The state averages presented in this paper show only the mean conditions associated with tornadoes during the 8 year period of study. These averages cannot be used to predict tornadoes but they do illustrate the weather conditions that have accompanied past tornadoes.

ACKNOWLEDGMENTS

The assistance of Mrs. Sandra Boyse is appreciated for typing the manuscript and the work of the NSSFC computer staff is also gratefully acknowledged.

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THE SOUTHWEST LOW AND "HENRY'S RULE"

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ABSTRACT

The two synoptic conditions which precede the eastward movement of the Southwest Low and form the basis for Henry's Rule are described. Henry's Rule is that a stationary low over the southwestern United States will accelerate to the east when its circulation weakens, and another low arrives at a position about 2200 km to the northwest.

1. INTRODUCTION

On many weather maps of the United States an upper-level cyclonic circulation is centered over the Southwestern States. This paper describes the occurrence and behavior of these lows and proposes a means of forecasting their movement.

The original research of this paper was started at Randolph Field, Texas because of the adverse weather for flying that these lows caused and our inability to forecast their behavior. The scope of the work was extended and was finalized in 1949 for a thesis at the University of Chicago with Dr. Walter J. Saucier as committee chairman. The thesis was entitled "On the movement of the Southwest Low". Being in the United States Air Force and having a demanding assignment, publication of a paper at that time did not seem to be very important. Later, Mr. Lawrence A. Hughes of the Chicago office of the United States Weather Bureau started using the methods described in the thesis and "Henry's Rule" came into being. In January of 1962 the USWB reproduced the thesis along with a few remarks by Mr. Hughes as OFDEV Technical Note No. 6. Reference to this "rule" has appeared in many of the various forecast discussions such as National Meteorological Center's twice daily map summary and the regional critiques. The procedures have been used for several years by many forecasters in the southwestern United States. Now that the National Weather Digest is trying to present useable forecasting methods it is time to publish "Henry's Rule".

A low was classified as a "Southwest Low" if its center was within the area bounded by 40°N to 25°N and 100°W to 125°W. The area was further subdivided into three sections, the mountainous area in the center (the stippled part on Figure 1), and the section east or west of the mountains. The 700 mb charts were used because they were the best upper air charts during the period of 1940 to 1949 when the rule was formulated. However, the reasoning and rule applies to the 500 mb map.

2. CHARACTERISTICS OF LOWS

The lows in this area are often "cutoff lows" indicating that they are separated from the prevailing westerly circulation of the hemisphere. At other times the long waves may be of high amplitude and the low still embedded in the westerlies. The lows are cold core lows. All lows which were in the area were considered and included in the final results.

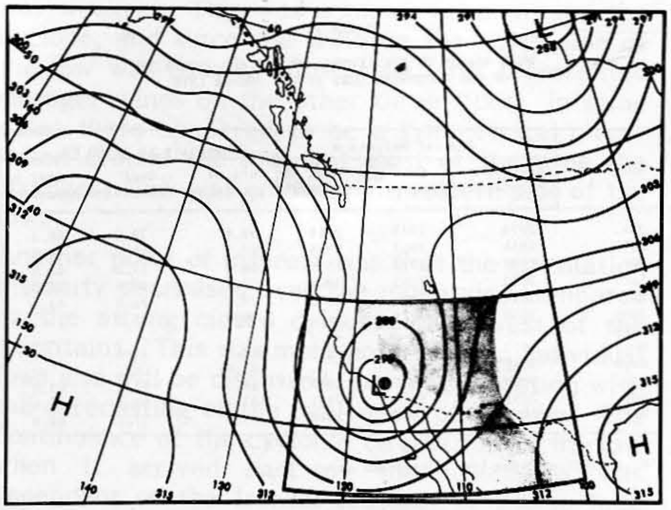

Figure 1. Typical 700 mb Chart with a Southwest Low. Heights are in dekameters. Shaded part represents the "over mountains area".

