(13) only copy

WEATHER BUREAU
Western Region

Salt Lake City, Utah
April 1969

Upper-Air Lows Over Northwestern United States

A. L. JACOBSON

Technical Memorandum WBTM WR-39

U.S. DEPARTMENT OF COMMERCE / ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

WESTERN REGION TECHNICAL MEMORANDA

The Technical Memorandum series provide an informal medium for the documentation and quick dissemination of results not appropriate, or not yet ready, for formal publication in the standard journals. The series are used to report on work in progress, to describe technical procedures and practices, or to report to a limited audience. These Technical Memoranda will report on investigations devoted primarily to Regional and local problems of interest mainly to Western Region personnel, and hence will not be widely distributed.

These Memoranda are available from the Western Region Headquarters at the following address: Weather Bureau Western Region Headquarters, Attention SSD, P. O. Box 11188, Federal Building, Salt Lake City, Utah 84111.

The Western Region subseries of ESSA Technical Memoranda, beginning with No. 24, are available also from the Clearinghouse for Federal Scientific and Technical Information, U. S. Department of Commerce, Sills Building, Port Royal Road, Springfield, Virginia 22151. Price $3.00.

Western Region Technical Memoranda:

No. 1* Some Notes on Probability Forecasting. Edward D. Diemer. September 1965.
No. 2 Climatological Precipitation Probabilities. Compiled by Lucianne Miller. December 1965.
No. 3 Western Region Pre- and Post-FP-3 Program. Edward D. Diemer. March 1966.
No. 4 Use of Meteorological Satellite Data. March 1966.
No. 5** Station Descriptions of Local Effects on Synoptic Weather Patterns. Philip Williams. April 1966.
No. 6 Improvement of Forecast Wording and Format. C. L. Glenn. May 1966.
No. 7 Final Report on Precipitation Probability Test Programs. Edward D. Diemer. May 1966.
No. 8 Interpreting the RAREP. Herbert P. Benner. May 1966. (Revised Jan. 1967.)
No. 9 A Collection of Papers Related to the 1966 NMC Primitive-Equation Model. June 1966.
No. 10* Sonic Boom. Loren Crow (6th Weather Wing, USAF, Pamphlet). June 1966.
No. 11 Some Electrical Processes in the Atmosphere. J. Latham. June 1966.
No. 12* A Comparison of Fog Incidence at Missoula, Montana, with Surrounding Locations. Richard A. Dightman. August 1966.
No. 13 A Collection of Technical Attachments on the 1966 NMC Primitive-Equation Model. Leonard W. Snellman. August 1966.
No. 14 Applications of Net Radiometer Measurements to Short-Range Fog and Stratus Forecasting at Los Angeles. Frederick Thomas. September 1966.
No. 15 The Use of the Mean as an Estimate of "Normal" Precipitation in an Arid Region. Paul C. Kangieser. November 1966.
No. 16 Some Notes on Acclimatization in Man. Edited by Leonard W. Snellman. Nov. 1966.
No. 17 A Digitalized Summary of Radar Echoes Within 100 Miles of Sacramento, California. J. A. Youngberg and L. B. Overaas. December 1966.
No. 18 Limitations of Selected Meteorological Data. December 1966.
No. 19 A Grid Method for Estimating Precipitation Amounts by Using the WSR-57 Radar. R. Granger. December 1966.
No. 20 Transmitting Radar Echo Locations to Local Fire Control Agencies for Lightning Fire Detection. Robert R. Peterson. March 1967.
No. 21 An Objective Aid for Forecasting the End of East Winds in the Columbia Gorge. D. John Coparanis. April 1967.
No. 22 Derivation of Radar Horizons in Mountainous Terrain. Roger G. Pappas. April 1967.
No. 23 "K" Chart Application to Thunderstorm Forecasts Over the Western United States. Richard E. Hambidge. May 1967.

*Out of Print
**Revised

A western Indian symbol for rain. It also symbolizes man's dependence on weather and environment in the West.

U. S. DEPARTMENT OF COMMERCE
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
WEATHER BUREAU

Weather Bureau Technical Memorandum WR-39

UPPER-AIR LOWS OVER NORTHWESTERN UNITED STATES

A. L. Jacobson
Principal Assistant
Great Falls WBFO, Montana

WESTERN REGION
TECHNICAL MEMORANDUM NO. 39

SALT LAKE CITY, UTAH
APRIL 1969

TABLE OF CONTENTS

LEGENDS FOR FIGURES

UPPER-AIR LOWS OVER NORTHWESTERN UNITED STATES

A. L. Jacobson
Great Falls, Montana

I. INTRODUCTION

Meteorology is characterized by developments which are difficult to forecast because they appear to depart from the common rules. Some of these developments group into a pattern which, if correctly interpreted, can become a very useful tool. The pattern discussed in this paper is one which appears frequently over northwestern United States during the warmer period of the year and occasionally over southern and central United States during the colder months.

Considered in three dimensions, low-pressure centers slope upward toward cooler air aloft so that an imaginary nearly straight line joins the surface low center with its associated low centers at 700 and 500 millibars (mb). Any synoptic situation where a surface low center is not aligned with the centers aloft would be abnormal or, as the term is used in this paper, one which is anomalous. Situations are also considered anomalous where the centers slope toward the south, surface to aloft, and in many of these cases no surface low center can be identified.

In the pattern studied here, the 500-mb low is found south or southwest of the associated 700-mb low and, during early stages of development, the lowest surface pressure is located southeast or east of the upper lows. A more normal position for the surface low would be at the point where a nearly straight line joining the upper-air low centers is projected to the surface. The abnormal pattern where the upper-air and surface lows are thus not aligned has been found to be associated with deepening of the northern portion of inverted surface troughs which lie east of the Continental Divide, resulting in rapid northerly movements of already existing surface lows and the looping of lows which sometimes takes place. This same pattern is also associated with most heavy general rains over Montana. Nearly all storms which have produced amounts in excess of one inch over large areas during the past 15 years have been associated with this anomalous pattern. All floods on the Sun River (which flows into the Missouri River at Great Falls) for which data are available were associated with the anomalous weather pattern defined above. Several of the most notable hailstorms in Montana and a number of tornadoes have also been associated with this abnormal upper-air structure.

Several studies have been made by other authors which are related, at least partially, to the type of development discussed in this paper.

One of these was a study made by K. D. Hage [1] in which he explained the development and deepening of Alberta lows using Petterson's development equation. He treated the related upper-air lows as cold lows, assuming a nearly vertical axis. D. L. Jorgensen [2] related winter precipitation to 700-mb lows. No attempt was made to relate this precipitation to the slope of upper-air lows with height.

II. ANALYSIS PROCEDURE

An auxiliary chart is prepared on which positions of low centers, surface and aloft, are plotted over a period of one to several days (see Figure 1 for example). The code given in the legend of Figure 1 is used on all maps which accompany this paper.

Since this study was begun, over thirteen years ago, a record has been kept of as many anomalous-type storms as possible. Maps similar to those which accompany this paper are on file for over fifty of these storms; however, this is not to imply that only fifty anomalous patterns occurred during this period, as only maps for the more important storms have been saved. Maps included in this study were selected to show:

1) General characteristics of anomalous lows.

2) Two types of flood-producing anomalous storms using record floods of 1953 and 1964, and the 1967 flood on the Musselshell River as examples.

III. MODEL

A) Surface Low.

There are two distinct types of surface lows associated with the anomalous pattern. The first and most frequent type of low forms near the Continental Divide in Wyoming or Montana during the warmer season and over or near Colorado during the colder months. It usually forms east of the mountains under or just south of the location where a westerly or southwesterly jet stream crosses the Continental Divide. It is a warm low; that is, it does not extend very far above the surface, and upper winds may be southwesterly over the low at more than 3,000 feet above ground. This surface low generally moves northeastward and then northward into the path of the upper lows, where it deepens rapidly (see Figure 1 for an example of this type).

The second type of surface low is infrequent and forms by deepening in the northern portion of an inverted trough extending from Wyoming northward into Montana. This type of surface low forms directly in the path of upper lows. No maps are available to illustrate this type as no good examples of this development have occurred over Montana in the past few years.

B) Upper-Air Lows.

The usual feature of the upper-air structure associated with anomalous patterns is the vertical tilt of these lows toward the southerly quadrant. Of course, all upper-air lows must tilt toward colder air. Therefore, in any anomalous pattern colder air must lie toward the south or southwest. Another feature of the anomalous pattern is that there may often be no directly associated surface low during early stages of development.

An unpublished study by W. W. Dickey established the fact that nearly fifty percent of upper lows over western United States have a southerly tilt with elevation during the months of January and February. No similar study has been made for any other period.

IV. PRECIPITATION AND WIND PATTERNS

A) Precipitation.

When northwest-tilting upper-air lows move into Montana, the moisture source is normally the Pacific Ocean. Much of this moisture is precipitated out over the western slopes of the mountains, and little precipitation falls in downslope areas east of the Continental Divide. However, when lows tilt toward the south, the moisture source is usually the warmer Gulf of Mexico region. Low-level moisture, as indicated by increasing surface dew points, frequently moves northward east of the Divide under these conditions. This moisture is then released when northward-moving moist air swings westward around the low and moves up the east slopes of the mountain ranges. Most of the rain falls north and west of the 700-mb low center. The air mass between the path of the upper lows and the surface lows becomes very unstable, and it is here that large hail and even a few tornadoes occasionally occur (see Figures 1 and 2).

B) Looping.

The pressure gradient west of a looping surface low center will increase as the surface low moves in a curve toward the north, the northwest, and then finally toward the west into the path of the upper low (Figure 1). The 700- and 500-mb low centers have, in turn, been approaching each other so that the axis of their centers becomes nearly vertical during the looping period. Although this resembles the structure of a cold low because of the nearly vertical axis, a pocket of colder air is still located to the southwest; and the low does tilt in this direction. However, because of the strong pressure gradient west of the surface low center and the relatively weak thermal gradient aloft west of the 500-mb low, the tilt is very slight. In this type of storm, winds to the west of the surface low are very strong at the surface, but decrease rapidly with height. Winds to the east of the storm increase with height, or are very strong at all elevations. Surface winds east of such a low have been observed to exceed sixty knots.

V. FLOODS ON THE SUN RIVER

All past floods on the Sun River for which there were sufficient data available to establish a reliable upper-air analysis have been associated with an anomalous pattern. Flood-producing storms can be divided into two types: In Type I, the heaviest rain falls in the mountains to the west; and in Type II, the heaviest rain falls over the plains and northern slopes of the mountains located east of the Continental Divide. It is assumed that greater water discharges at upstream dams than downstream indicated heavier rains in the mountains, while a smaller discharge at the dams than downstream indicated that heavier rains fell over the plains. Whenever available, discharge amounts are noted in the discussion.

The floods of June 1964, May 1957, and June 1916 were Type I, as substantiated by rainfall reports, water discharge reports, and eye witnesses. The June floods of 1967, 1953, and 1908 were Type II. In Type I, lows aloft move in a general easterly direction; and in Type II, movement is in a northeasterly direction.

A) Type I.

1) June 1964 Flood.

a) Meteorological Conditions. The largest flood of record on the Sun River and the heaviest rains of record over the mountains northwest of Helena, thence northward into Canada, occurred in June 1964 (see isohyetal map, Figure 3). Meteorological conditions associated with this flood are considered to be a good example of an anomalous low type of situation (a detailed description of this flood may be found in [3]).

Figure 4 shows that the required upper-air structure for heavy rains was present as early as 0500MST, June 7. Maps just previous to this time showed no closed lows aloft over northwestern United States. The upper low, as shown both at 700 and 500 mb, deepened rapidly as it moved eastward, thus strengthening the easterly flow against the Continental Divide. Anomalous lows on April 24 - 27, May 1 - 4, and May 27 - 30, 1964, also contributed to the disastrous effects of the June storm, because the ground over Montana east of the Rockies was well soaked by these earlier storms. Thus, conditions were ripe for any additional heavy rains to cause severe flooding.

b) Precipitation. Showers with a few thunderstorms were present over western Montana during the afternoon of June 6, 1964 (Saturday). A heavy shower was reported at Gibson Dam on Saturday afternoon. (Gibson Dam is on the Sun River, forty-five miles west of Great Falls. See Figure 3.) It is not known whether showers continued until the effect of the upper-air circulation was felt. However, a large stationary radar echo was observed over the Continental Divide west of Great Falls beginning Saturday night and continuing through Sunday, June 7.

It appears that the continuous rains which began at Missoula at 0300MST on the 7th, and were reported soon thereafter at other stations in and adjoining the flood area, were associated with the anomalous pattern. The rains continued for the next 30 to 40 hours and ended when the upper-air low moved well into the Dakotas. When the upper low had moved some distance east of the Continental Divide, upper winds shifted to northerly over south-central Montana, producing heavy rains and flooding over this area.

c) Upper-Level Winds. Upper-level wind reports at Great Falls (Table 1) show that the easterly circulation over the main flood area was very deep and strong. Strong easterly winds were also reported at Spokane, Washington. The isohyetal map for this storm (Figure 3) shows that the heaviest rains (up to an estimated 16 inches in 30 hours) fell over the Continental Divide northwest of Great Falls. There was a strong easterly flow over this area from June 7 - 9. Since the center of heavy rains was over the mountains, these rains were also responsible for floods west of Glacier Park, as well as east of the mountains. Water discharge on June 8 was 60,000 cubic feet per second at Diversion Dam (on the Sun River a few miles below Gibson Dam) and 53,000 cubic feet per second at Vaughn, 15 miles west of Great Falls.

The 10-000-foot temperatures at Great Falls (in Celsius) are entered above the 10,000-foot wind reports (Table 1). Above-freezing temperatures at this level indicate that there could have been considerable snowmelt prior to onset of the rains, but the freezing level dropped during the period of heavy precipitation. Considerable snow was still present over the higher mountains after the storm.

d) Surface Low. The lowest surface pressure was located well to the southeast of the flood area on June 6 and 7, and the surface low did not move northeastward into the path of the upper lows until about 1700MST on June 9 (Figure 4). This meeting occurred over northeastern South Dakota.

2) Storm of May 19 - 21, 1957 (Figure 5).

The upper-air structure of this storm was very similar to that of the June 1964 storm. There was one difference, however, as a weak surface low was present in the 1957 storm northeast of the 700- and 500-mb positions. Thus, the low had a southerly tilt; i.e., the 500-mb low was southwest of the 700-mb and surface positions. Rainfall amounts over Montana for this period are listed in Table 2.

