CYCLOGENESIS AND PRECIPITATION IN THE BLIZZARD OF MARCH 21–26, 1957

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1. INTRODUCTION

The arrival of spring over the eastern Rocky Mountain and southern and central Plains regions of the United States was closely followed by one of the most severe blizzards to occur in that area during recent years. The birth of the Low associated with this phenomenon occurred over southeastern Montana during the late morning hours (MST) of March 21. Throughout the next 30 hours this Low plunged rapidly southward along the eastern slope of the Rockies at an average speed of approximately 30 m. p. h. During this plunge the central pressure of the Low did not deviate from its original value of 998 mb. by more than 4 mb. and upon its arrival at Lubbock, Tex., the central pressure continued at 994 mb. However, the already strong upstream gradient between this center and the adjacent High center did intensify between 20 and 25 percent during the southward movement.

This increased pressure gradient plus the funneling effect obtained between the center of the Low and the high mountains to the west produced widespread cold northerly winds which attained measured speeds of whole gale force, and instantaneous local gusts reached well into the hurricane category. These blustery winds and attendant instability conditions resulted in sandstorms and blowing dust which restricted visibility. Later, as these winds whipped and whirled the falling and newly fallen snow, visibility was reduced to zero, and drifting and blowing snow soon produced drifts to depths of 20 feet or more. Thus, over southern Nebraska, eastern Colorado, most of Kansas, the northeastern corner of New Mexico, and in the panhandles of Texas and Oklahoma many automobiles became stalled, trains were stranded, and communications were completely disrupted with some cities and towns isolated. Over 40 lives were lost in this blizzard mainly from the inability of stalled motorists to reach satisfactory shelter. Livestock losses were excessive due both to death and to shrinkage of the stock. Monetary damages from the storm have been estimated in the millions, but, on the other hand, the moisture accumulation in these parts of the dust bowl was beneficial.

It is of interest from a synoptic standpoint to examine not only the conditions when the storm was most active, but also to investigate the factors which led to the inception of this Low over Montana as well as to its rapid southward plunge. Furthermore, it is believed that a study of the precipitation totals would be useful.

2. ANTECEDENT CONDITIONS

The parent Low, from which this storm had its inception, developed over eastern China prior to March 14, and was attended by a rather moderate zone of cyclonic vorticity at the 500-mb. level. Rather rapid development of this cyclone occurred as it moved eastward and northward about the periphery of an intense but weakening surface Low on the western tip of the Aleutian Islands. This occurred in association with a short-wave trough aloft that was moving out of the long-wave trough position over the far western Pacific Ocean. Throughout the next two days the storm moved rather rapidly north-northeastward, and by 0030 GMT of March 17 it was in the vicinity of Cold Bay, Alaska. The occluded and cold front had been carried far ahead of the cold surface trough in its northern portion, but the cold front as it trailed southwestward was near the trough. It was at this time that a stable wave was induced along the front as a second short-wave trough aloft with a zone of maximum cyclonic vorticity was approaching the cold front in the vicinity of 30° N. and slightly east of the International Date Line.

During the next 30 hours this stable wave moved northeastward at 40 to 50 knots, maintaining intensity as it passed through the virtually stationary but rather broad long-wave ridge position over the central Pacific. The Hovmöller chart [5] (not shown) indicated the presence of several short-wave troughs at 50° N. at approximately this time. Simultaneously there occurred a splitting of the Central Pacific long-wave ridge and an eastward progression at 6°–8° of longitude per day of the eastern segment. Concomitantly other major trough and ridge positions downstream began similarly to drift. This eastward progression was uninterrupted for approximately four days following which the eastern portion of the split Pacific long-wave ridge began to regress and consolidate with its western counterpart.

Through most of the period of March 13–18 a 1030-mb.

High center remained in the vicinity of 30°–35° N., 150° W. One cold Low moved eastward to a position off the Washington coast early in the period, then filled on the 16th when a new eastward-moving cold Low reached a position near 47° N., 139° W., then curved to a southwesterly track to approximately 400 miles west of Santa Maria, Calif., where it became stationary by 0030 GMT on the 18th.

By 0030 GMT of the 20th the previously mentioned stable wave had become unstable, deepened, and occluded prior to attaining the southern British Columbia coastline. This surface Low was attended in the upper air by a moderately developed trough. With this Low's eastward movement, the wavelength between this cyclone and the downstream Low off the California coast decreased until the southernmost Low, surface and aloft, moved inland over southern California and northern Mexico. Throughout this time interval the surface High and upper ridge were intensifying west of the deepening cyclone off the British Columbia coast while the High near 30° N., 150° W. dissipated.

From 0030 GMT March 20 to 0030 GMT March 21 the storm center persisted along the Canadian coast but weakened rapidly. However, the previously associated occluded and cold fronts moved inland with the surface trough elongating in a northwest-southeast line, and by the end of the period a new center had formed at the point of occlusion east of the Continental Divide. The Low previously over southern California and northern Mexico advanced rapidly eastward during these 24 hours, reaching a point slightly south of Del Rio, Tex. Intensification of the Low commenced as it was now east of the long-wave ridge at that longitude. In conjunction with the changes in shape and intensity of the Low cells, it might be well to note that the ridge between these two Lows had flattened.

Further indications that a definite break in the pressure pattern regime occurred on or about March 18 are given by the 500-mb. departure from normal charts (not shown). Prior to this date an above normal anomaly was present from the coast of Labrador westward across Canada and extended over 1,000 miles off the Oregon coast. By 0030 GMT March 20 this positive anomaly had divided, as a negative anomaly area approached the Pacific Northwest from the Gulf of Alaska, and these conditions continued into March 21.

3. SYNOPTIC CONDITIONS MARCH 21–26

Clearly discernible on the surface chart for 0030 GMT March 21 (fig. 1a) is the elongation of the low pressure area from northwestern Montana into Alaska, with a pronounced pressure gradient field to the southwest and a forceful northwesterly flow of cold air (fig. 1b). Over western Washington and Oregon and the nearby waters of the Pacific Ocean, the −35° C. isotherm and the 17,200-ft. thickness line encompassed approximately identical areas. Temperatures within this area were comparable to the minimum records for March as reported in [16]. Over the Pacific Northwest the strong cold front with its attendant thermal wind shear of 80 knots was progressing rapidly eastward as was the related 500-mb. trough line. The old Pacific Coast Low was by now located over northeastern Mexico and western Texas and its frontal system had attained moderate intensity as indicated by the thermal wind shear across the front. At this same time the ridge separating these Lows was rather weak and poorly defined, especially on the surface chart.

Six hours after the new Low formed, or at 0030 GMT March 22 (fig. 1c), it was centered at the intersection point of the borders of Wyoming, Nebraska, and South Dakota ready for a southward plunge. Rapid eastward motion of the strong cold front had continued, with the occluding process having occurred along the new warm front which had remained practically stationary. Thermal shear across this new front indicated weak intensity even though the thermal packing had increased considerably in the 24-hour period. To the west of the cold front the surface isobars had acquired a north-south alignment as well as a strong pressure gradient, indicating a rapid transport of cold air southward from Canada. This pressure field intensification and more northward flow resulted from the northeastward and eastward building of the strong Pacific High as the surface center progressed toward the west coast.

Definite intensification of the 500-mb. trough associated with the cold and occluded surface fronts was indicated by the upper air chart at 0300 GMT on March 22 (fig. 1d). West of the trough the building ridge had produced a veering of the upper winds to a more northwesterly direction over the far western States, with speeds up to 85 knots in the 500-mb. jet stream over western California. Concurrently ridging had occurred over portions of the Provinces of Alberta, Saskatchewan, and Manitoba. With this ridging the 500-mb. departure from normal chart indicated an increased area of positive anomaly over central Canada and a second area developing off the western coast of the United States; indications were for a possible return to ridging of the positive anomaly across western Canada as the negative anomaly had divided into two centers, one over Nevada and the other in the Gulf of Alaska.

