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An Operationally Useful Relationship Between the Polar Jet Stream and Heavy Precipitation

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ABSTRACT—The jet stream is recognized as an important atmospheric mechanism for vertical exchange processes. It follows that certain jet stream positions relative to moisture source regions bring about occurrences of extensive heavy rainfall. One type of such occurrence, mainly in the central United States, is identified with a "digging" polar jet stream. To better understand the meteorological relationships involved, we developed composite models from seven representative cases and studied one unusually heavy rainfall situation in more detail. For this type, there is a tendency for heavy rainfall to occur in an ellipsoidal pattern in advance of the polar jet stream.

1. INTRODUCTION

For many years, the jet stream has been acknowledged as a feature of much consequence in the atmospheric circulation. Research at the University of Chicago (1947) showed that there are two predominant, strong wind streams in the middle latitude westerlies: these are identified as the polar-front and subtropical jet streams. A number of investigators have reported on the practical application of jet stream theory to forecasting. The earliest extensive report that comprehensively presented the role of the jet stream in short- and long-range forecasting was by Riehl et al. (1954). Earlier, Fawbush et al. (1951) included the occurrence of a narrow band of stronger winds (exceeding 35 kt) in the middle troposphere as one requirement in a set of simultaneous meteorological criteria for the occurrence of tornadoes. Since then, the use of the jet stream in severe thunderstorm and tornado forecasting has become commonplace. In the present field of aviation, flight planning without winds aloft and jet stream forecast information would be hopeless.

Interest in the relationship between the jet stream and precipitation patterns soon followed the initial recognition of the jet stream as an integral part of the middle latitude atmospheric circulation. Riehl (1948) and Starrett (1949) reported on relationships between precipitation and jet stream patterns. Since then, many authors have commented, mostly in a general way, on observed interrelationships between these two atmospheric phenomena. Some of these appeared to be in conflict, and rightly so, because different authors were reporting on observed precipitation conditions with differing jet stream configurations. Then too, there is the consideration that, in general, the jet stream–precipitation relationship for heavy, convective-type precipitation should differ from that for heavy, stable-type precipitation. In each case under review in this study, the heavy precipitation areas were predominantly of convective nature.

The feasibility of using the jet stream in forecasting precipitation is best illustrated along the west coast of North America. There, the seasonal movements of heavy precipitation and faster speed westerlies correspond. Weather forecasters along the coast pay close attention to the observed and projected latitudinal positions of the jet stream (in most instances the polar-front jet stream). Although less obvious in the central and eastern United States, there is a correspondence between the latitudinal migration of heavy precipitation occurrences and the seasonal meridional displacements of the jet stream. In addition, objective measurements of vertical motion (Endlich 1953) support the hypothesis that jet stream environs are areas of possible heavy precipitation. He says, "The strongest isanabatic centers were located in or near the jet stream, and vertical velocity values greater than 5 cm/s were seldom found farther than about 300 mi. from the center of the jet." On an empirical basis, the members of the Quantitative Precipitation Forecast Branch at the National Meteorological Center (NMC) have long recognized the general validity of using jet stream concepts in forecasting heavy precipitation. Through observational experience, they realize the intricacy of the endless variation in patterns that may evolve in both jet stream and precipitation features and the complexity of relationships between the two. Yet, on an operational basis, the jet stream is considered a primary and integral part of the forecasting procedure.

Atmospheric modeling provides a means for better understanding complicated meteorological interrelationships. Modeling has also been used to communicate new knowledge to the meteorological profession. The purposes of this paper are: (1) to present a model for an identified type of jet stream–heavy rainfall interrelationship, (2) to describe an individual case history of this type, (3) to provide a forecasting methodology for this type, and (4) to stimulate renewed study of jet stream–precipitation interrelationships.

We have used the general term "jet stream" in reference to precipitation patterns without specific mention of either the polar-front jet or the subtropical jet. Both are recognized as mechanisms that are important to the vertical exchange processes. Yet, precipitation activity cannot always be identified as being related solely to one or the other; on many occasions the two are in such close juxtaposition that both are involved. There are times when the subtropical jet overrides the polar-front jet impeding satisfactory identification of either. To circumvent that difficulty in this study, we have composited the modular jet–heavy precipitation relationship from an individual class of polar-front jet cases. In this instance, the polar-front jet is conventionally defined as the maximum winds embedded in the middle latitude westerlies and associated with the polar front. On the 500-mb surface, a maximum gradient of temperature (polar front) marks the stream of fastest winds. On the average, this fast stream extends almost vertically upward from 500 mb to the level of the jet core. The wind increases most rapidly with height above 500 mb. The level of the jet core corresponds with a break in the tropopause where immediately to the north there is a lower tropopause and immediately to the south there is a higher one.