TABLE I

GREAT FALLS WINDS ALOFT

Elev. (ft.)	June 6	June 7				June 8				June 9				June 10	
	1600 MST	0400 MST	1000 MST	1600 MST	2200 MST	0400 MST	1000 MST	1600 MST	2200 MST	0400 MST	1000 MST	1600 MST	2200 MST	0400 MST	1000 MST
30000	2728	2138	1832	1515	1233	1244		1127	0410	0313	1416	1820	2141	1930	1717
25000	2730	1918	1317	1225	1323	1224		0717	0715	0417	0810	1016	2125	1734	1626
20000	2730	1712	1317	0818	1015	0931		0520	0527	1015	0912	1221	2314	1926	1726
18000	2625	1811	1115	0609	0914	1033		0724	0630	0717	1014	1321	2109	1713	1616
14000	2726	1911	0911		0919	1124		0726	0726	0524	1016	1513	1611	2105	1816
	6°	1°		0°		2°		0°		-3°	(10,000-ft. Temperatures)				
10000	2408	1708	1113	0618	0920	0921	0918		0426	0423	0818	1317	1313	2419	2013
7000	2910	1906	0304	0718	0626	1014	0511	0651	0431	0517	0910	0918	1323	1508	2211
5000	2914	2507	3108	0414	0428	1917	3408	0524	0331	0423	0605	0814	1318	1305	1806

TABLE 2 - RAINFALL MAY 19 - 21, 1957

Kalispell	.41	Whitehall	1.34	Missoula	2.25
Miles City	1.43	Bozeman	1.47	Great Falls	2.00
Cut Bank	.44	Livingston	.71	Havre	1.14
Lewistown	2.17	Dillon	1.60	Billings	1.95
Drummond	1.72	Helena	2.41	W. Yellowstone	.17
Butte	1.62	Broadus	.86	Gibson Dam	4.80

Rainfall at Gibson Dam was well below the 8 inches reported during the storm of June 7 and 8, 1964, but even this smaller amount resulted in a flood threat on the Sun River at Great Falls. Daily rainfall amounts at Great Falls are shown in Table 3.

TABLE 3 - RAIN AT GREAT FALLS MAY 1957

May 18	.15
May 19	.02
May 20	1.76
May 21	.22
May 22	.28

3) Flood - June 1916.

This flood was classified under Type I because Diversion Dam on June 21, 1916, had a flow of 32,300 cubic feet per second, while the flow downstream at Fort Shaw, on the Sun River 10 miles west of Vaughn, was 17,000 cubic feet per second. Records show that the bridge at Fort Shaw was washed away in this flood; however, historical weather maps and sparse upper-air data are insufficient to determine the meteorological conditions which caused this flood.

B) Type II

1) June 1953 Flood.

The floods of early June 1953 were caused by excessive rains east of the Continental Divide. Rainfall amounts for Great Falls (Table 4) show three periods of heavy rain: May 24 - 25, May 29 - 30, and June 2 - 3. The total at Great Falls for this period was nearly ten inches. Other areas east of the Divide--especially over the northern slopes of the Belt and Highwood Mountains, south and southeast of Great Falls--had rainfall amounts of up to twenty inches. The amount reported at Gibson Dam was not excessive.

TABLE 4 - RAIN AT GREAT FALLS - MAY-JUNE 1953

May	19	.28	June 1	.04
	20	.60	2	1.13
	21	.11	3	2.07
	22			
	23	T		
	24	1.75		
	25	2.05		
	26	T		
	27			
	28	T		
	29	2.40		
	30	.32		
	31	.06		
May Total		8.13		

The paths of the 500-mb lows, taken from historical weather maps, are shown in Figure 6. Indications are that a new 500-mb low developed over eastern Idaho by 0800MST on May 24. This low moved northeastward, producing the heavy rains of May 24 - 25. The primary 500-mb low, having first moved southeastward near the Pacific Coast, then turning northeastward, moved into southern Idaho on the 29th. This low caused the second downpour, May 29 - 30.

Positions of the surface, 700-mb, and 500-mb lows are shown (Figure 7) for the third heavy rain period, June 2 - 4, 1953. Note the southerly tilt of the low with elevation. The surface low first formed east of Sheridan, Wyoming, and moved into western North Dakota and then eastward. As a result of this storm, communities east of the Continental Divide were isolated because small streams became torrents, and bridges were washed out. Water discharge at Diversion Dam was 10,900 cubic feet per second, and at Vaughn 17,900 cubic feet per second.

2) June 1908 Flood.

The second highest flood of record on the Sun River was reported June 7, 1908. No upper-air data are available for this period. The path of the surface low (Figure 8), taken from historical weather maps, suggests that the heaviest rains should have fallen east of the mountains. Water discharge June 7 was 15,000 cubic feet per second at Diversion Dam, and 18,400 cubic feet per second on the Sun River. Table 5 gives some rainfall amounts for this storm. This table, plus other precipitation data, indicates that the heaviest rains fell over the Missouri River drainage above the present head of Fort Peck Reservoir.

TABLE 5 - RAINFALL OF JUNE 4 - 6, 1908

Havre	2.29
Helena	3.73
Kalispell	1.21
Great Falls	3.86
Missoula	2.13
Lewistown	2.60
*Evans	8.00

*30 miles southeast of Great Falls

During the June 1964 storm, the Waterton Lakes area in southern Alberta was exposed to extremely strong northeasterly and easterly winds, and the level of the lake was raised 8 to 12 feet. Residents reported that a similar rise occurred in June 1908. A looping low near Havre, with increasing pressure gradient to the west, could have produced strong northeasterly winds over the Waterton Lakes area.

3) June 1967 Flood.

Heavy rains on June 6 and 7, 1967, caused the Musselshell River to go above flood stage, reaching 11.96 feet at Roundup, Montana, on June 9 [4]. This was one foot higher than the previous record flood, which occurred June 18, 1948. A bucket survey was made of this storm by members of the Helena Weather Bureau staff. The isohyetal map for this storm (Figure 9) taken from [4] showed a maximum of 7 inches at Lavina, 6 inches southwest of Mosby, and 5 - 6 inches near Volberg and also near Ekalaka. Additional rains on June 13 - 15 raised the river to even higher readings.

The upper-air low first entered northwestern United States on May 30, moved southeastward into central Nevada by June 1, and thence slowly westward to a position off the coast of California. Figure 10 shows the subsequent movements of the 500-mb and 700-mb low centers for the period June 3 - 8. Although it is difficult to track precisely the position of the low centers at these levels, it appears that the primary low off the California coast on the 5th filled as it moved inland to central California, while a trough centered over the Pacific Northwest developed into the primary low by the 7th over southeastern Oregon and extreme northern Nevada. The presence of a single 500-mb low center over northeastern Nevada at 1700M on the 5th (Figure 11) is open to question, as there is evidence of another center over central California. It is evident, however, that a southward sloping or anomalous pattern developed as the 700-mb and 500-mb centers moved northeastward across southern Idaho into Montana (Figures 10,12, and 13).

The major forecast problem was the location of heaviest rains. Path of the upper low until 0500MST on the 6th suggested that the low would move north-northeast with the most likely area of heavy rains located west of Great Falls. Examination of the barotropic and 6-layer baroclinic prognostic charts based on 0500MST data of the 6th did not show any forecast closed circulations at 500 mb, although the barotropic prognostic charts moved the trough more to the east than the baroclinic. Fortunately, by 1700MST on the 6th it became evident that the upper low would move more northeastward, passing over southern Montana and suggesting that the heaviest rains would fall over central Montana.

Most of the precipitation at Billings and Miles City fell during thunderstorms on June 7, while these stations were to the east or right of the path of the upper low. Volberg, 45 miles south of Miles City, reported 6 inches of rain during the evening of June 6 (Figure 9).

Surface low positions for the June 6 - 8 storm are shown in Figure 14. There was an inverted surface trough extending northward through Wyoming into eastern Montana during the entire period of these rains, with lowest pressure located well to the south. However, this inverted trough was so located that there were light northeasterly surface winds in the rain area.

Cloud patterns associated with this storm at approximately 0900MST on June 7 and 8, as shown by ESSA II satellite pictures, are presented in Figures 15 and 16. These pictures indicate that this storm was not very large in area while over eastern Montana.

Another outbreak of rain and thunderstorms moved across Montana from southwest to northeast on June 13 to 15. This rain was locally heavy, and was caused by a short-wave trough moving through the state. This second rain, even though it was not as heavy as that which occurred June 7 - 8, caused the Musselshell and other rivers to rise considerably because the ground was already well soaked.

VI. SOME ADDITIONAL COMMENTS CONCERNING ANOMALOUS LOWS

NMC guidance should, of course, generally be followed with regard to predicting movement of low centers. However, the following rules, based on examination of more than fifty upper-air lows in northwestern United States, may also prove helpful:

1) 500-mb lows which move at a speed of about fifteen knots or more usually continue at that speed or accelerate, while lows which move at ten knots or less may suddenly change direction. Lows may move quite slowly while they change their direction of movement from southeast to northeast.

2) Changes in direction of movement of upper lows are associated with changes in strength or direction of the jet stream. When winds to the southwest of the low are strongest, the upper low usually moves southeastward; and when they are strongest to the southeast of the center, the low moves northeastward. This principle of steering by the strongest peripheral winds is a known forecast rule.

3) The main precipitation area associated with anomalous lows which move parallel to a strong westerly or southwesterly jet will be within 300 miles of and mostly to the left of the path of the 700-mb low. Figures 17 through 21 illustrate the typical association between 700-mb low path and storm isohyets (the latter have been smoothed considerably because of map scale).

4) Enough cases have been observed to suggest that there is a strong relationship between the so-called Colorado low, which deepens as it moves eastward away from the mountains, and the anomalous low structure. When the 500-mb low is located southwest of its associated 700-mb low as the lows move eastward, any surface lows which are present frequently move northward into the path of these upper lows. The deepening which occurs results in a very strong gradient on the surface, especially to the west of the surface low. In this manner, severe blizzards can develop in the colder season.

VII. CONCLUSIONS

Since there have been very few cases of extensive heavy rains over Montana without the anomalous pattern being present, tracking upper-air low centers is important for forecasting heavy precipitation. Experience has shown that the best way to do this is to place positions of the surface, 700-mb and 500-mb low centers on a single map, as illustrated in Figure 1.

Since 1892, there have been 84 days when one inch or more of rain has fallen in Great Falls, Montana. Forty-nine of these days occurred during May and June. This concentration is, no doubt, influenced by the frequency of anomalous lows during these months. The frequency distribution of anomalous lows over the Northwest for the months March - September, 1962-68, is shown in Table 6. Note the maximum in May.

TABLE 6 - ANOMALOUS LOWS - 1962 - 1968

March	1
April	5
May	11
June	7
July	-
August	3
September	1
Total	28

Dates of recent anomalous lows are given in Table 7. (X) indicates that the storm brought an inch or more of precipitation to Great Falls. All but three of the anomalous lows (May 7 - 8, 1964; May 12 - 13, 1965; April 2 - 4, 1968) were accompanied by over an inch of rain in some portions of Montana.

TABLE 7

May 11-13, 1962 (X)	May 5-9, 1965
May 19-23, 1962 (X)	May 12-13, 1965
May 23-25, 1962	May 21-24, 1965
June 20-23, 1962	June 24-25, 1965 (X)
April 1-3, 1963	April 26-28, 1966
May 11-12, 1963	June 29-July 4, 1966
	June 24-25, 1966
April 24-27, 1964 (X)	
May 1-4, 1964 (X)	April 27-28, 1967 (X)
May 7-8, 1964	June 6, 1967 (X)
May 27-30, 1964 (X)	
June 7-9, 1964 (X)	April 2-4, 1968
August 18-19, 1964	March 18-19, 1968
August 27-28, 1964 (X)	May 21-22, 1968 (X)
August 28-Sept. 1, 1964	June 7-10, 1968 (X)

The accumulation of case studies of anomalous lows, now on record at Great Falls, will be augmented as new cases occur. Even though some rules regarding behavior of these lows may be changed as new cases are studied, it is believed that the basic concepts outlined above have stood the test of time.

VIII. ACKNOWLEDGMENT

The author is grateful to the National Meteorological Center for making available many of the charts used in studying the June 1967 storm.

IX. REFERENCES

[1] K. D. Hage, "On Summer Cyclogenesis in Western Canada Associated With Upper Cold Lows". University of Chicago, Department of Meteorology, Contract AF19(604)-2179, Science Report No. 1, June 1957.

[2] D. L. Jorgensen et al, "Synoptic Climatology of Winter Precipitation from 700-mb Lows for Intermountain Areas of the West", JAM Volume 6, October 1967, pp. 782-790.

[3] R. A. Dightman, "Meteorological Developments Contributing to the Floods of June 1964 in Northwestern Montana," Geological Survey Water Supply Paper 1840-B.

[4] R. A. Dightman, "Central Montana Rainstorms and Floods, June 6 - 15, 1967". Monthly Weather Review, November 1968.