Throughout the next 24 hours the surface Low continued to plunge southward with only minor variations in the central pressure, and by 0030 GMT March 23 (fig. 2a) was centered near Lubbock, Tex. The high pressure cell had continued its eastward progression and was centered approximately 5 degrees west-northwestward of San Francisco, Calif., with a central pressure of 1036 mb. Although central pressures of the Low and of this upstream High had varied but slightly during the past 30 hours, the attendant pressure gradient had increased nearly 25 percent as the half-wavelength decreased. From the normal sea level pressure charts [17] the computed normal gradient between the New Mexico-Arizona Low and the center of the upstream High is 1 mb. per 180 nautical miles. In this present situation the gradient was 1 mb. per 30 nautical miles or 600 percent of normal. Computations over this half-wavelength using the average gradient of 1 mb. per 30 miles produced an average geostrophic wind of approximately 38 knots over a distance of more than 1200 miles. A few of the reported wind speeds are shown in table 1.

By 0300 GMT of March 23 the upper-air charts (fig. 2b) indicated a cut-off Low had formed to the northwest of the surface center with temperatures of −35° C. being reported slightly west of the center. Albuquerque, N. Mex. reported −34° C. at 500 mb. for one of the lowest temperatures recorded by that station for this level during any March [16]. The amplitude of the Pacific Coast ridge had continued to increase, thus veering the winds to more northerly direction over the States west of the trough. At the same time ridging split the trough over western Canada, bridging across to the strong positive anomaly center northwest of Hudson Bay. Little change had occurred in the amplitude of the downstream ridge over the southeastern United States at this time.

Between the 23d and 24th of March the surface center of the cyclone began to recurve with decreased speed, while in the upper air the movement was east-southeastward and slightly more rapid than at the surface, resulting in almost vertical centers (fig. 2c, d). Thermal packing to the rear of the front persisted, and with pronounced thermal wind shear across the front as indicated by the thickness lines, the frontal classification of strong intensity was continued.

A portion of the Pacific High moved inland and was located over central southern Idaho. As the central pressures in the cyclone and anticyclone had changed only slightly while the distance between the centers decreased, the pressure gradient had continued to intensify, increasing on the average to 1 mb. per 25 nautical miles. This gave an overall average geostrophic wind speed of 60 knots. At this time over portions of Nebraska, Colorado, New Mexico, Kansas, Oklahoma, and Texas geostrophic winds measured from the charts were near 150 knots. By now the surface ridge had bridged northward into Canada, and the area enclosed by the 1028 mb. isobar extended from 30° N., 125° W. northeastward to include the pole.

At 500 mb. there was progressive building of both the western or upstream ridge and the downstream ridge during the past 24 hours. By now a strong positive anomaly covered central Canada with the positive areas extending to the southeast and southwest about the northern portion of the blizzard-producing Low. Winds continued to "dig" southward at the 500-mb. level and were reported at 55 to 130 knots from 360° to 10° over Arizona and at 75 to 95 knots from 220° to 230° over Texas. Thus a very strong 500-mb. jet was indicated with the maximum winds passing just north of the apex of the occluding fronts.

During the next 24-hour period, ending with 0030 GMT and 0300 GMT, March 25 (figs. 3a, b), the eastward or northward progression of the cyclone was very slow, as might be anticipated with "digging" to the rear and the resultant downstream ridging ahead of the Low. Although the central pressure remained practically constant within the Low, it was at the intervening 12-hour period that the upper charts indicated maximum intensification. This period of intensification dovetailed very conclusively with preceding upstream and subsequent downstream amplifications of troughs and ridges, thereby indicating the possibility of downstream dispersion of energy (Rossby [13]).

TABLE 1.—*Fastest mile and average wind speed (mph) for selected stations March 22–26, 1957*

Station	MARCH									
	22		23		24		25		26	
	Fastest mile	Average speed	Fastest mile	Average speed	Fastest mile	Average speed	Fastest mile	Average speed	Fastest mile	Average speed
Fort Smith, Ark	15	9	22	14	17	9	21	11	15	11
Little Rock, Ark	16	8	26	12	32	12	24	11	20	10
Denver, Colo	30	26	42	33	39	24	26	14	18	13
Pueblo, Colo	57	25	68	33	52	28	27	8	19	6
Des Moines, Iowa	13	6	24	13	33	21	31	17	13	10
Dodge City, Kans	21	13	68	29	70	44	45	27	16	9
Goodland, Kans	22	16	42	32	40	34	27	16	17	9
Topeka, Kans	17	9	30	18	40	27	34	21	14	7
Columbia, Mo	14	7	21	11	34	19	23	15	17	10
Kansas City, Mo	12	9	21	16	35	20	25	18	17	9
Billings, Mont	33	22	28	17	26	14	23	10	34	19
North Platte, Nebr	26	10	45	29	43	31	27	16	16	8
Omaha, Nebr	17	7	28	15	32	20	30	20	13	6
Roswell, N. Mex	47	19	42	19	42	17	16	9	17	8
Oklahoma City, Okla	24	11	30	17	22	13	34	24	23	8
Amarillo, Tex	30	15	57	32	59	40	40	21	24	13
Dallas, Tex	16	9	29	16	27	17	38	20	16	10
Lubbock, Tex	29	16	53	34	69	44	37	25	25	14
Midland, Tex	29	14	29	13	29	21	29	10	14	8
Cheyenne, Wyo	47	33	49	36	41	25	32	17	37	19

On the upper-air chart ridges upstream and downstream had weakened slightly and the strong northerly flow southwest of the Low had ended with winds backing to northwest. Surface gradients remained strong to the west and north of the Low but winds had begun to diminish. The fastest miles as reported by first order stations were generally between 30 and 45 m. p. h. A new frontal system had moved into Montana and Idaho and a rather weak short-wave trough at 500 mb. was discernible near the coast of Washington and Oregon, thus indicating the likelihood that the blizzard Low might accelerate as it moved eastward.

The 0030 GMT and 0300 GMT charts of the 26th (figs. 3c, d) revealed the increased speed of the Low eastward as well as the decrease in the surface pressure gradient which resulted in abatement of the strong surface winds. Thus the blizzard had diminished and a new front and short-wave trough of much weaker proportions was moving into the Central Plains region.

A more extensive summary of the features of the general circulation during the formative period of the parent storm as well as during the period under discussion is given in the preceding article by Frazier [4].

