HYDROMETEOROLOGICAL REPORT NO. 35

METEOROLOGY OF HYPOTHETICAL FLOOD SEQUENCES IN THE MISSISSIPPI RIVER BASIN

Washington
December 1959

HYDROMETEOROLOGICAL REPORTS

(Nos. 6–22 Numbered Retroactively)

No. 1. Maximum possible precipitation over the Ompompanoosuc Basin above Union Village, Vt. 1943.
*No. 2. Maximum possible precipitation over the Ohio River Basin above Pittsburgh, Pa. 1942.
*No. 3. Maximum possible precipitation over the Sacramento Basin of California. 1943.
No. 4. Maximum possible precipitation over the Panama Canal Basin. 1943.
*No. 5. Thunderstorm rainfall. 1947.
*No. 6. A preliminary report on the probable occurrence of excessive precipitation over Fort Supply Basin, Okla. 1938.
*No. 7. Worst probable meteorological condition on Mill Creek, Butler and Hamilton Counties, Ohio. 1937. (Unpublished.) Supplement, 1938.
*No. 8. A hydrometeorological analysis of possible maximum precipitation over St. Francis River Basin above Wappapello, Mo. 1938.
*No. 9. A report on the possible occurrence of maximum precipitation over White River Basin above Mud Mountain Dam site, Wash. 1939.
*No. 10. Maximum possible rainfall over the Arkansas River Basin above Caddoa, Colo. 1939. Supplement, 1939.
*No. 11. A preliminary report on the maximum possible precipitation over the Dorena, Cottage Grove, and Fern Ridge Basins in the Willamette Basin, Oreg. 1939.
*No. 12. Maximum possible precipitation over the Red River Basin above Denison, Tex. 1939.
*No. 13. A report on the maximum possible precipitation over Cherry Creek Basin in Colorado. 1940.
*No. 14. The frequency of flood-producing rainfall over the Pajaro River Basin in California. 1940.
*No. 15. A report on depth-frequency relations of thunderstorm rainfall on the Sevier Basin, Utah. 1941.
*No. 16. A preliminary report on the maximum possible precipitation over the Potomac and Rappahannock River Basins. 1943.
No. 17. Maximum possible precipitation over the Pecos Basin of New Mexico. 1944. (Unpublished.)
*No. 18. Tentative estimates of maximum possible flood-producing meteorological conditions in the Columbia River Basin. 1945.
*No. 19. Preliminary report on depth-duration-frequency characteristics of precipitation over the Muskingum Basin for 1- to 9-week periods. 1945.
*No. 20. An estimate of maximum possible flood-producing meteorological conditions in the Missouri River Basin above Garrison Dam site. 1945.
*No. 21. A hydrometeorological study of the Los Angeles area. 1939.
*No. 21A. Preliminary report on maximum possible precipitation, Los Angeles area, California. 1944.
*No. 21B. Revised report on maximum possible precipitation, Los Angeles area, California. 1945.
*No. 22. An estimate of maximum possible flood-producing meteorological conditions in the Missouri River Basin between Garrison and Fort Randall. 1946.
*No. 23. Generalized estimates of maximum possible precipitation over the United States east of the 105th meridian, for areas of 10, 200, and 500 square miles. 1947.
*No. 24. Maximum possible precipitation over the San Joaquin Basin, Calif. 1947.
*No. 25. Representative 12-hour dewpoints in major United States storms east of the Continental Divide. 1947.
*No. 25A. Representative 12-hour dewpoints in major United States storms east of the Continental Divide. 2d edition. 1949.
No. 26. Analysis of winds over Lake Okeechobee during tropical storm of August 26–27, 1949. 1951.
*No. 27. Estimate of maximum possible precipitation, Rio Grande Basin, Fort Quitman to Zapata. 1951.
*No. 28. Generalized estimate of maximum possible precipitation over New England and New York. 1952.
*No. 29. Seasonal variation of the standard project storm for areas of 200 and 1,000 square miles east of 105th meridian. 1953.
No. 30. Meteorology of floods at St. Louis. 1953. (Unpublished.)
No. 31. Analysis and synthesis of hurricane wind patterns over Lake Okeechobee, Florida. 1954.
No. 32. Characteristics of United States hurricanes pertinent to levee design for Lake Okeechobee, Florida. 1954.
*No. 33. Seasonal variation of the probable maximum precipitation east of the 105th meridian for areas from 10 to 1,000 square miles and durations of 6, 12, 24, and 48 hours. 1956.
No. 34. Meteorology of flood-producing storms in the Mississippi River Basin. 1956.

---

* Out of print.

U.S. Department of Commerce
Weather Bureau

U.S. Department of Army
Corps of Engineers

HYDROMETEOROLOGICAL REPORT NO. 35

METEOROLOGY OF HYPOTHETICAL FLOOD SEQUENCES IN THE MISSISSIPPI RIVER BASIN

Prepared by
Vance A. Myers
Hydrometeorological Section
Hydrologic Services Division

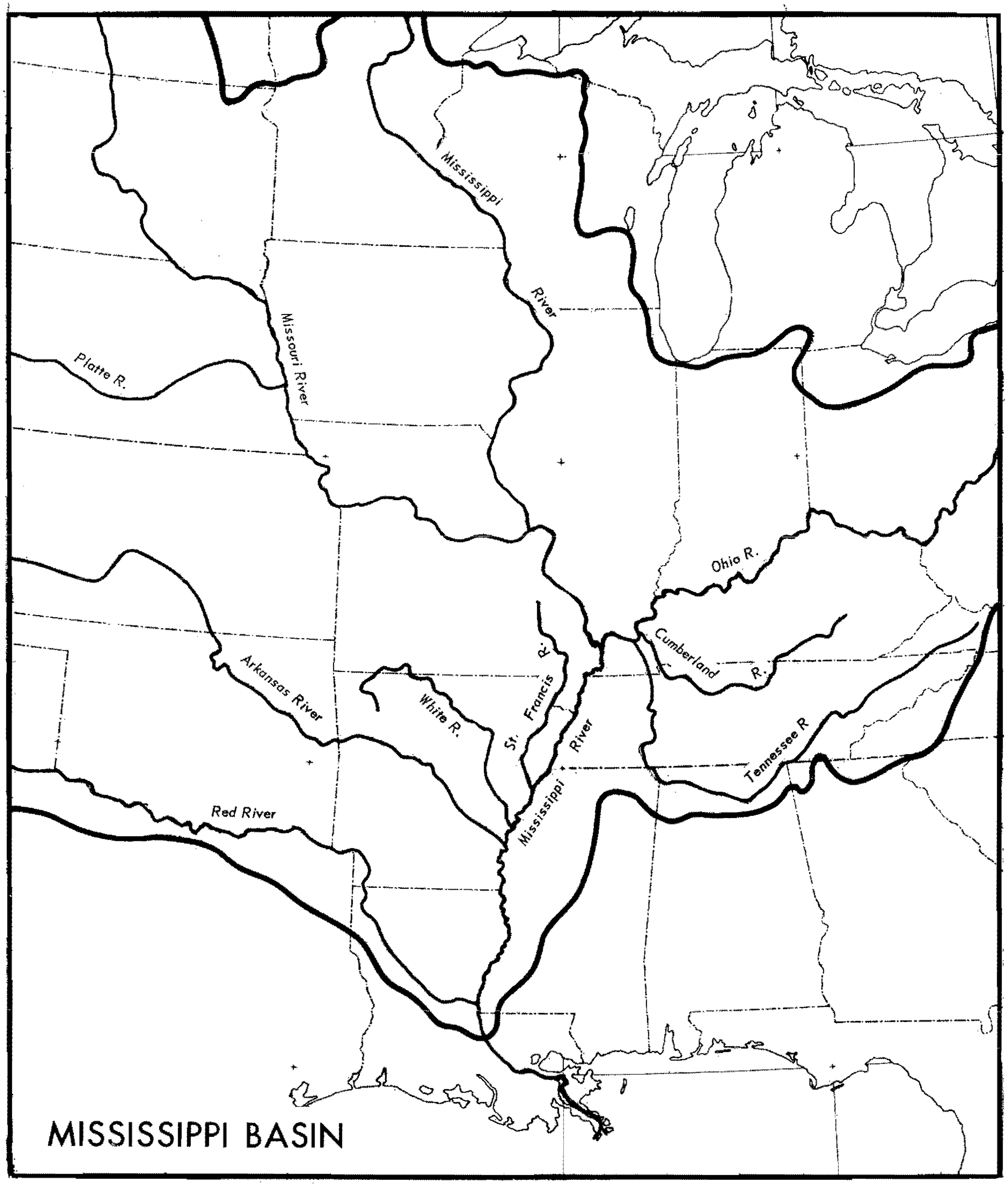
Washington, D.C.
December 1959

For sale by the Superintendent of Documents, U. S. Government Printing Office Washington 25, D. C. - Price 35 cents

CONTENTS

CONTENTS (cont'd)

FIGURES


MISSISSIPPI BASIN

I. INTRODUCTION

The Corps of Engineers, Department of the Army, recently conducted a comprehensive study of the flood potential of the Mississippi River and its major tributaries below St. Louis, Mo. The purpose was to bring up to date design criteria for flood control works in the Mississippi River Basin. The Corps of Engineers requested the assistance of the U. S. Weather Bureau on the meteorological phases of the study and supported the investigations financially. This is the second of the two final reports on the meteorological findings. The first, Hydrometeorological Report No. 34, "Meteorology of Flood-Producing Storms in the Mississippi River Basin", surveyed the meteorological causes of heavy precipitation in the central Mississippi Valley and gave detailed individual synoptic analyses of a number of the great rainstorms in the Valley. The present report covers the meteorological aspects of hypothetical floods that evolved from a number of conferences between the Office of Chief of Engineers, the Mississippi River Commission, and the Weather Bureau, and which have been adopted by the Corps of Engineers as the current basis for design in the Lower Mississippi River Basin.