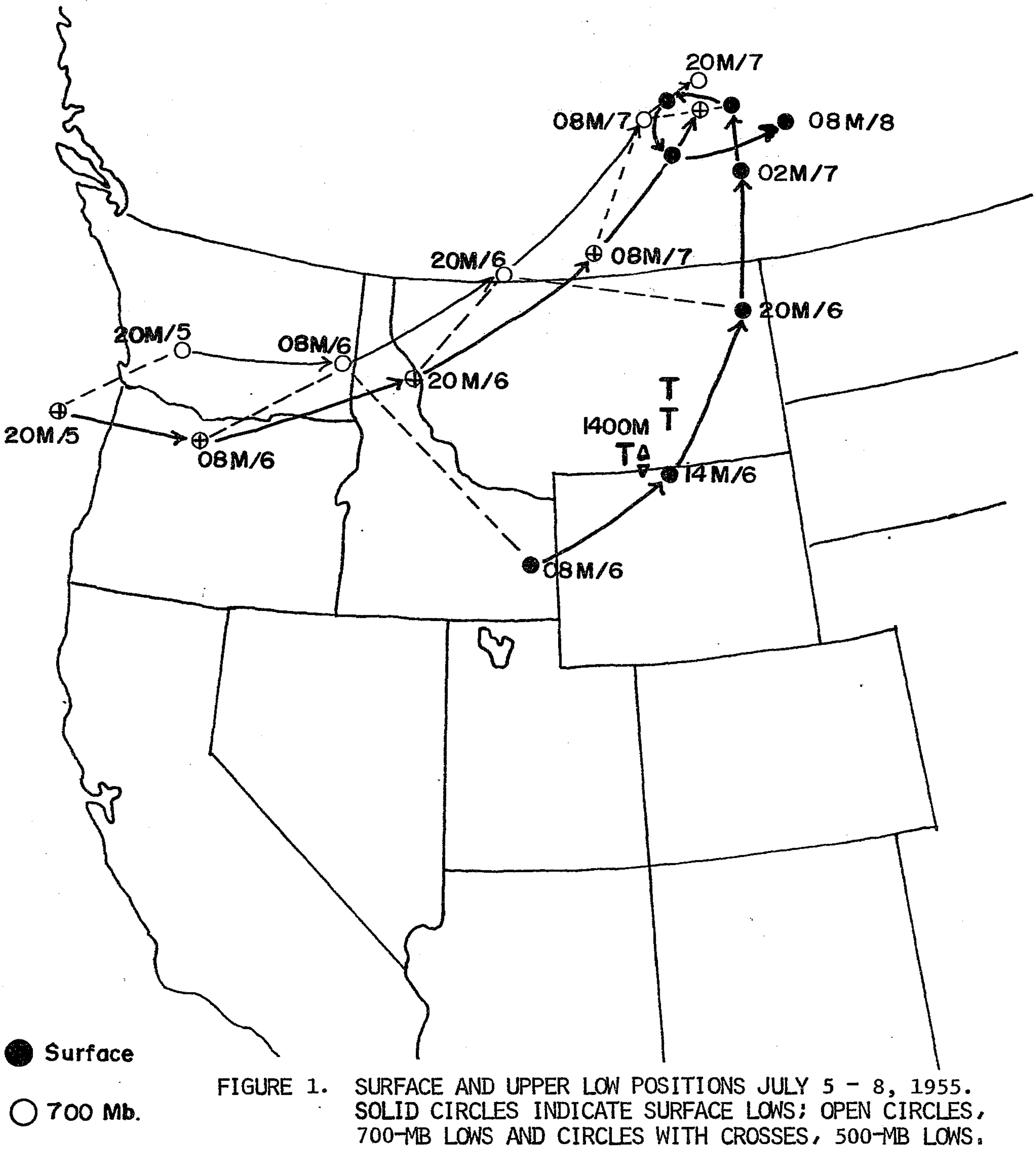


FIGURE 1. SURFACE AND UPPER LOW POSITIONS JULY 5 - 8, 1955. SOLID CIRCLES INDICATE SURFACE LOWS; OPEN CIRCLES, 700-MB LOWS AND CIRCLES WITH CROSSES, 500-MB LOWS. DASHED LINES CONNECT POSITIONS OF LOWS AT THE VARIOUS LEVELS. "T" INDICATES LOCATION OF REPORTED TORNADOES, ≜ HAIL (HEAVY HAIL WAS REPORTED AT BILLINGS). TIMES IN MST.

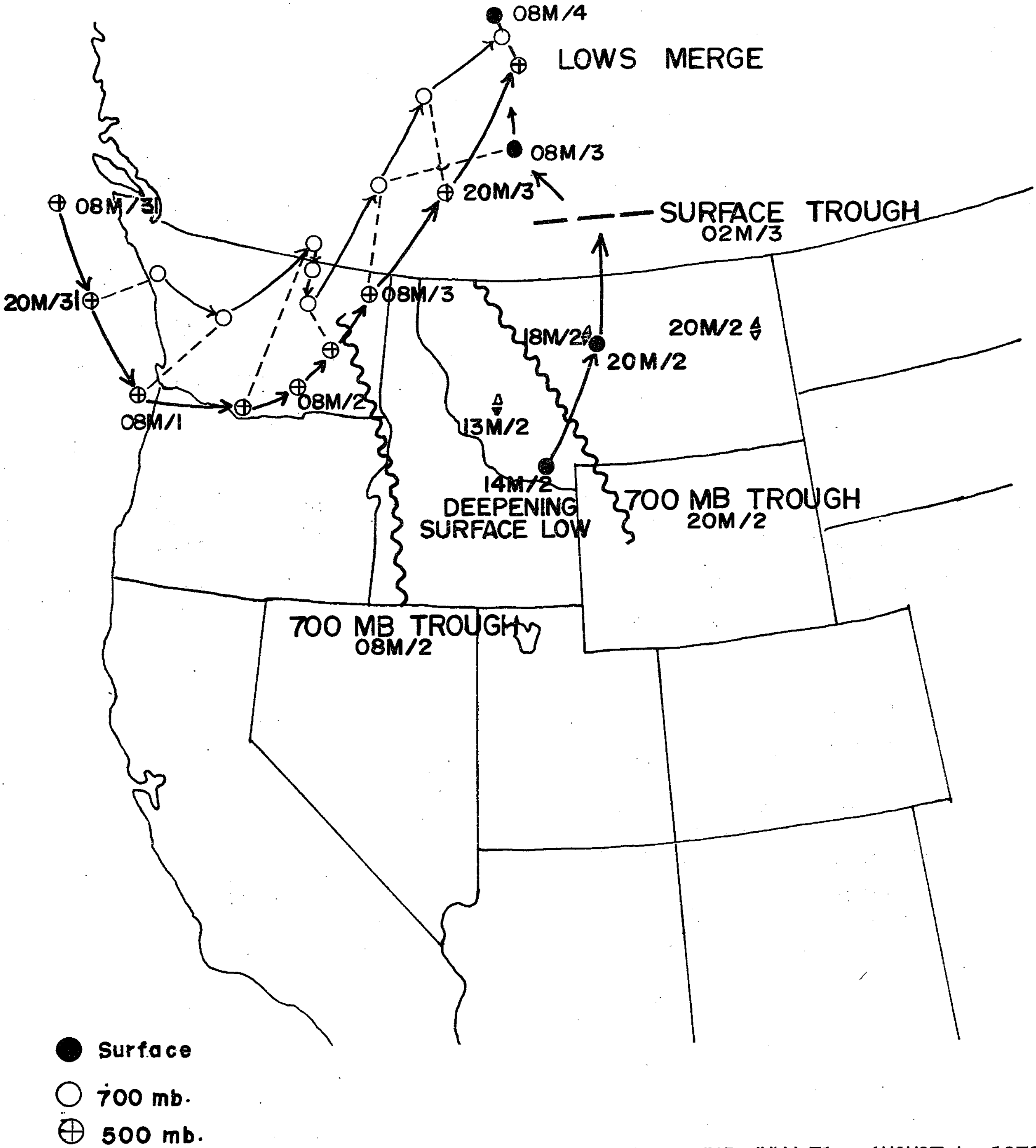


FIGURE 2. SAME AS FIGURE 1 EXCEPT FOR JULY 31 - AUGUST 4, 1956 (HEAVY HAIL WAS REPORTED AT CONRAD).

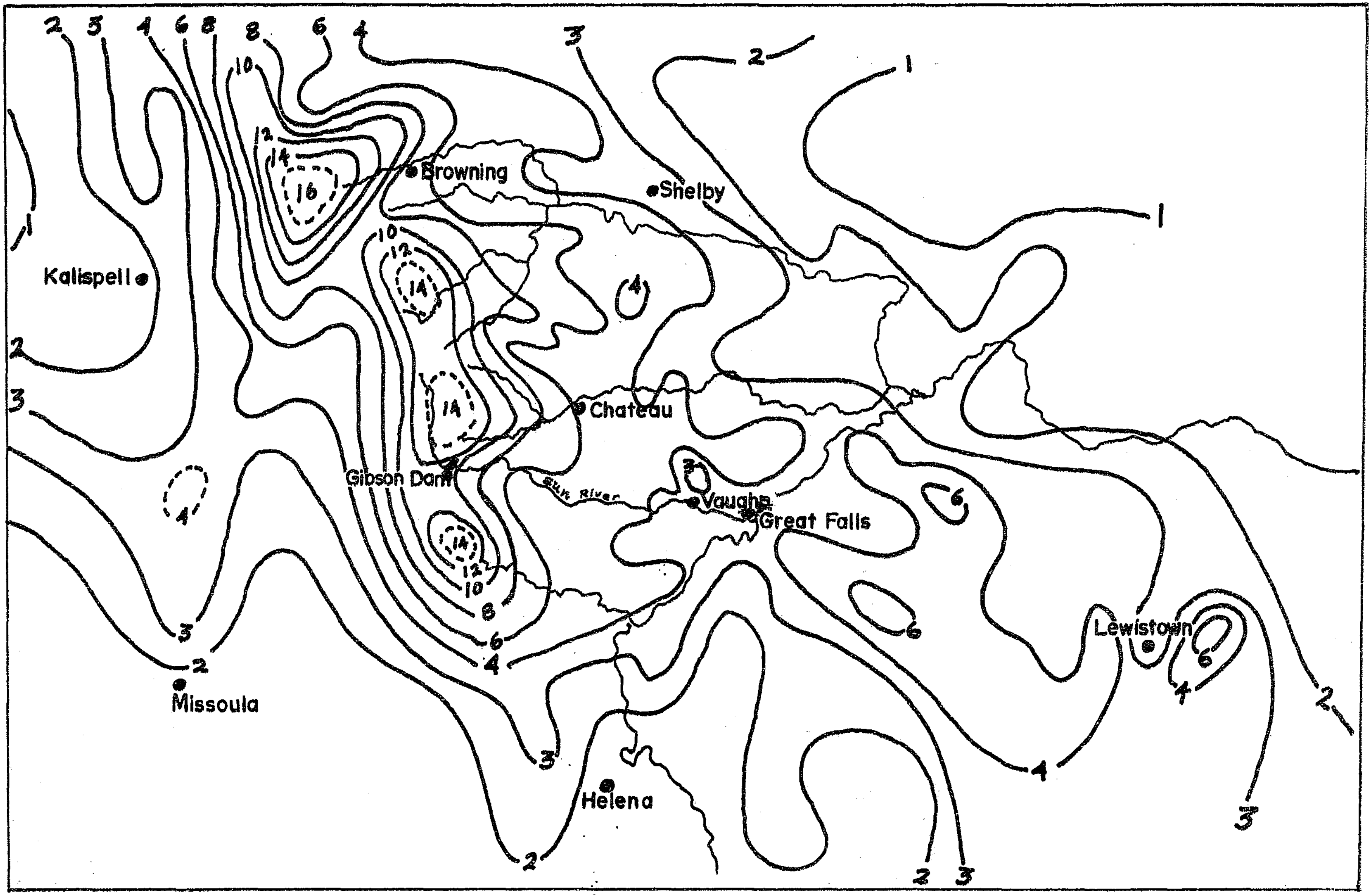


FIGURE 3. ISOHYETAL MAP FOR STORM OF JUNE 7 - 8, 1964 (AFTER DIGHTMAN).

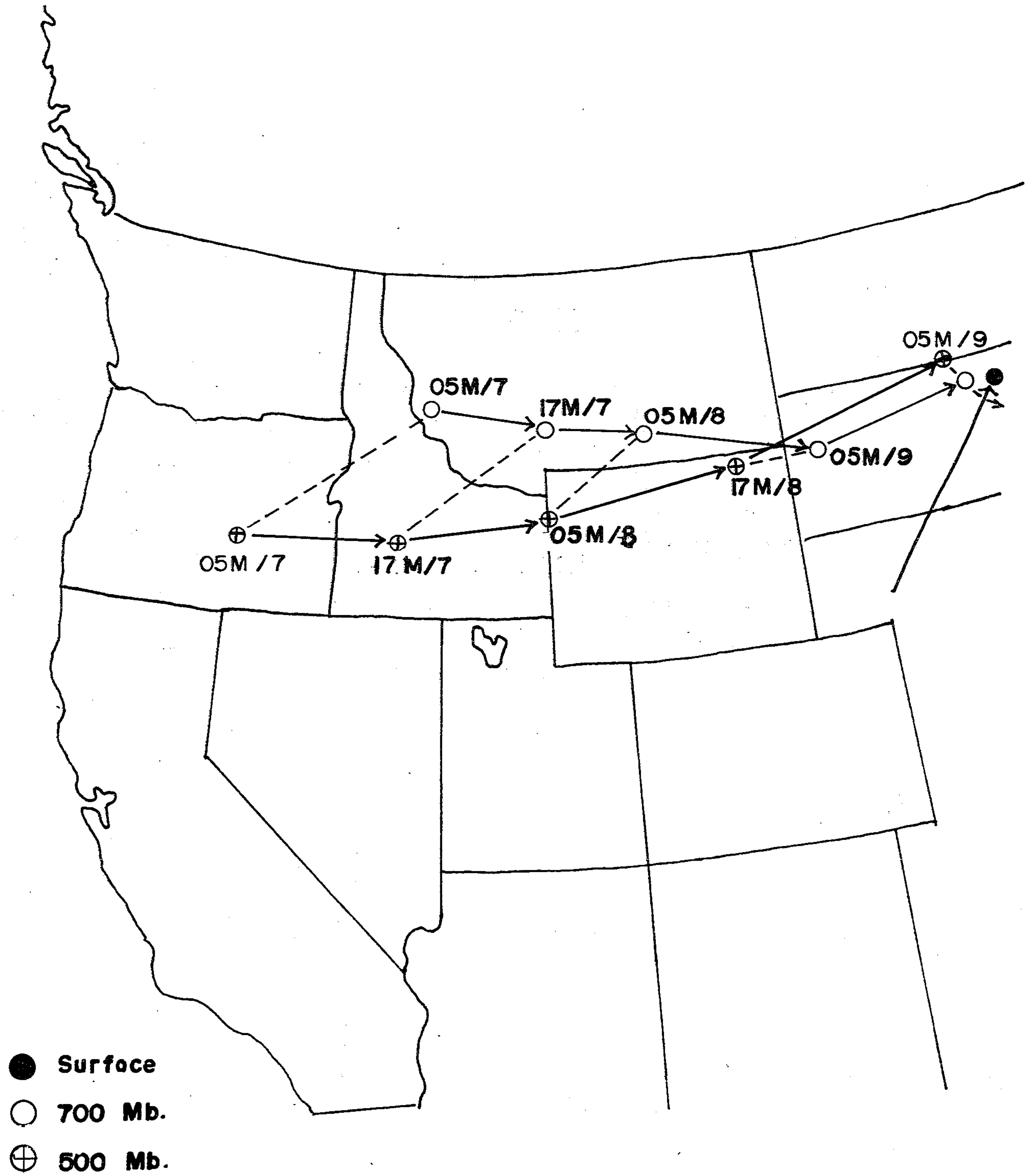


FIGURE 4. SAME AS FIGURE 1 EXCEPT FOR JUNE 7 - 9, 1964.

