FORECASTING TECHNIQUES

Forecasting Techniques Utilized by the Forecast Branch of the National Meteorological Center During a Major Convective Rainfall Event

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ABSTRACT

Meteorologists within the Forecast Branch (FB) of the National Meteorological Center (NMC) produce operational quantitative precipitation forecasts (QPFs). These manual forecasts are prepared utilizing various forecasting techniques, which are based on the subjective analysis and interpretation of the observed data and numerical model output. The manual QPFs from NMC generally have proven very successful in improving model QPF.

This paper discusses several of the forecasting techniques employed by the FB, emphasizing the importance of subjective interpretation of the model guidance. The use of these methods in preparing a manual QPF for a heavy convective rainfall and flash-flood event that occurred over the southern Plains on 27–28 May 1987 is then examined.

Results indicate that the manual QPF was quite successful in improving the models' QPF and generally related well to the observed rainfall of up to 8 inches in this case. Thus, the importance of utilizing subjective techniques in preparing precipitation forecasts is illustrated.

1. Introduction

The Meteorological Operations Division (MOD) of the National Meteorological Center (NMC) is the national analysis and forecast unit of the National Weather Service (NWS). Within MOD, the Forecast Branch (FB) is responsible for issuing operational heavy rainfall and snowfall forecasts for the contiguous United States through the use of surface, upper-air, radar, satellite, and numerical model data. In preparing forecasts, FB meteorologists employ the so-called "man–machine" concept (National Weather Service 1981), whereby the forecaster utilizes personal experience and knowledge to interpret subjectively the objective numerical model guidance. The subjective model interpretation provided at NMC is an important part of the total NMC guidance package that is transmitted to local NWS forecast offices and private users. Additional information concerning the FB and other MOD products is provided by Corfidi and Comba (1989).

In general, model forecasts of convective rainfall amounts and locations are often inadequate (Junker and Hoke 1990). For example, the nested-grid model (NGM) substantially underforecasts convective rainfall amounts (by a factor of two or more) over the eastern two-thirds of the United States in the presence of moderate-to-strong low-level inflow from the Gulf of Mexico. The model also occasionally underforecasts the speed of heavy rainfall events that exceed one-half-inch. In addition, the NGM, the limited-area fine mesh (LFM) model, and the global spectral (AVN) model generally all underforecast (bias less than unity) the areal extent of one-inch-or-greater convective rainfall amounts. Factors that restrain the NGM from predicting heavy convective rainfall have been explained in detail by Junker and Hoke (1990). These factors include 1) the small horizontal scale of convective rainfall events with respect to the NGM's (as well as the LFM's and AVN's) resolution, 2) the Kuo (1965) convective parameterization scheme within the NGM, which tends to stabilize the atmosphere by releasing latent heat higher in the vertical than would normally occur, and 3) the use of climatological values of moisture availability over land within the NGM.

Over the years, subjective quantitative precipitation forecasts (QPFs) produced within the FB have consistently shown improvement over model QPFs. This is depicted in Fig. 1, in which monthly threat scores, indicative of forecast accuracy, are shown for FB meteo-

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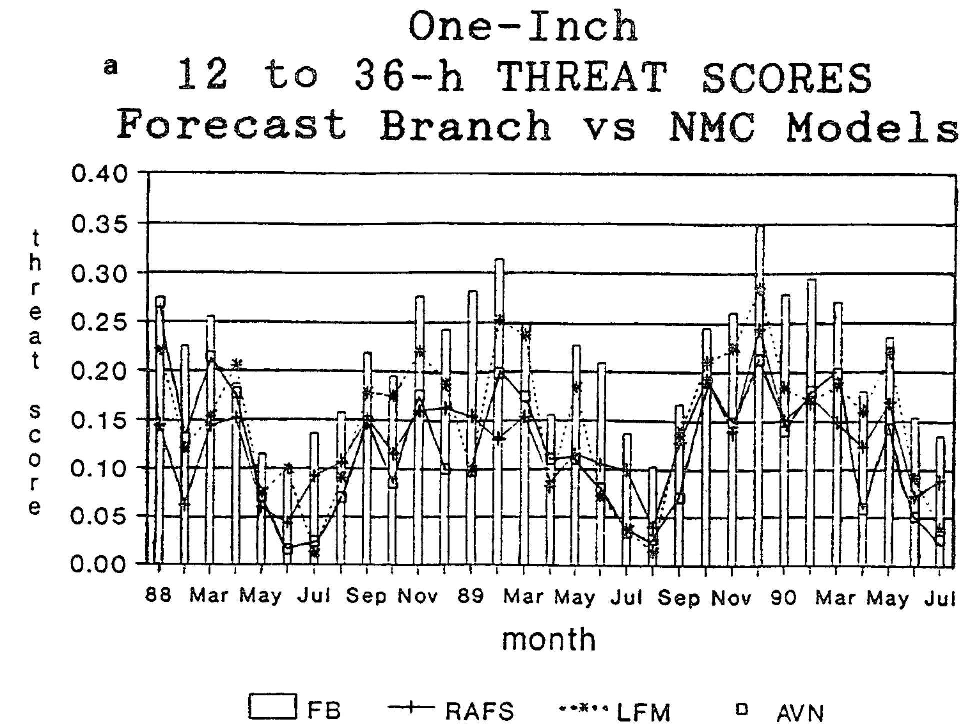
a



b

THREAT SCORES
MANUAL VS MODELS
Day 2 Manual vs Day 1 Models

Aug 90		Day 1	Day 2
RAFS	.50"	.171	- -
AVN	"	.074	.084
LFM	"	.094	- -
Manual	"	.235	.196
RAFS	1.00"	.038	- -
AVN	"	.013	.007
LFM	"	.002	- -
Manual	"	.146	.089
Jan 90			
RAFS	1.00"	.151	- -
AVN	"	.140	.038
LFM	"	.184	- -
Manual	"	.279	.202

FIG. 1. Monthly threat scores of one-inch rainfall amounts for the day 1 (12- to 36-h) forecast period since 1988 for NMC's Forecast Branch (FB) and for the NGM, LFM, and AVN (a). Also, day 1 and day 2 (36- to 60-h forecast) model and manual (FB) threat scores for half-inch and one-inch rainfall amounts for January and August 1990 (b).

rologists and the numerical models (Mostek and Junker 1989). Figure 1a reveals that the FB's national threat scores for forecast one-inch amounts since 1988 were consistently above that of the models. Figure 1b shows that the manual (FB) forecast scores for August 1990 and January 1990 were better than the models

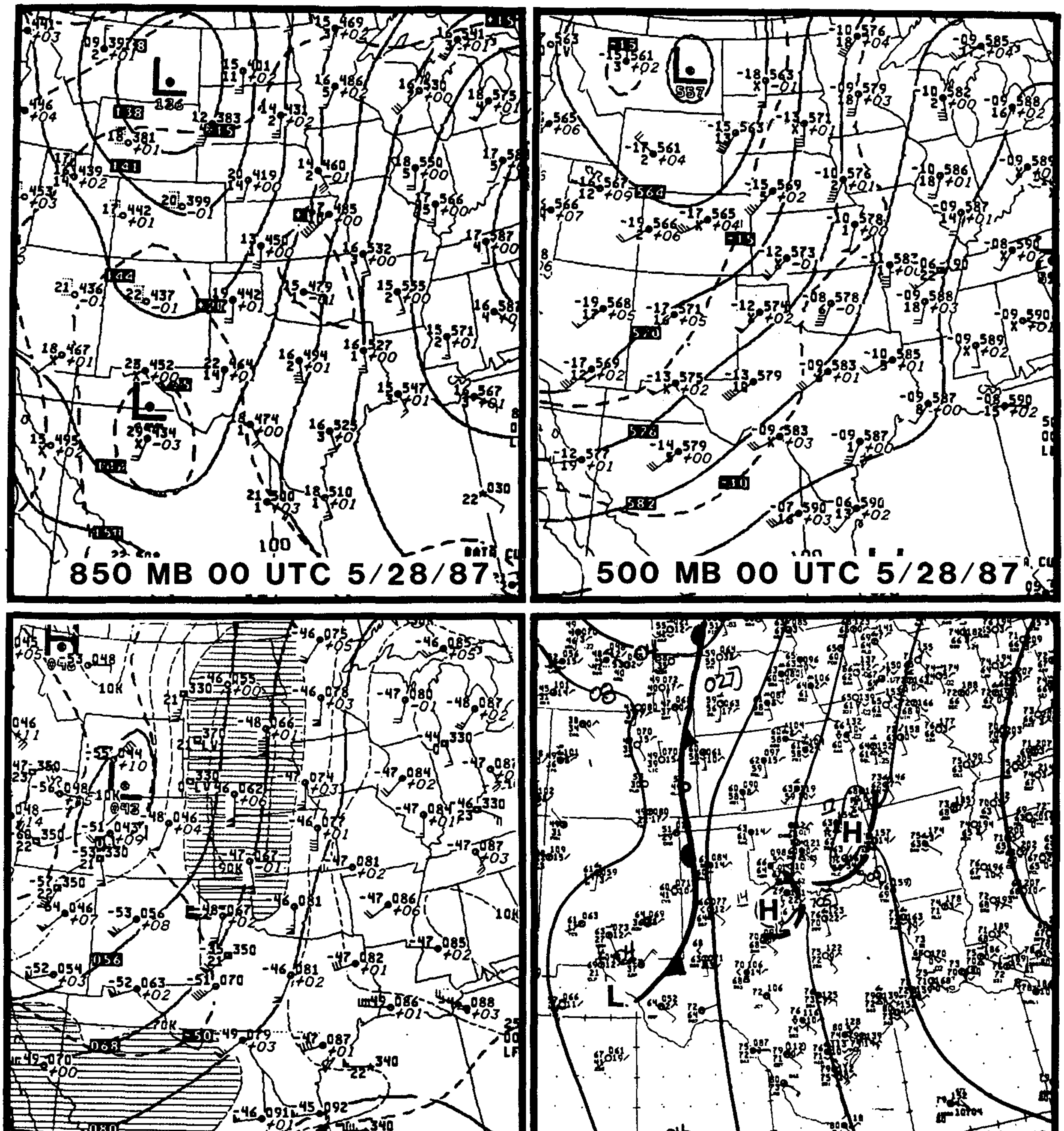


FIG. 2. Observed upper-air data at 0000 UTC 28 May 1987 and surface chart at 0600 UTC 28 May 1987.

for both half-inch and one-inch amounts. In fact, day 2 (36- to 60-h forecast) FB scores were better than the models' day 1 (12- to 36-h forecast) results. Thus, it is clear that manual interpretation of model data is critical for QPF preparation.