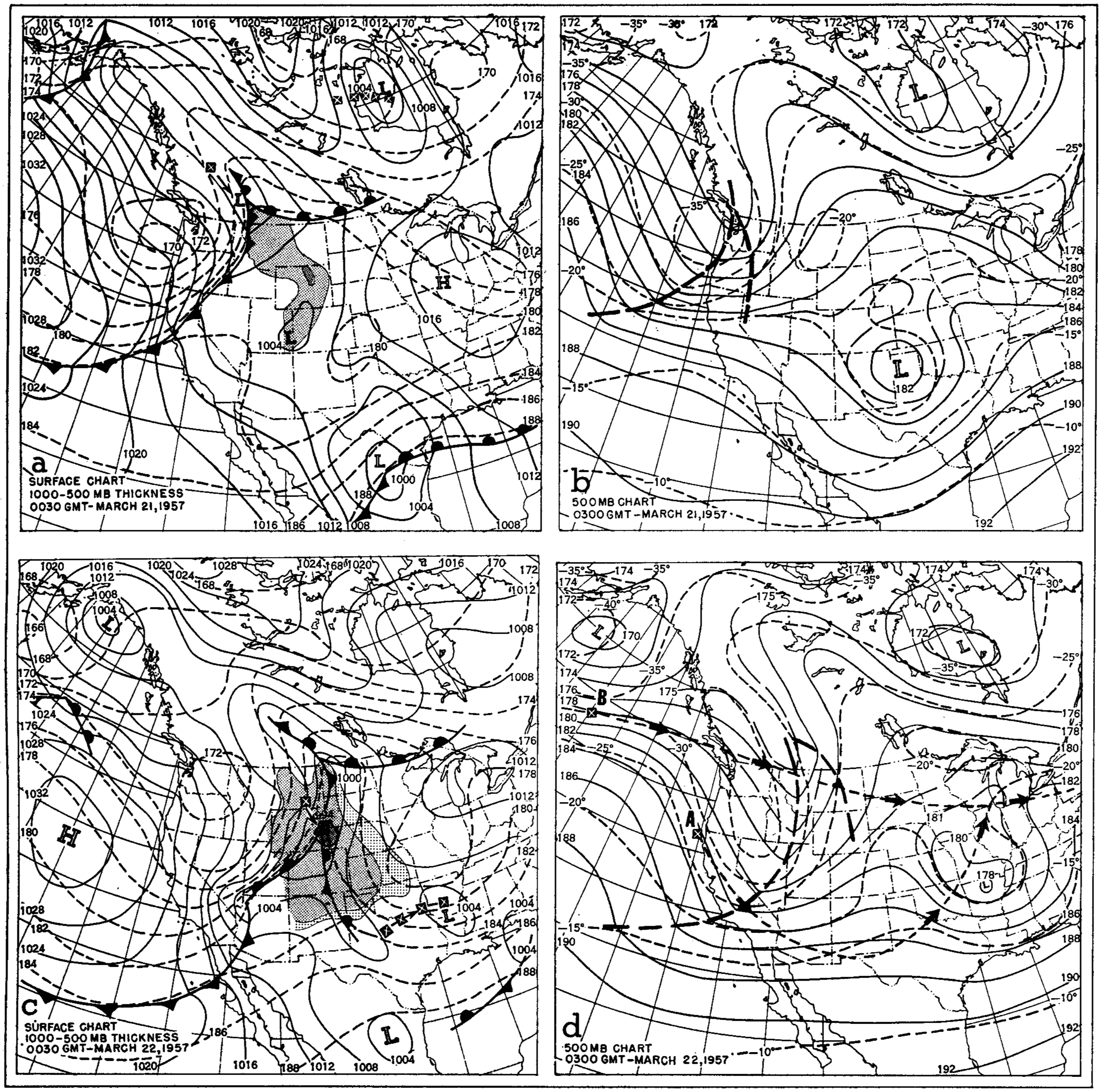

FIGURE 1.—Synoptic patterns for March 21 and 22, 1957. (a) 0030 GMT surface chart, March 21 (solid lines) with 1000–500-mb. thickness in hundreds of feet for 0300 GMT (dashed lines). Shaded areas represent precipitation during 24-hour period beginning at 0001 Local Standard Time of date of chart. Light shading indicates only rain occurred; moderate shading, rain and snow or snow with snow total under 4 inches; heavy shading shows 4 or more inches of snow. (b) 0300 GMT 500-mb. chart, March 21. Isotherms indicated by dashed lines. (c) 0030 GMT surface chart, March 22. (d) 0300 GMT 500-mb. chart, March 22, with heavy arrows indicating the path of the computed CAVT from the inflection points A and B.

4. DISPERSION OF ENERGY

It appears quite probable that one of the factors that led to the intensification of this upper-air Low on March 24–25 was the dispersion of energy downstream. As this process has been discussed in previous articles of this series during the past year it will not be discussed in detail for this case.

The Hovmöller diagram [5] (not shown) at 35° N. clearly illustrated the propagation of alternating troughs and

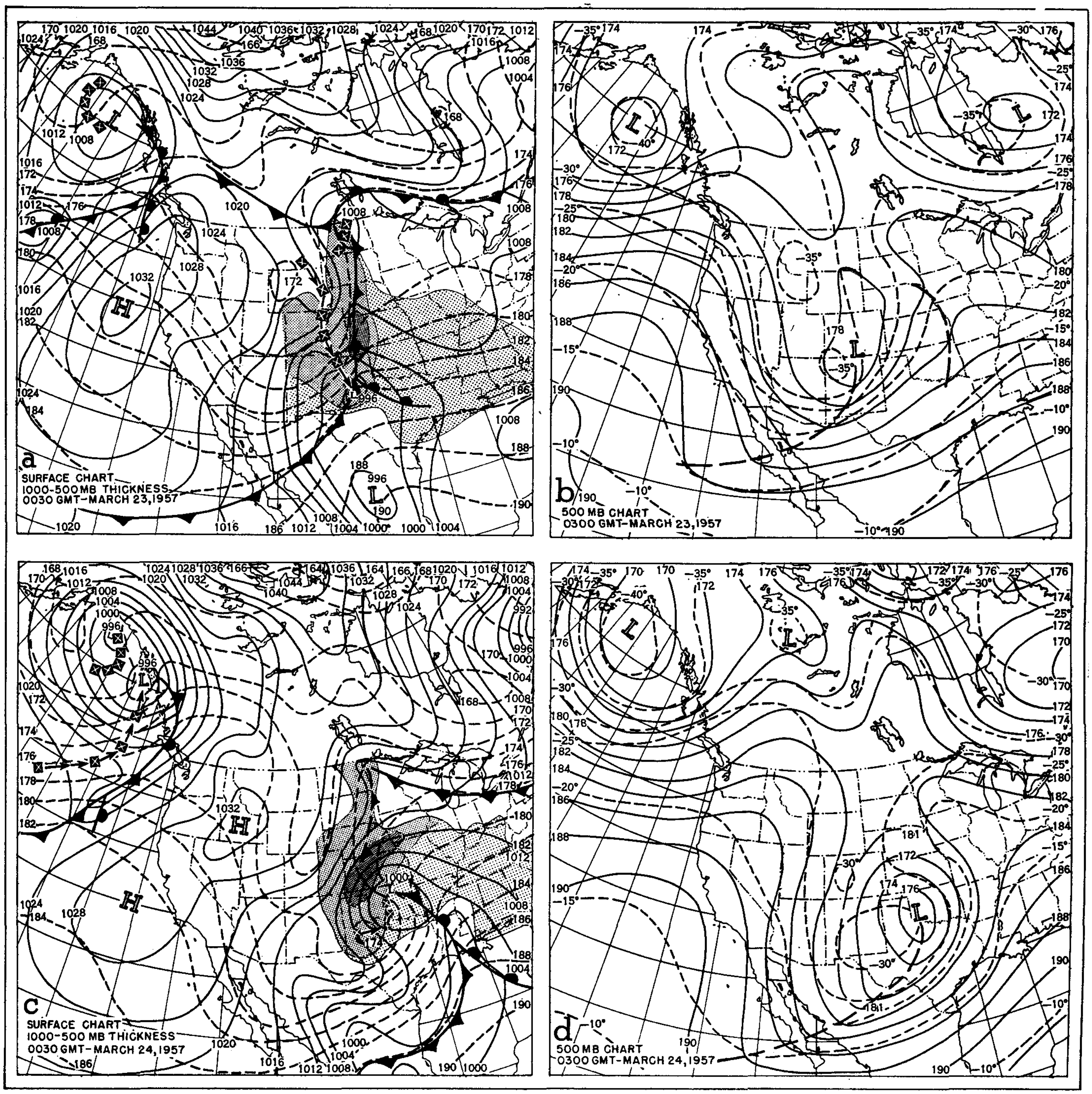

FIGURE 2.—Synoptic patterns for March 23 and 24, 1957. (a) Surface chart 0030 GMT and 1000–500-mb. thickness (dashed lines) 0300 GMT, March 23. (b) 500-mb. chart 0300 GMT, March 23. (c) Surface chart 0030 GMT and 1000–500-mb. thickness 0300 GMT, March 24. (d) 500-mb. chart 0300 GMT, March 24.

ridges at 500 mb. throughout the period from 0300 GMT March 22 to 1500 GMT March 27. During its downstream progression from 180° to 40° W., this energy reinforced three ridges and three troughs at 500 mb. During the 24 hours following 1500 GMT March 24, the blizzard Low reached maximum intensity at 500 mb. near 35° N., 95° W. It was at this time that the wave train was in phase with this short-wave trough. The rate of eastward progression of this downstream dispersion of energy was approximately 50 knots, which is somewhat more rapid than the average value found by Carlin [2] but less than the average given by Petterssen [12].