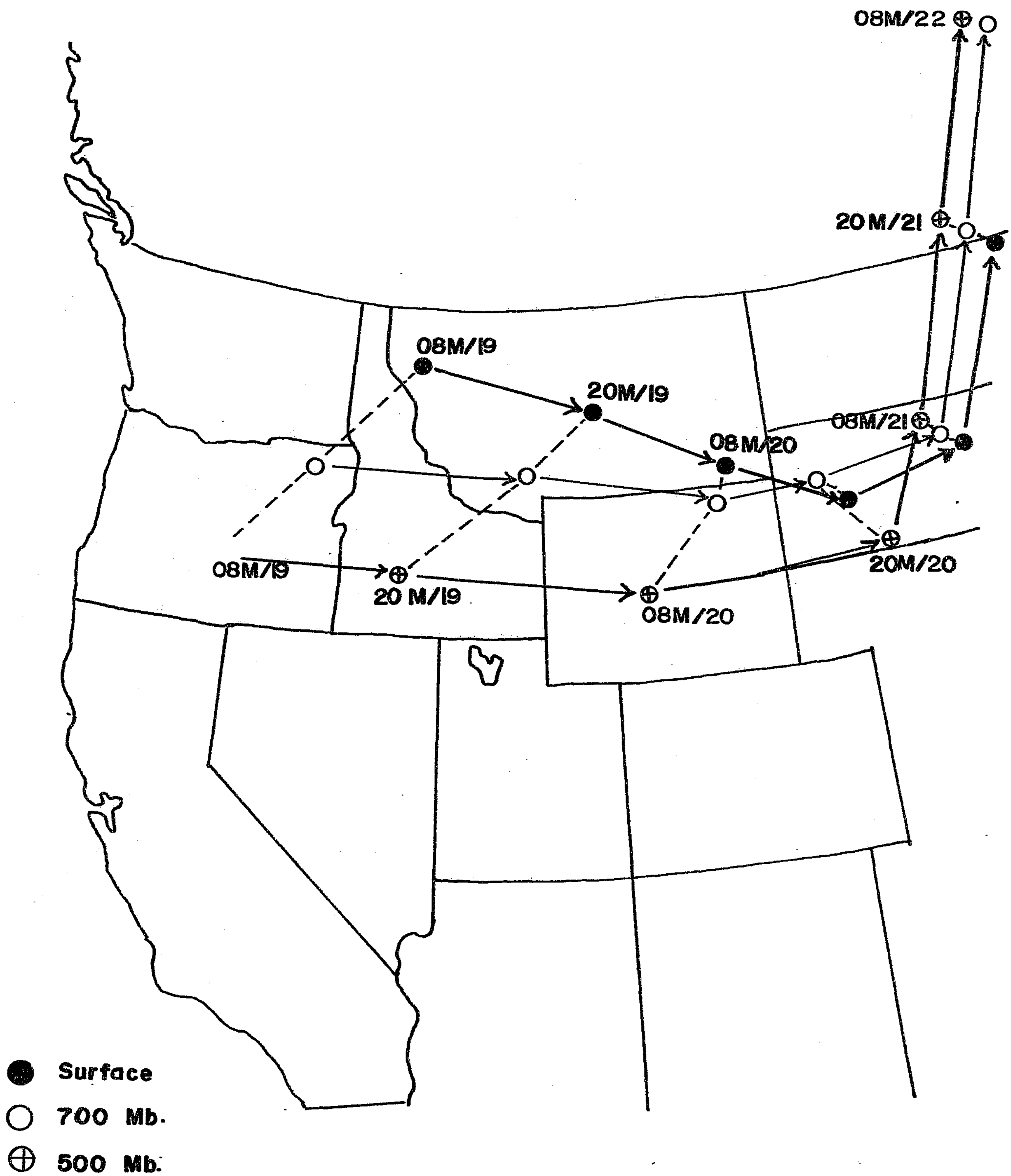


FIGURE 5. SAME AS FIGURE 1 EXCEPT FOR MAY 19 - 22, 1957.

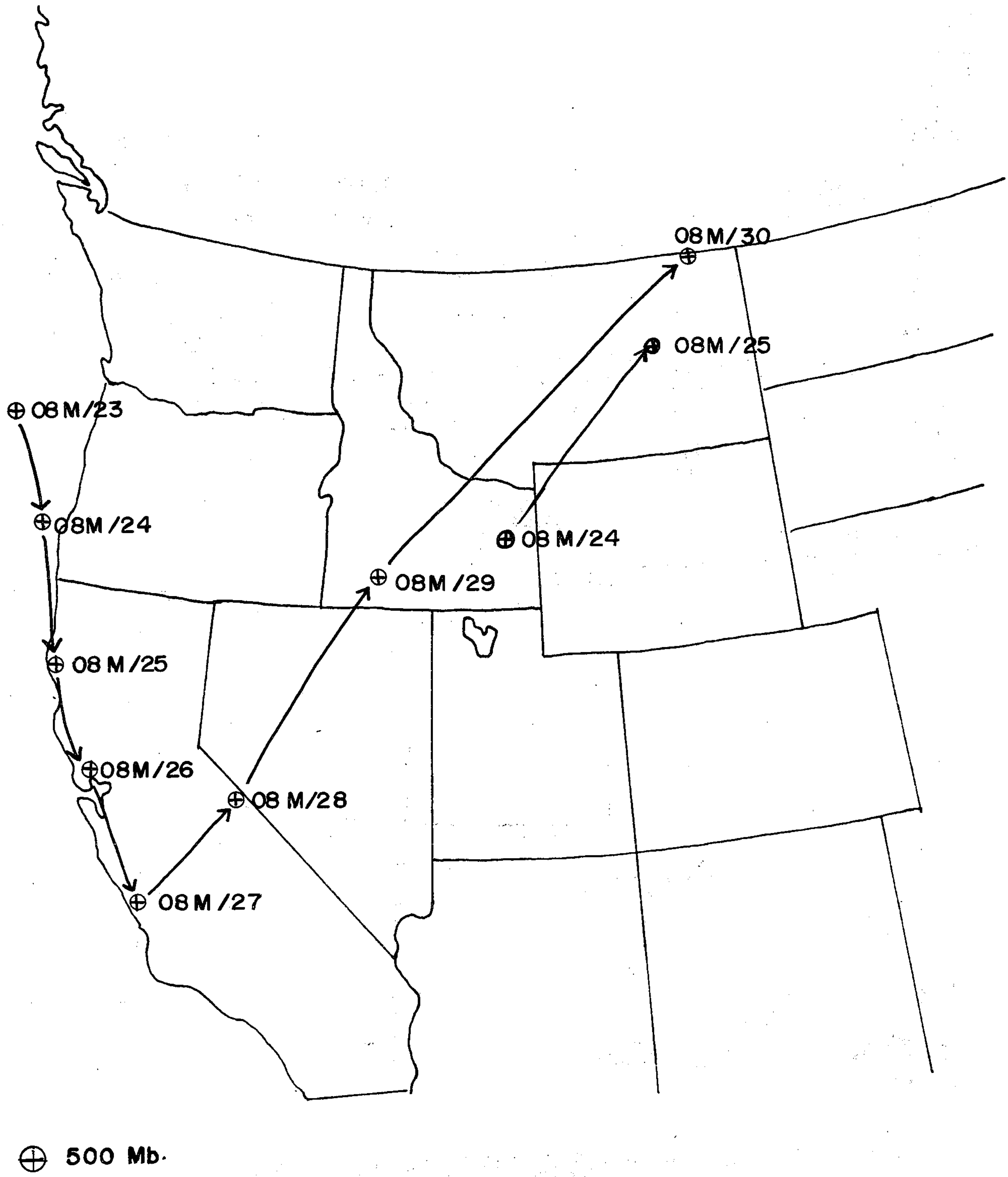


FIGURE 6. SAME AS FIGURE 1 EXCEPT FOR MAY 23 - 30, 1953.

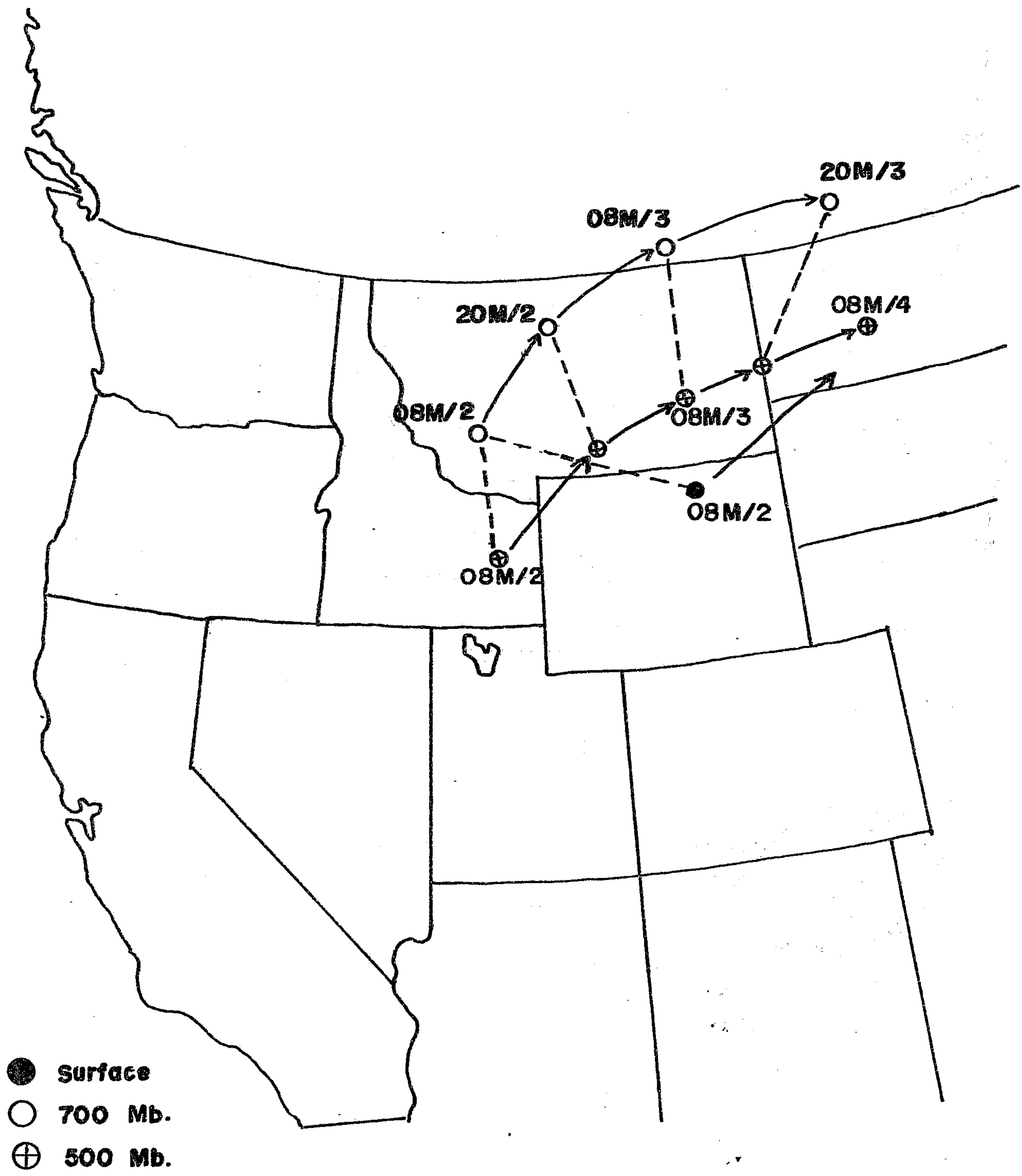


FIGURE 7. SAME AS FIGURE 1 EXCEPT FOR JUNE 2 - 4, 1953.

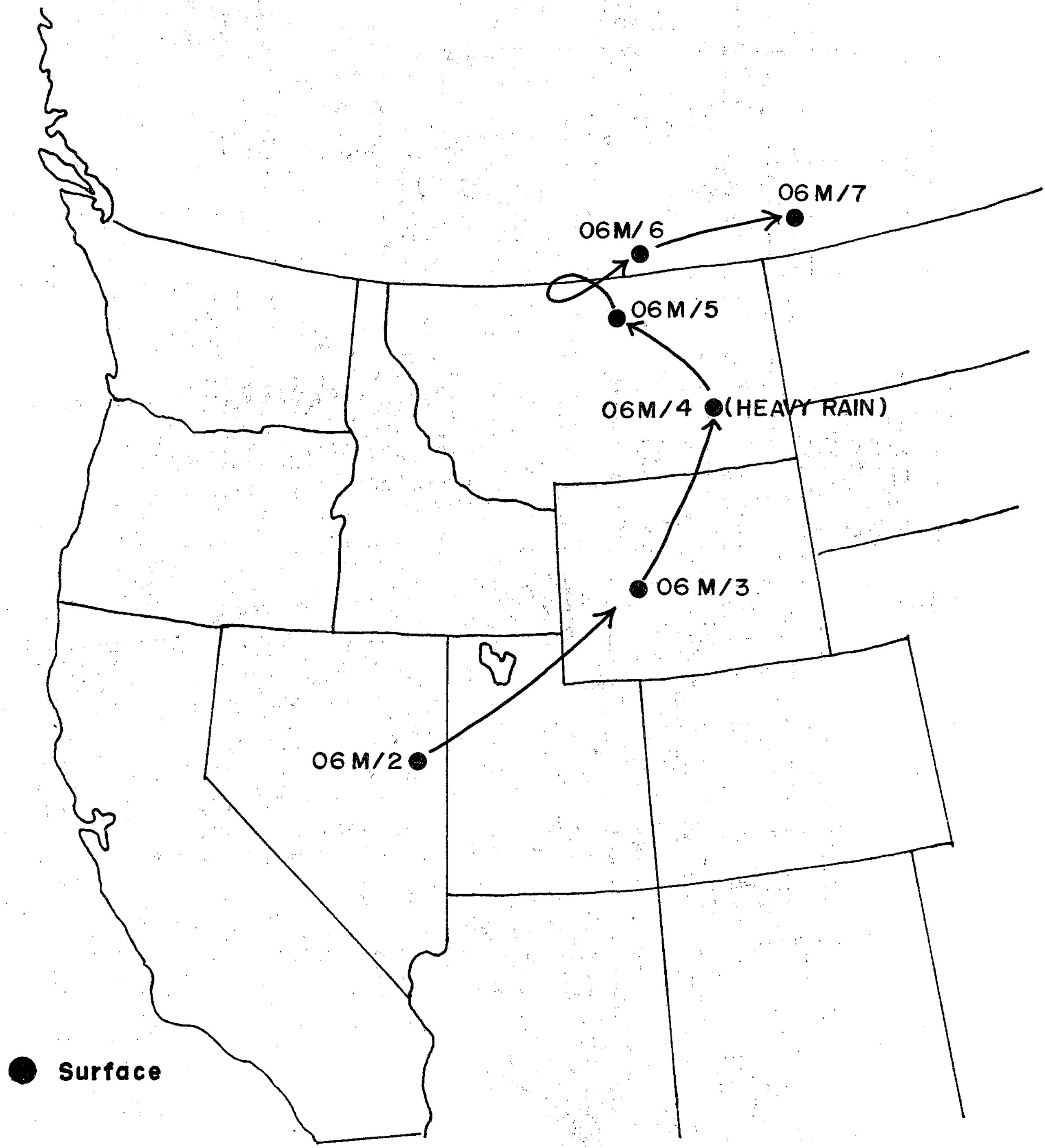


FIGURE 8. PATH OF SURFACE LOW, JUNE 2 - 7, 1908.