2. DEVELOPMENT OF POLAR JET STREAM–HEAVY RAINFALL COMPOSITE MODELS

One of the many difficult problems in quantitative precipitation forecasting is determination of the time of outbreak of a heavy rainfall occurrence in the central United States with an associated increase in amplitude of the circulation pattern aloft. In the particular instances studied, there appeared to be a consistent relationship between heavy rainfall distribution and jet stream configuration. These situations were characterized by southward displacement of cold, polar air over the Rocky Mountains into the Great Plains States as moist, unstable air moved northward from the Gulf of Mexico. A vigorous, "digging" short-wave upper trough was a common feature of these instances. In view of the noted similarities, a composite model relating heavy rainfall distribution to the jet stream pattern was derived from representative cases. Composite 500-mb height contours and 1000- to 500-mb thickness contours were also developed for the same set of cases.

Seven representative cases (table 1) of this type were used in making the composite models. These were selected from a number of heavy rainfall cases during the period October 1967 through November 1968 for which jet stream information and 12-hr rainfall maps (0000–1200 GMT only) were available. Broadscale heavy precipitation activity of this type is more likely to occur during the autumn and spring circulatory transitional periods when heavy moist air from the Gulf of Mexico flows into the central United States. Heavy rainfall was related to the synoptic polar-front jet stream pattern using a moving grid in a manner similar to that used by Jorgensen (1963), Fawcett and Saylor (1965), and others. The southernmost position in the jet stream trough (latitudinal

TABLE 1.—*Area (10^3 n.mi.^{2}) of observed 12-hr rainfall verifying at 1200 GMT within standard isohyets*

Case No.	Date	Isohyet (in.)		
		0.50	1.00	2.00
1	Oct. 16, 1967	194	39	1
2	Oct. 30, 1967	239	144	42
3	Mar. 22, 1968	141	55	2
4	Sept. 17, 1968	171	62	12
5	Oct. 9, 1968	193	73	8
6	Oct. 16, 1968	132	67	15
7	Nov. 27, 1968	173	94	10

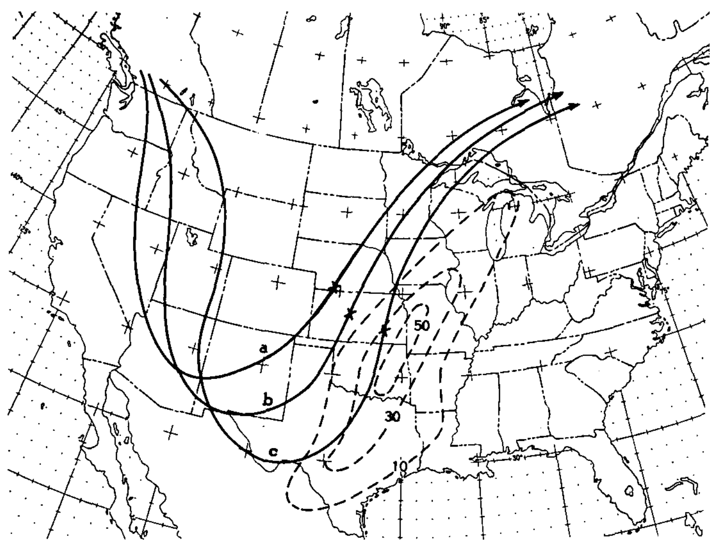

FIGURE 1.—Percentage frequency of occurrence of 1 in. or more rainfall (dashed lines) with composite polar jet stream patterns (a) 12 hr before the beginning, and at the (b) beginning and (c) ending of the 12-hr measurement period. Approximate points of inflection in jet stream patterns are indicated by X.

extremum) and a north–south axis through that point served as the basic anchoring coordinate in developing composite polar jet stream patterns at 12-hr intervals and for obtaining the relative distribution of heavy rainfall occurrences. In each individual case, the orientation of the jet stream trough line was approximately north to south.

Figure 1 shows the digging tendency in the polar jet stream trough for these seven situations. Note the extensive meridional aspect of the jet stream pattern and comparative shortness of wavelength. The distance from the jet stream trough extremum to the downstream point of inflection (fig. 1) averaged about 350 n.mi. In the mean, a uniform movement of the overall jet stream pattern prevailed. This movement is in accord with the theory of mutual adjustment between winds and pressure; that is, deep jet maxima tend to conserve their momentum and move quite regularly in time over 24-hr periods. In figure 1, the smoothed pattern of frequency of occurrence of 1 in. or more rainfall shows a band of comparatively higher frequency of occurrence about 250 n.mi. in advance of the jet stream position at the time of the beginning of the rainfall measurement period. The smoothed average rainfall configuration (fig. 2) is very similar to the frequency