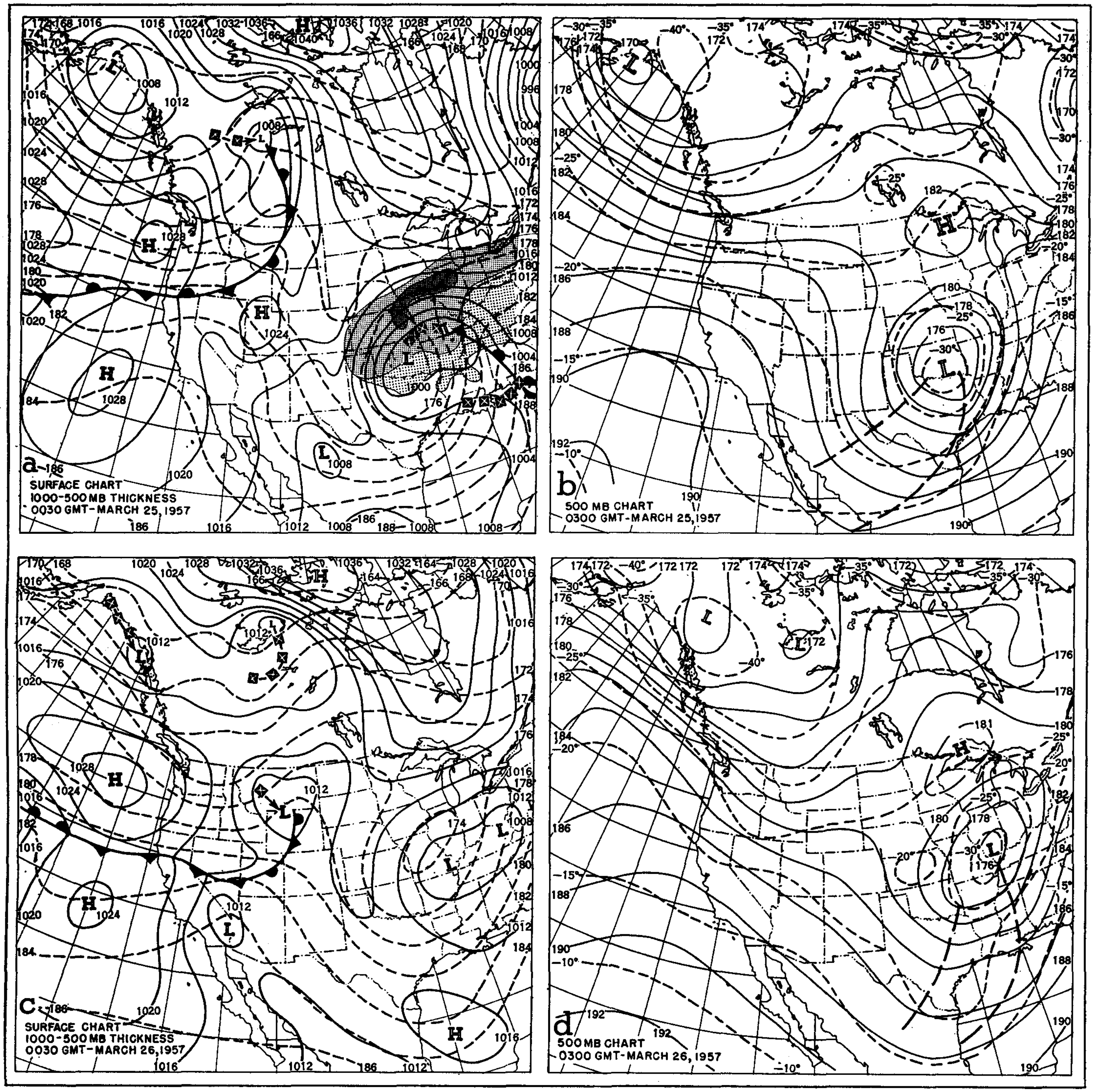

FIGURE 3.—Synoptic patterns for March 25 and 26, 1957. (a) Surface chart 0030 GMT, and 1000–500-mb. thickness (dashed lines) 0300 GMT, March 25. (b) 500-mb. chart 0300 GMT, March 25. (c) Surface chart 0030 GMT, and 1000–500-mb. thickness (dashed lines) 0300 GMT, March 26. No precipitation indicated since blizzard conditions had ended. (d) 500-mb. chart 0300 GMT, March 26.

5. FRONTOGENESIS AND CYCLOGENESIS

Within the 24 hours between figure 1a, b and figure 1 c, d, several developments of major importance occurred. The cold air in association with the old Pacific Low over southern California was carried rapidly eastward both at the surface and in the upper levels, while a tongue of warm air persisted over the Great Basin and the central and northern Mountain States. At 0300 GMT March 20 the eastern limits of this warm tongue, as defined by upper air charts, extended northward over the Mountain and western Plains States, with cooler air to its east but with a rather flat thermal gradient. However, by the morning of the 21st the old Pacific Low, both at surface and aloft, was located over the Southern Plains region (fig. 1a, b) and the anticyclonic circulation which had been present over the Plains on the preceding days was replaced by cyclonic flow.

There also appeared on the 0300 and 0030 GMT charts of March 21 (fig. 1a, b) a weak col or field of deformation located near or within the pool of warm air. The 850-mb. and the 700-mb. charts (not shown) more clearly defined the hyperbolic streamlines and showed the axis of dilatation of this field of deformation was parallel and coincided with the direction of the isotherms. Bjerknes [1] has stated that frontogenesis by horizontal advection operates when a field of deformation is maintained in a baroclinic air mass, and that maximum efficiency in this development occurs when the axis of dilatation of the field of deformation coincides with the direction of the isotherms.

Between the early morning and the early afternoon synoptic charts March 21 (GMT) at both the surface and other low levels considerable advection of the cold air occurred over the Northern and Central Plains. This change in the thermal gradient appeared not only in the spacing of isotherms on all of the upper-level charts but also in the increasing wind shear, approaching 25 knots, over western Montana, eastern Dakotas, and northeastern Wyoming.

Another item of probable importance was the upper cold trough that extended southeastward over eastern Washington and Oregon on the 0300 GMT upper-air charts of March 21 (fig. 1b). The southern portion of this cold trough extended considerably in advance of the trough associated with the strong surface cold front. However, upon its passage temperature falls of from 8° to 12° C. at 500 mb. were observed. This cold trough first appeared as it entered the west coast between 1500 and 0300 GMT of the 20th and 21st, respectively. Corresponding temperature falls at the 500-mb. level were noted at successive 12-hour intervals as this area of maximum cyclonic vorticity passed northeastward on March 21 and 22.