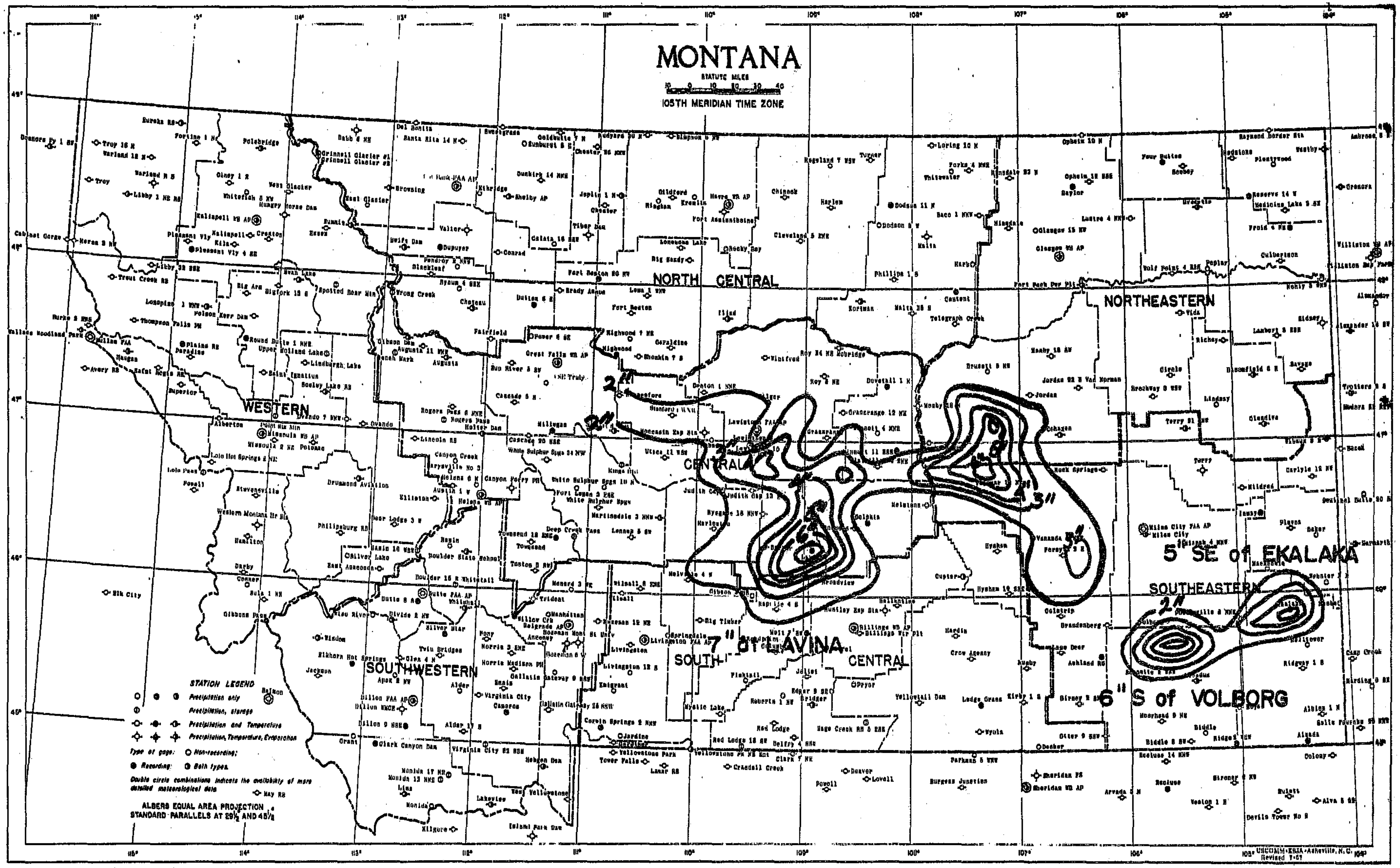


FIGURE 9. ISOHYETAL MAP, MUSSELSHELL DRAINAGE, JUNE 6 - 7, 1967.

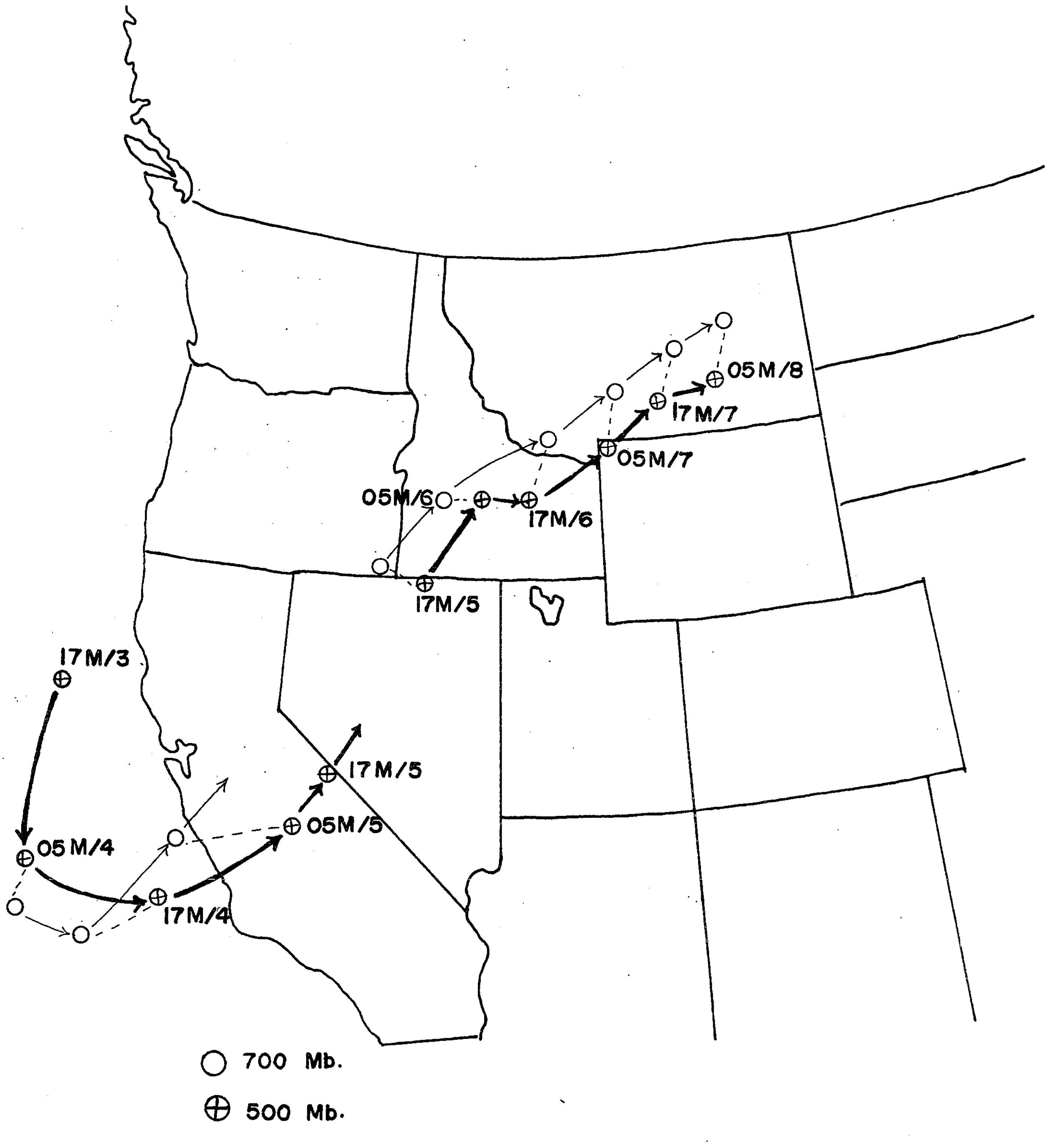


FIGURE 10. SAME AS FIGURE 1 EXCEPT FOR JUNE 3 - 8, 1967.

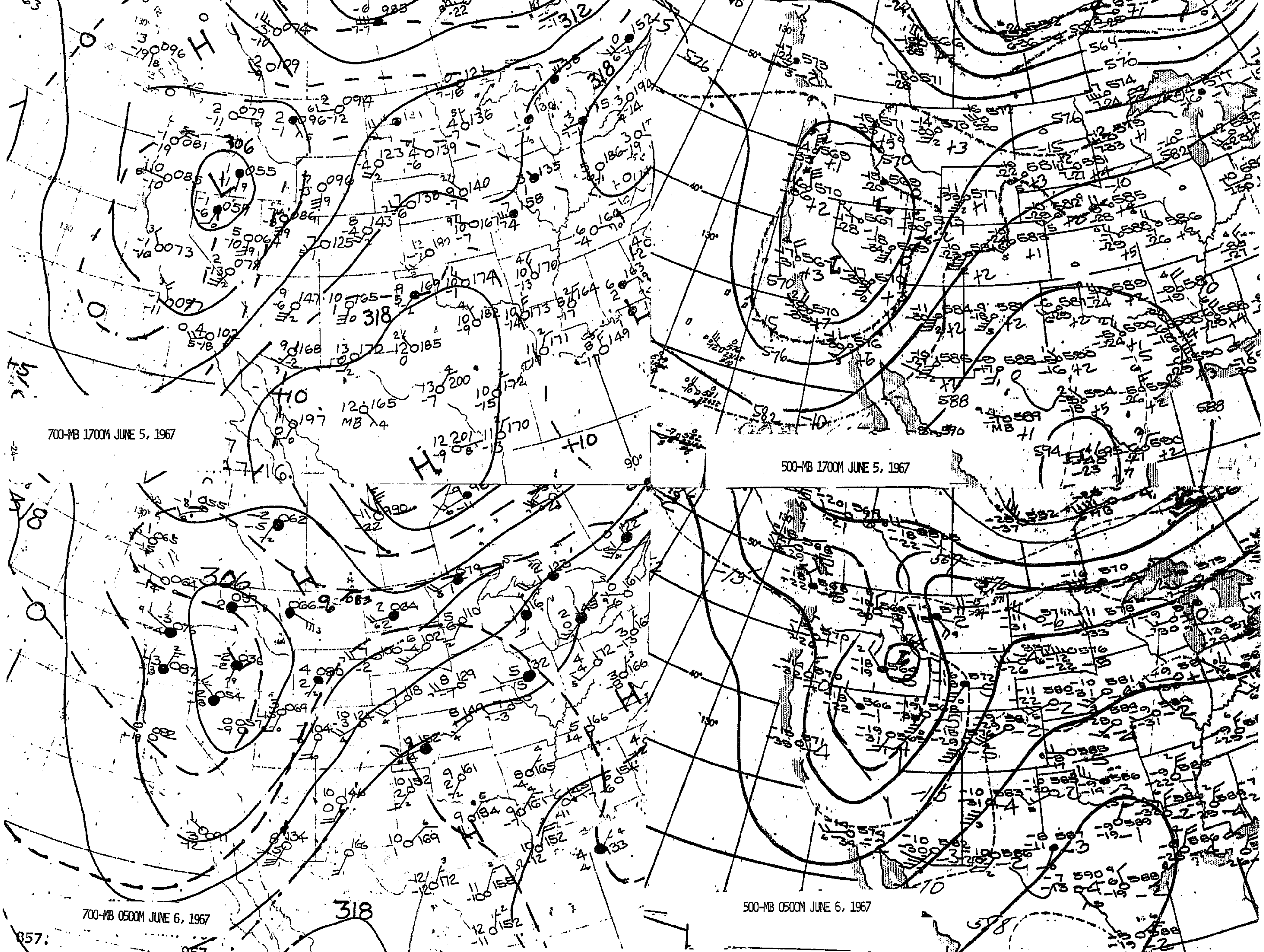
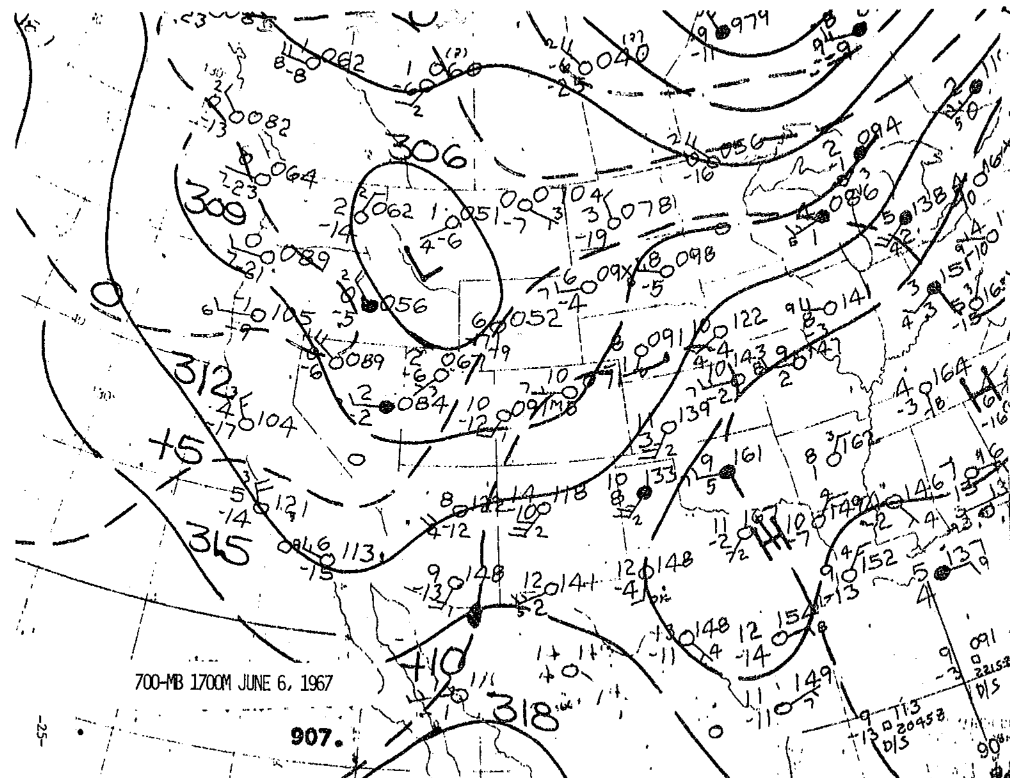
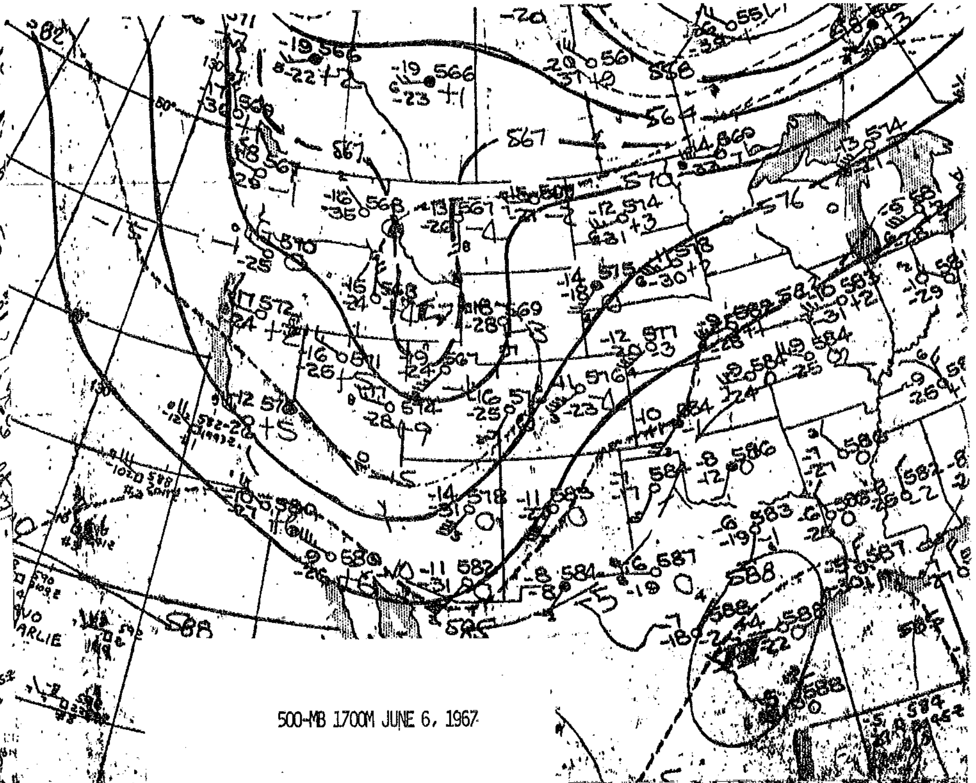