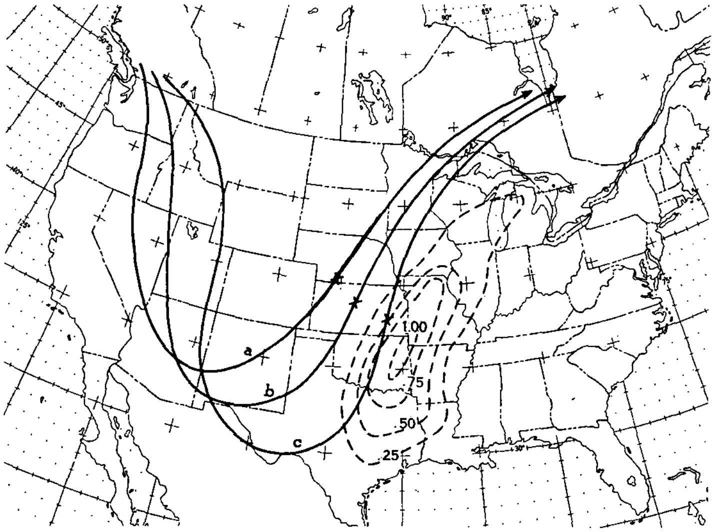

FIGURE 2.—Composite rainfall isohyetal pattern (dashed lines) with composite polar jet stream patterns (a) 12 hr before the beginning, and at the (b) beginning and (c) ending of the 12-hr measurement period. Approximate points of inflection in jet stream patterns are indicated by X.

pattern in figure 1 although the southern portion of the axis of relative maximum shifts a little to the east. From these figures, one notes that, on the average, the most common area for heavier rainfall (30-percent frequency of occurrence and 0.50-in. isohyet) is about 180 n.mi. wide with the western edge about 250 n.mi. in advance of the jet position at the beginning of the 12-hr rainfall measurement period. The latitudinal extent of the area of heavier rainfall is about 700 n.mi., extending northward from a base determined by the average latitude of the jet stream trough extremum during the measurement period.

The areal extent of 12-hr rainfall measuring 0.50 in., 1 in., and 2 in. is shown in table 1. The 144,000 n.mi.[2] area on Oct. 30, 1967, was the largest 1-in. area of record for the time period going back through 1963. In three cases (2, 5, 6), the breakout of heavy rainfall activity occurred mainly during the 12-hr measurement period with relatively little or no heavy rainfall prior to 0000 GMT. In the other cases, heavy rainfall had begun prior to the beginning time of the specified measurement period.

Composite 500-mb height and 1000- to 500-mb thickness contour maps were also prepared for these seven cases. The position of the fastest winds in the 500-mb trough line and the north azimuth served as the anchoring coordinate in preparation of these composites. Figure 3 shows the marked amplitude of the average 500-mb height and 1000- to 500-mb thickness patterns while figure 4 provides information on the 12- and 24-hr changes in these features.

3. THE CASE OF OCT. 29–30, 1967

The notable case of heavy rainfall in the eastern gulf States on the night of October 29–30 will be used as an example situation. As pointed out earlier, the analyzed area of 1-in. rainfall or more exceeds any other since