In the hours between 1500 GMT March 21 and 0300 GMT of the 22d the zone of thermal packing reached a maximum over the northern and central Plains as the advection of cold air in the lower levels continued. In fact, the intensity of the thermal packing at the 850-mb. level over South Dakota, Nebraska, and southward equalled that behind the strong cold front. In agreement with this intensification, but to a lesser degree, may be noted the increase in the contour gradient of the 1000–500-mb. thickness chart for 0300 GMT March 22 (fig. 1c). The 1000–700-mb. thickness chart indicated similar thermal packing. Thermal shear across this area of thermal packing had now definitely exceeded the range necessary to qualify for the existence of a weak front. Thus a weak stationary front was introduced in this area on the 1830 GMT surface chart of the 21st.

Simultaneously with this development, and in fact as if synchronized with the inauguration of the stationary or possible warm front, was the formation of a new Low center over southeastern Montana at the point of the intersection of the new front and the strong cold front. This development of a new Low center occurred at approximately the same time the previously mentioned cold trough aloft with its area of maximum cyclonic vorticity was approaching this apex of the new frontal structure. Thus it is believed that this surge of cold air and area of maximum cyclonic vorticity was one of the primary contributing factors to the formation of this Low.

Another factor that must not be discounted is the field of deformation which may have aided in the formation and development of this cyclone. Petterssen [12] has stated that "Cols of cyclonic vorticity represent a potential cyclogenesis," and in line with this statement it is believed that this cyclonic vorticity was at least partially responsible for development and intensification of the Low.

6. DISCUSSION OF FORECASTING TECHNIQUES

The prognostic charts that were issued by NAWAC and others on or near March 21 did not indicate, for the most part, the southward plunging of the surface Low along the eastern slope of the Rockies, nor the strong southward "digging" of the upper trough and attendant transport of extremely cold air. Generally these prognoses for the 22d through the 24th of March indicated a more normal southeastward or eastward progression of the surface Low and related upper-air trough.

With this in mind, we have undertaken the study of other possible subjective or objective approaches to forecasting the motion of this storm, ones that probably were not utilized in the preparation of these various prognoses.

One of the first methods tested in this study has been used by the Tokyo Weather Central [10] and involves the advection of thickness anomalies. This method was selected because the continuity of the thickness anomalies provides a convenient means for following the trajectory of, and mean virtual temperature changes in, the various associated air masses while serving as a tool to aid in the locating of surface fronts. The Tokyo Weather Central method employs a contour pattern obtained by graphical addition of the 1000-mb. chart and one-half the 1000–500-mb. thickness normal. The geostrophic wind computed from these contours is used as the instantaneous flow acting to advect the thickness anomalies. This technique was applied specifically to the negative thickness anomaly associated with the blizzard-producing Low from the time it entered the Pacific Northwest on March 20 until the storm began to subside over the eastern Plains on March 25.

The results of this investigation were as follows:

1. Flow from the derived contours tended to advect the anomaly centers too rapidly due to the strong "digging" and to hold them too far west.
2. This technique produced its greatest error on the 23d

after the storm had become quasi-stationary over Oklahoma. Instead of a southeastward transport into the Gulf of Mexico, the true path curved northeastward in the wake of the 500-mb. Low. In this latter case we also used the Wilson grid [19] in attempting to average the isallobaric flow produced by the negative anomaly and the flow indicated by the derived chart; the resulting position was approximately half-way between the observed position and the previously computed position.

The second method attempted was introduced by Scherhag [14] and briefly consists of the following procedure: (1) Advect the 24-hour surface pressure changes with 50 percent of the 500-mb. gradient winds. (2) Move the 24-hour 1000–500-mb. thickness changes with 80 percent of the surface geostrophic wind. (3) Add these displaced patterns (with surface pressure changes converted to 1000-mb. height changes) to the current 500-mb. chart to obtain a 24-hour 500-mb. prognosis.

The results obtained by use of this method on the 0300 GMT charts of March 21–23 were as follows:

1. A 500-mb. Low with a central height of 17,000 feet was forecast over central Washington with a trough extending southwestward to 36° N., 130° W. for 0300 GMT of the 22d.

2. The Low was forecast to be near 40° N., 113° W., with a trough extending southwestward to 31° N., 120° W., by 0300 GMT of the 23d.

3. The prognosis for 0300 GMT of the 24th forecast a 500-mb. Low with a central value of 17,400 feet over western New Mexico.

In comparison with the actual positions of the trough on the days in question, the indicated movements of the 500-mb. center and trough were much too slow.

In the investigation of the deepening or intensification of the 500-mb. Low, a method recently suggested by Hughes [6] was applied. This method allows for the computation of the 500-mb. height tendency using the observed surface pressure tendency and an appropriate portion of the 1000–500-mb. thickness advection. The period of change is for the next 12 hours. The 500-mb. height tendencies were computed over several critical areas, principally near the 500-mb. trough, in an effort to determine the deepening or filling of the 500-mb. Low. However, in this case study, the computed tendencies by the Hughes method differed from the verifying 12-hour changes by amounts ranging from +430 feet to −580 feet with the average error nearly 280 feet.

Numerous other methods suggested by members of NAWAC were applied to these problems; a few are noted here:

1. Could the 1000-mb. anomaly be advected accurately with the 1000-mb. winds or the 1000-mb. space mean flow? The answer to this was no, as the results were unsatisfactory.

2. Would the trajectory of some closed contour of the low tropopause follow the advection course indicated by the 1000-mb. chart or the 1000-mb. space mean flow? Again the answer was negative.

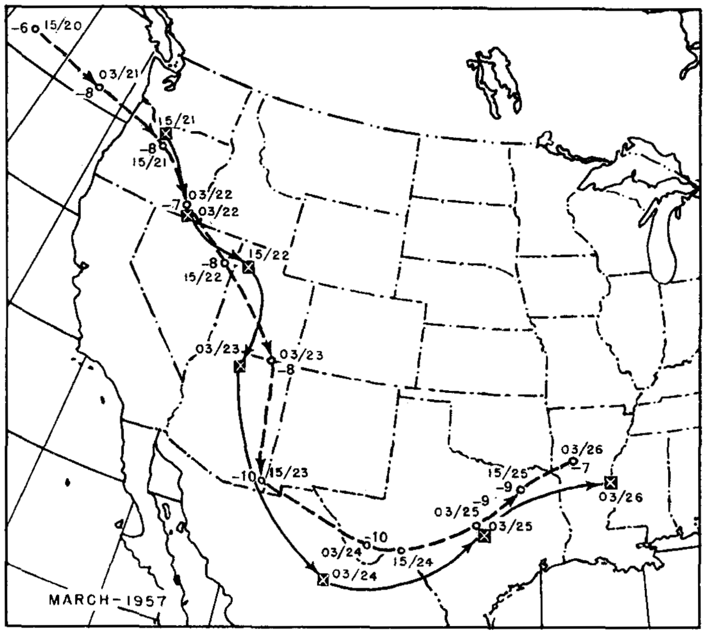

FIGURE 4.—Track of the departure from normal of the 1000–500-mb. thickness, 1500 GMT March 20 to 0300 GMT March 26, shown by dashed lines. Anomaly central values shown in hundreds of feet on actual track. Solid line track shows forecasted advection for 24-hour periods with "X" marking the location of the points.

3. Would the trajectory of the negative 500-mb. departure from normal follow the (a) 500-mb. space mean flow? (b) 1000-mb. space mean flow? (c) sum of the 500-mb. and the 1000-mb. space means divided by 2? The answer to these was unfavorable with the latter tending to be the most favorable of the three.