Subjective forecasts incorporate knowledge of model strengths and weaknesses as well as various forecasting techniques developed by NMC. These techniques are based on empirical relationships of various meteorological parameters to heavy precipitation, and rely, in part, on conceptual models for heavy rainfall, such as those described by Maddox et al. (1979) and Spayd and Scofield (1983). This paper discusses the importance of pattern recognition as well as several of the

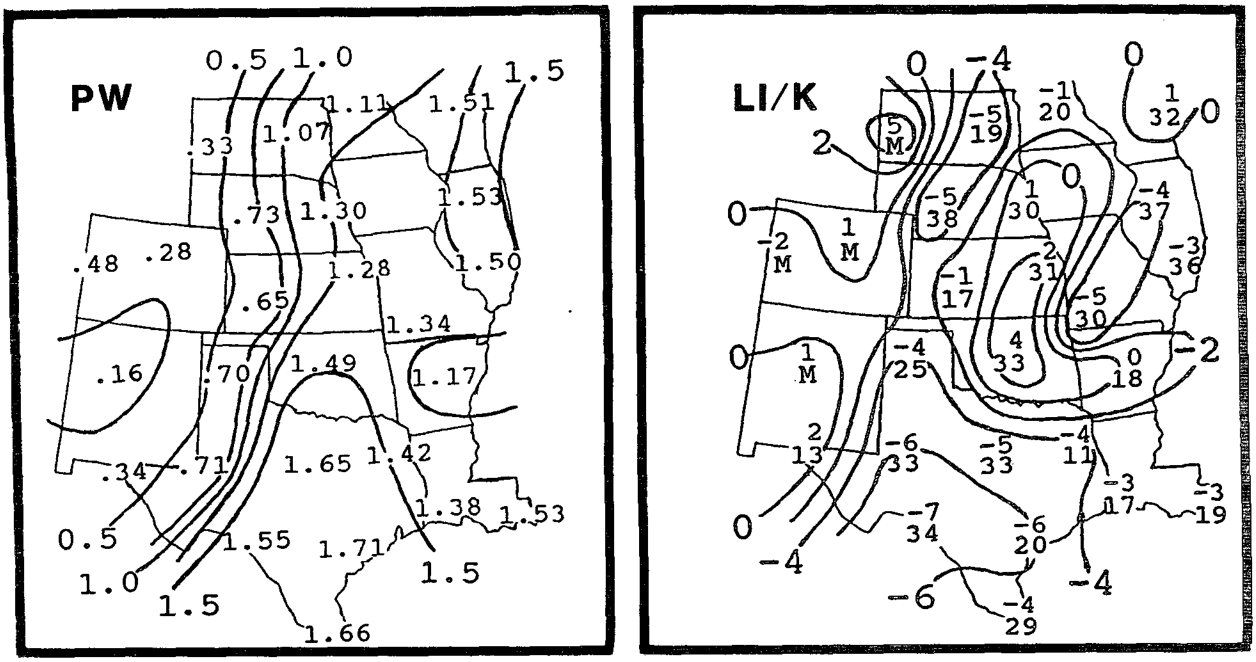


FIG. 3. Precipitable water (*PW*, in inches) and lifted index (*LI*, top number, contoured)/*K* index (bottom number) at 0000 UTC 28 May 1987.

empirical methods that the FB utilizes to modify model QPFs and prepare manual 24-h QPFs and excessive rainfall potential outlooks. These schemes include the relationship of heavy rainfall to moisture availability, low-level inflow, jet-stream structure, low-level equivalent potential temperature (θe), thickness values and patterns, and several empirical "rules of thumb." In discussing these techniques, the period of 28–29 May 1987 is examined, which featured heavy-to-excessive convective rainfall and flash flooding across Texas and Oklahoma. The case was selected because it provided an excellent illustration of how the above schemes are employed operationally to alter model guidance and prepare subjective QPFs for major rainfall events.

2. Synoptic situation

The 24-h forecast period in this case was valid from 1200 UTC 28 May to 1200 UTC 29 May 1987. The 0000 UTC 28 May model and upper-air information, and the latest surface, radar, and satellite data up to 1000 UTC (release time for the FB's final 24-h QPF) were available as forecast input. The upper-air data (Fig. 2) revealed southerly, very moist flow at 850 mb (dewpoints 12° to 17°C) across the southern Plains, while an upstream trough axis at 500 mb maintained southwesterly flow across the region. In addition, diffluence existed at 250 mb over the southern Plains between the polar jet across the central Plains and the subtropical jet over Mexico. The 0600 UTC surface chart (Fig. 2) showed warm, moist air [temperatures and dewpoints generally in the 70s (°F)] extending northward through Texas ahead of a stationary front, while convective outflow boundaries were evident over northern Texas and Oklahoma. (A mesoanalysis of the 0600 UTC surface chart is shown later.) High precipitable water (*PW*) values and very unstable air also existed over the southern Plains (Fig. 3). Meanwhile, satellite imagery (Fig. 4) depicted a mesoscale convective system (MCS) across Oklahoma during the period 0030 through 0930 UTC 28 May, with a new area of developing thunderstorms over western Texas near the end of this period.

3. Model forecast guidance

Numerical model guidance from 0000 UTC 28 May indicated that synoptic conditions would change little during the forecast period (i.e., the 12- to 36-h model forecast period). The 500-mb analysis from the LFM and the 12- to 36-h forecast from the NGM (Fig. 5) showed weak shortwaves rotating through a quasi-stationary longwave trough axis over the southwestern United States. Despite the presence of these shortwaves, geopotential height values were forecast to remain nearly constant across the south-central United States. The LFM analysis and NGM 12- to 36-h surface forecast (Fig. 6) and NGM 24-h, 850-mb prog (Fig. 7a) indicated that strong southerly flow would continue across the central part of the nation similar to that observed at 0000 and 0600 UTC 28 May (Fig. 2). The NGM 24-h, 250-mb jet-stream forecast (Fig. 7b)

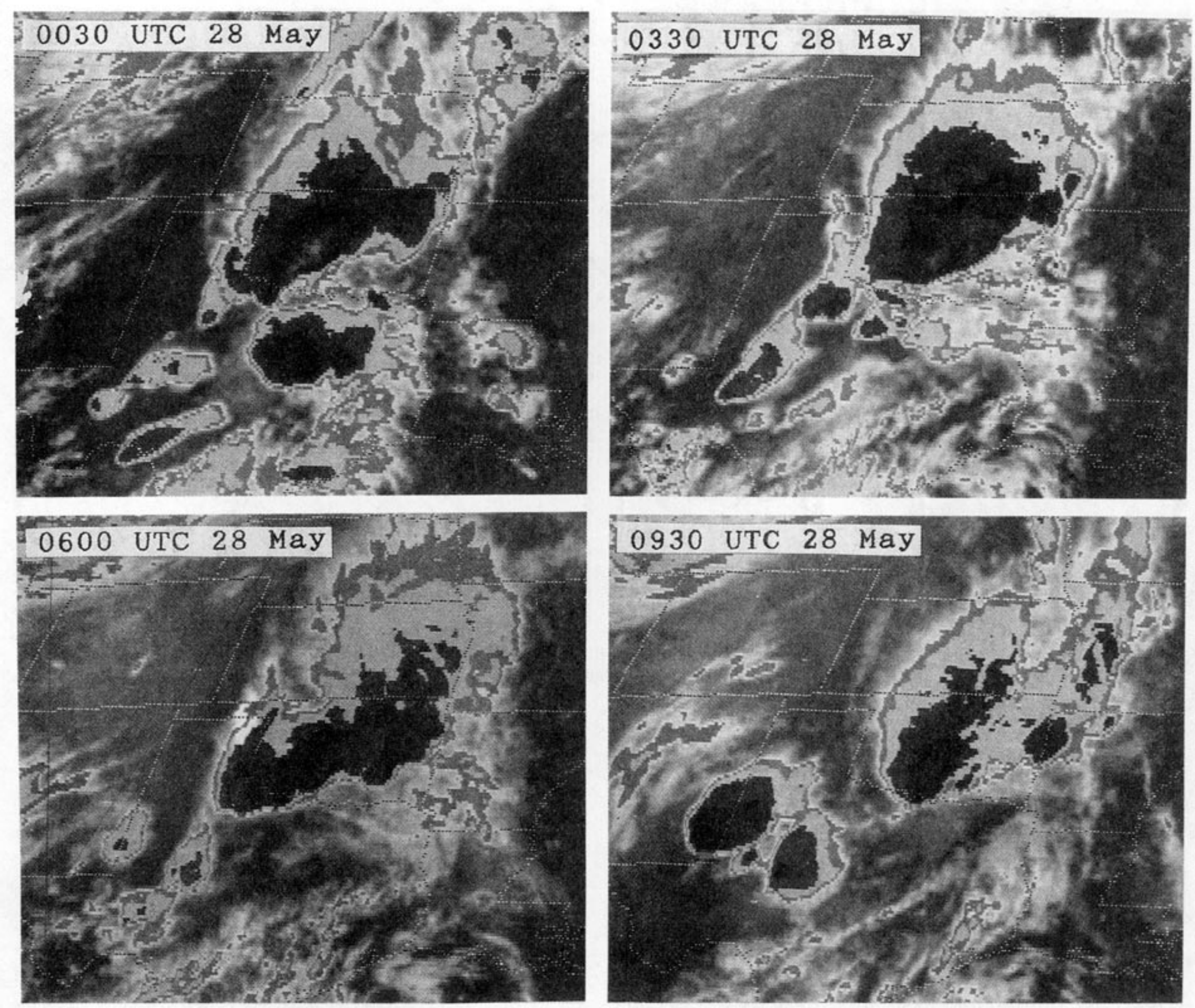


FIG. 4. Enhanced IR satellite imagery (MB enhancement curve) from 0030 to 0930 UTC 28 May 1987.

showed the polar jet over the Plains and the subtropical jet over Mexico, similar to that observed 24 h earlier (Fig. 2).