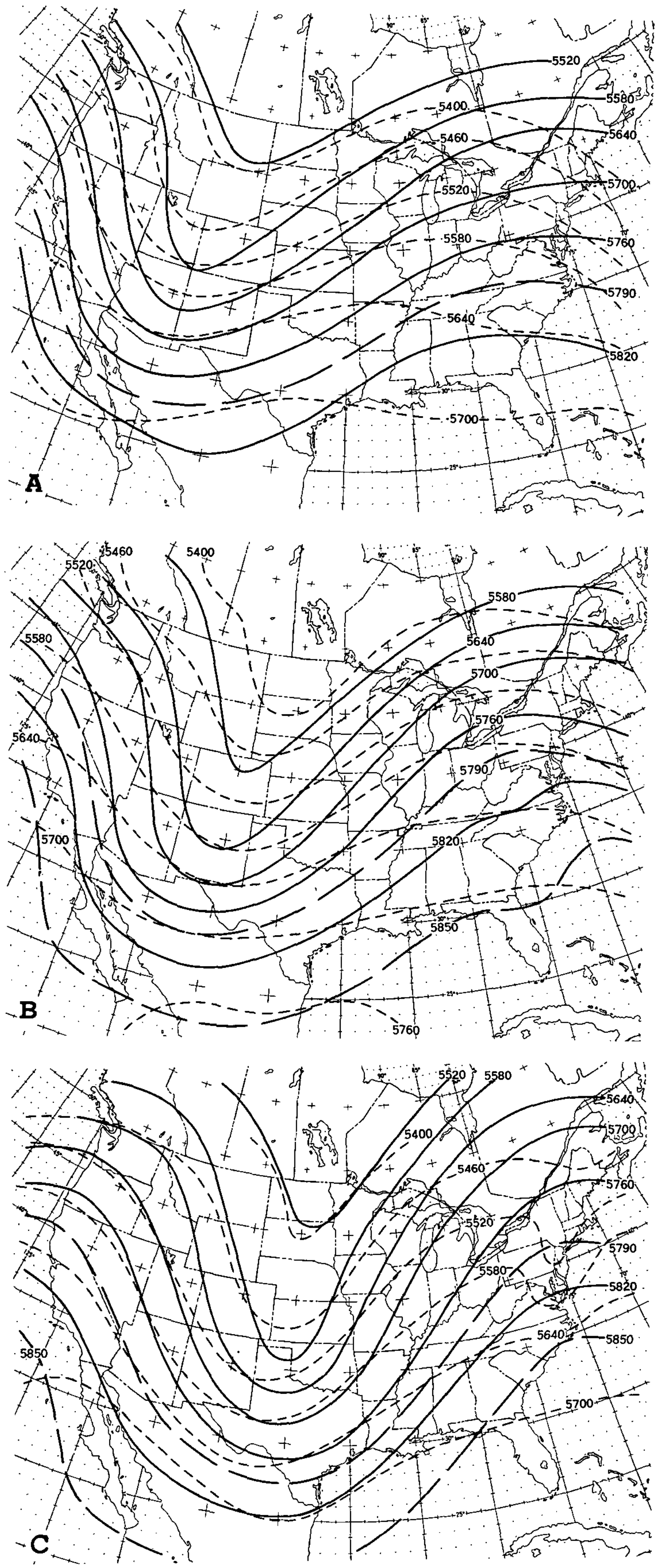

FIGURE 3.—Composite 500-mb height (m, solid lines) and 1000- to 500-mb thickness (m, dashed lines) for (A) 12 hr before the beginning of the rainfall measurement period, (B) at the beginning of the 12-hr rainfall measurement period, and (C) at the end of the 12-hr rainfall measurement period.

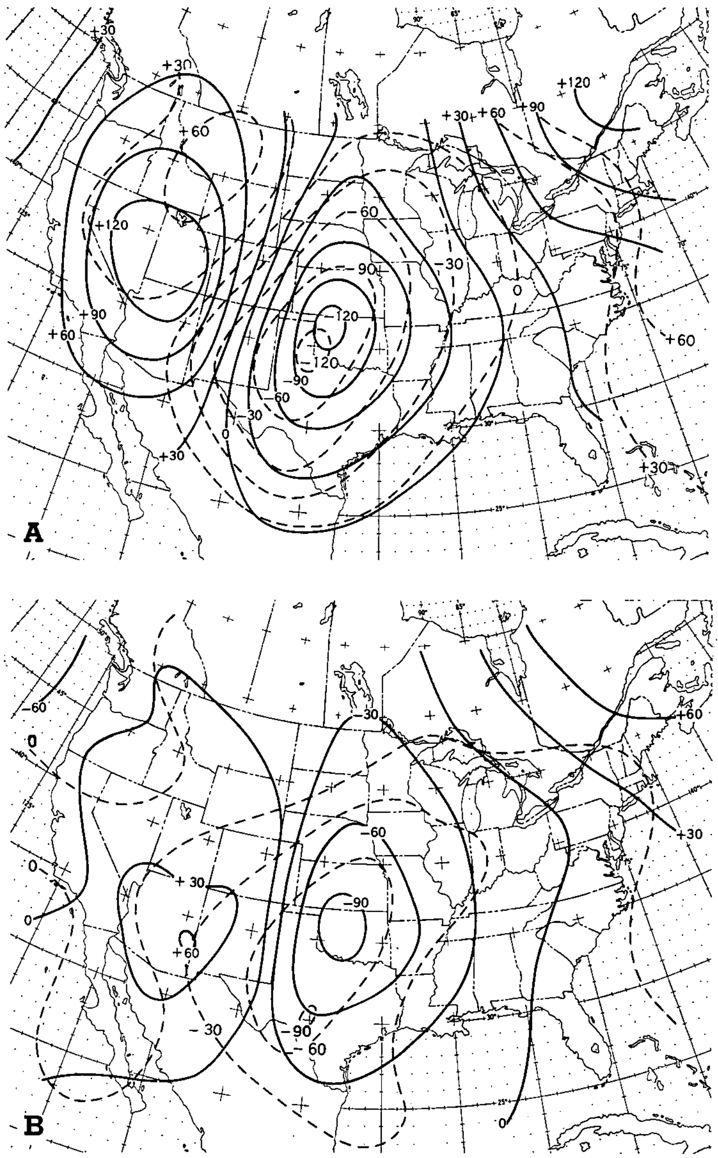

FIGURE 4.—Composite 500-mb height change (m, solid lines) and 1000- to 500-mb thickness change (m, dashed lines) (A) for the 24-hr period preceding rainfall measurement time and (B) during the 12-hr rainfall measurement period.

