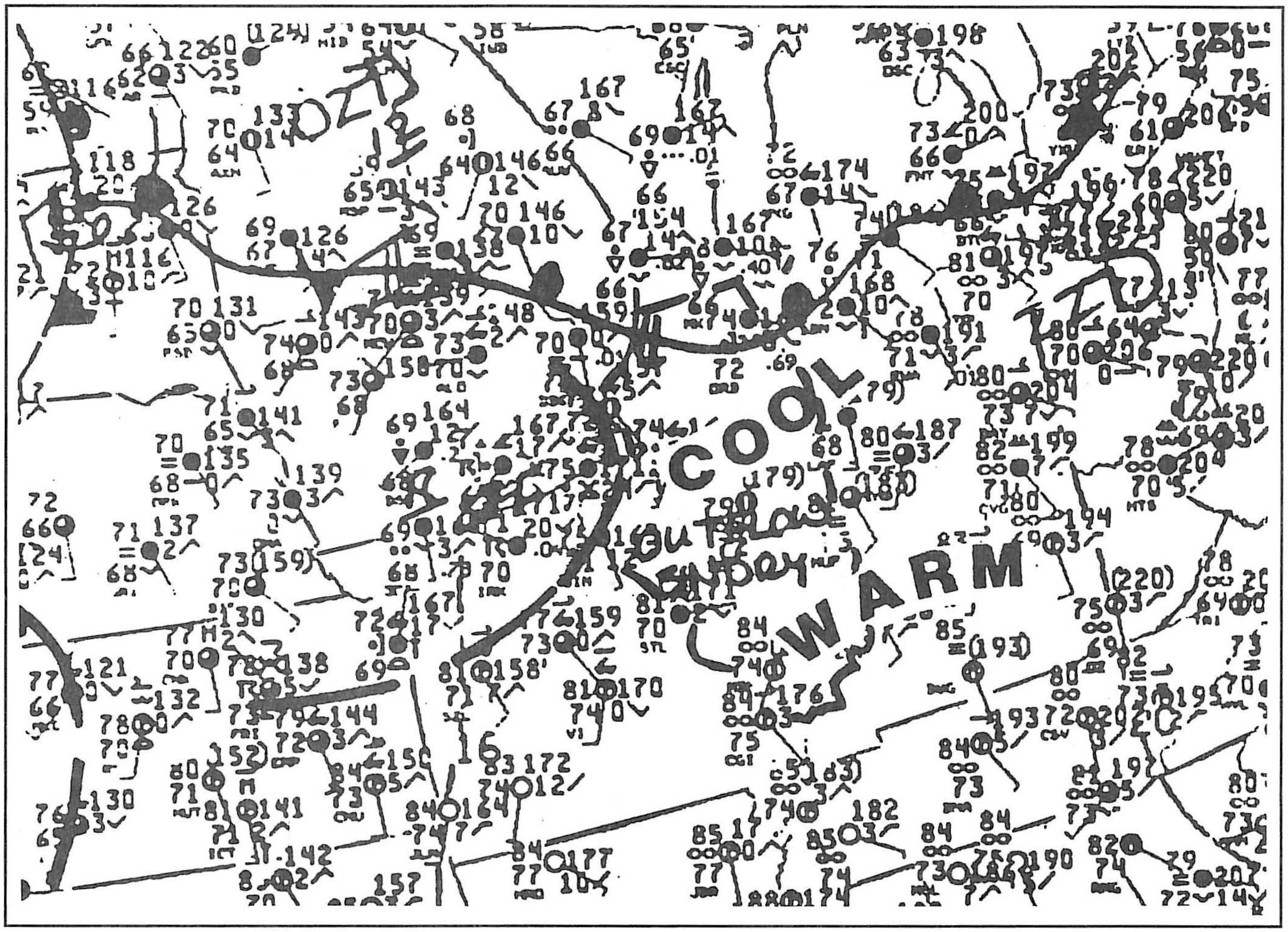

Fig. 21. Surface analysis for 1500 GMT 28 August 1989.