The models' 24-h composite QPFs (valid for the same time period and used as general guidance for the FB's manual QPF) are shown in Fig. 8. The NGM QPF predicted over an inch of rain from southwestern Texas to eastern Iowa, with a 2.18-inch (55-mm) maximum located in southern Kansas (Fig. 8a). The 24-h LFM QPF (Fig. 8b) predicted a maximum over Oklahoma with heavy amounts extending northward into Iowa, although much of this rainfall was erroneously related to an apparent model convective-feedback problem (as discussed later). Finally, QPF from the AVN model (available at NMC) (Fig. 8c) focused the maximum rainfall over Oklahoma, eastern Kansas, and western Missouri.

In general, for any particular situation, mass, wind, and precipitation forecasts from the NGM, LFM, and AVN models will differ from one another to varying degrees. These discrepancies are related to inherent differences in the analysis and forecast component of each model, as described by Gerrity (1977), Hoke et al. (1989), and Kanamitsu (1989), among others. As a result, the models each exhibit certain strengths, weaknesses, and biases that affect their QPF performance (Junker et al. 1989). Other model limitations include 1) the limited observed-data network, especially over the Pacific and Atlantic oceans and Gulf of Mexico, which influences the models' ability to forecast precipitation, and 2) the simplifying assumptions contained within numerical weather prediction. For these reasons, model output cannot be utilized directly for producing a QPF. Instead, forecaster intervention is critical to

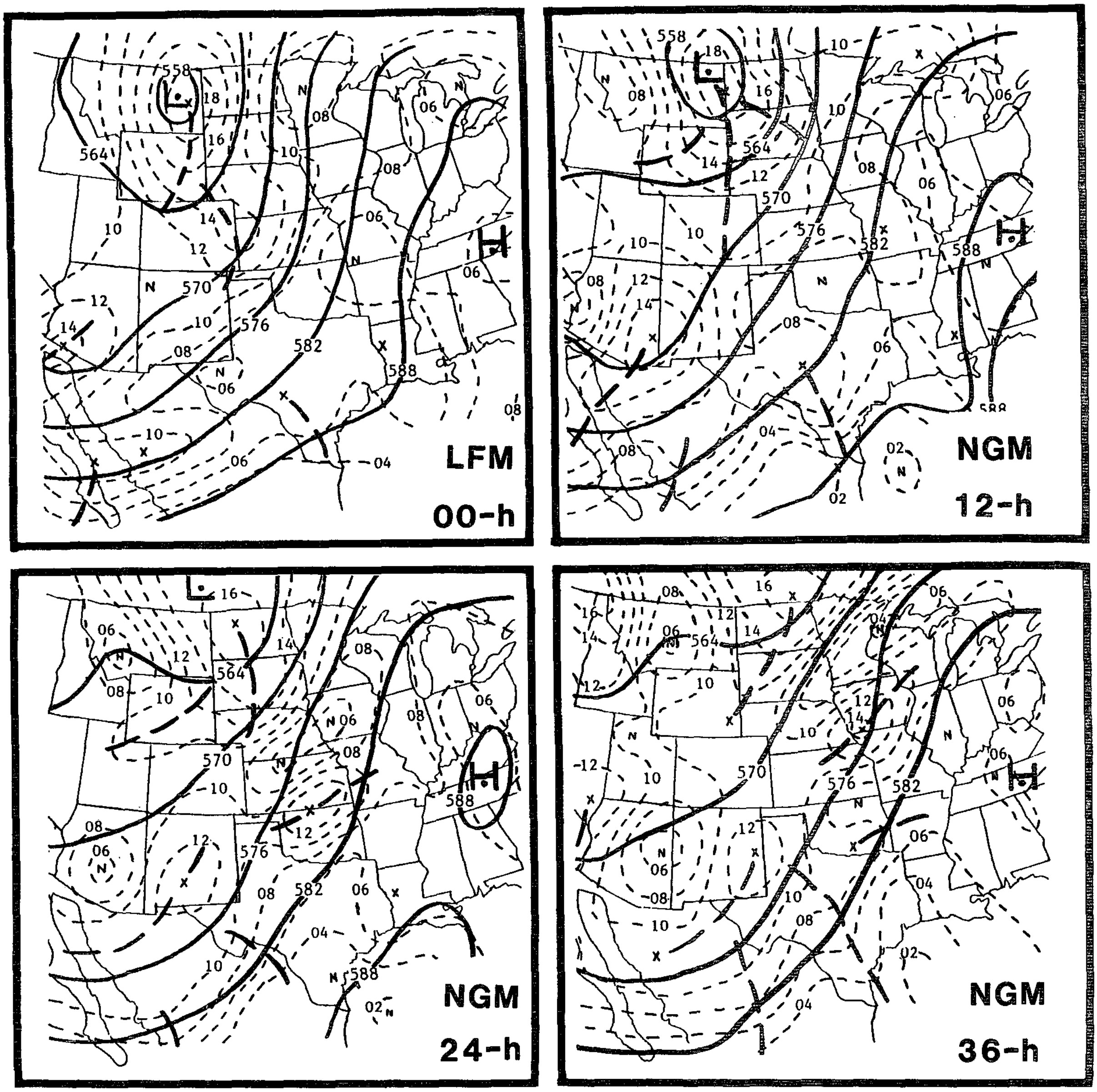


FIG. 5. LFM analysis and NGM 12- to 36-h forecast of 500-mb heights (bold solid lines) and vorticity (thin dashed lines) from 0000 UTC 28 May 1987. The bold dashed lines represent the locations of shortwave trough axes.

recognize typical model idiosyncrasies, determine which model forecast appears most reasonable, and make adjustments in models' mass, wind, and QPF output, as necessary. In adjusting the models' QPF, several forecasting techniques are employed by FB meteorologists as described below.

4. Forecasting techniques

a. Pattern recognition

Pattern recognition is extremely important and is the foundation for forecasting heavy precipitation within the FB. It is essential that FB forecasters recognize the various synoptic and mesoscale patterns within the observed and forecast data that produce heavy or excessive rainfall. Pattern-recognition skills are built upon 1) a thorough knowledge and understanding of heavy rainfall climatology, including spatial and temporal frequency distributions of the various types of heavy-precipitation-producing systems that affect the United States, and 2) conscious recall of previous heavy rainfall events within specific synoptic and mesoscale environments.

Maddox et al. (1979), Spayd and Scofield (1983),

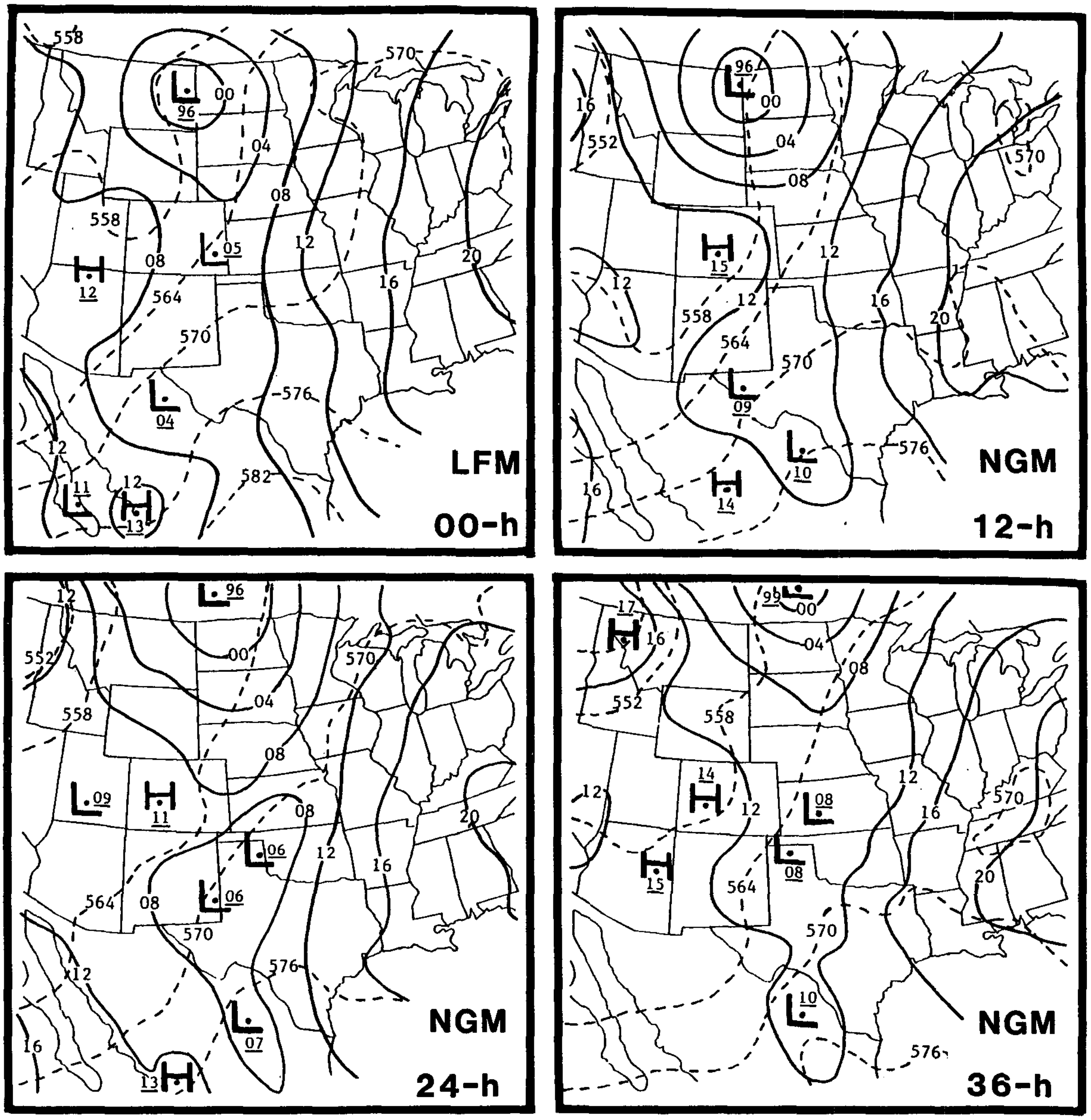


FIG. 6. LFM analysis and NGM 12- to 36-h forecast of surface and 1000–500-mb thickness (dashed lines) from 0000 UTC 28 May 1987.