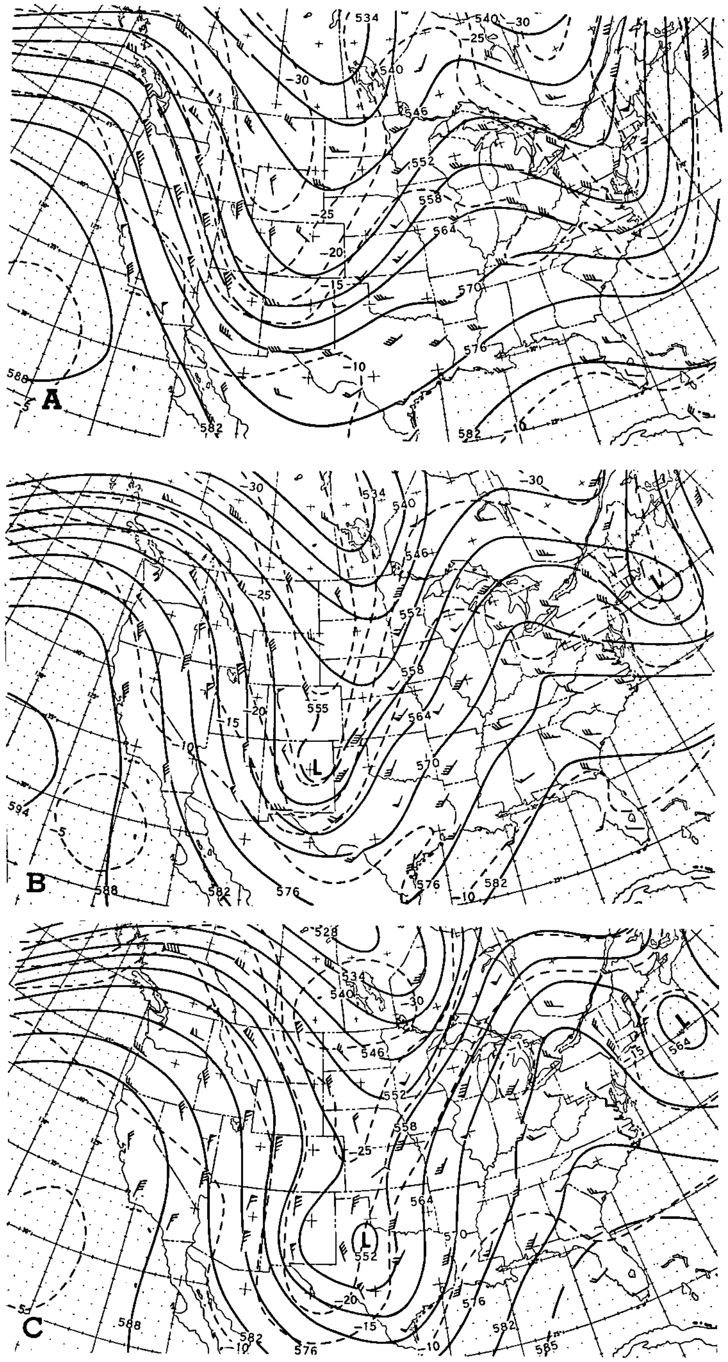

FIGURE 5.—Analyzed 500-mb heights (dekameters) for (A) 1200 GMT, Oct. 29, (B) 0000 GMT, Oct. 30, and (C) 1200 GMT, Oct. 30, 1967.

records for the 12-hr period ending 1200 GMT were begun in 1963. This situation was typically characterized by a vigorously digging short wave moving southeastward out of the Central and Northern Rocky Mountains and into moist and unstable air moving northward from the Gulf of Mexico.

Figure 5 shows the 500-mb patterns at 12-hr intervals beginning at 1200 GMT on October 29. The associated heavy rainfall is shown on figure 6B. Note the clear indication on figure 5A of digging over the Southern Rocky Mountains by the trough-isotherm lag and wind field (stronger winds on the west side of the trough). This is not as clearly evident 12 hr later at 0000 GMT on October 30. However, the polar-front isotherm ribbon (maximum temperature gradient at the 500-mb surface) and associated fastest winds continued to press south-southeastward in Texas throughout the night. At higher levels, the polar jet stream analyses (fig. 6) again show the large amplitude of the wave pattern. The maximum winds in these isotach analyses were obtained from the standard levels (25,000 ft and above) on the NMC winds aloft plotting charts. Note that isotach maxima tend to prefer the anticyclonic and inflection portions of the jet stream pattern, not the cyclonic trough portion. Attempts to maintain continuity of jet maxima from the rear of the trough, through the trough, and out the other side were not successful.