FIGURE 11. NMC 700-MB AND 500-MB ANALYSES, 1700M JUNE 5 AND 0500M JUNE 6, 1967

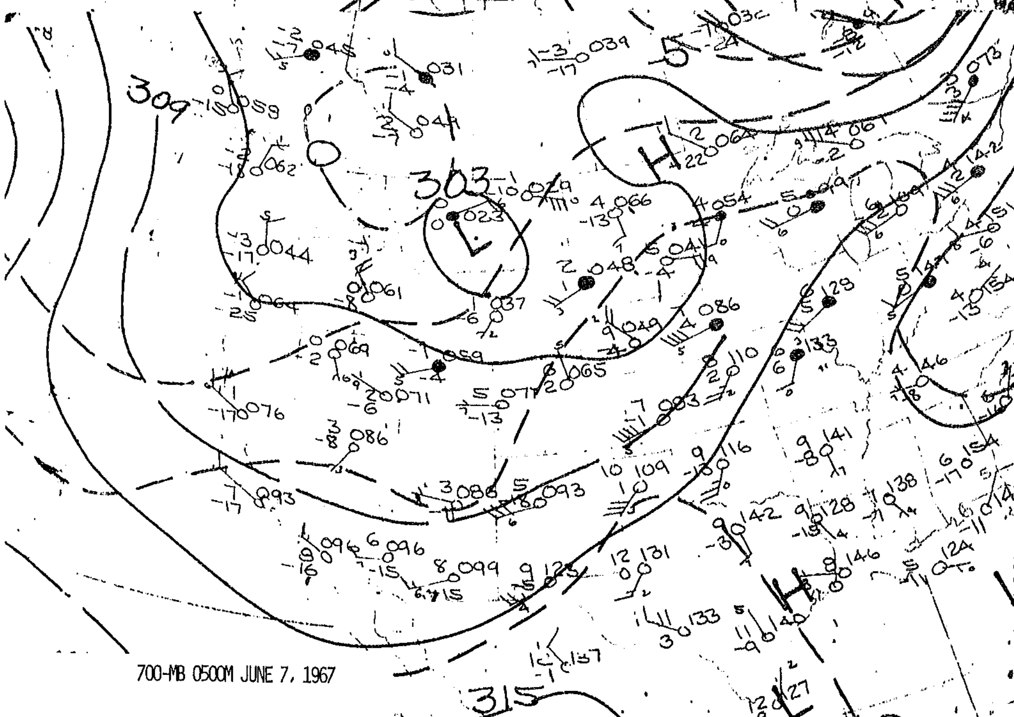


700-MB 1700M JUNE 6, 1967

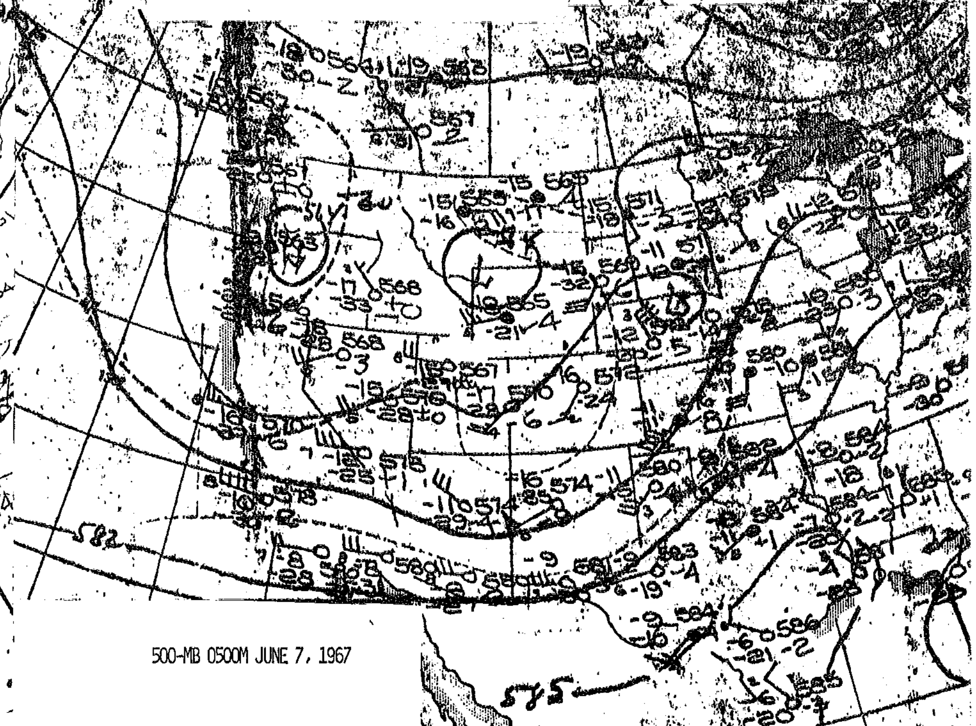


500-MB 1700M JUNE 6, 1967

907.



700-MB 0500M JUNE 7, 1967



500-MB 0500M JUNE 7, 1967

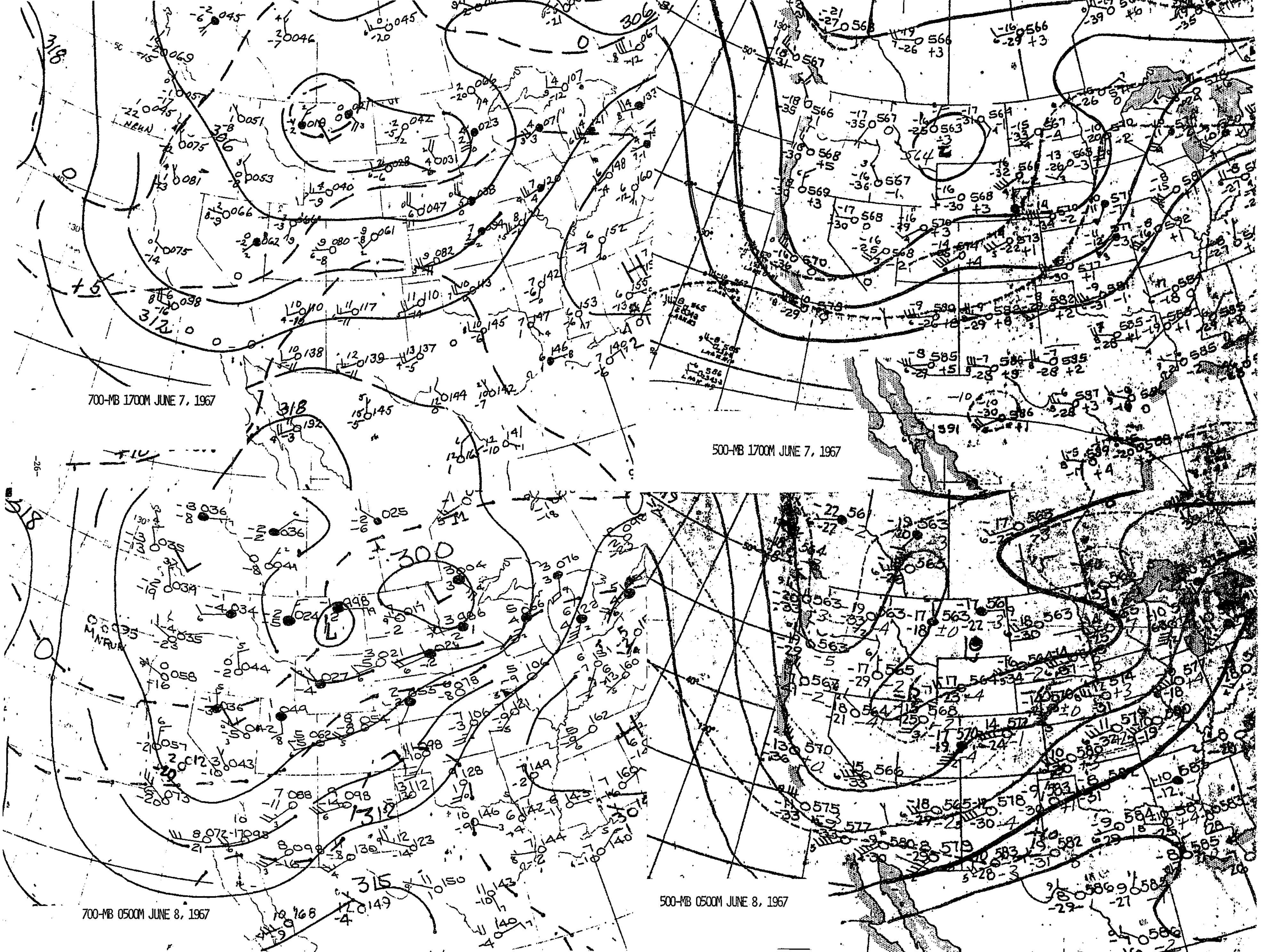


FIGURE 17. NMC 700-MB AND 500-MB ANALYSES, 1700M JUNE 7 AND 0500M JUNE 8, 1967

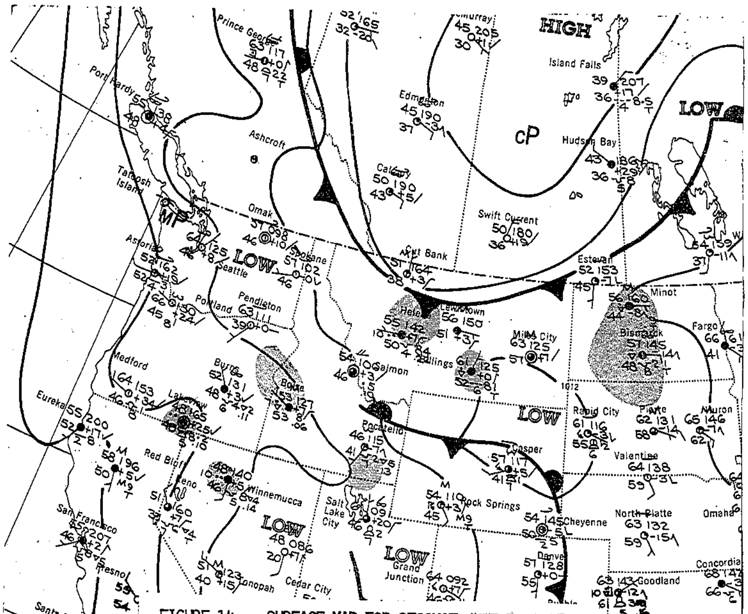


FIGURE 14A. SURFACE MAP FOR 2300MST JUNE 5, 1967.

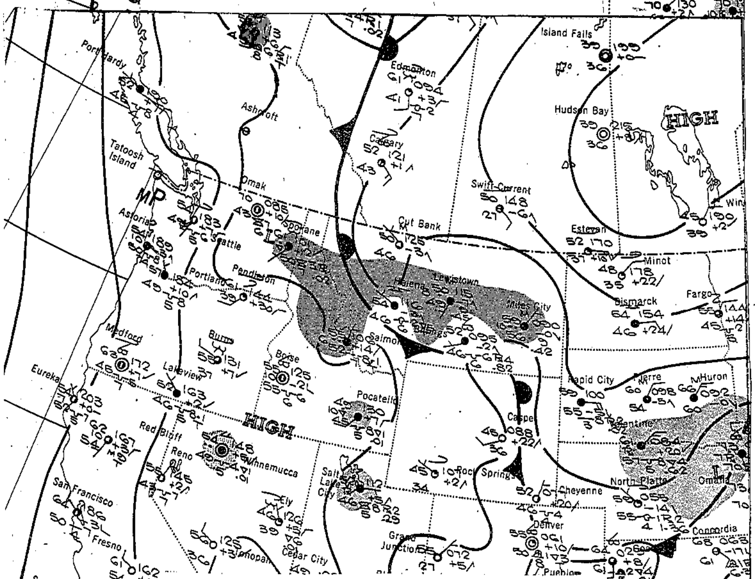


FIGURE 14B. SURFACE MAP FOR 2300MST JUNE 6, 1967.

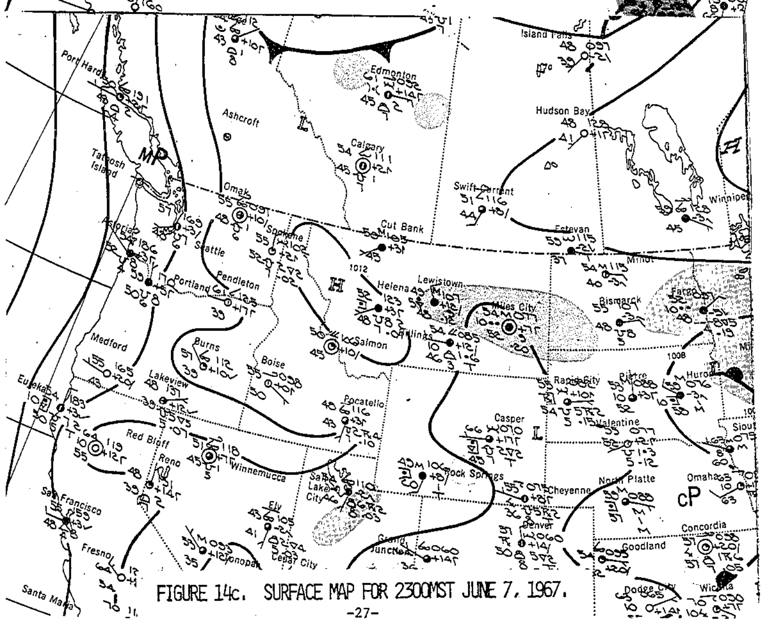


FIGURE 14C. SURFACE MAP FOR 2300MST JUNE 7, 1967.