and Fleming and Spayd (1986) have developed atmospheric composites of several environments conducive to heavy rainfall and flash flooding. In addition, Funk (1987), Fleming and Spayd (1986), Fleming et al. (1984), and Hoxit et al. (1978) have categorized the types and frequency distributions (monthly and diurnal) of convective systems over specific regions of the country. These studies reveal that many convective flash-flood events over the central United States occur at night, while the majority of those in the western and eastern United States occur during the afternoon and evening. Finally, Scofield (1985) has also presented characteristics of heavy-rainfall-producing convective systems in satellite, conventional, and radar data. In general, very heavy rainfall and significant flash flooding are associated with convective systems that are long-lived, quasi-stationary or slow-moving, and/or regenerative over the same area.

In this case, the observed surface and upper-air data prior to the forecast period (Fig. 2) shared quite similar characteristics with the Maddox et al. (1979) "synoptic"-type heavy convective rainfall and flash-flood conceptual model (Fig. 9). "Synoptic" events are categorized by weak shortwaves at 500 mb within a slow-

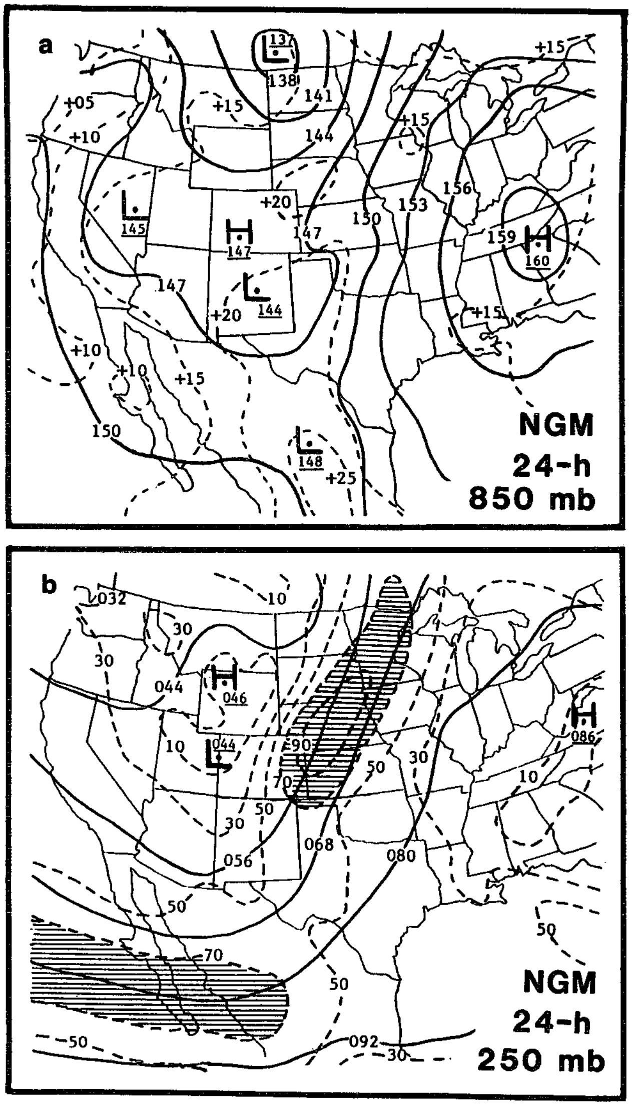


FIG. 7. NGM 24-h 850-mb forecast from 0000 UTC 28 May 1987 (a), where dashed lines are temperatures in degrees C. Also, NGM 24-h 250-mb forecast (b), where dashed lines are isotachs in knots.

moving longwave trough, a surface front that is often quasi-stationary, and convection that regenerates and propagates over the same general area. In addition, a mesoanalysis of the 0600 UTC 28 May surface chart (Fig. 10) was characteristic of the Maddox et al. (1979) "mesohigh"-type event (not shown), in which convective outflow boundaries focus the necessary convergence for new thunderstorm development. In the current case, well-defined surface-outflow boundaries and mesohighs (also known as "bubble" highs) were evident at 0600 UTC 28 May over the southern Plains (Fig. 10). One boundary extended from southwestern Missouri to southern Oklahoma, while another bowed across north-central Texas. The mesoscale boundaries were providing surface convergence for ongoing convection over Oklahoma and northern Texas prior to the forecast period (Fig. 4). In addition, the numerical model guidance (Figs. 5, 6, and 7) suggested that the overall synoptic pattern would change little during the 24-h forecast period. Thus, FB forecasters recognized that a potentially heavy-to-excessive convective rainfall and flash-flood event would occur over the southern Plains.

b. Moisture availability

It is well known that high ambient and/or inflow moisture must be present and maintained for an extended period of time for a heavy or excessive convective rainfall event to occur. Moisture availability and depth are best indicated by PW values and the *K* index. As empirically determined by FB meteorologists, critical PW and *K* values (ambient or inflow) for heavy rainfall generally are above one inch and above 30, respectively. In fact, a *K* value approaching or exceeding 40 indicates a very good potential for heavy or excessive rainfall. In the warm season, high ambient or inflow surface dewpoints exceeding about 17°C and 850-mb dewpoints approaching or especially exceeding 12°C are also good indicators for heavy rainfall. Dewpoints below these values may still be adequate for heavy rainfall during the winter season. In this case, the observed (Fig. 3) and model-forecasted (not shown) PW values across the southern Plains were at or above 1.50 inches (38 mm) throughout the period, while that of the *K* index (observed values in Fig. 3) were in the lower-to-middle 30s.

An invaluable tool in assessing moisture availability within NMC is the VAS Data Utilization Center (VDUC), as described by Mostek and Siebers (1987). Among a wide range of capabilities, this system allows NMC forecasters to view and animate graphics of model-forecasted PW values, which are of great value in determining potential rainfall amounts and locations.

c. Low-level inflow and convergence

An important ingredient considered in forecasting heavy precipitation is the degree of low-level (surface and 850-mb) inflow and convergence. Experienced NMC QPF forecasters have determined that the center of the initial low-level inflow generally is a favorable location for the maximum convective rainfall over the following 12 to 24 h. In addition, persistent moderate-to-strong moist southerly inflow of 30 kt (15 m s^{-1}) or more converging toward a quasi-stationary surface to 850-mb frontal or outflow boundary (especially those that are east–west oriented) often signifies the possibility of heavy-to-excessive convective rainfall amounts approaching or exceeding 5 inches (127 mm) in a 24-h period. In this case, significant observed

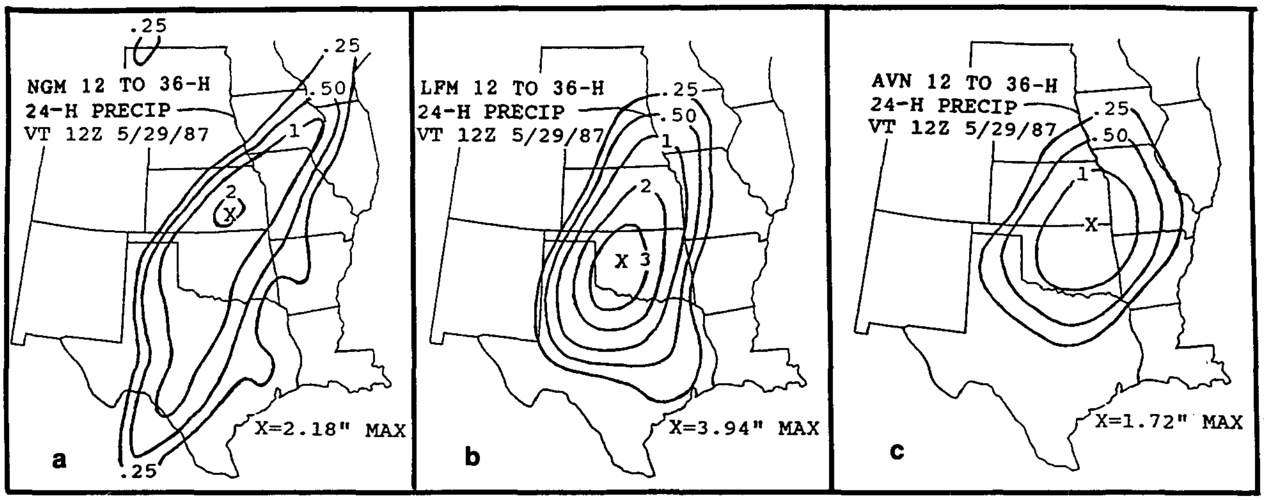


FIG. 8. Model 24-h QPF from the NGM (a), LFM (b), and AVN (c) from 0000 UTC 28 May 1987. Valid period 1200 UTC 28 May to 1200 UTC 29 May.

southerly convergent inflow (Figs. 2 and 10) was forecast to continue throughout much of the 24-h period over the southern Plains (Figs. 6 and 7). Therefore, the potential existed for very heavy rainfall amounts over Texas and southern Oklahoma, generally south of model QPF guidance (Fig. 8).

d. Jet-stream structure

The structure of upper-level jet streams and especially jet streaks is extremely important for developing and maintaining convection. Riehl et al. (1952) and Beebe and Bates (1955), among others, showed that upper-level divergence associated with a straight jet streak produces upward vertical motion in the left exit (front) and right entrance (rear) quadrants of the jet streak. In addition, Uccellini and Johnson (1979) showed how the intensification of the low-level jet is coupled to the mass adjustment within the exit region of an upper-level jet streak. This coupling process provides a basis within which the veering of the wind with height can convectively destabilize the preconvective environment and force the low-level moisture transport toward a region where the upper-level divergence is increasing with time.