The surface weather map at the middle (0600 GMT) of the 12-hr rainfall period (fig. 7B) shows the marked contrast in thermal properties across the frontal zone in the southern plains. The frontal locations and isobaric pat-

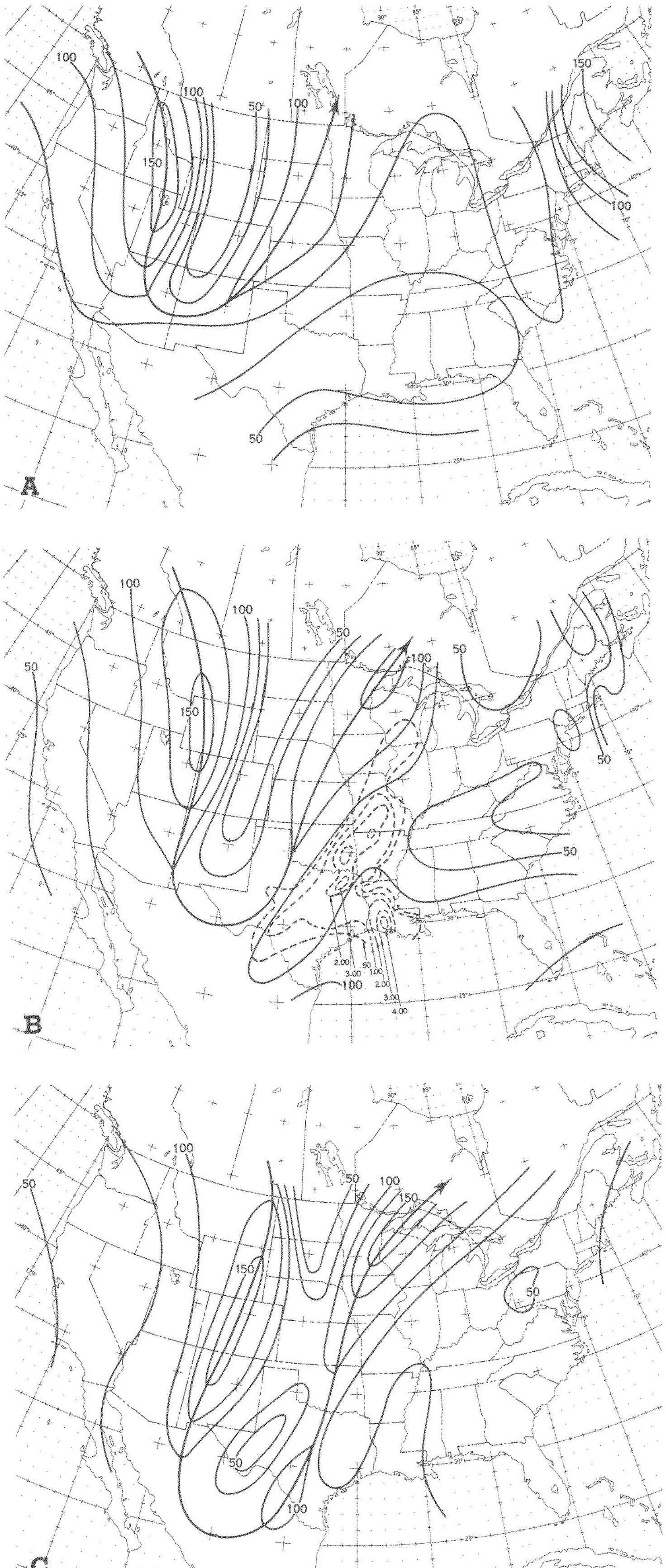

FIGURE 6.—Analyzed maximum wind isotachs (kt) for (A) 1200 GMT, Oct. 29, (B) 0000 GMT, Oct. 30, and (C) 1200 GMT, Oct. 30, 1967. Chart B shows analyzed rainfall (in.) for the 12-hr period ending 1200 GMT, Oct. 30, 1967.