Precipitation characteristics of historical floods

Extraordinary floods are necessarily preceded by precipitation that is extraordinary in some way, excepting snowmelt floods which are not of great consequences in the Lower Mississippi Basin. The precipitation must be extraordinary because, through erosion and sedimentation, the stream channels have been adjusted to carry ordinary precipitation.

Precipitation producing an extraordinary flood may have as its extraordinary characteristic great intensity, long duration, or remarkably precise placement in the flooded basins so as to obtain optimum coincident rises from converging streams, or it may have all of these. The larger and more complex the basin, the more critical the placement factor. For example, the January 1937 flood on the Ohio River began with repeated rains over virtually the same area. The highest flood crest resulted when the last burst of rain stretched along the Ohio River in such a way that large volumes of water found their way into the main stream quickly. This same flood produced the highest stages of record on the Mississippi from Cairo, Ill., to the mouth of the St. Francis River. Below there, lacking sufficient reinforcement from the Arkansas and White Rivers, the flood was of lesser consequence. The disastrous Mississippi Flood of 1927 culminated in April of that year when large discharges down the Mississippi were reinforced by a major flood from the Arkansas. In May 1943 two record-breaking storms, only five days apart, produced the highest stages of record on much of the Arkansas River, but this flood was of little consequence on the Mississippi because there was no synchronized reinforcement from north of the mouth of the Arkansas.

II. METHODS OF ESTIMATING POSSIBLE FUTURE FLOODS

Requirements for project flood

All estimates of floods larger than any observed are extrapolations beyond observed data. There are several rational ways in which this extrapolation can be carried out. The choice of method for a large and complex basin like the Mississippi is governed by practical as well as scientific considerations. The specific objectives of the Mississippi Project Flood as stated in the "Interim Report, Mississippi River Project Flood Study", prepared in the office of the President of the Mississippi River Commission, Vicksburg, Mississippi, November 1954 were:

> "(1) To determine the meteorological situations and related rainfall quantities that may be reasonably expected to produce critical discharges at key discharge stations along the Mississippi River from St. Louis to Latitude of Red River Landing, considering logical alternative combinations of major tributary contributions.
>
> "(2) To develop hypothetical hydrographs of runoff for the key discharge station near the mouth of each major tributary and for key stations on the Mississippi River.
>
> "(3) To select the hydrographs that will be used by the various Division Offices in determining the effects of reservoirs at the key station of each major tributary."

The over-all purpose is "to determine flood magnitudes that will be used as a basis for establishing levee grades on the main stem of the Mississippi River and for planning, designing, and determining works within the Mississippi River Basin".

No single flood event would be expected to produce maximum discharges in all parts of the Mississippi Basin below the mouth of the Missouri. Several hypothetical floods, with the heaviest rain in each falling in a different portion of the Basin, are required to cover the entire Basin. The "Project Flood", then, is not a single flood but rather the name applied to the highest of several hypothetical floods over each reach of the Basin. As the seasonal variation of precipitation of flood-producing proportions varies considerably within the Lower Mississippi Basin, the various hypothetical floods would be expected to pertain to different months of the year.

Maximum-flood-of-record method

Most of the design of levees on the Mississippi River before 1900 referred to the biggest known flood up to the particular time. While this was an obvious and logical first goal for flood protection in the days when flood-protection works were first constructed, a higher degree of protection is required today. The period of record is too short to have revealed more than a small sampling of the possible floods that can be produced in the Mississippi Basin.

Combination-of-discharges method

In 1928 the Weather Bureau made an estimate of maximum discharge at Cairo, Ill., by combining the maximum Ohio River Flood observed up to that time with coincident peak flows from the Upper Mississippi, Cumberland, and Tennessee Rivers. The Mississippi River Commission independently made an estimate that was very nearly the same. The maximum for Arkansas City, Ark., consisted of this flood routed downstream, plus synchronized maximum flows from the Arkansas and White Rivers. An estimate made by the Weather Bureau in 1938 combined the Ohio River flood of the previous year with what was considered a maximum permissible simultaneous discharge from the Upper Mississippi. The Mississippi River Commission made an estimate routing this flood down to the mouth of the Arkansas River and combining it with the 1927 flood from the Arkansas and White Rivers.

Combination-of-precipitation-storms method

Another approach is to combine the precipitation storms over various tributary basins rather than combining discharges directly. The advantages of this approach are twofold: the reasonableness of combinations can be more adequately examined, and the adjustments to historical events used as prototypes can be made on a more rational basis. An example of such an adjustment is shifting a rainstorm slightly so that more of the rain falls within the boundaries of a particular basin. This combination of precipitation storms is the method of the present design-flood estimates. Two or more historical precipitation storms were combined into hypothetical flood sequences and the resulting discharges computed by hydrologic techniques.

Probable-maximum-precipitation method

A technique pioneered by the Corps of Engineers and the Hydrometeorological Section of the Weather Bureau for estimating maximum possible or probable maximum floods for spillway design of dams is to divide the rainfall into its component parts on the basis of atmospheric physics, make climatological studies of the magnitudes of each causative factor in the region, then recombine appropriate extreme values of each cause and compute the resulting rainstorm. The reasoning is that the maximum observed wind flow from a moisture-bearing direction, combined with the maximum observed moisture charge in the atmosphere in the region, plus maximum efficiency of storm mechanism, etc., will yield a maximum possible storm. The concept of a maximum possible thunderstorm, for example, is a simple one of continuity of flow (implementation of the concept with numbers is not always so simple) and is analogous to estimating the maximum number of automobiles that can pass over a highway bridge of a certain width in a specified length of time. However, as the area and duration of a rainstorm are extended, a maximum possible or probable maximum precipitation concept becomes more analogous to estimating the maximum number of automobiles that could be operating on all the highways of a state at a given time. The total physical capacity of all the highways is no longer the logical controlling factor. The continued deposit for several days throughout an area as large as the Lower Mississippi Basin of a rate of precipitation computed from a sustained maximum inflow of moist air with a maximum moisture content, and released by repeated development of maximum storm mechanisms, would be many times greater than what is experienced in our largest storms and would be meaningless as a practical estimate of what might occur. For areas of several states and durations of several days, the probable maximum precipitation concept based on continuity of flow is inappropriate and was not used in the Lower Mississippi Basin Study.

Statistical-extrapolation method

There are several standard techniques for estimating a smooth frequency curve from an array of highest annual floods or other similar statistics. These techniques are eminently useful for determining floods of specified short average return periods, such as ten years, in a consistent and objective fashion. Statistical frequency analyses of maximum annual mean daily flows at four points on the main stem of the Mississippi have been carried out by the Mississippi River Commission by a modification of Gumbel's theory of extreme values. (Interim Report, Mississippi River Project Flood Study, Mississippi River Commission.) Because the characteristics of the frequency distribution curve are not known with sufficient precision, this type of statistical method is satisfactory for extrapolating well beyond the data only when used in conjunction with another method. The form of the curve in the area of the body of data can be determined, but this gives no assurance that the curve can be specified accurately on the outer limbs where a very small variation in the frequency curve makes a difference of 100% or more in the mean recurrence interval of a flood of given magnitude. In a recent textbook on hydrology* it is stated that "no statistical frequency curve can be more than a guide to the judgment of the designing engineer."

Statistical frequency analysis can also be applied to the rainfall rather than directly to the flood discharges. This, however, would merely transfer the indeterminacy from the flood discharge to the precipitation.

---

*R. K. Linsley, Max A. Kohler, and J. L. H. Paulhus, "Applied Hydrology", 1949, page 545.

III. HYPOTHETICAL FLOOD SEQUENCE TECHNIQUE

The hypothetical combination of precipitation storms into sequences was adopted as the basic method for estimating the Project Flood for the Lower Mississippi Basin. In spite of its somewhat subjective nature, this method is more applicable at the present time -- with present day limitations on data and state of knowledge -- than any of the other methods listed in section II. The application of this technique, as it evolved in the Lower Mississippi Basin Study, is described in this section.

Definition of a storm

The flood-sequence technique involves putting two or more rainstorms in a sequence with the intention that the storms be separate distinct entities. A storm is defined as ending when relatively dry air sweeps over the area concerned. This frequently occurs when a distinct cold front, associated with a deep occluding Low, is swept to the Gulf Coast or beyond.