In this case, the observed (Fig. 2) and forecast (Fig. 7b) 250-mb wind charts revealed that both the right entrance region of the polar jet and the left exit region of the subtropical jet were positioned over Texas. Thus, this coupling of both favored quadrants of two independent jet streaks implied strong upper-level diffluence, which could act to focus and intensify the southerly low-level inflow and convergence, thereby greatly enhancing the vertical motion and potential for a

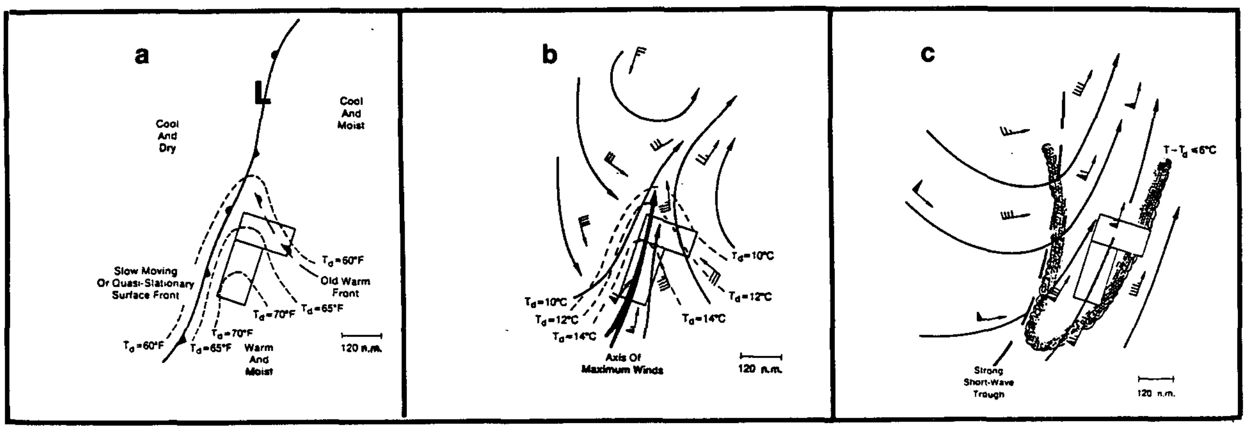


FIG. 9. Typical environmental pattern at the surface (a), 850 mb (b), and 500 mb (c) for the Maddox et al. (1979) "synoptic"-type flash-flood event. Rectangles indicate the likely location of maximum convective rainfall. Winds are in knots, with a full barb equal to 10 kt (5 m s^{-1}) and a flag equal to 50 kt (25 m s^{-1}).

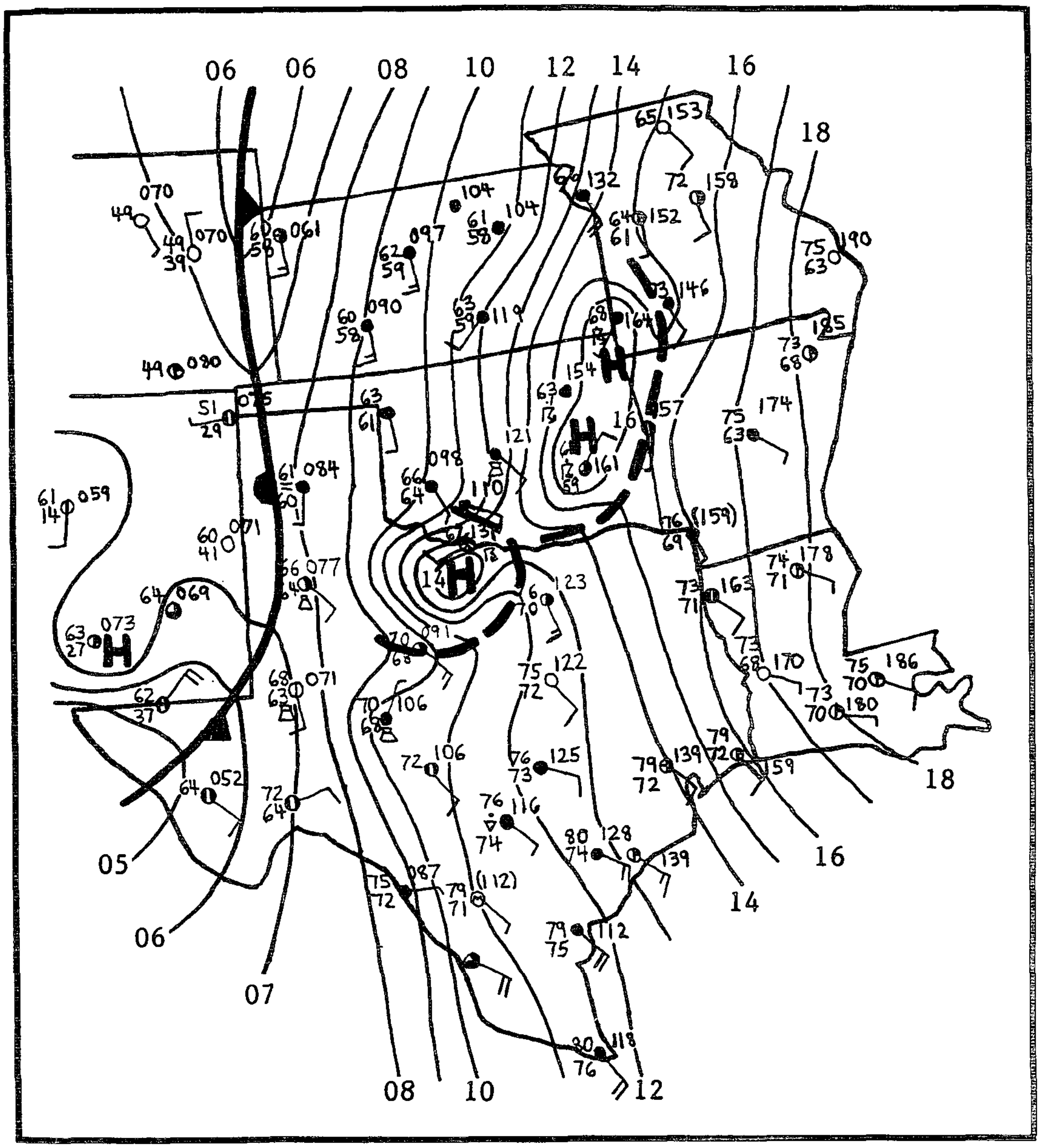


FIG. 10. Mesoanalysis of the surface chart at 0600 UTC 28 May 1987. Thin solid lines are isobars at 1-mb increments (label of 08 = 1008 mb). The bold solid line is the synoptic-scale front, while bold dashed lines are analyzed mesoscale outflow boundaries.

steady-state or regenerative convective system over Texas. This location is south of where all the numerical models were predicting the heaviest precipitation (Fig. 8). Belville and Stewart (1983) have documented similar upper-level jet streak coupling and its association to heavy convective rainfall across the lower Mississippi Valley.

e. Low-level equivalent potential temperature

Equivalent potential temperature (θe) is a thermodynamic property dependent on moisture and temperature, where higher values represent a warmer and/or wetter air mass that is more conducive to convective development. Juying and Scofield (1989) and Shi and Scofield (1987) have shown that warm-sector convection often develops along or near the θe ridge axis at 850 mb in the presence of unstable air and a lifting mechanism. Assuming upstream instability and low-level inflow directed toward the convective system are maintained, the convection may then either 1) propagate upstream along the ridge axis toward higher values of θe, or 2) propagate downstream within moderate-to-strong middle-level winds but with possible

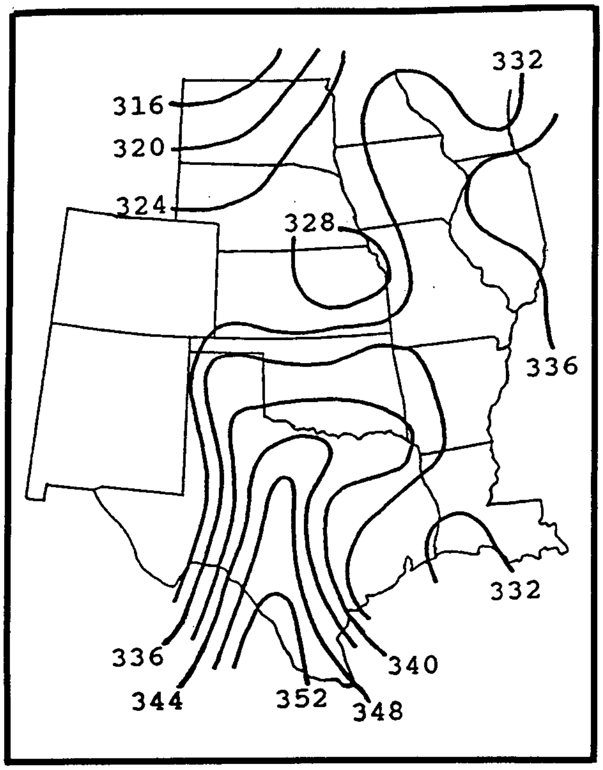


FIG. 11. 850-mb equivalent potential temperature (θe) analysis (K) at 0000 UTC 28 May 1987.

regenerative cells developing within the higher θe air upwind of the convective system.