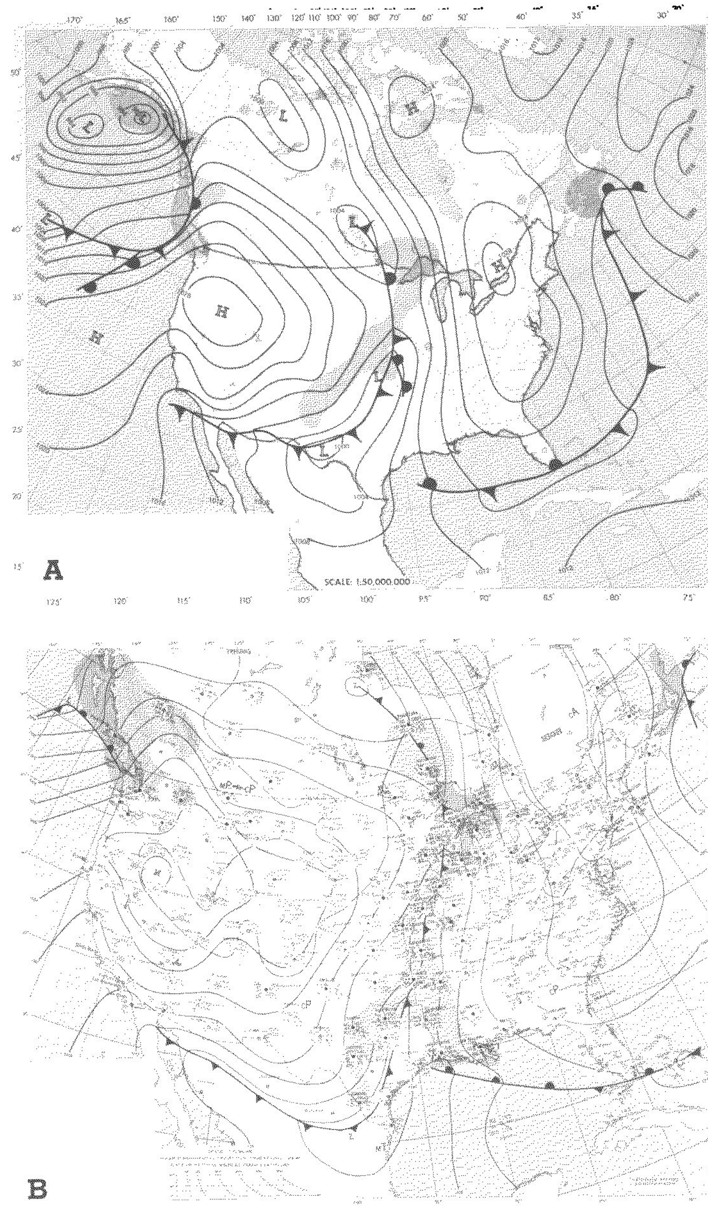

FIGURE 7.—Surface charts for (A) 1800 GMT, Oct. 29, and (B) 0600 GMT, Oct. 30, 1967.

tern (1800 GMT, Oct. 29) before the dramatic outbreak of heavy rainfall activity are shown in figure 7A. The predominant portion of rainfall occurred along and in advance of the surface cold front during the period 0000–1200 GMT on October 30. The extensive amounts of water vapor available and the degree of saturation and instability as shown by the Showalter (1953) index at the beginning of the 12-hr rainfall measurement period can be noted in figure 8.

Several aspects of important relationships found in the composite picture (figs. 1, 2) are relevant to this individual case. First is the regularity of movement of the polar jet stream pattern during the digging phase. In this instance, the jet stream trough dug southeastward at about twice the rate of the eastward movement of the northern portion of the jet stream pattern. In both pattern regions, the

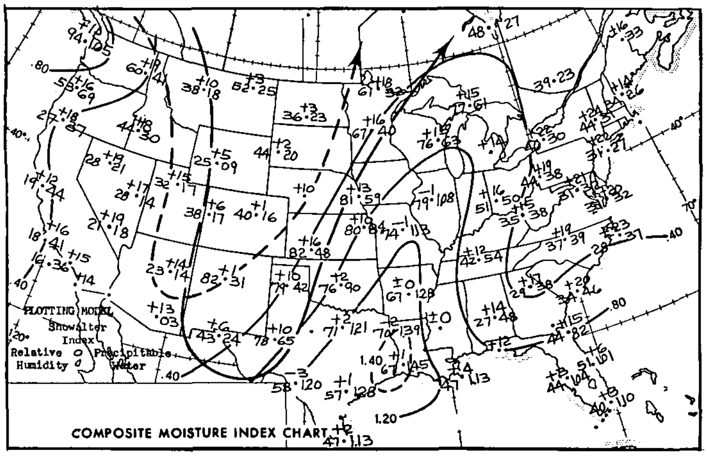

FIGURE 8.—Composite moisture index chart for 0000 GMT, Oct. 30, 1967, showing precipitable water (analyzed at 0.40-in. intervals), average relative humidity (percent) from surface to 500 mb, and Showalter stability index. Concurrent polar jet stream and its position 12 hr earlier are given by heavy solid and dashed curves, respectively.