Combinations of storms

The first step in developing a hypothetical flood sequence was to select two or more storms to form the sequence. Criteria for placing storms in the same sequence were: (1) occurrence in the same season, or approximately so, (2) magnitude of the rain that fell, (3) location over the major tributaries that experience showed would make the biggest contributions to main-stem floods in that season, and (4) existence of compiled precipitation data and stream flow data. The total number of storms meeting all these requirements is not large. The order of the storms in the sequence was dictated by the obvious requirement that the upstream storm occur first. With one exception, the precipitation data had been compiled and analyzed in the Corps of Engineers storm study program.*

Meteorology of transition from one storm to another

The second step in developing a hypothetical sequence was to study the surface weather charts for each of the two storms to be combined, including the charts for a number of days following the first storm and preceding the second storm. Where storms were recent enough for good upper-air charts to be available, these, too, were studied. Next an evolution of weather events was worked out in terms of motions of principal Highs, Lows, and troughs, and development of warm flow from the south and cold flow from the north into the Mississippi Basin. If no satisfactory evolution could be worked out, that hypothetical sequence was discarded.

---

*Corps of Engineers, Department of the Army, "Storm Rainfall in the United States, Depth-Area-Duration Data", Washington, 1945.

In large-area cold-season type rainstorms requirements for reestablishment of heavy precipitation in the Mississippi Basin after clearing weather are: (1) a southerly flow of high moisture content (this is usually around the western edge of a Bermuda High), (2) production of a strong temperature contrast in a frontal zone, and (3) presence at upper levels of a trough of low pressure to the west of the rain area. The simplest manner in which this transition can take place is for the first rainstorm to terminate with the passage of a strong cold front, with the High behind it moving steadily to the western Atlantic, becoming, or amalgamating with, the subtropical Bermuda High, and then the development of a strong southerly flow from the Gulf of Mexico northward on the western edge of the High. This would be followed by the movement inland and redevelopment of an old Pacific trough, with the injection of cold arctic air from Canada into it. This would result in a sharp, but slow-moving, front in the trough with a well-developed cold High behind the front. A more complicated, but perhaps more common,method to reset the stage for precipitation in the Mississippi Basin is somewhat as follows. The first High moves off the coast as just described, followed by one or more lesser Lows moving eastward near the Canadian border. These tend to draw warm air into the Lower Mississippi Basin and gradually rebuild the temperature contrast in the central part of the Valley. Finally, there is a southward push of very cold Canadian air behind one of these Lows with the associated establishment of a strong quasi-stationary front across the Mississippi Basin.

A third method by which the conditions for precipitation might be reestablished is for the front moving out at the end of the first rainstorm to slow down and stall just south of the Gulf Coast. New Lows are induced on this front near the Texas coast by low-latitude troughs across the southwestern United States from the Pacific. With this type, rain can spread very quickly into the southern part of the central Mississippi Basin.

Time interval

In working out the flood routings for a number of hypothetical flood combinations, hydrologists of the Corps of Engineers found that, in general, for maximum combined stage, the optimum time interval between two separate storms was quite short. The practical limit on the shortness of the time interval was not what was hydrologically critical but rather what was meteorologically acceptable. The most difficult decision for the meteorologist then, and the one he was least equipped to handle by present knowledge, was what minimum time interval between two storms would be reasonably characteristic both of the area and of weather processes in general. It was found that the most satisfactory way to make decisions on time intervals and to document them was to reduce the general synoptic evolution, worked out in accordance with the principles in the preceding paragraph, to hypothetical weather maps.

Hypothetical map series

Hypothetical surface weather charts were constructed for each sequence for an area covering the United States and a considerable region beyond. Real maps were adhered to through the first 0600 CST map after the end of significant precipitation in the first storm and again beginning with the 0600 CST chart before the start of significant precipitation in the second storm. Hypothetical maps were constructed for the intermediate period at 24-hour intervals. These depicted one possible transition between the two storms. The assumption inherent in this technique is that if all the important features of the map at the beginning of the second storm, over a sufficiently large area, can be developed in a meteorologically logical way, then all the necessary and sufficient conditions for the second storm have been met. The successive hypothetical maps were patterned to the greatest extent possible after the real maps following the first storm and preceding the second storm. In several instances it was possible to find a map following the first storm that was rather similar to a specific map preceding the second storm. In such cases the similar map was used in the hypothetical sequences as the point of transition from the first storm to the second.

At times it was necessary to rely on more general experience. Using daily weather maps since 1900, weather situations similar to the selected storms were studied for other clues on the behavior of weather systems. Synoptic features such as Highs, Lows, and fronts in various regions and seasons were allowed to move and change in accordance with what was found on the maps. The intent was to let the major features move and change at a rate that was somewhat faster than average but yet not unusual. The resulting hypothetical sequences are intended to depict <u>one</u> possible transition from one storm to another.

The hypothetical sequences would be established on an even firmer basis if they were carried out at upper levels as well as at the surface. This was done with one sequence. Construction of hypothetical weather charts is a time-consuming process even when working in only two dimensions with surface weather charts. In three dimensions, however, the work is multiplied several-fold and is not considered worthwhile for all sequences, especially for the many storms that occurred before the era of upper-air data.

Relation of hypothetical sequences to duration, intensity, and placement of precipitation

The hypothetical sequence technique augments the <u>duration</u> of the intense flood-producing precipitation more than any other characteristic. The duration of less intense precipitation is further extended indirectly by allowing the first precipitation storm of a sequence to start with a specified <u>antecedent flow</u> in all streams. This is higher than the actual antecedent of most of the storms but is not extraordinary. The antecedent flows were taken mostly from minor floods.

The second factor that the hypothetical sequence technique makes more critical is placement of the precipitation. Storms were chosen for tributary basins in an order that will allow flood crests to be amplified as they move downstream. The fit of storms over individual basins was improved in some sequences by moving the isohyetal pattern of the prototype storm. Most such transpositions were on the order of a few dozen miles. One was several hundred miles. This is discussed in more detail in section VII.

The intensity factor in flood precipitation was augmented least in the hypothetical sequences. The precipitation on no one day, by itself, is extraordinary. In one storm the prototype precipitation was increased by 10% in the place of occurrence. In another the intensity was changed to allow for transposition. In other storms used in the present report the intensity of the observed precipitation was not modified.

Repetition of a storm

In the complex broad-scale circulation pattern of the atmosphere there is from time to time a persistence of the same general type of flow for days or weeks. This persistence is an important factor in floods and droughts and has led synoptic meteorologists reviewing this report to comment that in a hypothetical sequence, repetition of a storm is at least as likely as the combination of two different storms. It would be reasonable on purely meteorological grounds to develop a hypothetical flood by repeating a precipitation storm after an appropriate time interval. If this is done, one of the two identical storms should be transposed a short distance from its observed location to avoid the hydrologic anomalies that would result from repeating the local high spots in the isohyets over exactly the same creek or small river. A smoothing of the isohyetal pattern would accomplish the same purpose.

In this report, in order to illustrate a greater variety of possibilities, the same storm is not used more than once in any sequence.

IV. HYPOTHETICAL WINTER FLOOD*

Tributary basin variations

Many of the fronts between cold and warm airmasses that pass through the Mississippi Basin every few days in winter, and their attendant Lows, are effective producers of precipitation over the eastern and southern portions of the Basin. This is because in winter those parts of the Basin are readily accessible to the flow of warm, humid, tropical air from over the Gulf of Mexico and the Caribbean Sea that is necessary to support heavy precipitation. In the northern and western portions of the Basin, however, winter precipitation is much lighter, since penetration of strong moist currents into these areas would require a shifting of the normal, persisting, westerly winds aloft over the United States at this season to a deep southerly current. Any penetration of warm humid air from over the Gulf into, for example, Kansas or Iowa, is infrequent in winter and is short-lived when it does occur. Rather precise wind directions are required for a moist current to reach Kansas undiluted with drier air from either the southwest or the southeast; furthermore, such currents are usually associated with deepening and occluding Lows, a process which itself rapidly changes wind directions. By contrast, a moist current from the western Gulf of Mexico northeastward into the Ohio Valley can persist for days oriented generally parallel to, and to the right of, a quasi-stationary front without any occluding Lows to advance the front and disrupt the moist current.

Dominant weather pattern for floods over eastern tributaries

The frequency of Lows and fronts in combination with the moist currents necessary for heavy precipitation in the southern and eastern parts of the Mississippi Basin varies greatly from week to week and from season to season. The paths of these features and their configurations are controlled in large measure by the broad-scale features of the flow pattern in the lower 30,000 to 40,000 feet of the atmosphere. The position and intensity of the dominant Highs in the eastern Pacific and in the Atlantic exert an important control. The usual circulation pattern for heavy precipitation in the eastern or southern portion of the Mississippi Basin is for the East Pacific High to be well developed and fairly close to the North American Continent, for the Atlantic High to protrude into the eastern United States, and for a well-developed upper-air trough of low pressure to lie over the western United States. The location, intensity, and persistence of these features varies greatly from one winter season to another and from time to time during each season. A severe Ohio or Lower Mississippi flood in winter is invariably associated with a well-marked and persistent atmospheric circulation pattern of the type just described.