a. Climatology of the Lows

The distribution of the lows by month and by location is shown in Table 1. It should be pointed out that the area of the section west of the mountains is about twice the area of each of the other two sections. Even with that consideration the tendency for the low to remain west of the mountains was noticeable. The position of each low center was transferred from each 700 mb chart to a topographic map. This showed that the low areas tended to favor the regions of lower terrain and avoid the elevated regions. There were very few cases with the low located over areas where the height of the terrain was greater than 1800 m. The locations were concentrated along the coastal lowlands, and when the lows moved eastward their paths were between the major mountain ranges. This indicated that the mountains were an important factor in controlling the location and paths of the Southwest Low. The individual lows often moved 950 km in twelve hours as the low crossed the mountains, a movement far in excess of that before or after it moved over the mountains. Wintertime lows were more frequent than summertime lows. Also during the winter they normally moved eastward and could be identified over the mountains, and east of the mountains. They are an important factor in the circulation of the southwestern part of the United States since they are present about twenty-five per cent of the time during the winter season. Cyclonically curved flow over this area without a closed circulation occurs a much greater portion of the time.

Summertime lows (June, July, August and September) appeared as closed circulations only to the west of the mountains. In general, they moved northward or southward along the coast, without any inclination to move eastward and across the mountains. Closed lows occurred infrequently in the summer, but those that did occur persisted for some time. It is noted that two lows in June lasted 3.5 days (d) while a low in the winter lasted only about 2.5 d on the average. July seemed to be free of closed lows; however, if a longer period had been considered they might well have appeared.

b. Paths of Lows

Approximately one-third of the lows started in the Aleutian Low, moved southeastward along the coast and down into the designated area. This process occurred when there was a trough of large amplitude over the west coast. These lows became quasi-stationary over Southern California for two or three days, then moved eastward rapidly. In this case the polar jet stream contained troughs and ridges of large amplitude. A ridge usually extended into the Gulf of Alaska and the ridge line had a north-south orientation. The trough line was oriented north-south, or north-northwest to south-southeast. A ridge was present over the Mississippi Valley but of less intensity than the one in the Eastern Pacific. Figure 1 shows a schematic map of a low in the Southwestern United States and the general pattern.

The other lows could be classified into four groups, each containing about one-sixth of the total. One group of the lows retrogressed into the region; that is, they moved southward from Montana or Wyoming to a position over lower California where they remained for an indefinite time, then moved northeastward across the United States. The general circulation pattern for this group was about the same as described in the preceding paragraph. The only noticeable difference was that the orientation of the trough line was northeast to southwest. After the low reached the southern-part of its movement the trough line often became north to south in its orientation.

TABLE 1

MONTHLY DISTRIBUTION OF SOUTHWEST LOWS BY SECTION AT 700-mb LEVEL
(Closed Centers Only) (1940 to 1948)

Month	Average Number per Month	Average No. of Days per Low	Average Number of Days Low Is in Each Section of Area: West of Mtns.	Over Mtns.	East of Mtns.	Per Cent of Month Low Exists
Jan.	3.5	2.75	1.57	0.72	0.46	29.6
Feb.	2.5	2.20	1.10	.90	.20	19.6
Mar.	2.3	2.21	1.29	.79	.14	12.5
Apr.	1.0	2.84	1.83	.83	.17	9.4
May	1.3	2.50	1.63	.50	.37	10.8
June	.7	3.50	2.84	.67	.00	11.7
July	.0	.00	.00	.00	.00	.0
Aug.	.7	2.25	2.05	.20	.00	4.8
Sept.	.3	1.50	1.50	.00	.00	.2
Oct.	2.3	2.57	1.86	.57	.14	20.0
Nov.	2.0	2.33	1.25	.92	.17	15.6
Dec.	2.5	2.50	1.45	0.80	0.25	20.8

Another group of lows had a path that was almost west-east. They came into the area from the west, continued through the area, and moved out eastward. Seldom was their path south of 35°N and these had a constant rate of movement. They did not have the pause over Southern California which characterized the two types discussed previously. The general circulation in these cases was more zonal, and the polar jet was south of its normal position.

Some lows appeared to form in the area. These were usually the true "cutoff lows". Once formed they remained almost stationary for two or three days before making any noticeable movement eastward. The general flow pattern for the "cutoff" was a trough of large amplitude and a large pressure ridge to the west in the Eastern Pacific. After the "cutoff" was completed the main westerly current had less amplitude and became located north of the "cutoff low", usually at about 55°N.