With the results in mind from all of the preceding experiments we decided to compute a mean flow chart for near the 700-mb. level. Using the sum of a 1000-mb. space mean chart and ½ of the 500-mb. space mean chart, we arrived at a chart that in reality would equal a 700-mb. space mean plus ½ of the 1000-mb. space mean minus a stability factor which Showalter [15], [11], calls "F." It was thought that a smoother contour pattern would be obtained by using the space mean flow charts and at the same time consideration of the mean flow of the present conditions might produce somewhat better results.

This resultant space mean chart, which was prepared for 0300 GMT of the period March 21–25, 1957, was then used to advect the 1000–500-mb. thickness anomaly centers at the measured geostrophic wind speed. It was noted that for full values of the computed geostrophic winds the forecast centers were carried beyond the actual position 24 hours later by between 30 and 40 percent. Then remembering that Scherhag used approximately 80 percent of the surface geostrophic and 50 percent of the 500-mb. geostrophic winds we decided to use a value of 65 percent of our geostrophic winds. The results of this one experiment are illustrated by figure 4. Of the advected movements of the anomaly centers for the period March 21–25, one advected position was essentially perfect at 0300 GMT March 22. The greatest discrepancy was approximately 250 miles at 0300 GMT March 24, and the average error was in the order of 100 miles. While the results were rather good, in this case, further investigation would be necessary before any conclusion could be drawn about the use of these charts in other situations.

It might be of interest to state that two charts were prepared using the 700-mb. constant pressure chart and the 1000-mb. constant pressure chart. The first chart was obtained by adding the 700-mb. chart to ½ the 1000-mb. chart. The results were similar to those obtained previously by use of the space mean flow chart with the error under 100 miles. The second chart was obtained from the first by subtraction of the mean value of F on the current month. The latter results were not satisfactory. In these cases where mean flow charts were not used, 75 percent of the geostrophic wind flow was used.

We next turned our attention to the objective method developed by the Kansas City Forecast Center [7] for the forecasting of "Colorado" type developments. A development of this type is considered one of the most acute forecast problems of the Great Plains region. This system utilizes a series of antecedent steps reduced to their simplest form and applicable to the 500-mb. level. Briefly these steps are:

1. A shift in the wind flow to a northerly component at Seattle and/or Tatoosh, Wash. This northerly component must be retained through the entire period of development.

2. A fall in temperature at Medford, Oreg., reaching a value of −25° C. or lower. In many cases this step may appear to occur simultaneously with 1.

3. A subsequent fall in the temperature at Ely and/or Las Vegas to −25° C. or lower, attended or shortly followed by a distinct temperature rise at Medford.

That these conditions prevailed prior to and attending the development of this storm may easily be observed from table 2.

Another principle investigated was the use of the Constant Absolute Vorticity Trajectory (CAVT) method for forecasting trough-ridge motion and development. Empirically it has been found that the first maximum or minimum point downstream on the CAVT usually coincides with the 500-mb. trough or ridge position 24 hours hence. Two of the several computations made in testing this rule are shown on figure 1d with the points of beginning marked by A and B. The trajectory from point A indicated a favorable position for the trough at the point of first minimum near El Paso, Tex., and the point B trajectory indicated the position of the ridge for 24 hours later with good accuracy at the point of first maximum.

TABLE 2.—*Data for checking Kansas City forecast technique* [7]

	500-mb. data for March 1957										
	20	21		22		23		24		25	
Time (GMT)	15	03	15	03	15	03	15	03	15	03	15
Seattle wind direction (deg.)	210	350	320	310	310	300	270	230	280	260	270
Tatoosh wind direction (deg.)	180	320	300	300	300	280	290	220	270	260	280
Medford temperature (°C.)	−20	−28	−35	−32	−28	−24	−23	−19	−21	−19	−23
Ely temperature (° C.)	−20	−19	−23	−31	−33	−30	−23	−22	−20	−18	−19
Las Vegas temperature (°C.)	−19	−18	−18	−24	−32	−30	−21	−19	−19	−18	−18

It might also be noted that the trajectories from points A and B do point out the validity in this case of the "overshoot" [1] and "undershoot" [2] principles as described by the Tokyo Weather Central [10] and originally stated by Bjerknes [1].

In "overshoot" conditions, the winds in the area downstream from the current ridge can be expected to be stronger and in a more northerly direction in the following 24 hours, with intensification of the downstream trough. Persistent "overshoot" conditions will usually result in deepening and stagnation of a "cut-off" Low in the area previously occupied by the trough.

In "undershoot" conditions winds downstream from the current trough "back" and strengthen, with building of the downstream ridge. Analogous to the "overshoot" conditions, persistent "undershoot" circumstances will often result in continued building of the downstream ridge, and finally, a cut-off blocking-type High.

As may be noted from the 500-mb. charts (figs. 2b, d), the cut-off Low developed, with building occurring in the downstream ridge, thus stalling the eastward movement of the surface and upper-air centers for over 24 hours.

7. PRECIPITATION

Areas of precipitation associated with this storm are indicated by shading on the surface charts in figures 1, 2 and 3. Different types of shading were used to depict where only rain fell, where rain and snow or just snow with light to moderate accumulation on the ground occurred, and where heavy snow was observed by the accumulation of 4 or more inches on the ground in 24 hours. The areas and totals illustrated are for 24-hour periods beginning at midnight local standard time.

Dodge City, Kans. over a period of 72 hours accumulated 2.48 inches of precipitation (in the form of 18.5 inches of wet snow) the maximum reported by a Weather Bureau first-order station during the blizzard. This total of 2.48 inches for this storm exceeded the Dodge City March monthly normal of 1.15 inches by more than 100 percent and shattered the record of over 50 years standing (2.00 in.) for the wettest March. The 18.5 inches of wet snow also exceeded the previous March monthly snowfall total for the city. The area near Dodge City or within 125 miles southwestward experienced the brunt of the heavy snowfall, but snowfall totals elsewhere over the

[1] "Overshoot" defines the condition where a CAVT computed from a band of strong winds at an inflection point on the upstream side of a sharp 500-mb. ridge is essentially in phase with those 500-mb. contours from the inflection point up to the current contour ridge line but then diverts radically, cutting across the current 500-mb. contours toward lower heights and weaker gradient.

[2] "Undershoot" describes a situation where a CAVT computed from an inflection point on the upstream side of a trough cuts across the contours of that trough into well-defined southwesterly current "feeding" the downstream ridge.

TABLE 3.—*Precipitation totals (inches) during the blizzard of March 1957*

Station	Elevation (ft.)	Thickness values [8] for equal snow-rain probability (hundreds of ft.)	March											
			21		22		23		24		25		26	
			Precipitation total	Snow depth	Precipitation total	Snow depth	Precipitation total	Snow depth	Precipitation total	Snow depth	Precipitation total	Snow depth	Precipitation total	Snow depth
Sheridan, Wyo	3,942	178	0.52	5.2	0.03	0.3								
Casper, Wyo	5,322	179	.22	3.3	.13	1.7	T	T						
Cheyenne, Wyo	6,131	180			.34	3.6	.03	0.3	T	T	T	T	T	T
Denver, Colo	5,292	180			.23	2.3	.01	0.1						
Pueblo, Colo	4,639	180			T	T	T	T						
Alamosa, Colo	7,536	182			.07	1.1								
Raton, N. Mex	6,379	181			T	T	.20	2.0	0.01	0.1				
Clayton, N. Mex	4,969	180			.08	0.6	.45	4.1	.02	0.2				
Roswell, N. Mex	3,612	179					T	T						
Rapid City, S. Dak	3,165	178			.10	1.0	.01	0.1						
Scottsbluff, Nebr	3,950	179			.46	4.2								
Lincoln, Nebr	1,166	177.5					.33		1.64	8.4	.36	2.7		
Grand Island, Nebr	1,841	178			.02		.58	0.1	.60	1.0	T	T		
Omaha, Nebr	978	177					T		1.00	6.6	.41	4.8		
Goodland, Kans	3,645	179			.09	1.4	.47	3.6	.44	2.4	T	0.2		
Dodge City, Kans	2,594	178			.21	0.9	1.19	9.3	.82	6.5	.26	1.8		
Concordia, Kans	1,375	178.5			T		.51		.85	1.6	.17	1.7		
Topeka, Kans	865	177			T		.71		1.02	.4	.54	5.4		
Wichita, Kans	1,321	177.5			T		1.09		.15	T	.01	0.9		
Oklahoma City, Okla	1,280	177.5					.02		.02		.04	0.1		
Tulsa, Okla	672	177.5			T		.41		.02		T	T		
Amarillo, Tex	3,950	178.5			.04	T	.25	2.7	.84	8.4	T	T	T	
Lubbock, Tex	3,243	178.5					.08	0.7	.17	1.7				
Midland, Tex	2,854	179					T	T	T	T				
Abilene, Tex	1,759	178.5			T		T	T	.02	T				
Fort Worth, Tex	544	178					.07		.03		T			
Des Moines, Iowa	948	177							.39	2.8	.30	5.9		
Kansas City, Mo	741	177					.43		1.41	T	.20	T	T	T
Fort Smith, Ark	458	178					.40		T		.11			
Columbia, Mo	778	177					.50		1.46		.18	1.8	T	T