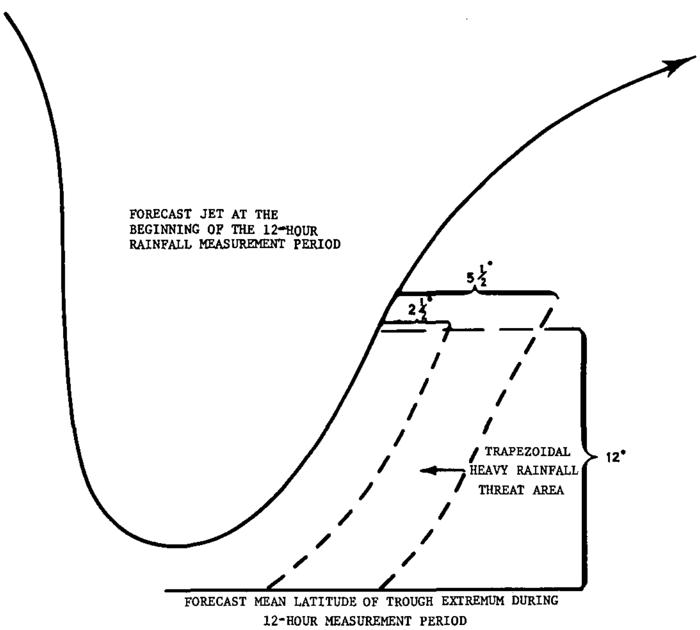

FIGURE 9.—Model for forecasting 12-hr heavy rainfall combining the more significant aspects of figures 1 and 2 into a more useful composite form.

progression was quite regular. Second, a trapezoid (3° of latitude wide with the western edge 2½° in advance of the 0000 GMT jet stream position and 12° of latitude long with the southern edge at the mean latitude of the trough extremum for the period 0000–1200 GMT) would encompass a major portion of the heavy rainfall area. Third, the main axis of heavy rainfall occurred about 4° of latitude in advance of the 0000 GMT jet stream position with extremely heavy precipitation amounts on this axis, mainly in advance of the inflection point.

4. A FORECASTING AID

Quantitative precipitation forecasters are regularly confronted with the situation whereby the atmospheric precipitation-producing components are evaluated as suitably disposed for occurrence of a heavy rainfall event. At this point, some help is provided by numerical guidance precipitation forecasts. In general, the main forte of this guidance has been in the area of occurrence of measurable precipitation, rather than the heavy variety. Of the seven cases in this study (table 1), the six-layer primitive-equation model (Shuman and Hovermale 1968) forecasted no 1-in. precipitation on three occasions, and on one occasion not even 1/2 in. was predicted. Additional objective assistance is needed to determine location, orientation, and magnitude of the associated forecast isohyetal pattern. If the synoptic situation fits properly into the type studied here, regularity of movement of the upper short wave and associated polar jet stream pattern is quite dependable during the digging phase. Also, if careful evaluation of numerical surface and upper air circulation prognostic charts indicates a continued digging trend for at least another 24 hr beyond the latest complete upper air analysis, then relationships shown in figures 1 and 2 become pertinent to making a reasonable quantitative precipitation forecast. Figure 9 summarizes these systematically obtained relationships for use in making quick forecast decisions. Notations on the figure make its use self explanatory. In actual operation, the observed 0000 and 1200 GMT maximum wind polar jets are transferred onto the corresponding-time initial 500-mb analysis for either the barotropic or baroclinic forecast models. Initial contour value-jet relationships are assumed to persist for an additional 12 or 24 hr, but considerable care must be taken to maintain reasonable continuity in the overall jet pattern.

Forecasters who keenly observe high-level winds will note that the 2½°–5½° rule for locating heavier rainfall, is also helpful for cases of active, lesser amplitude short waves in well-defined polar jet streams. However, a word of warning seems appropriate. Past experiences with composite models show that forecasters often tend to apply models indiscriminately to situations dissimilar to the developmental data with unsatisfactory results. This practice soon leads to disillusionment and early disenchantment with a valid forecast tool.

5. SUMMARY

The jet stream environs are recognized as an area of vertical exchange processes integral to major features of middle-latitude circulation. Appropriately, attention should be focused on the jet stream region for occurrences of larger scale heavy precipitation activity. Observational experience reveals that either the polar or subtropical jet streams, or both, are involved in many heavy precipitation happenings. In general, the relationships between jet streams and heavy precipitation are extremely complex, and there has been little attempt to systematically organize these relationships into a form usable for forecast assistance. In this paper we have identified one synoptic situation that occurs predominantly in the central United States whereby a generalized relationship between rainfall distribution and polar jet stream configuration may be of benefit in forecasting.

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