---

*Hypothetical Flood No. 58A in Corps of Engineers and Weather Bureau Interim Reports.

Dominant weather pattern for floods over southwestern tributaries

Winter floods over the Arkansas and Red Rivers are much more infrequent than over the Ohio, but they do occur. An example of a winter flood in the Arkansas-Red River area is that of February 1938. The salient features of the weather situation with this flood, illustrated by the weather map for February 15, 1938, figure 8D, are: general low pressure and cyclonic activity in the southwestern United States; a protrusion of the Atlantic High into the Gulf of Mexico, necessary to sustain the southerly flow from the Gulf to the flood area; a High or a portion of a High over the northeastern United States blocking the advance of Lows in Texas, containing them there, and deflecting the rain to the west or north of the usual track of the moist current; the Pacific High centered far to the south and low pressure in the Gulf of Alaska. This pressure distribution over the eastern Pacific is in marked contrast to that which typically prevails for heavy rains in the Ohio Valley. See for example the weather maps of January 18, 1937, and January 4, 1950, figures 1C and 4C.

Tributary combinations for Mississippi winter flood

South of Cairo, Ill., the Mississippi River has no major tributaries from the east. It thus becomes evident that, from the point of view of synoptic meteorology, the winter flood threat to the Lower Mississippi Basin would consist of a long persistence of the typical circulation pattern for Ohio Valley rain, flooding that stream and its tributaries, followed by a shift to the more unusual pattern typified by the February 1938 flood in order to develop a major flood contribution from the western tributaries, principally the Arkansas and Red Basins. This would synchronize with the main-stem crest moving down past Memphis. The great combined flood crest would then continue downstream to Baton Rouge and New Orleans. The lowest reaches of the western tributaries would have received heavy rain at the same time as the Ohio, and local streams in this area would be swollen before the final crests arrived.

Prototype hypothetical flood sequence

A hypothetical flood of the kind described is synthesized by combining persistence of the Ohio Valley rain-favoring patterns followed by a shift to the situation of February 1938. Once-a-day weather maps for the hypothetical flood are shown in figures 1 through 9. These are reproductions of actual weather maps except for two 3-day transitions between storms. The first maps are from the famous January 1937 flood, followed by a series of January 1950, and finally with the February 1938 storm already referred to. Both January 1937 and January 1950 were months of extreme persistence of an over-all circulation pattern. This does not mean of course, that Highs and Lows were stationary, but that they repetitively traveled along the same general tracks. Records were broken in both these months for cold temperatures in the Northern Rockies, for warm temperatures during January in the eastern United States, and for total monthly rainfall volume over the eastern United

States. The highest dewpoints of record by far for January at Buffalo, N. Y., showing the northward penetration of tropical air, were experienced on January 3 and 4, 1950.

The maps of figures 1 through 7 reveal great variety detail of formation of Lows and waves on fronts and fluctuations of the basic circulation pattern for Ohio Valley precipitation pattern. Detailed discussion of the individual features of such storms is found in Hydrometeorological Report No. 34, pages 21-24 (for the January 1937 storm) and pages 54-55 (first part of the January 1950 storm).

Approximate isohyets on weather maps

The heavier precipitation areas are shaded on the daily weather maps. The area shaded is that over which more than half of the Weather Bureau Cooperative Stations in a given region reported one inch or more of precipitation as the 24-hour total. All such one-inch areas east of the Rockies and within the United States are shown on each map. The time of measurement for these stations varies somewhat, ranging from about the time of the weather chart to 10 or 12 hours later. The plotted numbers within the shaded areas give 24-hour amounts, in inches, at rainfall centers. Only centers in excess of three inches are marked in this way.

Transition from eastern tributary to southwestern tributary precipitation

The transition in the hypothetical weather maps from the January 1950 storm to the February 1938 storm (figures 7C-8C) warrant particular attention. There are many similar features in the chart of hypothetical date February 11 (actual January 16, 1950), figure 7C, and the ensuing chart of hypothetical date February 15 (actual February 14, 1938), figure 8C, which is hypothesized to occur four days later. The principal similarities include the distribution of pressure over the eastern Pacific with a High off lower California cut into by a Low farther north off the Washington-Oregon coast, a High centered over the Canadian Rockies -- a very cold High with very high pressure—a low-latitude band of high pressure at about 30° from the mid-Atlantic to the Gulf, and a front curving across the southern United States. A transition is hypothesized by allowing the cell of high pressure over Iowa in figure 7C to drift eastward and amalgamate with the Atlantic High in a very typical fashion (figures 7D, 8A, and 8B), and the Canadian High to settle southward protruding into the eastern United States. The Low off the Washington-Oregon coast is then allowed to redevelop in the Rockies and be forced southward by the great High to the north, eventually becoming the predominant Low in Texas in the final flood rains (figure 8D). Some meteorologists reviewing this report were of the opinion that the upper-air features on January 16, 1950, (figure 7C) and on February 14, 1938, (figure 8C) would not be as similar as the surface features over the East Pacific and Canada and that the transition shown represents a rather abrupt shift in the over-all broad-scale circulation. (Upper-air conditions were not observed in February 1938 beyond the continental United States.) These critics point out that the big Highs in western Canada on the two charts involved had quite different histories preceding them. All agree, however, that the rain associated with this particular transition, especially in regard to placement and time lag, is quite reasonable and take issue only with some of the details of the charts.

Itensification adjustments

The final step in developing the hypothetical flood before scaling precipitation amounts from charts and computing resulting flood discharges is what might be called an intensification adjustment. Many changes can be hypothesized for the early part of the sequence that would result in higher flood flows, such as increasing some of the minor bursts of rain to intensities more comparable with the larger bursts or placing some of the bursts closer together in time.

As representative of all the adjustments that could be made, the precipitation on each hypothetical date through January 25 was increased 10% over what was measured in the prototype January 1937 storm, and the precipitation for hypothetical dates February 15-20 was transposed slightly from where the precipitation was measured in the prototype February 1938 storm to obtain a better fit to the Arkansas and White Basins. This transposition consisted of moving the observed isohyets 90 miles north and rotating 20° in a clockwise direction. The latter intensification adjustment has been reflected in the weather maps of figures 8C-9A by moving the fronts and isobars in the area of heaviest precipitation the indicated 90 miles and with a slight rotation. On the scale of this map, ninety miles is a small distance. The first intensification adjustment would correspond to a slightly increased moist inflow. No attempt has been made to reflect this in the charts. With respect to the 10% intensification adjustment in the January 1937 storm, it should be noted that the same result could have been obtained in a different way. Transposing the isohyets about 240 miles upstream along the Ohio Valley without increasing the rainfall depths would have resulted in a more critical placement with respect to the Basin and would augment the computed flow of the Ohio River at Cairo, Ill., by very nearly the same amount as the 10% increase in the place employed in this hypothetical sequence.