The last group consisted of the remaining miscellaneous cases. It included the few summertime lows which developed through the various methods discussed above; after remaining a few days off the coast they either filled or shifted northward before moving eastward. South of 40°N there was no tendency for these summer cyclones to move toward the east. Also in this last group were a few lows that appeared to drift in from the south. After some time they drifted southward again and disappeared. Because of lack of data the exact nature of these cyclones was not known, but it was suspected that each was connected with a disturbance in the tropical easterlies. When the low from the south moved into the area the main westerly current was usually zonal and located at about 50°N. The large scale circulation pattern was different for the individual cyclone cases.

A closed low pressure area in the southwestern United States usually had little movement for a period of 36 to 72 h. Then suddenly it moved eastward or northeastward rather rapidly. At times it may have appeared to "split" with one part remaining stationary or retrogressing and the other part moving eastwardly rapidly; this process was associated with a quasi-stationary pattern of the westerly current. The sequence of events under these circumstances revealed that the actual splitting was very rare. Usually a weak pressure trough moved in from the northwest and formed a second low to the west of the original low which was displaced eastward. Also the original low moved eastward as a weak wave while a new low formed to the west of the position of the former. This gave the appearance of a westward movement of the cyclonic center. In a few instances the low filled so rapidly that after twelve hours there was little trace remaining of a closed cyclonic flow.

TABLE 2

MEAN VALUES OF THE CENTRAL HEIGHT AND INTENSITY OF THE SOUTHWEST LOWS AT THE 700-mb LEVEL

Month	Central Heights m			Intensity ΔH m/880 Km		
	West of Mountains	Over Mountains	East of Mountains	West of Mountains	Over Mountains	East of Mountains
Jan.	2979	2973	2961	98.8	78.0	66.1
Feb.	2954	2947	2995	87.5	85.0	84.1
Mar.	2995	2939	2995	86.3	71.0	68.6
Apr.	3008	3053	3048	79.2	37.2	42.7
May	3019	3006	3043	77.1	71.6	63.4
June	3028	3075	....*	90.8	53.9	....
July	....	....	....	....	....	....
Aug.	3072	3170	....	83.5	12.2	....
Sept.	3042	....	....	81.4	....	....
Oct.	3026	3026	3063	87.1	73.2	63.4
Nov.	2951	2959	2995	103.3	90.0	107.6
Dec.	2955	2930	2972	93.3	77.1	89.9

*.... Indicates no lows during the month

c. Mean Circulation of Lows

The average gradient around each closed low was taken to be a measure of intensity. The radius of 880 km was selected arbitrarily and the height difference from the center in four directions was determined, averaged and called ΔH. The value of ΔH was equivalent to the average gradient around the low. (With additional computation the relative vorticity could be determined from the average gradient.) The intensity of each low was determined every 12 hours (h) by this method. The results for each month are compiled in Table 2.

In considering these results the fact that only closed lows were measured masks the results. Any low that weakened and formed a trough as it moved eastward was evaluated only as long as it had a closed circulation at the 700 mb level. The values given for the sections over the mountains and east of the mountains were somewhat higher than they would be if a cyclone could be followed all the way across. A closed circulation weakened as it crossed the mountains, as will be discussed later, and usually became a trough. Only the stronger lows retained their identity while crossing the mountains; therefore, the average values of ΔH for the two eastern sections in Table 2 were exaggerated relative to the average values for the western section.

This table indicates that the lows had the lowest central height during the winter months. In winter the lowest central height was inland, while during the warm months the lowest central height was over the coast. This follows the seasonal temperature distribution. In winter the surface was colder over the mountains, and in summer the coast and ocean had the cool surface.

The intensity of the circulation also was dependent upon the season, with the most intense circulation being in winter. A value of ΔH of 100 m is equivalent to a geostrophic wind of 25 kt. Because of the cyclonic curvature the actual wind was weaker. This was a mean value around the cyclone, and since the wind on the north side of the low was usually quite weak, this represented stronger winds on the other three sides. In some cases there appeared to be a symmetrical circulation around the low, but most of the time the strongest flow was on the southwestern side of the low.

Another point of interest was that the circulation intensity decreased over the mountains compared to the strong closed cyclonic flow west of the mountains. This was more noticeable in individual lows and will be discussed later in connection with the forecasting of the movement of the low. The continuance of the cyclonic circulation of the low when it arrived east of the mountains was dependent on the frontal features of the surface map. The conditions needed by the low to persist will be discussed in conjunction with methods of forecasting the weather associated with the storm that the low may cause.