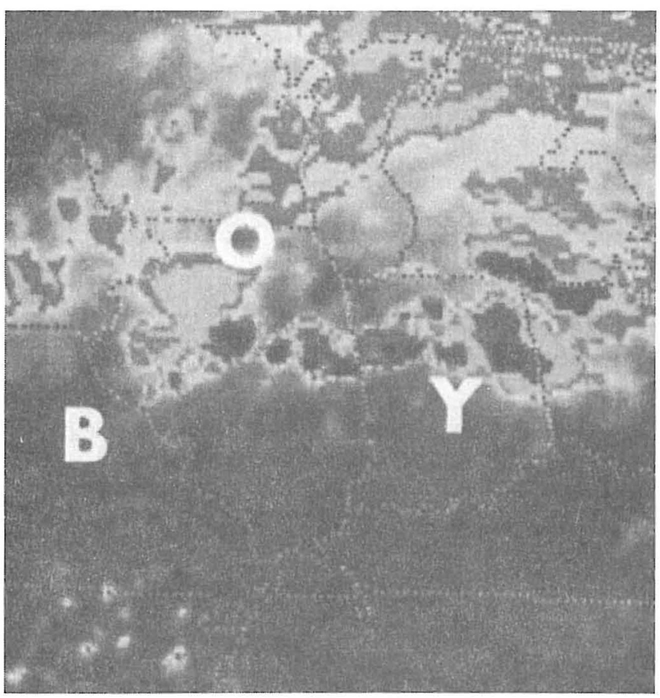

Fig. 22. Enhanced infrared imagery (MB Curve) for 1800 GMT 28 August 1989.

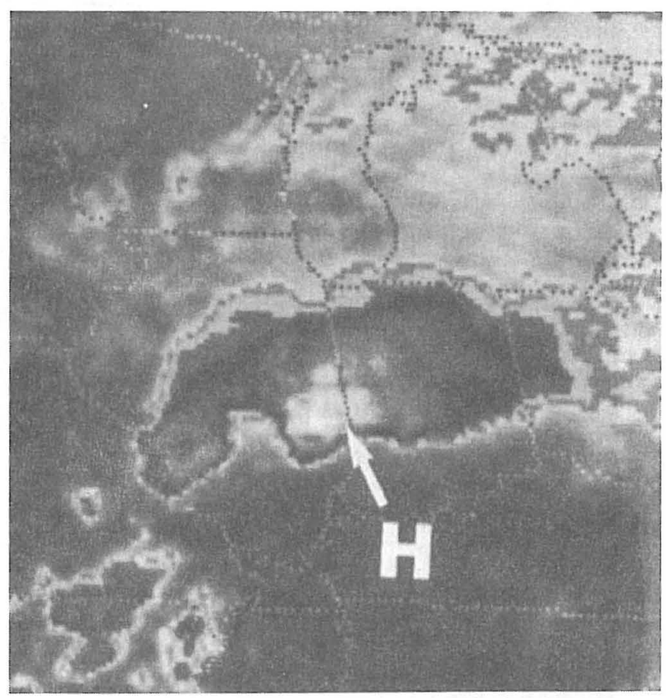

Fig. 23. Enhanced infrared imagery (MB Curve) for 2100 GMT 28 August 1989.