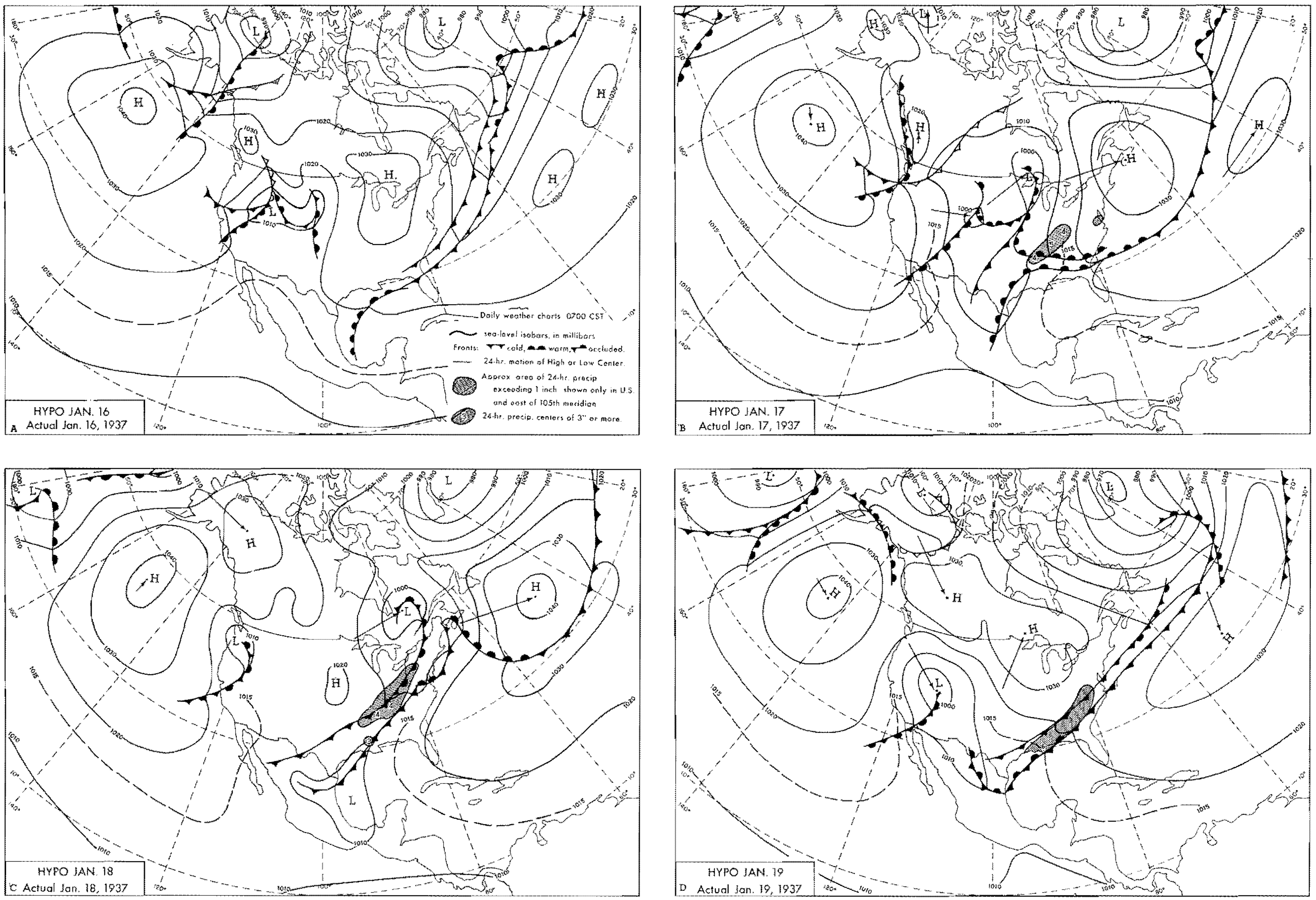


Figure 1. WINTER SEQUENCE (Hypo Flood No. 58A)

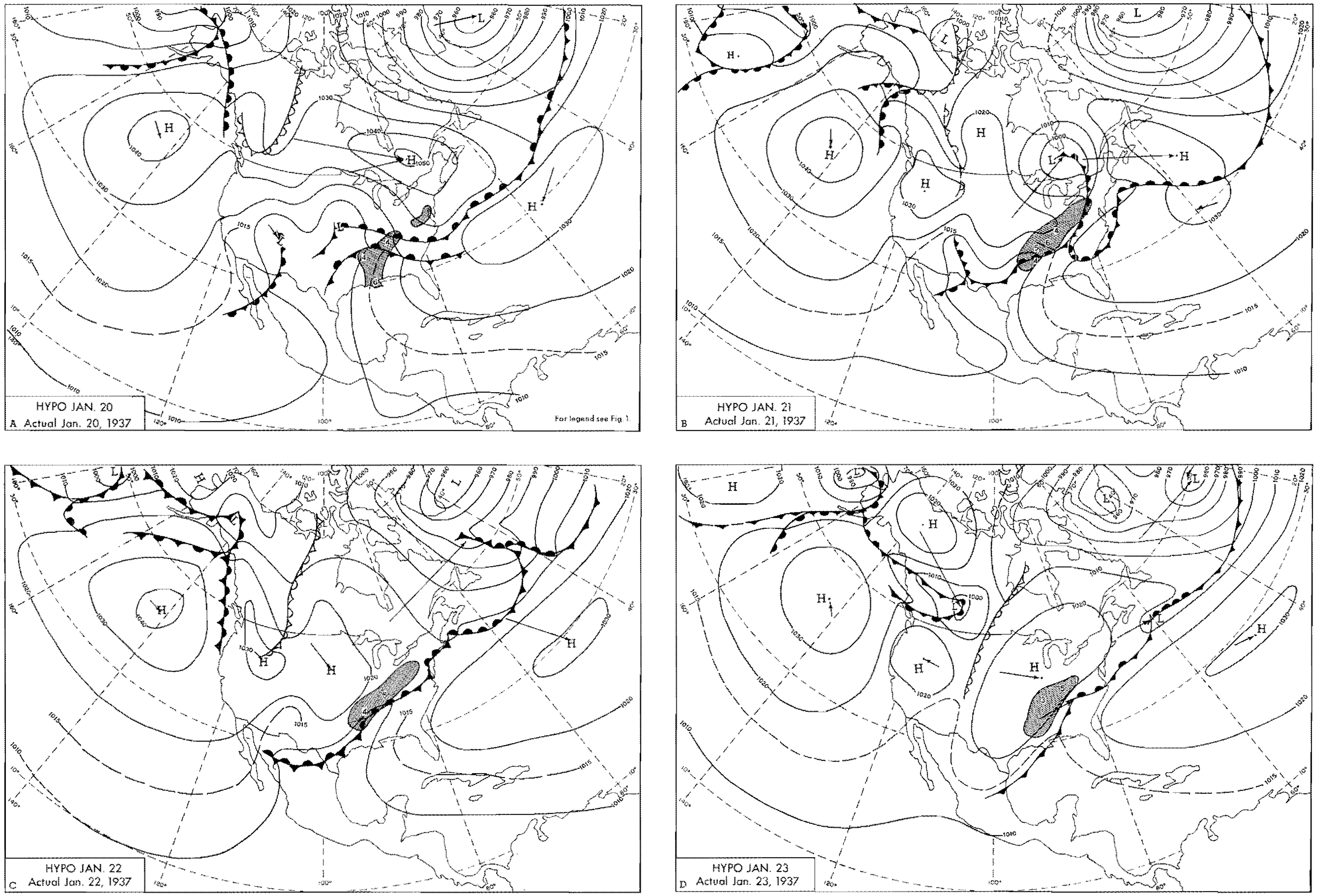


Figure 2. WINTER SEQUENCE (Hypo Flood No. 58A)

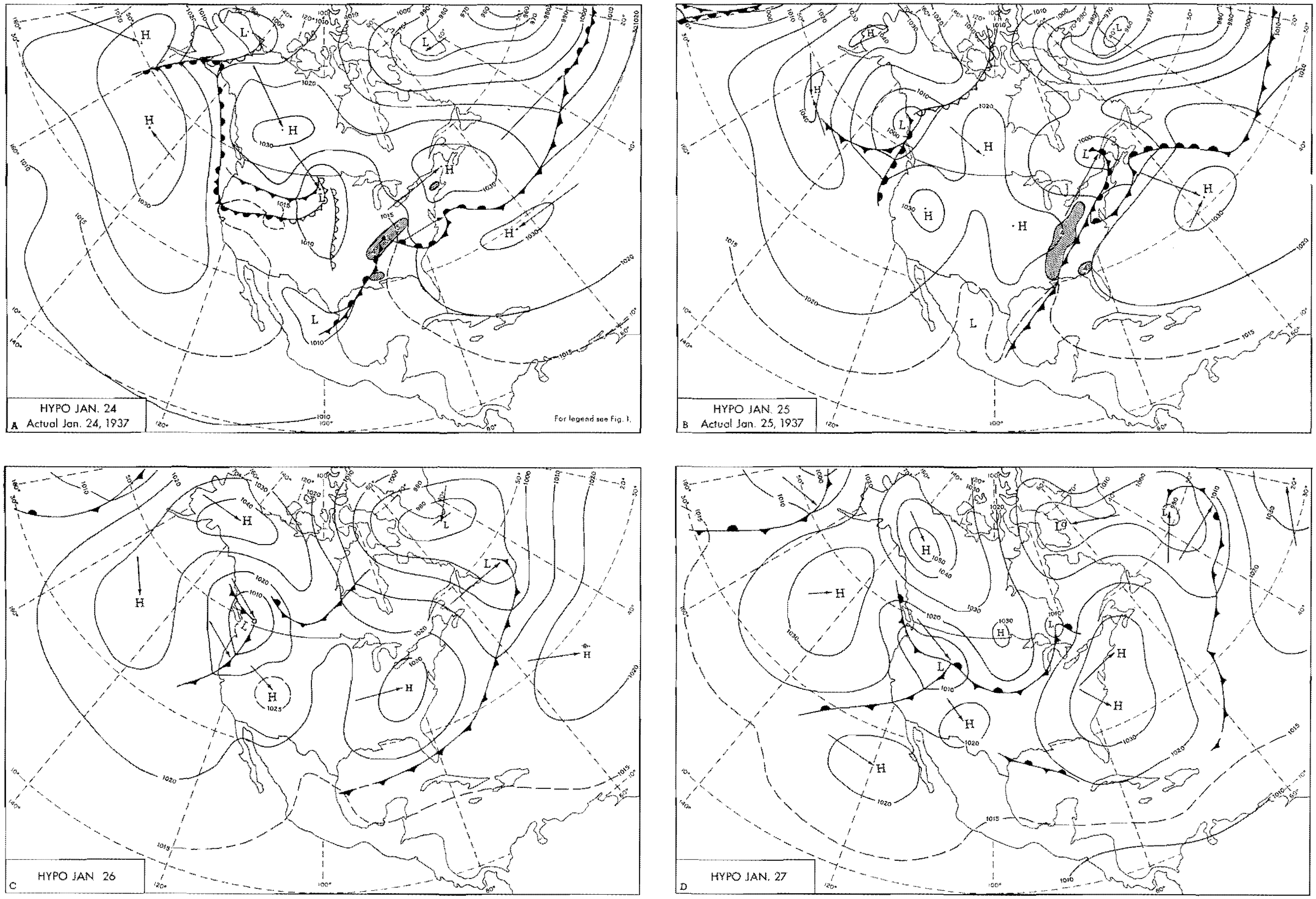


Figure 3. WINTER SEQUENCE (Hypo Flood No. 58A)