3. WEATHER WITH LOW

With all weather events there may be great variations. The weather patterns associated with the Southwest Low are variable also. West of the mountains the low causes much cloudiness. The heavy rainfall in Southern California in winter has been caused by this low. With some lows the rain extended into Mexico. When the low moved over the mountains it was usually weaker and moved rapidly so the weather was characterized by clouds and some light rain.

When the low encountered a strong ridge over the Mississippi Valley it usually continued to weaken and moved around the periphery of the ridge. Little precipitation and some cloudiness has been associated with this condition.

Often however, the ridge was weak or a weak trough extended southwestward from Hudson Bay. With this favorable condition a Southwest Low could intensify over the Great Plains. During the winter months a polar front generally was along the east slopes of the mountains even if not shown on the analysis of the National Meteorological Service. The Southwest Low generated waves on the fronts. Then snow, rain or freezing rain fell over the Great Plains and the upper Mississippi and Ohio Valleys. The storm often developed into blizzard conditions. In Texas, Oklahoma, Arkansas, and Louisiana thunderstorms occurred, followed by rapid clearing as the trough aloft passed. Often in springtime tornadoes and dust storms occurred whenever the Southwest Low entered the Plains States. In summary, many times severe weather of some type has formed as the Southwest Low moved to the east side of the mountains. Therefore timing of the movement of the low became important.

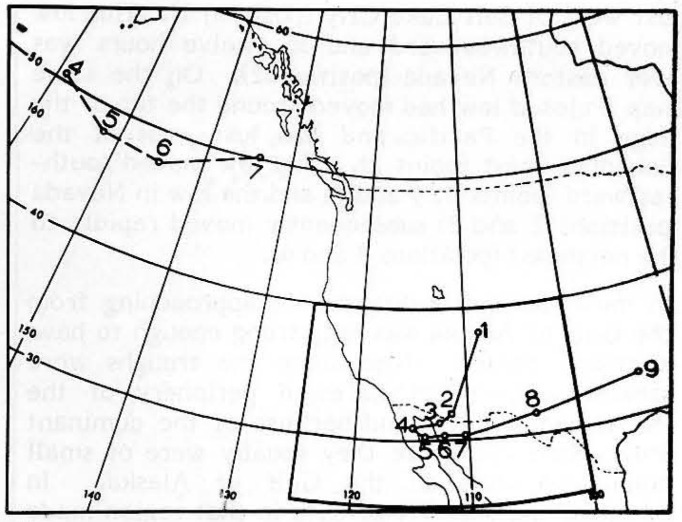

Figure 2. Path of low (solid line) and isallobaric minimum to the northwest (dashed line) for 11 to 15 January 1946, inclusive.

Code: 1 - 11 January:1500 GMT; 2 - 12:03; 3 - 12:15; 4 - 13:03; 5 - 13:15; 6 - 14:03; 7 - 14:15; 8 - 15:03; 9 - 15 January:1500 GMT.

4. FORECASTING THE MOVEMENT OF THE LOW

The forecast problem is to decide when the low will start to move eastward across the moutains. Two synoptic conditions have a bearing on the movement, a) the intensity of the low and b) a trough approaching from the west.

a. <u>The Intensity of the Low</u>

It was found that the strong lows with large values of ΔH did not move far, at least not eastward. A low that was weakening tended to move eastward rapidly. An example is shown in Table 3 and Figure 2. Because of the sparse data both positions of the lows could not be determined exactly and some indicated movement may be due to analytical techniques, but the jump eastward following point 7 was much more than variation of analysis. Also the decrease of ΔH by a factor of two was more than the whim of an analyst.

To consider all cases, note Figure 3. It illustrates the relationship of the ΔH value and the distance moved during the subsequent twelve hours. As can be seen the strong lows move slowly. Also important was the decrease of ΔH as well as the actual value of ΔH.

b. <u>A Trough to the West</u>

It also was noted that whenever a low approached from the northwest that the Southwest Low moved eastward. This series of events is shown in Figure 4 where the twelve-hour position of both lows are shown. On the 700 mb map of 27 October 1948, at 1500 GMT a low was centered just west of Salt Lake City (position 1). This low moved southwestward and in twelve hours was over eastern Nevada (position 2). On the same map a closed low had moved around the top of the ridge in the Pacific and was just west of the Canadian coast (point 2). This low moved southeastward (points 3, 4 and 5) and the low in Nevada (positions 2 and 3) subsequently moved rapidly to the northeast (positions 3 and 4).