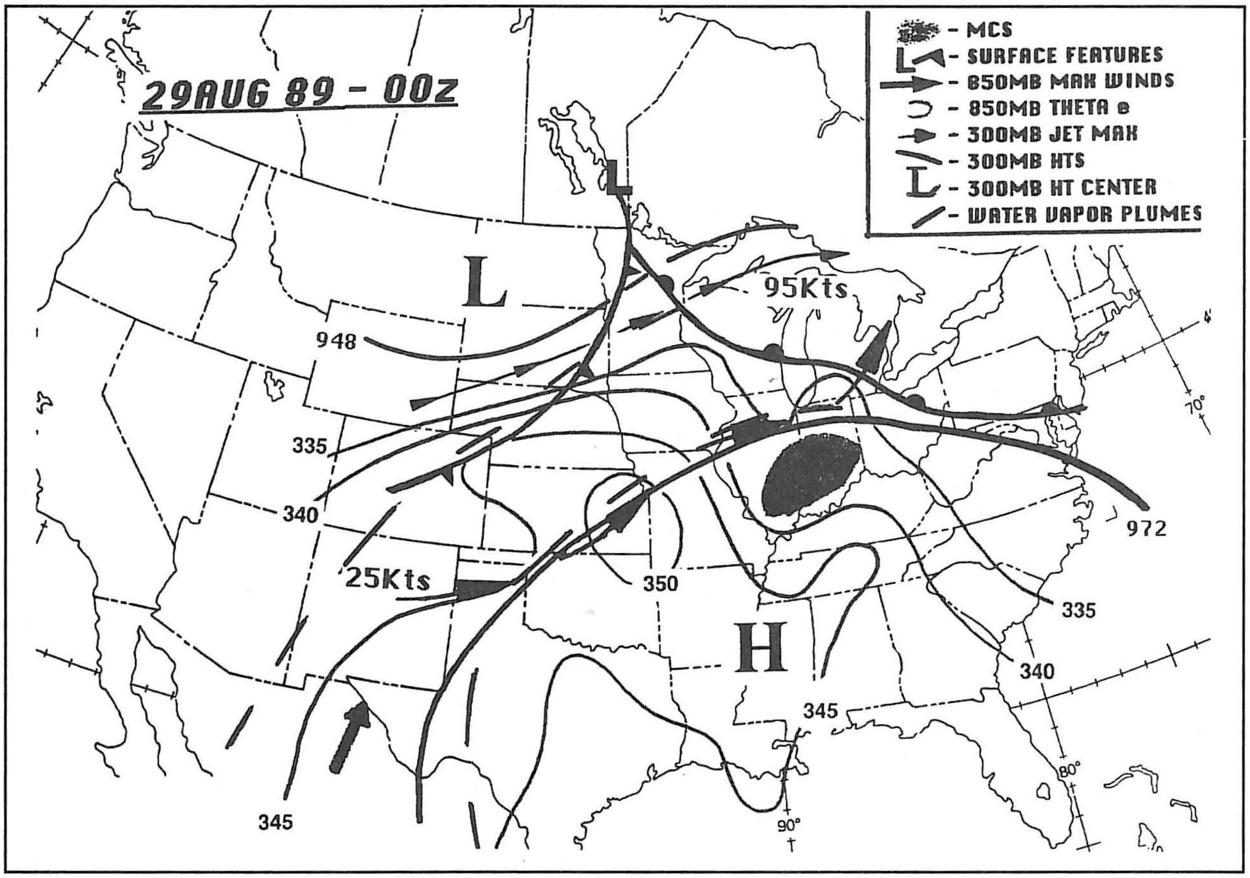

Fig. 24. Surface and upper air composite of meteorological features associated with extreme heavy rainfall MCSs for 0000 GMT 29 August 1989.