In this event, the 850-mb θe analysis at 0000 UTC 28 May (Fig. 11) showed a very pronounced ridge axis over western Texas with highest values across southwestern Texas and lower values extending from Oklahoma northward. Therefore, the θe analysis also suggested that the heaviest convective rainfall likely would remain across Texas and southern Oklahoma during most of the period, as the overall synoptic pattern was expected to change very little (Figs. 5, 6, and 7).

f. Thickness diffluence

Warm-sector convection has been observed by NMC forecasters to develop frequently near or within a region where the 1000–500-mb thickness isopleths are diffluent. Thickness diffluence can imply an alongstream variation in the geostrophic wind, or where the ageostrophic flow and upper-level divergence likely would exist in the exit region of a jet streak (Uccellini and Johnson 1979).

Illustrations of two possible ways thickness diffluence can occur are presented in Fig. 12 (figure provided by Fritsch, personal communication). In the first example (Fig. 12a), *Vu* (the upper-level geostrophic wind) is the same at points A and B, while *Vl* (the lower-level geostrophic wind) is greater at B than at A. Thus, the thermal wind (*Vth*), which parallels the thickness contours and is defined as the vector difference between *Vu* and *Vl*, is diffluent. This scenario implies low-level speed convergence and, therefore, possible convection between points A and B. In the second example (Fig. 12b), the thermal wind (thickness) can be diffluent if *Vl* is the same at both points A and B, but if *Vu* turns clockwise from A to B. This implies upper-level diffluence, and again, possible convection in the thickness diffluent region between points A and B. Figures 12a and 12b present only two of several possible ways thickness diffluence can occur. Actual cases may reflect some combination of the two situations shown here. Schematics of thickness diffluence and surface fronts versus possible regions for convective development, assuming enough moisture and lift are present, are shown in Fig. 13.

In general, although model data indicate diffluent thickness regions, no definitive correlation has been noted by FB forecasters between these areas and the models' maximum QPF. Thus, the meteorologist can adjust the location of the models' QPF maximum if warranted. Rainfall placement based on this technique is complicated by various model thickness forecasts that may be potentially incorrect.

In this case, the NGM's 12- to 36-h thickness progs (Fig. 6) revealed that, although the gradient was weak, a broad region of thickness diffluence was forecast over most of Texas and Oklahoma. Therefore, the model

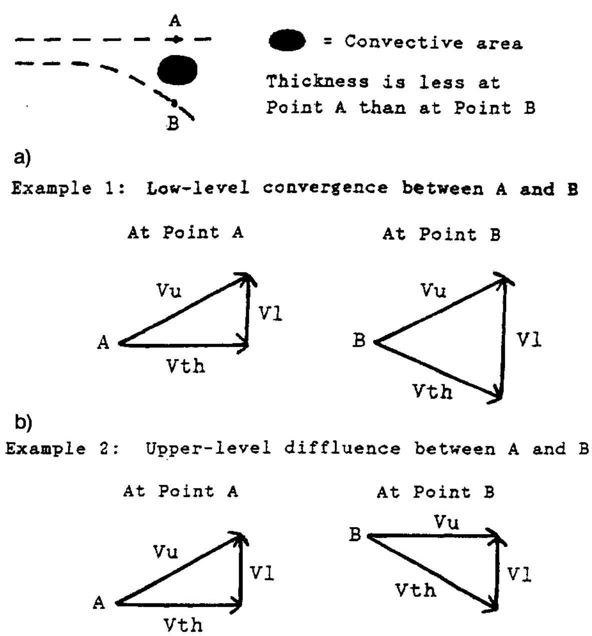


FIG. 12. Vector diagrams showing two possible ways thickness diffluence can occur. Dashed lines are thickness contours; *Vu* and *Vl* are the upper-level and lower-level geostrophic wind, respectively; *Vth* is the thermal wind, which parallels the thickness contours and is defined as the vector difference between *Vu* and *Vl*. The length of the wind vectors is proportional to the wind speeds.

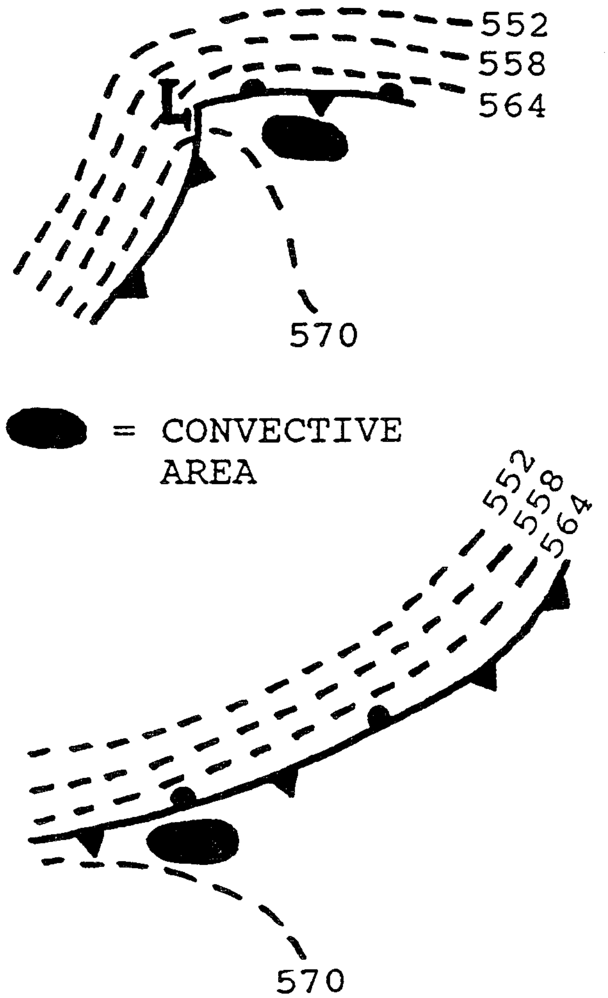


FIG. 13. Schematics of surface fronts and 1000–500-mb thickness configurations (dekameters) versus possible regions of convective development. Convection is depicted within a region of thickness diffluence.

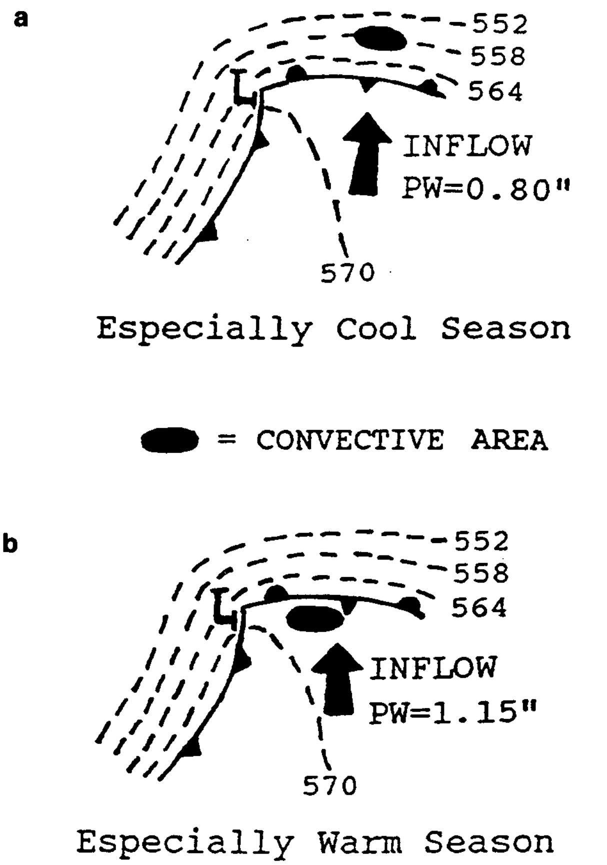
implicitly showed that this general area would remain a favorable region for additional heavy convective rainfall, and not farther north from Kansas to southern Iowa as model QPF indicated (Fig. 8). However, since the forecast region of thickness diffluence was rather broad, exact placement of the manual QPF over Texas and Oklahoma was dependent on other techniques. During heavy rainfall events with greater baroclinicity and thermal contrast, thickness diffluence usually is better defined over a smaller region.

g. Thickness saturation

Through observation and empirically derived relationships between moisture availability and heavy rainfall, FB forecasters have determined that heavy-rainfall-producing convection occurs most often when the ambient or inflow PW values represent approximately 70% saturation of an air column with a given 1000–500-mb thickness value. In other words, the lack of sufficient moisture within a very warm air column (high thickness) usually will preclude organized heavy rainfall. Saturation thickness represents a useful tool for determining the approximate southernmost location for the possible development of deep convection capable of producing heavy rainfall, especially during the warm season when environmental forcing is weak. During this season, model data may predict heavy rainfall over a certain area, but due to sufficient saturation by high ambient or inflow moisture, the convection may actually develop farther south, where the model QPF is too dry (Junker and Hoke 1990). Lowry (1972) has examined saturation thickness and its climatological relationship to PW values and precipitation.

It must be emphasized that this technique is most applicable for mesoscale convective systems that produce organized heavy rainfall. It can be less applicable for scattered diurnal convection and also for severe convection, in which saturation of the air column may be less than 70%. In these cases, sufficient low-level moisture (primarily in the boundary layer) and instability can result in convective cloud development that penetrates through dry air above the boundary layer due to sufficient upward vertical motion. However, severe convection with limited moisture availability may only produce large hail and/or damaging winds without organized heavy rainfall. Hybrid situations also can occur, in which convection may be initially severe, but then later produce heavy rainfall if the convective system is slow-moving and entrains increasingly moist air resulting in sufficient saturation within the convective environment. For example, slow-moving thunderstorms initially produced considerable severe weather, but eventually up to 11 inches of rain and major flash flooding in and near Minneapolis, Minnesota, on 23–24 July 1987 (Schwartz et al. 1990).