In most cases the disturbance approaching from the Gulf of Alaska was not strong enough to have a closed center. Also since the troughs were steered around the northern periphery of the Pacific anticyclone and because of the dominant anticyclone curvature they usually were of small amplitude while in the Gulf of Alaska. In addition, the scarcity of data in that region made it difficult to follow these troughs precisely. Therefore, an objective alternative was taken to locate the center of activity of those small waves. Since in the belt of the westerlies the position of a twenty-four hour isallobaric minimum is a good approximation to the position of the associated pressure trough, it was decided that the location of the katallobaric centers be investigated. The isallobaric fields were determined from the analyzed 700 mb charts by subtracting the contour heights on one chart from the heights of a chart 24 h later. This was done at 12 h intervals for the eastern north Pacific area whenever there was a Southwest Low. The centers of pressure fall (katallobaric centers) and the centers of pressure rises moved in the general direction of the steering current.

When the data from two years (1946 and 1947) were tabulated it was found that the results were about the same as if a closed cyclone coming out of the Aleutian Low could have been tracked. When the katallobaric center approached from the northwest, the low moved eastward. An example of this is given in Figure 2.

This low was one of a series that formed during January 1946. Cyclones moved eastward from the Southwest on the 4th, 8th, 10th, 14th and 18th of January 1946. The low shown in Figure 2 "backed in" from Colorado and its path is indicated by the solid line. The location of the low is shown each 12 h. After it arrived in the vicinity of the Gulf of California, its movements were insignificant until after 14 January at 1500 GMT. The katallobaric center in the meantime had been moving eastward across the North Pacific. Its 12 h positions are indicated in Figure 2 by a dashed line for the period of 13 January at 0300 GMT to 14 January at 1500 GMT, inclusive. When the center of the low and katallobaric center had the relative positions shown on the map of 14 January at 1500 GMT (point 7 on Figure 2) the low began to move eastward. Such a relationship between the Southwest Low and the upstream katallobaric center was evident in other cases, and worthy of

TABLE 3

RELATION OF INTENSITY AT 700-mb LEVEL AND MOVEMENT OF THE SOUTHWEST LOW OF 11 to 15 JANUARY 1946, INCLUSIVE

Code Figure	Day	Time GMT	ΔH m/880 Km	Subsequent Twelve-Hour Movement: Distance Km	Direction
1	11	1500	74.7	685	SW
2	12	0300	128.0	75	S
3	12	1500	152.4	165	SW
4	13	0300	147.9	75	S
5	13	1500	140.2	165	NE
6	14	0300	115.9	185	E
7	14	1500	51.8	556	NE
8	15	0300	54.9	835	NE

further study. In this case the katallobaric center became the next Southwest Low and moved eastward on the 18th.

For each cyclone the location of the low center and of the effective katallobaric center were determined from the last chart before the cyclone began to move eastward. The distance and direction from the low to the isallobaric minimum were obtained from the map. When the lows were given a common location it was found that the positions of the isallobaric minima showed pronounced clustering. This distribution is shown in Figure 5. The location of the points on the map are not the exact geographical positions of the katallobaric centers; they were the positions of the katallobaric centers with respect to the Southwest Low. It was the relationship of the isallobaric minimum to the low that was important. The actual strength of the katallobaric center did not seem to have much effect. Thirty-four lows (all that occurred in 1946 and 1947 except during the summer) were checked. All these lows had a katallobaric center located to the northwest when they began to move. Only once did a katallobaric center appear in the proper relationship to the low, and the low did not move. That time the ΔH value of the low was greater than 160 m/880 km, a very high value (see Figure 3).

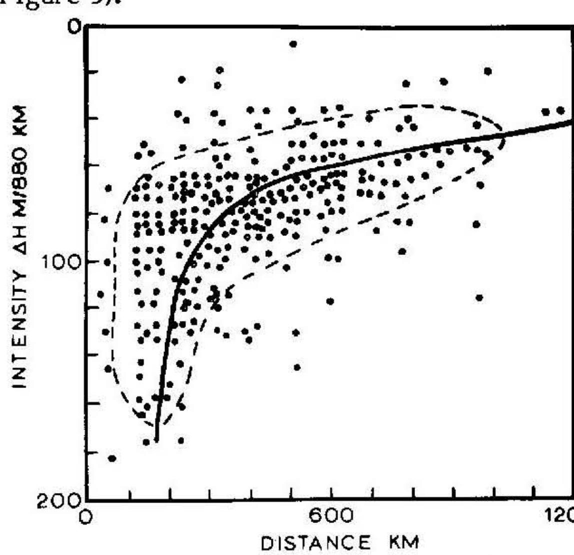

Figure 3. The relationship of the 12 h eastward movement to the intensity of the Southwest Low.