Plains must not be discounted, as many areas from the Texas Panhandle northward and northeastward into southern Nebraska and Iowa recorded totals of from 4 inches to locally 12 inches of snow during the period under study. The totals of rain or snow as reported in the Local Climatological Data forms are shown in table 3.

On March 21 at the beginning of this storm the moisture content of the air was relatively low due to the existing cool temperatures at both surface and aloft. Previous cyclonic systems had progressed rapidly eastward and thus there had been insufficient time for strong southerly flow to develop and advect tropical air northward from the Gulf of Mexico. Generally at this time the 850-mb. dewpoints were slightly below 0° C. near the center of the storm, but by 0300 GMT of March 23 a pocket of air with dewpoints slightly above 0° C. at the 850-mb. level became associated with the storm center. Also it should be stated that at this level the temperature-dewpoint separation over the central States was, and had been since the 21st, generally less than 4° C. During the next 24 hours as the Low moved very slowly eastward the 0° C. isodrosotherm at 850 mb. was carried north and northwestward along the east of the occluded front. Topeka, Kans., and Kansas City, Mo., were the northern limits reached by the 0° C. isodrosotherm during the storm period.

Accompanying this previous action was the occurrence of down-slope winds to the south and west of the cyclonic center with attendant drying over much of Texas outside of the Panhandle region. This drying extended gradually eastward and northward into the extreme western sector of the southeastern quadrant of the Low. By 0300 GMT on the 25th the 850-mb. chart indicated that this drying condition had almost completely encircled the Low except in Missouri where some moisture was continuing to flow from the southeast. But in general, precipitation was decreasing rapidly over the Middle West, and by the morning of the 26th, was confined mainly to an area east

TABLE 4.—*Vertical velocity (cm./sec.) at 500 mb. computed from 1500 GMT data for March 1957*

Stations	March				
	21	22	23	24	25
Sheridan, Wyo	<+1	+1	<+1		
Casper, Wyo	<+1	+1.5	<+1		
Cheyenne, Wyo	<0	+2.5	+1.0	<+1	
Denver, Colo	−1.0	+2.5	+1.0	<+1	
Pueblo, Colo	−1.5	+2.5	+1.5	<+1	
Alamosa, Colo	−1.0	+1.0	<+1		
Raton, N. Mex	−2.0	+2.0	+1.0	<1.0	
Clayton, N. Mex	−2.0	+3.0	+2.0	<1.0	
Roswell, N. Mex	−3.0	+2.0	+1.5	<1.0	
Rapid City, S. Dak	0	+2.0	+1.0	<1.0	
Scottsbluff, Nebr	−0.5	+3.0	+1.5	<1.0	
Lincoln, Nebr	0	+0.5	+2.5	+4.0	+1.0
Grand Island, Nebr	0	+1.0	+3.0	+3.0	<1.0
Omaha, Nebr	0	+0.5	+2.0	+4.0	+1.0
Goodland, Kans	−1.5	+3.0	+3.0	+1.0	<1.0
Dodge City, Kans	−1.5	+2.0	+4.0	+3.0	<1.0
Concordia, Kans	0	+1.0	+3.5	+4.0	<1.0
Topeka, Kans	+1.0	0	+3.0	+5.0	+1.0
Wichita, Kans	0	+0.5	+4.5	+5.0	<1.0
Oklahoma City, Okla	−1.0	0	+5.0	+3.0	<1.0
Tulsa, Okla	+1.0	0	+5.0	+4.0	<1.0
Amarillo, Tex	−2.5	+2.5	+2.5	<1.0	
Lubbock, Tex	−3.0	+2.0	+2.5	<1.0	
Midland, Tex	−3.0	+1.5	+2.0	<1.0	
Abilene, Tex	−2.0	+1.0	+2.5	<1.0	
Fort Worth, Tex	0	+0.5	+5.0	+1.0	<1.0
Des Moines, Iowa	+1.0	−1.0	+1.5	+6.0	+3.0
Kansas City, Mo	+1.0	0	+3.0	+5.5	<1.0
Fort Smith, Ark	+3.0	−1.0	+4.0	+4.0	<1.0
Columbia, Mo	+2.0		+2.0	+6.0	+3.0

of the Mississippi River and northward from Tennessee. Generally the 24-hour totals were small but locally over western Pennsylvania exceeded .25 of an inch.

Early in the life of the Low which formed over Montana little or no precipitation occurred as the cold front moved southeastward and the rapidly forming occlusion moved eastward. However, within a few hours after the passage of these fronts the northerly or northeasterly upslope flow brought the moisture content to near saturation and snow began to occur.

Vertical motion over the area of precipitation during this period is shown in table 4. These values were interpolated from the Joint Numerical Weather Prediction Unit charts. It is possible that due to the size of the JNWP grid the maximum values may not be rigorously defined.

Sheridan, Wyo., recorded on the 21st an accumulation of snow slightly over 5 inches in depth with most of this total having fallen within a 6-hour period. This period of heavy snowfall occurred about mid-period of the dates shown in table 4, or approximately at the time the vertical motion was at a maximum value. Upslope conditions or orographic lifting from the north would have accounted for approximately .02 to .03 inch per hour with the existing wind speed and dewpoint. However, in a 2-hour period .30 inch of moisture or 3 inches of snow was recorded. Thus, strong convergence must have occurred to produce the vertical velocity necessary for such totals in a 2-hour period.

Cheyenne, Wyo., recorded nearly 4 inches of snow but this total occurred during a 48-hour period following the frontal passage. Here the precipitation rate of fall agreed quite closely with the orographic lifting inflow and the available moisture.

Dodge City, Kans., as previously mentioned, received the largest total of moisture and snowfall during this blizzard. This was in part due to the elevation of the station, its location with respect to the storm center, the related flow of the moist tongue, the length of time the storm was near Dodge City, and the fact that the weakening and dissipating occlusion remained in a north-south line over Dodge City for nearly 18 hours during the period of heavier snowfall. Table 4 shows that the vertical motion at Dodge City was a large positive value for three days.