Thickness diffluence and thickness saturation cannot be utilized independently. This point is illustrated in Fig. 14 (Bell and Lindner 1982). Considering thickness diffluence only, convective development might be expected within the diffluent region south of the stationary or warm front (Fig. 14a). However, if the inflow air is relatively dry, e.g., PW of 0.80 inches (20 mm) (Fig. 14a), the moisture content would be insufficient to saturate the 5640–5700-gpm thickness values within the diffluent region at the 70% level. Therefore, the air would need to be lifted adiabatically farther north, where it could support heavy-rainfall-producing convection near and north of the 5580-gpm value. This is typical of overrunning convection and cool-season rainfall. Conversely, if the inflow air is relatively moist, e.g., a PW of 1.15 inches (29 mm) (Fig. 14b), it can achieve saturation and thus support organized convection south of the front within the thickness diffluent region. Values of PW necessary to produce 70% satu-



SATURATION THICKNESS

c 70 PCT SATURATION THICKNESS

ΔZ	PW	ΔZ	PW
528	.27	564	1.05
534	.35	567	1.15
540	.43	570	1.25
546	.55	573	1.40
552	.70	576	1.55
558	.80	579	1.70
561	.90	580	1.90

FIG. 14. Precipitable water (PW) values (in inches) needed to produce 70% saturation at the indicated 1000–500-mb thickness values (in dekameters) (c). Also, schematics of possible regions for convective development where 70% thickness saturation is achieved given the indicated inflow PW values (a and b).

ration of the indicated 1000–500-mb thickness values are shown in Fig. 14c. Meteorologists within the FB utilize VDUC to evaluate model PW versus thickness forecasts to determine where saturation will likely occur.

In the current case, the observed (Fig. 3) and forecast (not shown) PW values were at or above 1.50 inches (38 mm) over the southern Plains, more than enough to support convection at the progged thicknesses over the area throughout the 24-h forecast period (Fig. 6). Therefore, given low-level forcing (Figs. 6 and 7a), this factor again warranted a manual adjustment of the QPF farther south into Texas, compared to the models' QPF maximum in Oklahoma and Kansas (Fig. 8).

h. Preferred thickness

Meteorologists within the FB of NMC have noticed that heavy rainfall of an inch (25 mm) or more in a 12-h period tends to fall within a narrow range of 1000–500-mb thickness values, and that this "preferred" thickness ribbon varies according to season, geography, and moisture availability (Bohl and Junker 1987). This particular technique can also be useful in forecasting the location of initial or additional convective development when forcing mechanisms are weak. The scheme generally is less effective during the development or deepening of a major synoptic-scale system. The seasonal and geographical distributions were determined by dividing the country east of the Rocky Mountains (since the technique is less applicable in the western United States) into six sectors in which monthly preferred thickness ranges and median values were calculated. Moisture availability is also important, in that heavy rainfall tends to occur in the upper portion of a thickness range within a very moist air mass and in the lower portion of a range when the ambient or inflow moisture is limited.

Results for areas 3 (Kansas, Missouri, Arkansas, Oklahoma, and northern Texas) and 5 (most of Texas and Louisiana), the regions of concern in this paper, are shown in Fig. 15. The graphs show that the preferred or climatologically favored thickness range across the southern Plains is between approximately 569 and 574 dekameters for late May. In this case, however, the favored value would be in the upper portion of the range, due to the high ambient moisture (Fig. 3). Figure 6 reveals that this preferred thickness range was located across Texas throughout the forecast period, generally south of the models' maximum QPF (Fig. 8).

1) RULES OF THUMB

Based on years of experience and observations of different types of convective systems within various synoptic and mesoscale environments, many empirical "rules of thumb" have been developed by NMC forecasters, which are considered in preparing manual

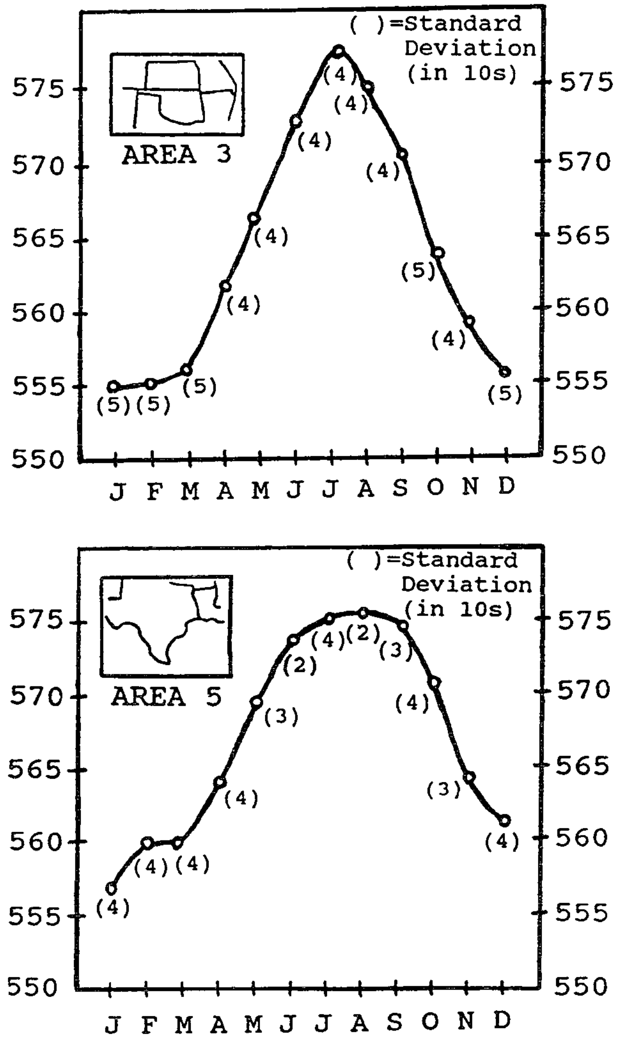


FIG. 15. Monthly preferred 1000–500-mb thickness values (in dekameters) for heavy rainfall over the areas shown in the upper left corner of each diagram. Standard deviation values (in tens of meters) indicate that a narrow range of favored thickness exists for each month.

QPFs and in modifying model guidance. In this study, several of these "rules" applied.

(i) Large-volume convective rainfall tends to be located farther south or southeast with time over the central United States if outflow boundaries from current or previous convection can intercept moist inflow from the Gulf of Mexico. Model data usually fail to resolve these boundaries and, thus, forecast the heaviest rainfall too far north (Olson 1985). However, in some instances, a quasi-stationary convective system can be maintained along or north of an outflow boundary if the southward push of the boundary and low-level convergence is balanced by strong, deep-layered southerly inflow. In this case, moist flow into surface convective outflow boundaries in northern Texas and southern Oklahoma (Fig. 10) and satellite imagery (Fig. 4) suggested additional convection during the forecast period would most likely develop across northern Texas, generally south of model guidance (Fig. 8).

(ii) Using model-forecasted 500-mb absolute vorticity charts, vorticity-minimum ("*N*" on model forecasts) ridge axes often mark the location of heavy convection and maximum rainfall. These ridge axes usually are located near the leading (downstream) edge of the vorticity isopleth gradient. The 24-h NGM 500-mb forecast, valid 0000 UTC 29 May (Fig. 5) (midway through the forecast period and near the maximum diurnal heating time), depicted a generally north–south-oriented vorticity-minimum ridge axis located across central Texas.

(iii) Strong convection can occur *behind* a weak shortwave when moist, unstable inflow continues to be directed toward a low-level boundary. The lift provided by the approaching shortwave may initiate convection, but the impulse is too weak to significantly alter the synoptic-scale situation so that low-level forcing continues after the shortwave passes. Thus, post-shortwave convection and heavy rainfall can continue despite weak negative-vorticity advection (NVA) as the low-level lifting mechanism becomes dominant. This notion is supported in theory by the quasigeostrophic omega equation, as synoptic-scale upward vertical motion can occur due to maximum warm-air advection despite the presence of NVA. In the present case, the NGM 12- to 36-h 500-mb progs (Fig. 5) revealed weak shortwaves in the southwesterly flow across the southern Plains, which would aid thunderstorm development. However, these impulses likely would be unable to end or dislodge all of the activity with their passage, as persistent southerly low-level convergent inflow was forecast throughout the 24-h period (Fig. 6).

(iv) NMC forecasters have noted that when a well-defined connection of mid- and high-level tropical moisture is observed in water vapor imagery, the potential exists for heavier rainfall amounts than would normally be expected given the synoptic situation. Scofield and Robinson (1990) and Johnson and Montimer (1981) have documented this moisture connection and its relationship to heavy convective rainfall over the United States. In this case, the water vapor imagery (not shown) revealed a moisture connection extending from Mexico and the tropical Pacific Ocean northeastward into the southern Plains.

(v) Models are subject to "convective feedback," whereby they develop deep convection and generate high values of vorticity through strong vertical velocities and latent heat release (Koch 1985; Koch et al. 1985). It is true that large amounts of latent heat release within mature mesoscale convective complexes can result in the development of midtropospheric warm-core mesolows and subsequent increases in positive relative vorticity (Maddox 1979; Rasmussen 1979). These "mesoscale vorticity centers" can then move downstream and cause new convective development, given the presence of a convergence boundary within a moist, unstable air mass (Johnston 1982). Unfortunately, these convective-feedback vorticity maxima usually are generated erroneously by model data or else drastically overdone. The model data then advect these vorticity maxima downstream to produce additional rainfall. As a result, the models' QPFs show too much precipitation too far downstream from the actual event (Junker et al. 1989).

In this case, the NGM (Fig. 5), AVN (not shown), and especially the LFM (not shown) all contained an apparent convective-feedback shortwave near the Kansas–Oklahoma border on their 24-h forecast, which the models intensified and advected downstream to near the Nebraska–Iowa border by 36 h. Therefore, the models' QPFs (Fig. 8) likely were depicting too much rainfall too far north, extending in a line directed from Oklahoma to Iowa.