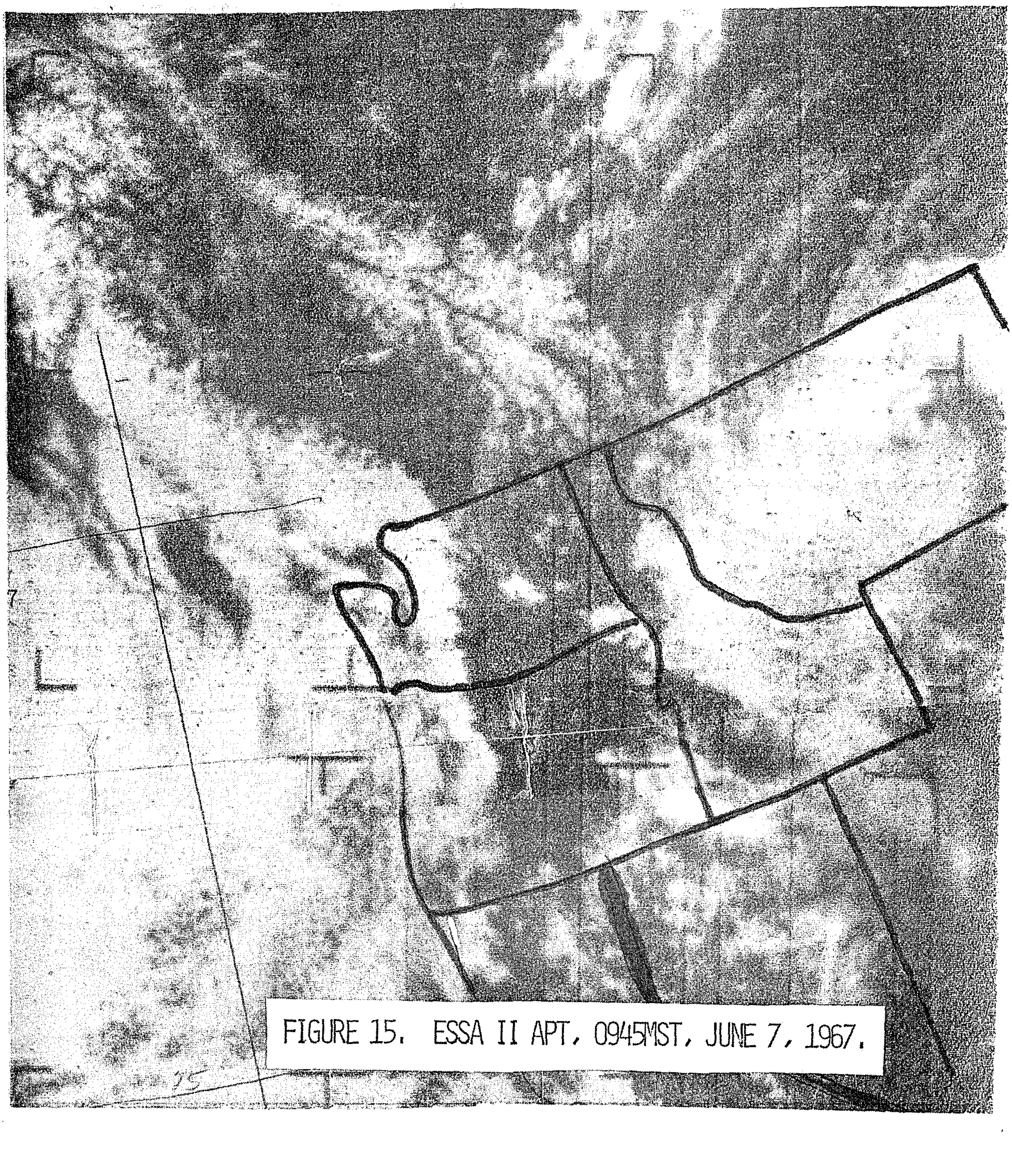


FIGURE 15. ESSA II APT, 0945MST, JUNE 7, 1967.

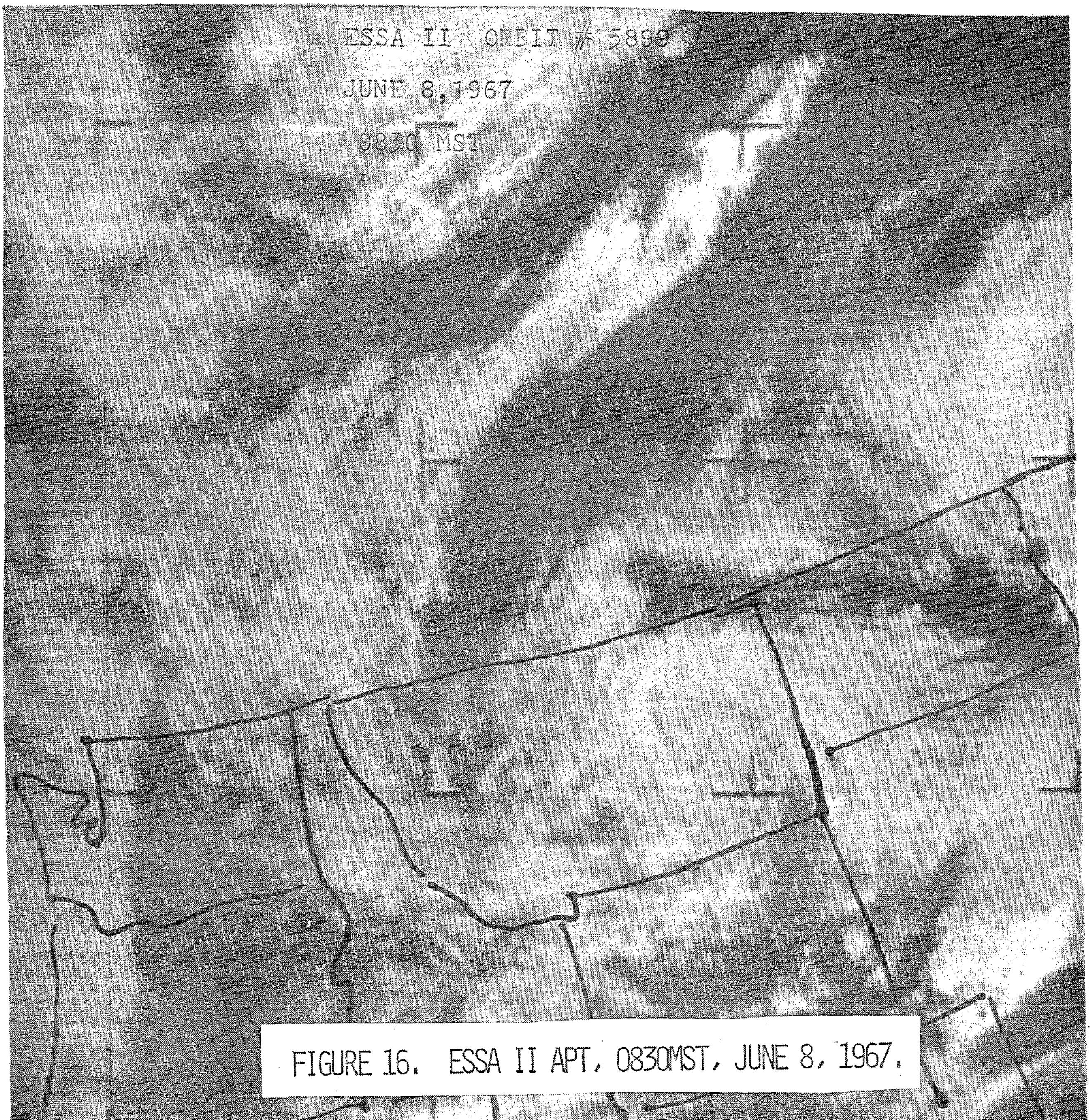


FIGURE 16. ESSA II APT, 0830MST, JUNE 8, 1967.

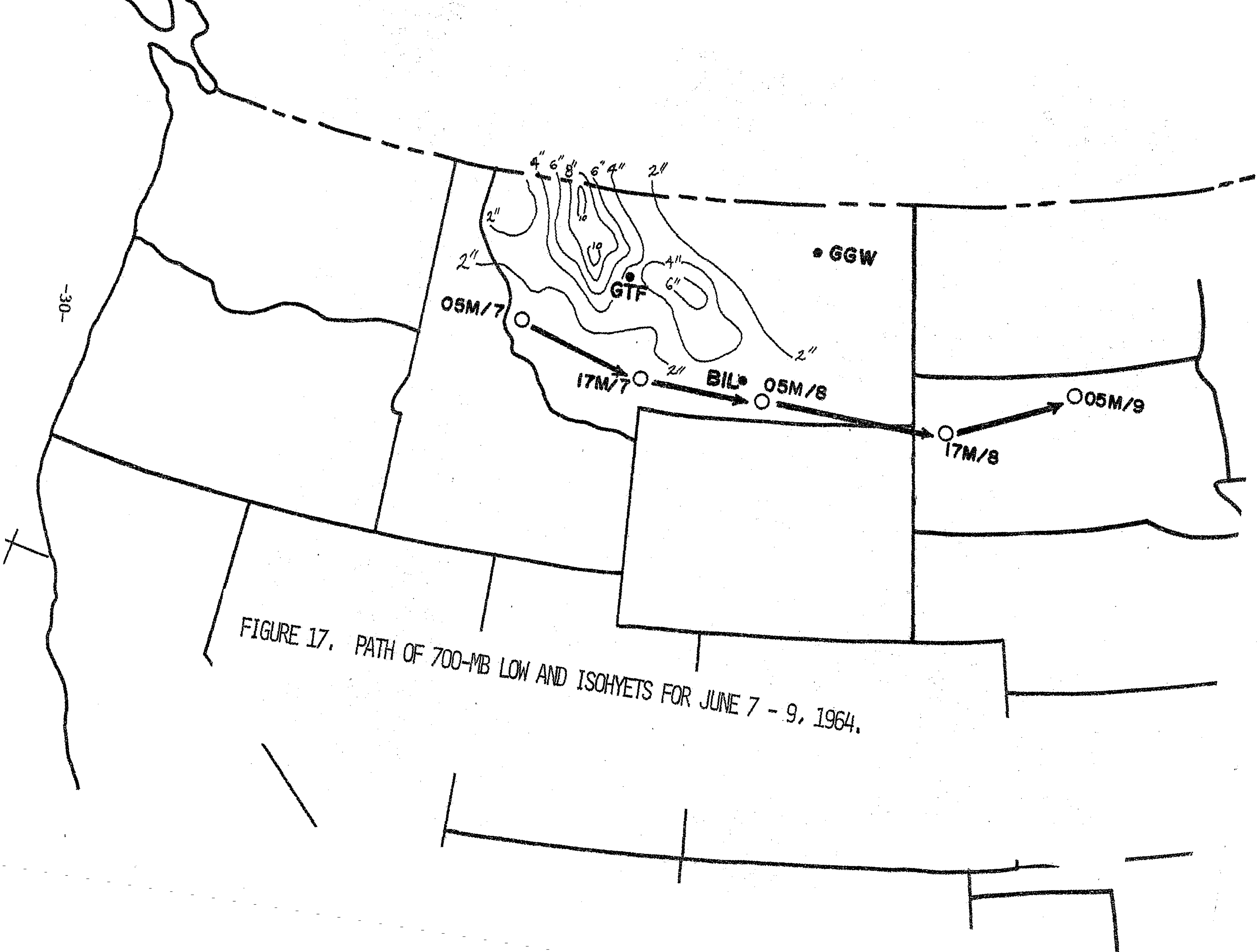


FIGURE 17. PATH OF 700-MB LOW AND ISOHYETS FOR JUNE 7 - 9, 1964.

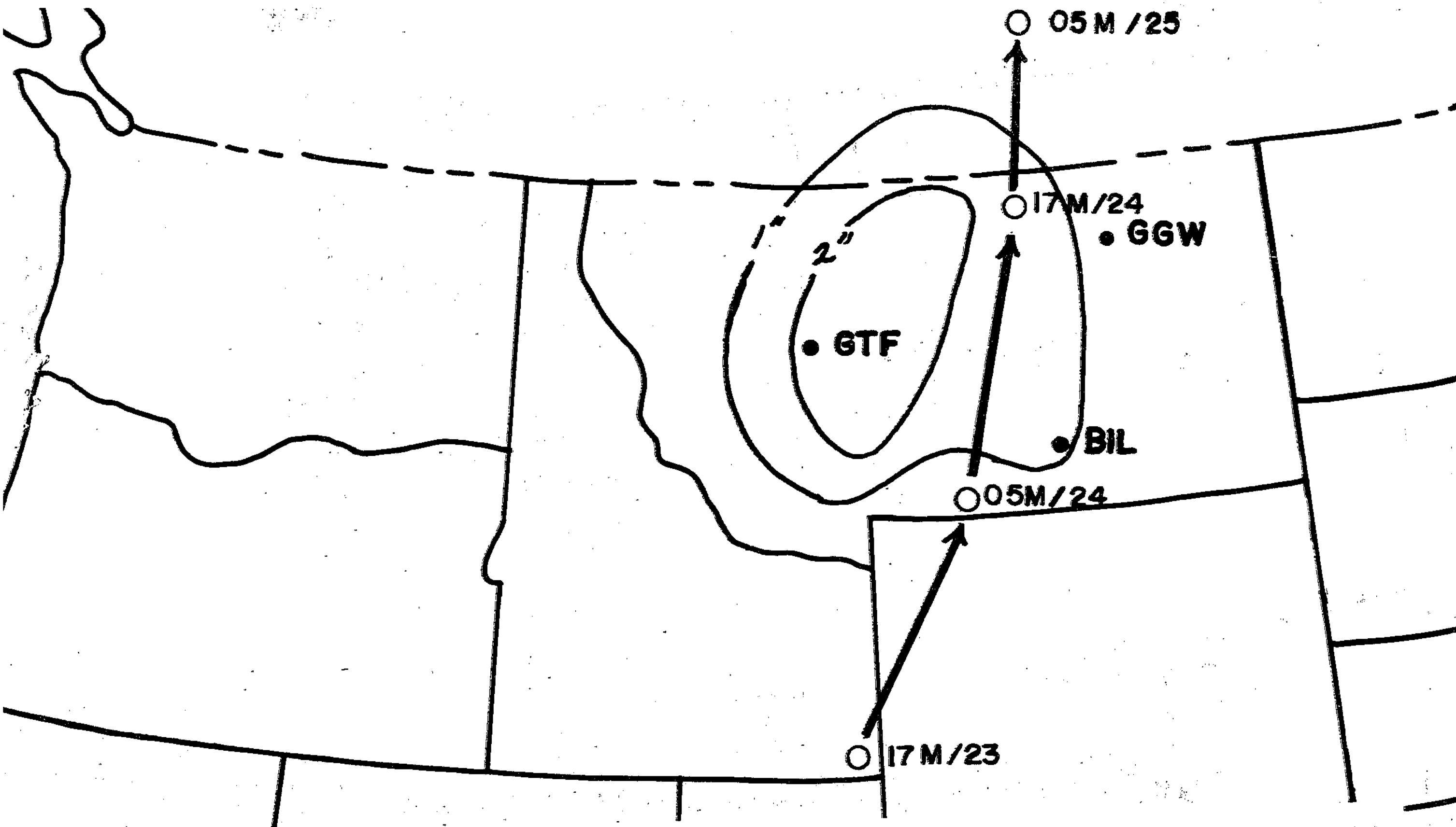


FIGURE 18. PATH OF 700-MB LOW AND ISOHYETS FOR JUNE 24 - 25, 1965.