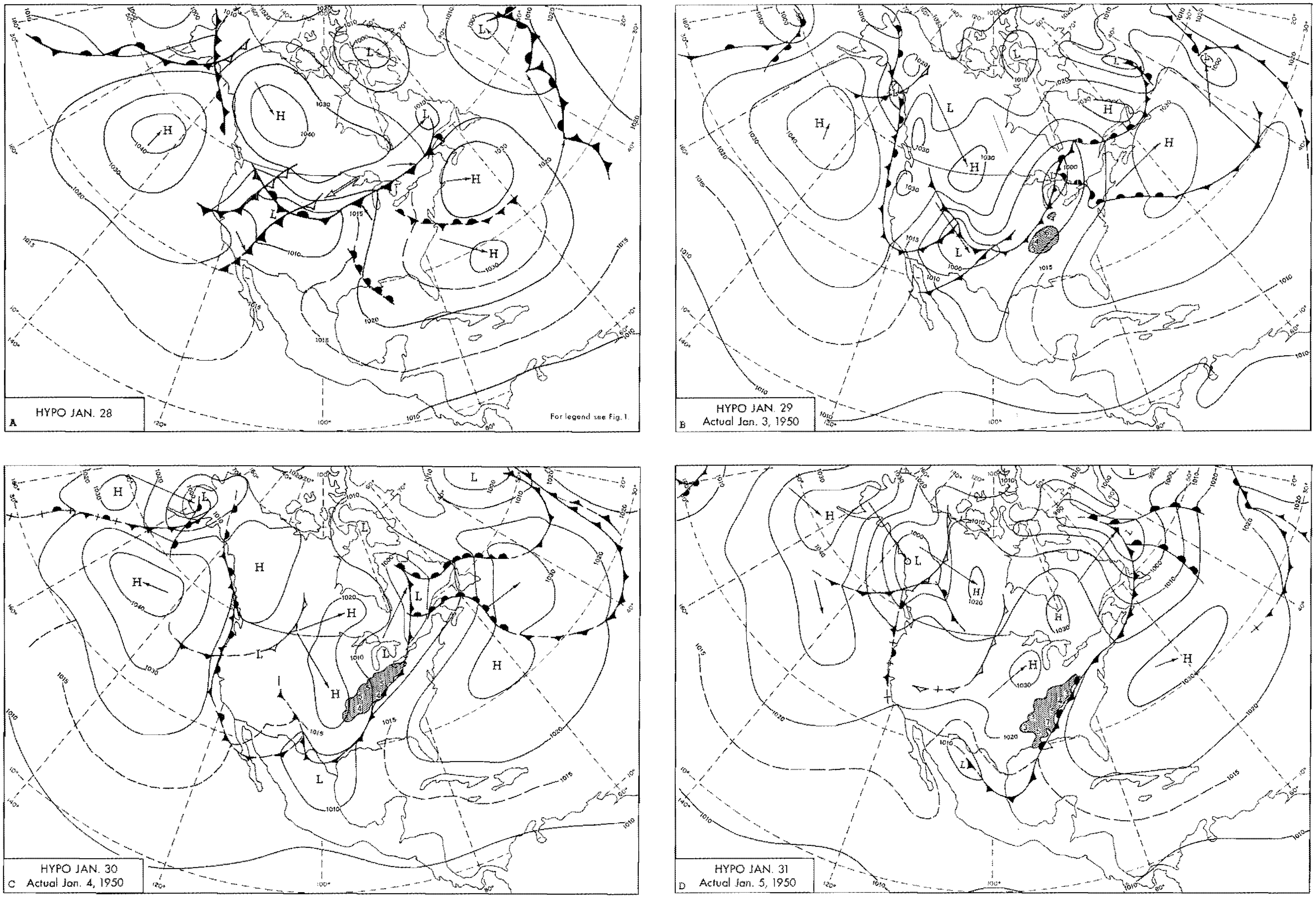


Figure 4. WINTER SEQUENCE (Hypo Flood No. 58A)

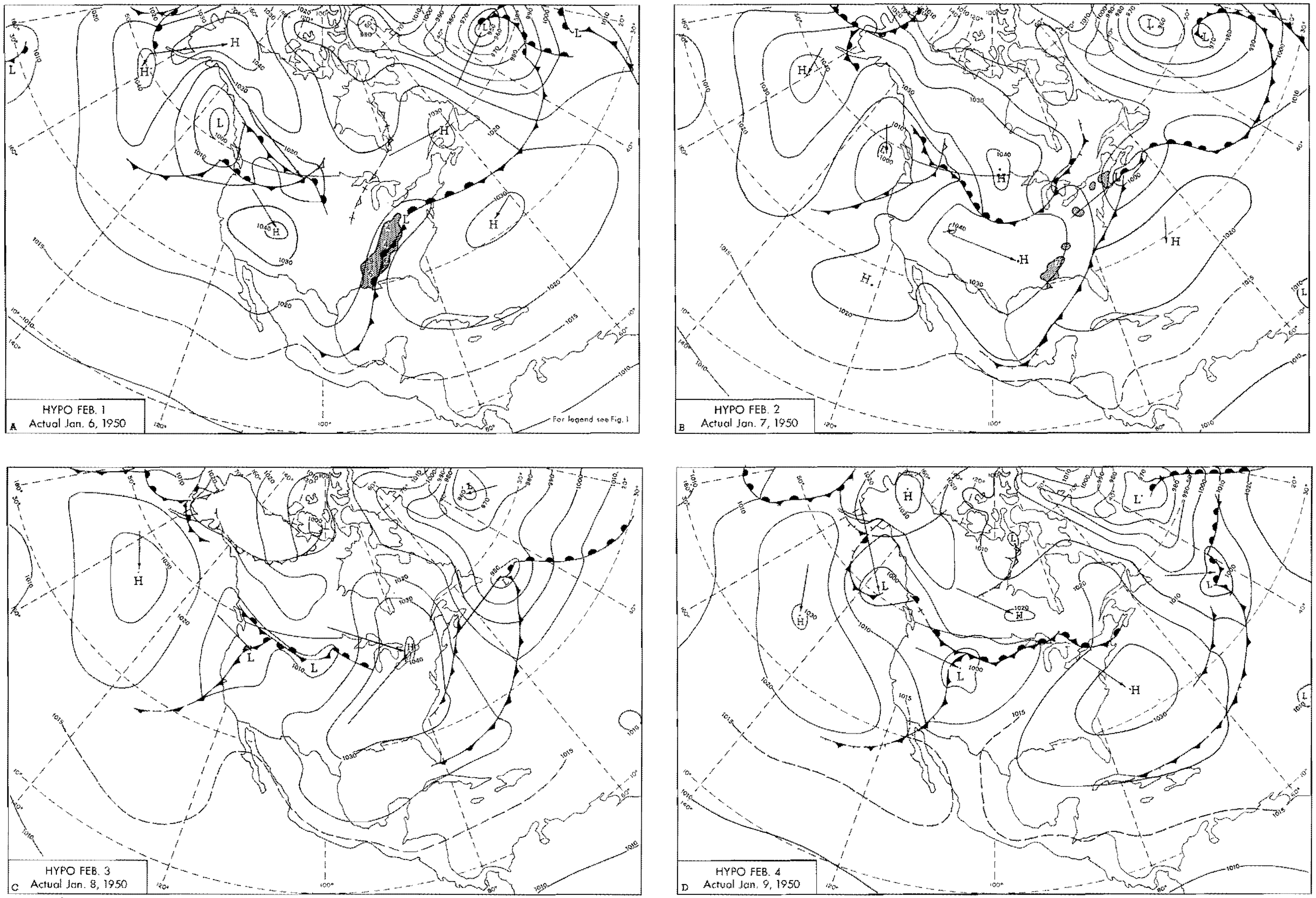


Figure 5. WINTER SEQUENCE (Hypo Flood No. 58A)