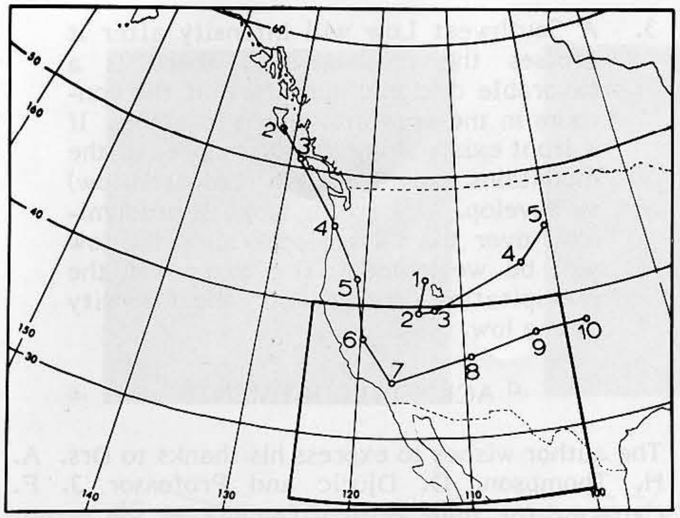

Figure 4. Path of lows of 27 October to 2 November 1948 inclusive at the 700 mb level.

Code: 1 - October 27:1500 GMT; 2 - 28:03; 3 - 28:15; 4 - 29:03; 5 - 29:15; 6 - 30:03; 7 - 30:15; 8 - 1:03; 9 - 1:15; 10 - 2 November:0300 GMT.

The positions shown in Figure 5 are well clustered, especially if the accuracy of the analysis over this part of the ocean is considered. Also a time lag could enter into the relationship of the katallobaric center and the low. The low could start moving, even before the time of the map and not move enough to give a positive indication of movement, or it could wait several hours after the map time to start moving. Therefore there could be up to eight or nine hours time difference between the different locations of the isallobaric minima. Even without these substantiating considerations the locations of the points cluster well, and if more information were available they could cluster even better. Therefore, whenever there is a low in the Southwestern United States a forecaster may expect it to move whenever a katallobaric center is located about 2200 km to the northwest of the low.

On today's maps the positive vorticity maximum may be used in lieu of the closed low or the katallobaric center. All three are indications of cyclonic activity. The positive vorticity maximum, the low, and the katallobaric center at the 500 mb and 700 mb levels are not at the same geographic location on all maps, if on any. However, given the accuracy of the analysis in the Gulf of Alaska and the diversity of points on Figure 5, any of the indications will suffice.

The same technique was used for a period of 24 h before movement. The points were somewhat scattered and did not seem to be of much use. The isallobaric minimum had a rather erratic movement.

It was a common occurrence for the katallobaric center to move into the trough and form another

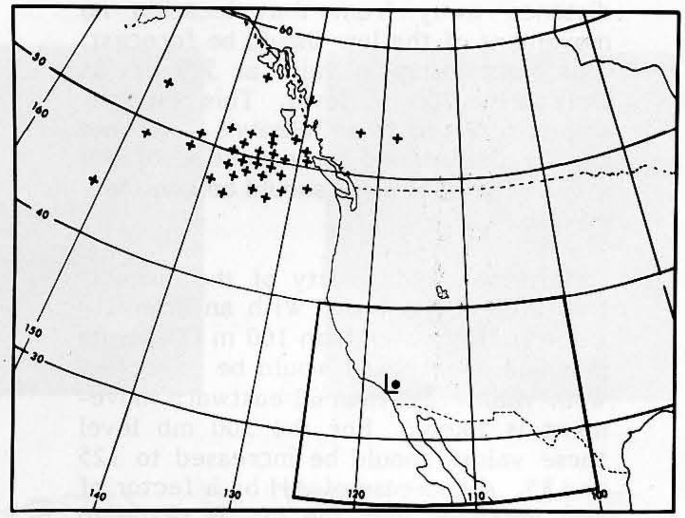

Figure 5. Location of isallobaric minima to the Southwest Low when the low started to move rapidly. The + marks the position of each isallobaric minima.