(vi) Finally, FB forecasters have noticed that when warm-season convection develops in Texas within a very moist air mass (PWs well above one inch *and* surface-to-500-mb relative humidities at or above 70%), the convection frequently occurs farther south and/or west in Texas than the models' QPFs suggest.

5. Rainfall forecast from the FB

The manual 24-h QPF issued in this case is shown in Fig. 16. Based on the above techniques and reasoning, excessive convective-rainfall amounts of 5 to 8 inches (127 to 203 mm) were predicted over north-central Texas. These amounts, as indicated in the accompanying manual-QPF discussion (not shown), were based on the persistence of the well-defined outflow boundaries over southern Oklahoma and northern Texas (Fig. 10), which could intercept low-level inflow and, therefore, focus strong moisture convergence throughout much of the forecast period. Overrunning of weakened outflow boundaries would allow moisture to stream farther northward; thus, moderate to heavy amounts were forecast over southern Oklahoma and western Arkansas. Finally, heavy amounts were predicted over southwestern Texas along and east of the synoptic-scale frontal boundary (Fig. 10). Considering the strong steady-state forcing mechanisms throughout the 24-h period, forecast amounts were increased substantially (by a factor of two or more) compared to that predicted by model guidance (Fig. 8). In addition, the above reasoning warranted placement of the heaviest amounts south from where all model guidance indicated.

The accompanying 24-h excessive rainfall outlook (Fig. 16) revealed that rainfall potential exceeded flash-flood guidance values from southwestern Texas to the southern half of Oklahoma. Within this area, the "hatched" region indicated that rainfall potential exceeded 5 inches (127 mm) over north-central Texas during the 24-h forecast period.

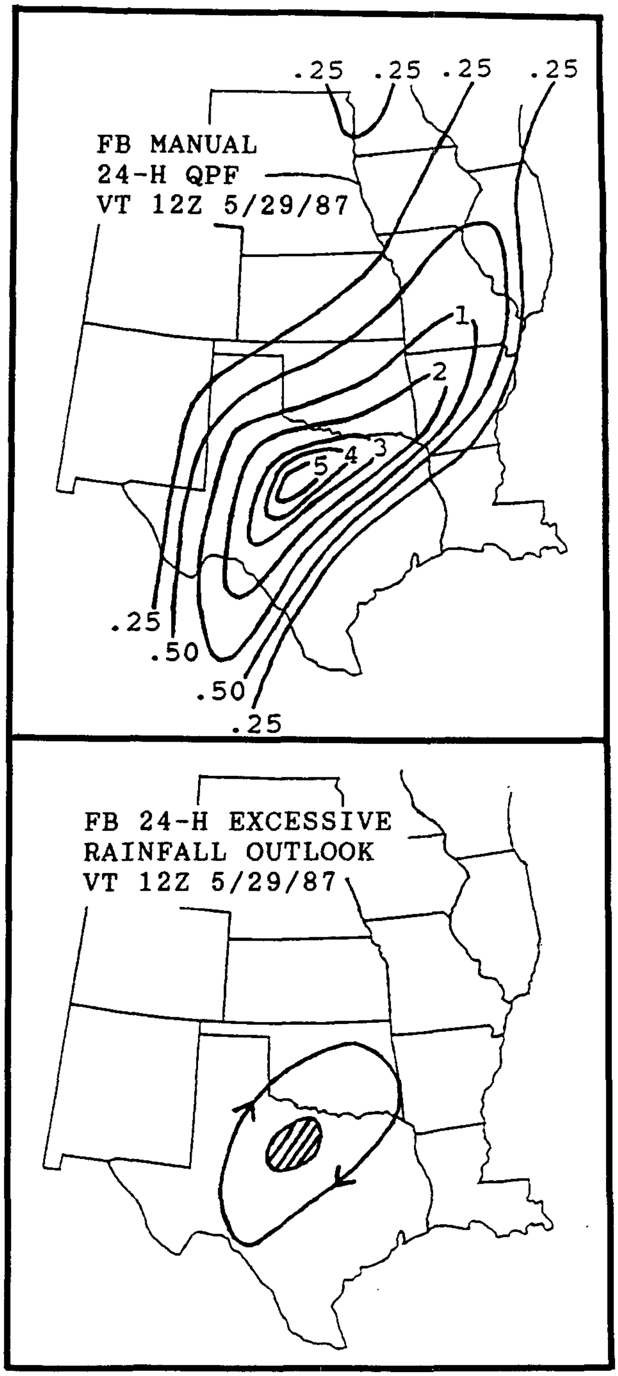


FIG. 16. NMC/FB manual 24-h QPF and excessive rainfall potential outlook valid from 1200 UTC 28 May to 1200 UTC 29 May 1987 (same valid period as in Fig. 8).

6. Forecast verification

Verification for the models' and FB manual 24-h QPFs is shown in Fig. 17. The observed rainfall reports

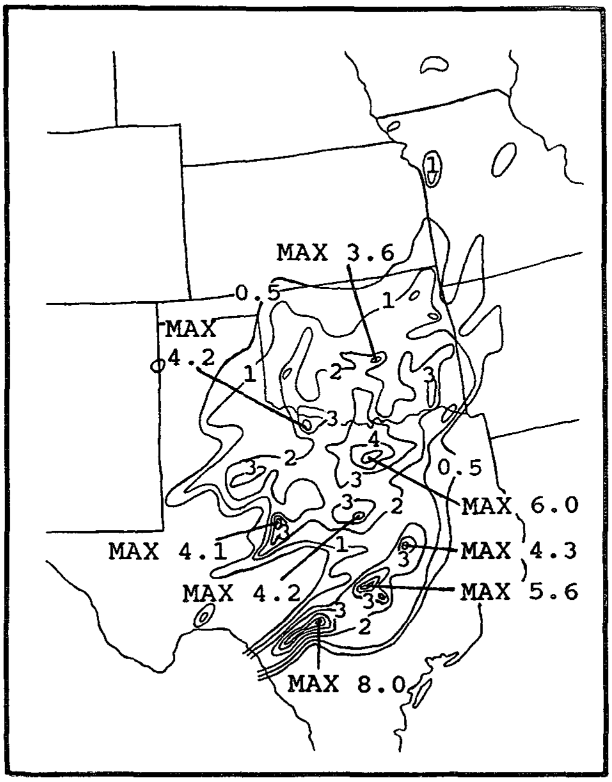


FIG. 17. Observed 24-h rainfall verification data (in inches) from 1200 UTC 28 May to 1200 UTC 29 May 1987.

show that heavy to excessive amounts fell across Texas and southern Oklahoma, with light amounts extending northward into eastern Kansas and Missouri. Generally, 2 to 4 inches (51 to 102 mm) were common across the southern Plains, with maximum amounts of 6 inches (152 mm) located over north-central Texas and an 8-inch (203-mm) report in southwestern Texas. In this case, the heavy convective rainfall amounts over southern Oklahoma and north-central Texas contained no distinct diurnal maximum, as strong convection occurred throughout the 24-h period. However, the narrow axis of 8-inch (203-mm) maximum rain over southwestern Texas resulted from nocturnal MCS development very late in the forecast period. The manual QPF (Fig. 16) compares very well with the heavy to excessive amounts observed across Oklahoma and Texas and the lighter amounts farther north. Conversely, the excessive amounts over southwestern Texas compare less favorably with the manual FB forecast, although this rainfall was handled better by updated 6-hourly QPFs and excessive rainfall potential outlooks issued by the FB later in the forecast period.

The 24-h manual QPF was a large improvement over that from the models (Fig. 8), in that all of the models predicted the heaviest precipitation to occur too far north, except in Oklahoma. In addition, the models substantially underforecast rainfall amounts, despite implicitly showing the potential for heavy to excessive amounts in Texas in the predicted mass and wind fields. The NGM QPF (Fig. 8a), however, was at least on the right track in predicting an axis of heavy rain to be located across southwestern and central Texas. It is clearly evident that the subjective forecasting techniques employed by the FB during this case were quite valuable in generating a QPF that proved much superior to those produced by the numerical models.

7. Summary and conclusion

Many of the parameters and techniques that the Forecast Branch of NMC utilizes operationally to prepare 6-h and 24-h QPFs and excessive rainfall potential outlooks are described. These techniques rely on the subjective interpretation of observed data and numerical model forecasts, and include pattern recognition, moisture availability, low-level inflow, warm-air advection, jet-stream structure, low-level equivalent potential temperature, diffluent, saturation, and climatologically preferred thickness, and several "rules of thumb."

The various techniques have been discussed in relative order of importance. However, if heavy rainfall is expected during periods of weak synoptic and/or mesoscale forcing (e.g., many summertime events), then the latter techniques (thickness considerations and rules of thumb) may become increasingly important. In applying the above techniques, caution must always be exercised. No one scheme can be blindly utilized by itself without consideration of all other parameters. Furthermore, due to the nonlinearity of the atmosphere, the above techniques 1) occasionally may not work well, resulting in a somewhat inaccurate QPF, or 2) may work well in one particular case but not as well in the next, despite the apparent similarity in convective environments. Thus, knowing how and when to apply such techniques in conjunction with other data can be difficult, but is essential in making successful forecasts. Considerable experience and knowledge of the atmosphere, heavy precipitation systems, and the model data, along with a mental image of how various precipitation systems may unfold, are crucial.

In the 28–29 May 1987 case presented in this paper, and in many other events, the QPF forecasters at NMC have been quite successful, as represented by the statistical analysis presented in Fig. 1. However, some situations are not forecast well by model or manual methods. As long as this is the case and the observed-data network remains inadequate to properly represent the intricacies and nonlinearities of the atmosphere, a thorough understanding of meteorological theory and the ability to apply subjective forecasting techniques utilizing objective model guidance will continue to be necessary.

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