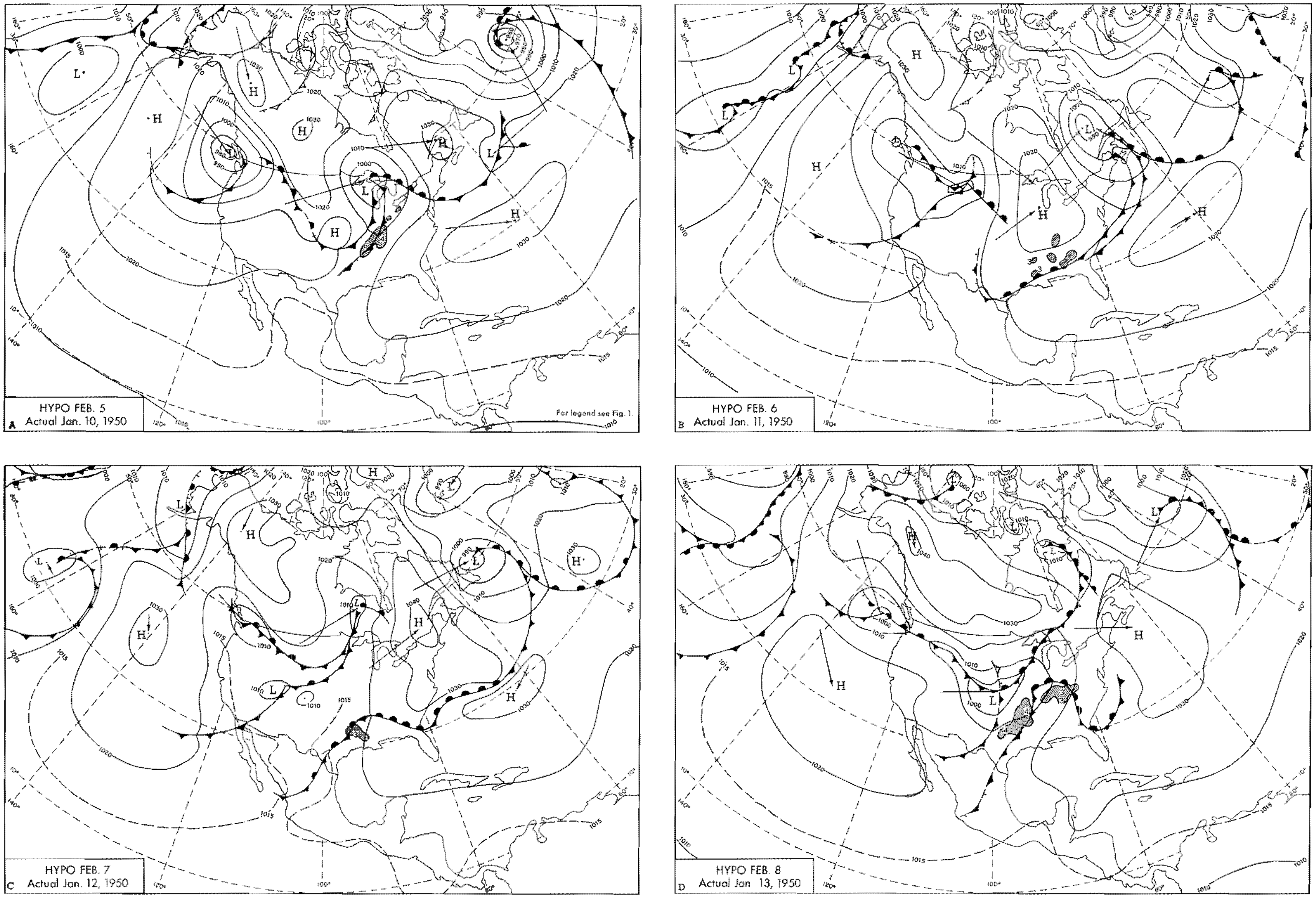


Figure 6. WINTER SEQUENCE (Hypo Flood No. 58A)

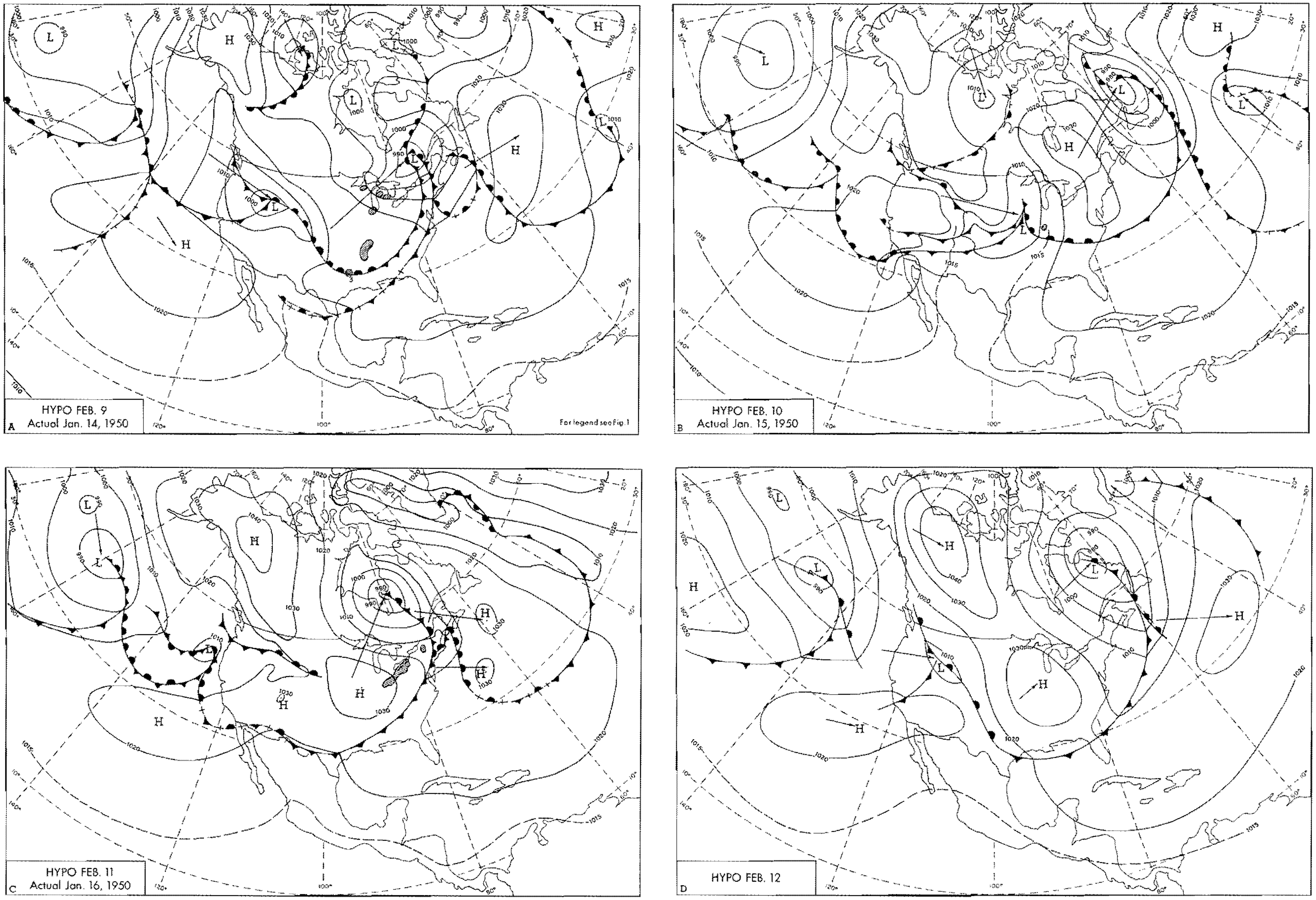


Figure 7. WINTER SEQUENCE (Hypo Flood No. 58A)