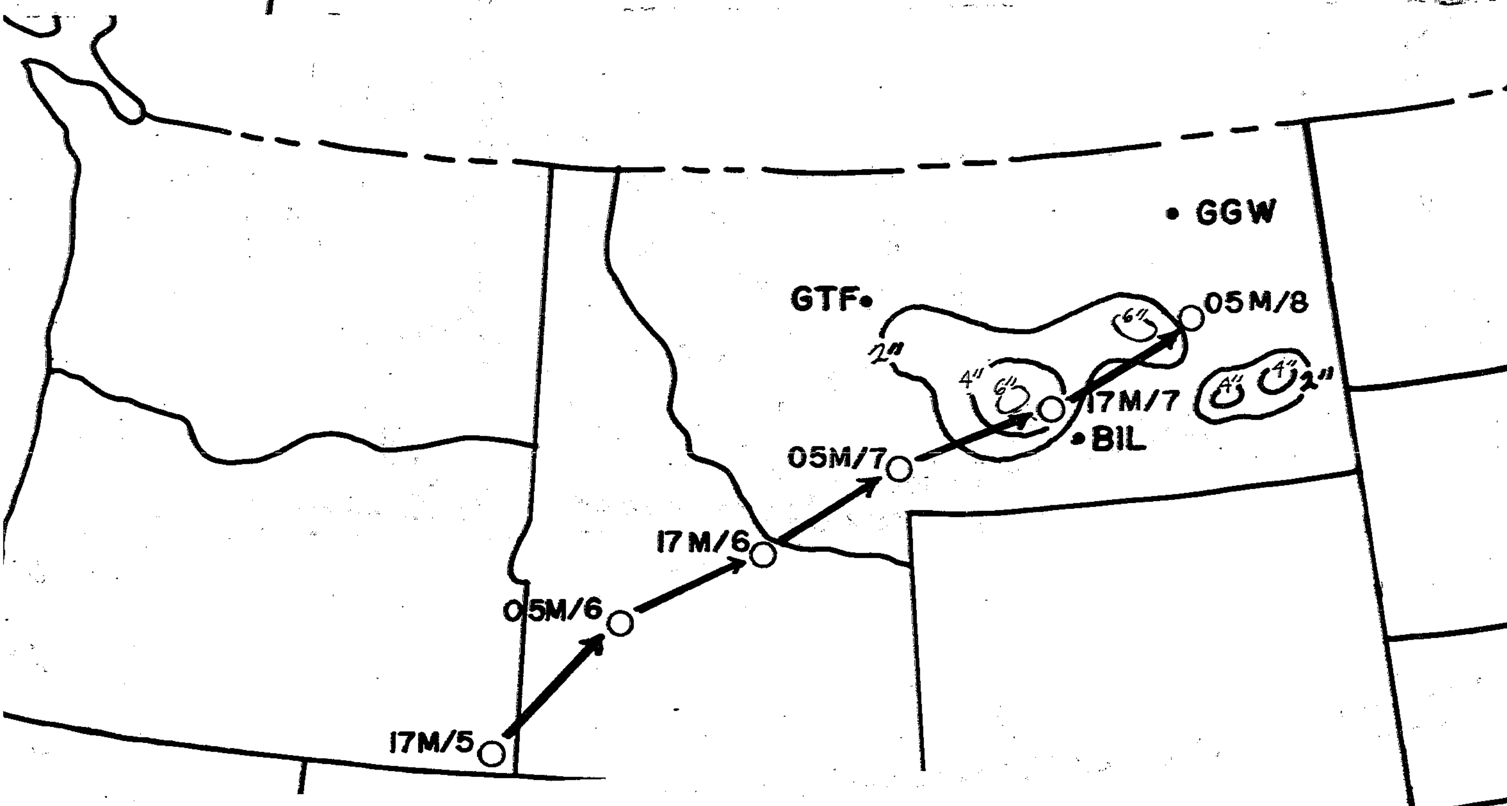


FIGURE 19. PATH OF 700-MB LOW AND ISOHYETS FOR JUNE 6 - 8, 1967.

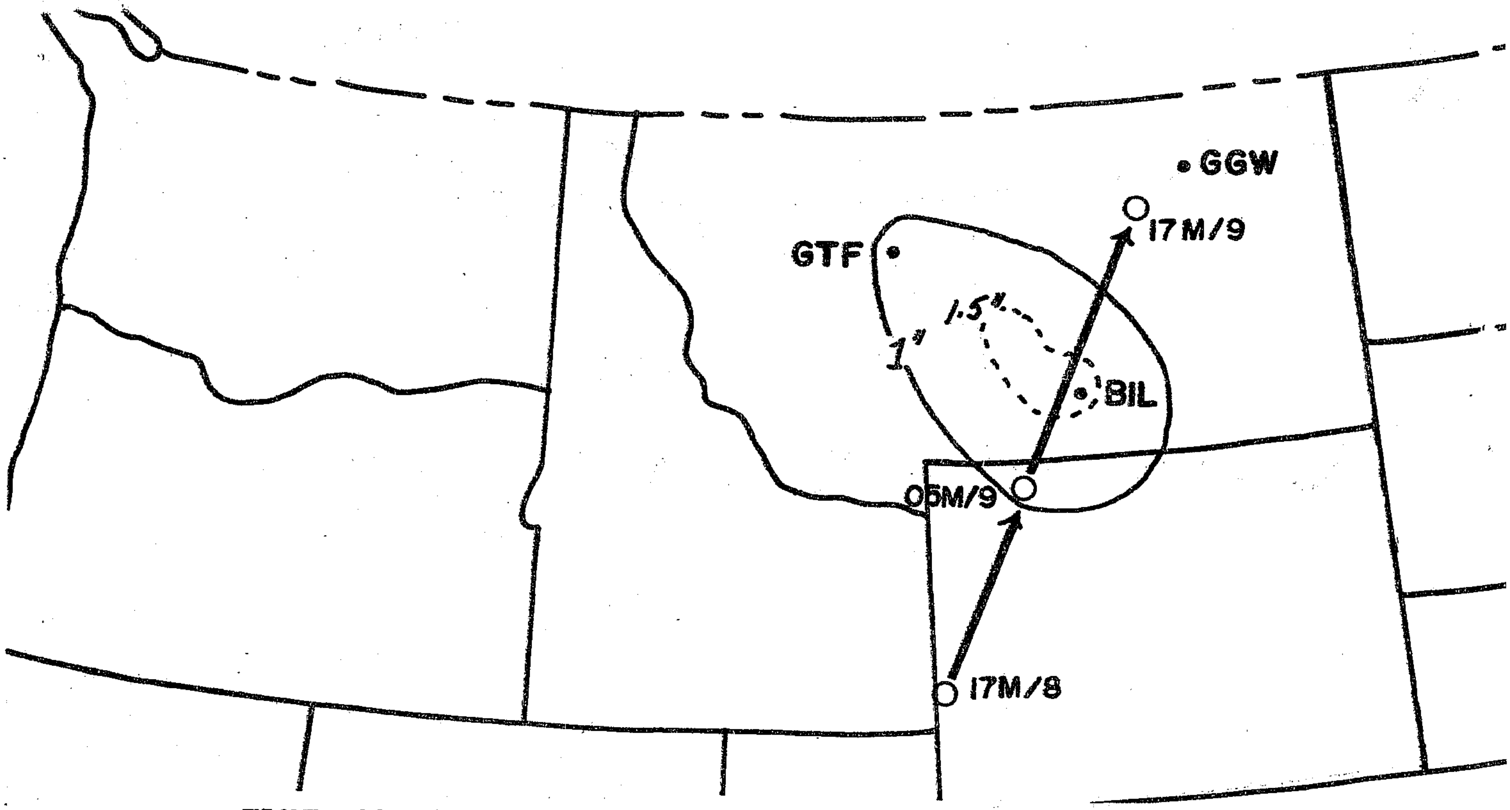


FIGURE 20. PATH OF 700-MB LOW AND ISOHYETS FOR JUNE 8 - 10, 1968.

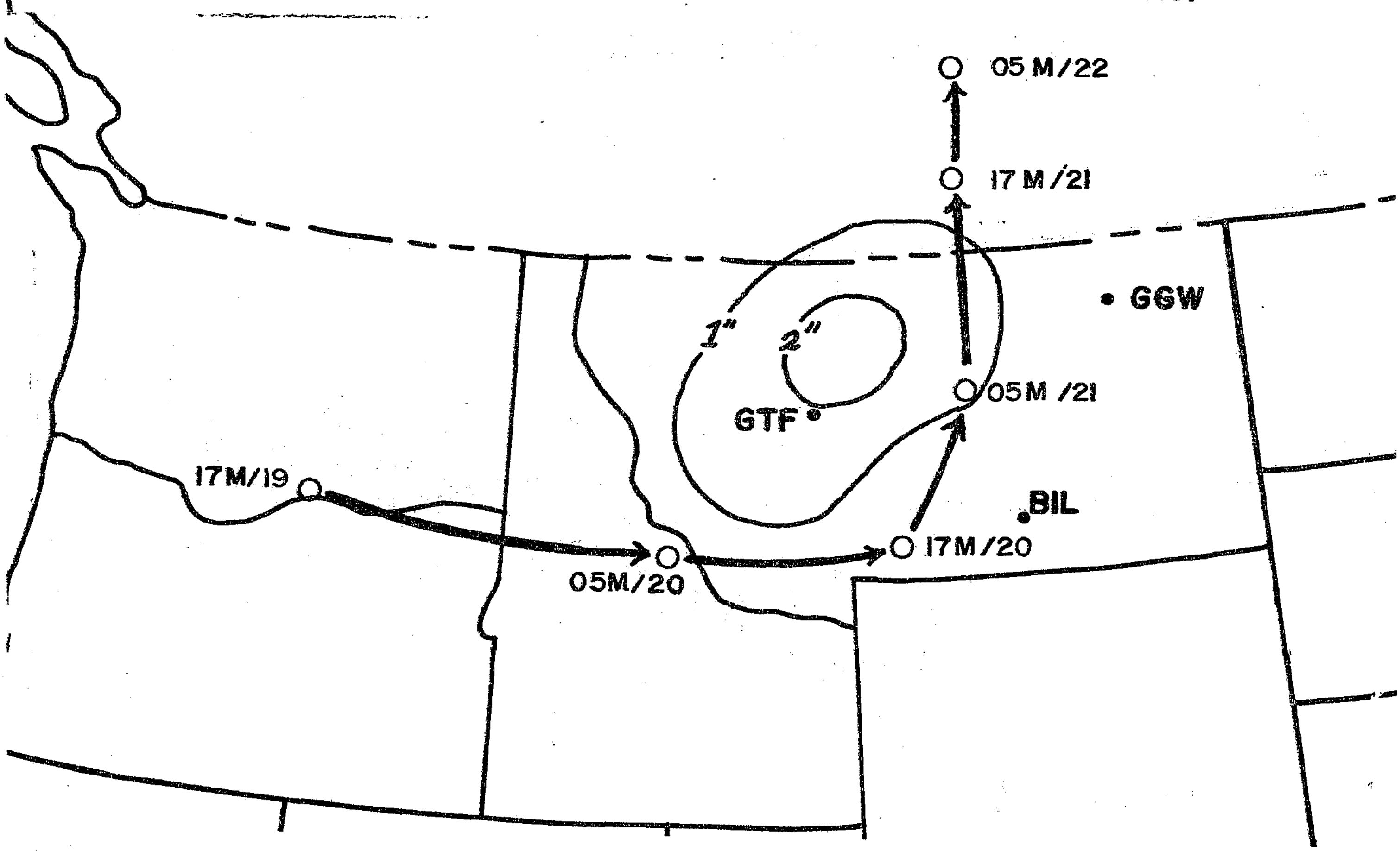


FIGURE 21. PATH OF 700-MB LOW AND ISOHYETS FOR SEPTEMBER 20 - 22, 1968.

Western Region Technical Memoranda: (Continued)

No. 24 Historical and Climatological Study of Grinnell Glacier, Montana. Richard A. Dightman. July 1967.

No. 25 Verification of Operational Probability of Precipitation Forecasts, April 1966 - March 1967. W. W. Dickey. October 1967.

No. 26 A Study of Winds in the Lake Mead Recreation Area. R. P. Augulis. January 1968.

No. 27 Objective Minimum Temperature Forecasting for Helena, Montana. D. E. Olsen. February 1968.

No. 28** Weather Extremes. R. J. Schmidli. April 1968.

No. 29 Small-Scale Analysis and Prediction. Philip Williams, Jr. May 1968.

No. 30 Numerical Weather Prediction and Synoptic Meteorology. Capt. Thomas D. Murphy, U.S.A.F. May 1968.

No. 31 Precipitation Detection Probabilities by Salt Lake ARTC Radars. Robert K. Belesky. July 1968.

No. 32 Probability Forecasting. Harold S. Ayer. July 1968.

No. 33 Objective Forecasting. Philip Williams, Jr. August 1968.

No. 34 The W ... tana. R. Granger. Octob ...

No. 35 Joint ... lance Program. Herbert P. Benne ... .

No. 36 Tempe ... Heat Island. Anthony D. Lenti ...

No. 37 Dispo ... ge to Air Quality. Owen ...

No. 38 Clima ... dli, P. C. Kangieser, and R ...

**Revised