cyclone as the original low moved into the area east of the mountains. If the former low lost its circulation and became a weak wave, then the low appeared to "jump" westward, especially if the time interval between charts was greater than twelve hours. The low that formed was a new low and usually not a retrogression of the former. If the new low formed while the former low was still over the mountains their outer circulations might have combined, and as the low to the east moved across the mountains it often appeared that the low split.

In a few cases when the katallobaric centers were moving extremely fast they caught the Southwest Low, and then a double low did form. This was an unstable condition and the "split" took place with the low to the east moving very rapidly, forming a trough of small amplitude. The few lows that occurred during the summer did not move eastward while south of 40°N. For this reason they pose problems only to forecasters on the west coast.

5. SUMMARY

In conclusion the following outline for forecasting the movement of the lows that occur over the southwestern part of the United States and the adjoining Pacific Ocean is presented.

1. Determine the relationship of the katallobaric (or positive vorticity maximum) center to the northwest of the low. If a moving trough or closed cyclonic circulation can be located, it may be used in lieu of the isallobaric minimum. Whenever any indicator has the proper relationship to the low, that is, located approximately 2200 km to the northwest (see Figure 5), the low should move. When the isallobaric minimum is some

distance away from that location no movement of the low should be forecast. This relationship is valid at 500 mb as well as the 700 mb level. This relationship is referred to as "Henry's Rule" and can be determined by inspection of the maps. The next parts should be considered also.

2. Determine the intensity of the circulation around the low. With an intensity value (ΔH) greater than 100 m (25 kt) no movement eastward would be expected. With values less than 60 eastward movement is likely. For the 500 mb level these values should be increased to 125 and 85. A decrease of ΔH by a factor of two indicates that the low is ready to move.

3. A Southwest Low will intensify after it crosses the mountains if there is a favorable cyclonic curvature of the contours in the area into which it moves. If a front exists along the east slopes of the mountains expect a wave (Colorado-low) to develop. If a strong ridge is predominant over the Mississippi Valley the low will be weakened. The extent of the precipitation depends upon the intensity of the low.

ACKNOWLEDGEMENTS

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MESOSCALE LOW LEVEL VORTICITY CENTERS ASSOCIATED WITH CONVECTION AS VIEWED BY SATELLITE

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Several times during the spring and summer of 1977, an interesting small scale cloud feature was observed in morning satellite pictures and persisted throughout most of the day. This phenomenon, which displayed certain similar characteristics with each occurrence, apparently became a factor in significant weather developments later in the afternoon. Four examples will be shown here, with more detailed comments on the first two. This is by no means a complete study, but merely an initial presentation of some cases noted during this particular convective season.

The most striking example occurred on September 7 over Iowa and west central Illinois. A cluster of thunderstorms over central Iowa (Figure 1a, taken at 1000Z), was gradually decreasing in intensity. By 1500Z, most of this convection had dissipated, leaving behind a small area of clouds over southeastern Iowa with tops to mid levels (Figure 1b). As this cloud mass moved eastward, it gradually assumed a comma-shaped configuration, much like a well developed synoptic-scale vorticity center (Figure 1c, taken at 1630Z). A definite cyclonic twisting motion could be seen in the movie loops at the time.

The 12Z LFM initial analysis (Figure 1d) did not indicate anything of this nature over the area of interest. The prog for 00Z was equally unimpressive over Illinois (Figure 1e). (Barotropic and PE similar.) Furthermore, the morning 500 mb chart (Figure 1f), indicated anticyclonic directional and speed shear, as well as marked diffluence over the area.

Nevertheless, this cloud feature remained intact as it drifted eastward toward the Illinois border. By 18Z (Figure 1g), the first signs of new convective development appeared near the Iowa-Illinois border, just downstream from the twisting cloud mass. Weather radar indicated tops to 36,000 feet half an hour later. The succeeding chart depicted a small cluster with tops above 40,000 feet just ahead of the apparent circulation center. The largest cell can be clearly seen on the 20Z picture (Figure 1h).