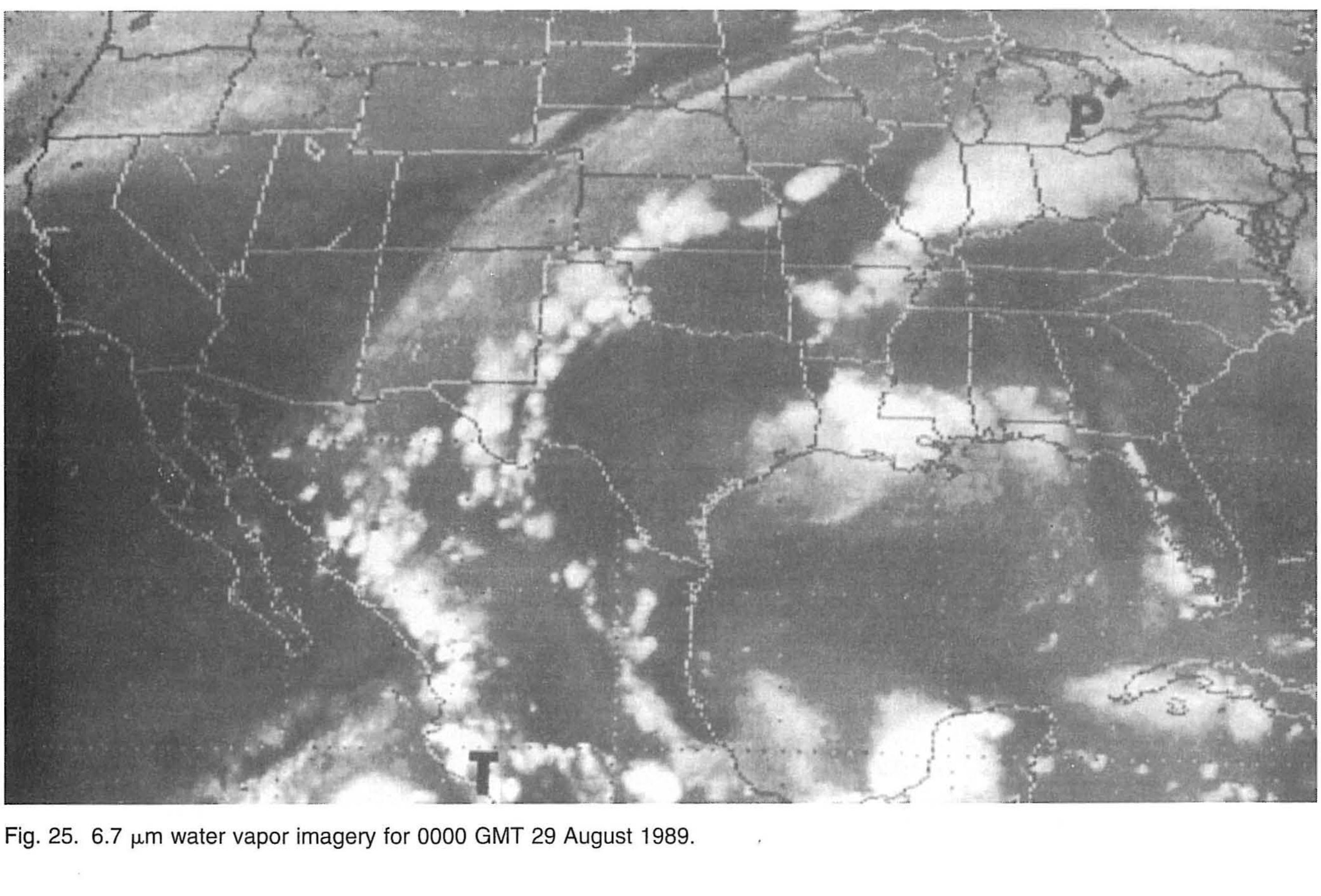

Fig. 25. 6.7 μm water vapor imagery for 0000 GMT 29 August 1989.

spectral images, GOES 8 and 9-derived sounding data, and SSM/I data, a better understanding of the multiscale nature of heavy precipitation will be achieved. As a result, this "better understanding" will allow us to modify and refine the conceptual models and the satellite forecasting funnel (Thiao et al. 1993) for predicting heavy precipitation.

Acknowledgments

The authors thank Frances Holt and Donald Miller of the Satellite Applications Laboratory of NESDIS and LeRoy Spayd, Jr., Training Program Leader for the NWS, for their constructive criticism in the preparation of this manuscript. Special thanks goes to Roger Weldon for his help on our case studies and to Sheldon Kusselson of the Synoptic Analysis Branch of NESDIS for his enlightening discussions. Finally, we thank Lori Paschal and John Shadid for the layout and Paige Bridges, Phil Golden, John Shadid, and Dick Pritchard, for the preparation of the illustrations.

This work was done while the first author held a USA National Research Council Research Associateship at NOAA, NESDIS, SAL.

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