On March 23 and 24 the moist tongue, such as prevailed during this period, was flowing over or near Dodge City from the south, southeast, or east, the direction of flow being dependent upon the time and location of the Low. Temperatures, surface and aloft, were relatively low with the 850-mb. readings near or slightly below 0° C. and the dewpoint equal to or within 1° C. of the temperature. Consideration of these dewpoints and the existing winds in a purely orographic lifting process indicates the maximum precipitation obtainable would have been approximately .02 inch per hour. However, on the 23d when the occluded front was in the vicinity of Dodge City, the precipitation totals for 14 hours ranged from .05 to .12 inch per hour. Strong convergence along this front was definitely indicated as the primary means of increasing the vertical motion for producing these greater hourly amounts. At approximately this time the computed vertical motion was 4.00 cm. per sec. at 500 mb. (table 4). Following this period the precipitation rate decreased to near or slightly above the orographic lifting value.

Amarillo, Tex., and the surrounding area was another region seriously affected by the blizzard. But in this locality the accumulated snowfall was approximately one foot in depth during a time period of nearly 50 hours. Since the winds were from the east for only a short period of time on the 23d and had a relatively low moisture content, the orographic upslope precipitation was of short duration and quite light. As the winds backed to the northeast and north the hourly precipitation totals from orographic lifting decreased, even though the station at that time came under a more direct flow of moist air, because the slope of the terrain decreased. However, at approximately 1500 GMT of the 24th the upper trough passed over Amarillo (fig. 3b), and precipitation totals increased with hourly totals up to .14 inch. It is believed that most of the heavy snow was associated with the vertical motion that prevailed in connection with that trough.

One of the most interesting factors in connection with this storm was the lack of precipitation over most of Texas outside of the Panhandle area and also over a goodly portion of Oklahoma. It appeared quite favorable from the surface charts on the 22d and 23d that precipitation would occur. In table 4 it may be observed that strong positive vertical motion was indicated at both Fort Worth and Oklahoma City on the 23d. However, just prior to this increase in vertical velocity a surge of cold dry air swung eastward ahead of the upper trough and rapidly reduced the moisture content of the air so that by early morning (CST) the temperature at Oklahoma City had lowered 4° C. at the 500-mb. level, and the dewpoint 13° C. with a separation of 15° C. By late evening the moisture content in the air had fallen to a level that required the reporting of "motorboating," or approximately 20 percent relative humidity or lower. Some 24 hours later moisture again moved into the Oklahoma City region but by that time the vertical motion had subsided.

A similar change occurred at Fort Worth, Tex., and thus resulted in the lack of any appreciable precipitation in that area also. Another station affected in the same way was Topeka, Kans. Approximately 12 to 15 hours after the occurrence of the "motorboating" report at Oklahoma City, the dry air reached Topeka. However, Topeka remained in this dry surge for only approximately 12 hours after which the precipitation commenced again. Columbia, Mo., was also under the influence of this dry cool surge but to a lesser degree. There precipitation diminished sharply and at times ceased during a 9-hour period prior to noon of March 24 (CST). In the Columbia area the moisture content at 500 mb. did not decrease to "motorboating" at either of the 12-hour synoptic observations.

It is interesting to note in comparing tables 3 and 4 that in general the hydrometeor totals in excess of .20 inch occurred only when vertical velocities were 2 cm. per sec. or higher.

The occurrence of snowfall as related to the thickness of the 1000–500-mb. layer was rather clearly defined in this present study. It has been found by Lamb [8] over the British Isles that the thickness value for equal probability of rain or snow ranges from 17,100 to 17,300 ft. The cutoff point is not sharply defined but greater thickness usually produces a higher probability of rain and lower values an increasing probability of snow. Over the United States, the National Weather Analysis Center [9] has found that the critical thickness value is considerably more variable with the equal probability of rain and snow ranging from 17,200 to 18,200 ft. or higher. The thickness value required for the occurrence of snow in the area near sea level along the Pacific Coast was found to be near the value observed by Lamb for snow in the British Isles because in this area the airmass is also of similar climatic regime. But inland over the United States, the values have been considered as nearer 17,800 feet, with that value increasing with elevation. Thus the higher the elevation the greater the thickness value would be for an equal chance of rain or snow.

Recently Wagner [18] completed a more thorough study of this equal probability of snow or rain over the United States. He finds that along the west coast the thickness value is near 17,200 feet but that it increases rapidly inland and reaches a maximum thickness value of 18,160 feet or slightly higher near Lander, Wyo. His highest thickness contour (18,100-foot line) for the 50 percent cutoff value extends along or in the proximity of the Continental Divide from Yellowstone National Park to Albuquerque, N. Mex., and also encloses a small portion of Nevada and Utah. Eastward from the Divide the thickness values decrease until an area over northern Missouri and southern Iowa is enclosed by the 17,700-foot contour. Then these equal probability values rise to slightly higher values over the Appalachians and decrease again to 17,600 feet or slightly less along the eastern seaboard from Boston, Mass., southward. Wagner also found that the probability toward rain or snow increased to 75 percent with the change of plus or minus 170 feet respectively, and that with a change of 270 feet the chance of rain or snow increased to 90 percent. A few of the interpolated values obtained from his diagrams are listed in table 3.

It may be noted in table 3 that snow occurred at Columbia, Mo., and Topeka, Kans., but that only traces were recorded at Kansas City, Mo. According to Wagner [18] snow at these three stations would have a 50–50 chance at 17,700-ft. thickness value. Topeka cooled below that thickness late on March 24 and remained at lower thickness, but Kansas City did not drop below

TABLE 5.—*Comparison of amounts of precipitation forecast by Estoque [3] method and observed amounts (inches)*

Station	March 1957					
	22		23		24	
	Forecast	Observed	Forecast	Observed	Forecast	Observed
Columbia, Mo.	0.00	0.00	0.26	0.50	0.25	1.46
Kansas City, Mo.	.03	.00	.23	.43	.08	1.41
Topeka, Kans.	.08	T	.30	.71	.00	1.02
Omaha, Nebr.	.05	.00	.08	T	.04	1.00
Grand Island, Nebr.	.05	.02	.10	.58	.00	.60
Dodge City, Kans.	.18	.21	.17	1.19	.00	.82
Wichita, Kans.	.01	T	.40	1.09	.00	.15

the 75 percent value until near the end of the precipitation at that station, and with temperatures at or slightly above freezing, within the city the snow which occurred did not accumulate on the surface of the ground. However, at Columbia the precipitation ended later, the thickness value was lower prior to the end of the hydrometeors, and the surface temperature minimum was 2° lower that day being 2° F., below freezing.

In a recent publication Estoque [3] presented a rather simple approach to quantitative precipitation forecasting. His method, which for a forecast area the size of the United States can be completed in approximately two hours, employs only four main charts: the current charts of the 1000-mb. level and the 1000–500-mb. thickness, plus the 24-hour prognostic charts for the 1000-mb. level and the 1000–500-mb. thickness. On the basis of Estoque's findings, it was decided to apply his method to the forecasting of the precipitation that occurred during this storm, using actual charts instead of the prognostic maps. Furthermore, it is to be expected that areas of orographic lifting will produce larger amounts of precipitation than would be forecast by this method. Also, unless the airmass is saturated throughout the entire sounding the precipitation totals will be less than forecast.

Table 5 gives the results of these computations for the three days of heavier precipitation during the blizzard period. The precipitation at Dodge City was probably affected strongly by orographic lifting.

8. CONCLUSION

The above described investigations of various charts and devices suggest that the method used at the Kansas City Weather Bureau Forecast Office, the CAVT technique, and space mean charts of the 1000-mb. plus half of the 500-mb. contours tended to furnish the better clues to the probability of this storm "digging" during the early stages of development. However, that some of the other widely used techniques did not indicate the trajectory of the storm's path during this particular study is not a justifiable basis for assuming that they are unreliable in general.

In this case, Wagner's findings appeared to furnish useful indications of the probability for the type of hydrometeor at several stations. Therefore, it would be desirable to make further applications of his work and to derive any adjustments that may be required in the local thickness value.

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