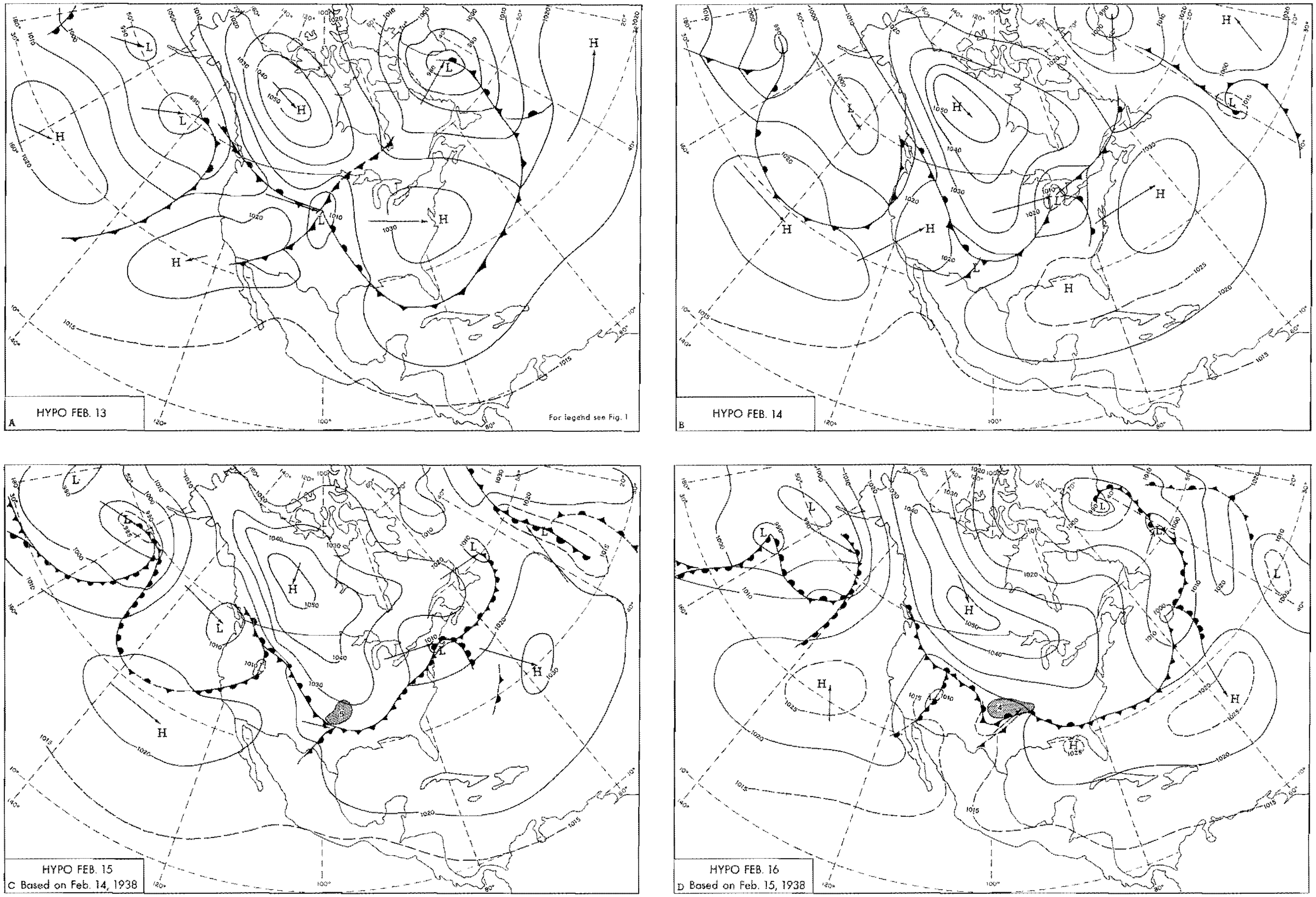


Figure 8. WINTER SEQUENCE (Hypo Flood No. 58A)

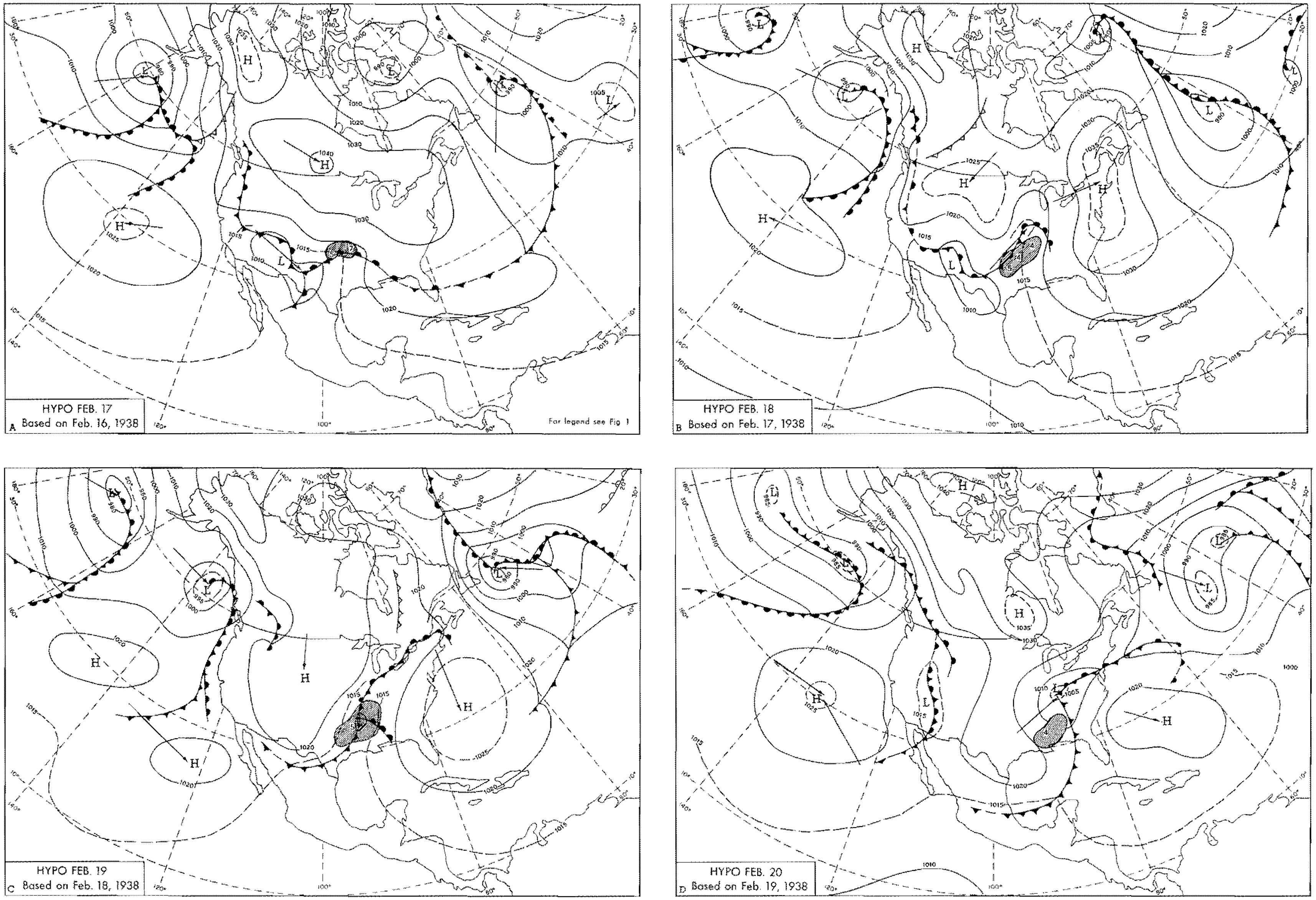


Figure 9. WINTER SEQUENCE (Hypo Flood No. 58A)

V. HYPOTHETICAL EARLY SPRING FLOOD*

Tributary variations and dominant weather patterns

In the spring, the probability of rainfall of flood-producing proportions over those tributaries of the Lower Mississippi that flow into the main stream from the west increases rapidly. This is associated with the atmospheric circulations that usually prevail. As pointed out in section IV, moisture-bearing winds from across the Gulf of Mexico during winter generally acquire a southwest direction as they blow into the United States and only rarely extend with the persistence necessary for a flood into, for example, central Oklahoma. During the spring, circulations in which the winds from the Gulf of Mexico blow directly from the south are more frequent and more persistent. This admits moisture into Oklahoma, Kansas, Nebraska, Missouri, and Iowa. There is much less seasonal variation of flood probabilities or of storm types over the eastern part of the Mississippi Basin.

A threat for a major flood on the Lower Mississippi in the spring, then, is for a winter-type storm over the Ohio, Cumberland, and Tennessee Basins to be followed in a few days by a change in circulation regime and a spring-type storm over the Red, Arkansas, and White Basins. The weather situation for the Ohio-Cumberland-Tennessee flood would most likely be that common type, quasi-stationary fronts persisting or repeatedly aligning themselves over the Basin, interspersed with passages of occluding Lows.

The principal meteorological ingredients of the second part of the flood would be a deep persistent Low in Texas, or nearby, and a High with its center somewhere near the East Coast of the United States rather than in the more common position in the vicinity of Bermuda. The deep Low in this instance would be a closed counterclockwise circulation extending many thousands of feet upward into the atmosphere. This is not the type of Texas Low which forms as an open wave on a southwest-northeast quasi-stationary front in Texas or the western Gulf of Mexico with a closed circulation extending only a few thousand feet into the atmosphere and which moves out rapidly to the northeast or east-northeast. The synoptic situation for the flood over the Arkansas River and adjacent basins would be what meteorologists call "low index" over the United States, that is, less than normal westerly component of the winds, Lows at abnormally southerly latitudes. Highs at fairly high latitudes, and slow movement of all systems with greater than usual south to north and north to south circulation.

Prototype hypothetical flood sequence

The hypothetical flood described in the previous paragraphs can be approximated by combining the March 1913 Ohio flood with the rains of April 12-16, 1927, over the lower central Mississippi Basin. Once-a-day weather maps for such a sequence are shown in figures 10-12. This series shows the

---

*Hypothetical Flood No. 56 in Corps of Engineers and Weather Bureau Interim Reports.

real weather maps associated with the March 1913 storm and the April 1927 storm with two hypothetical maps making the transition between them. Approximate areas of 24-hour precipitation in excess of one inch are shaded on the maps. These areas were determined in the manner described on page

The hypothetical sequence begins with the Pacific High in a favored position for precipitation in the central United States and the Atlantic High moving into this position as it was in March 1913 (figure 10A). Isobars, which approximate low-level trajectories, curve from the Caribbean Sea into the Mississippi Basin, indicating the flow of very moist tropical air into the Basin. The first rains over the Ohio Basin are in this strong moist current, in part north of a warm front (figure 10A). A Low intensifying over the Rockies quickly moves over the Great Lakes and into eastern Canada. Additional rains fall near the principal cold front which advances in connection with the Low and continues in the general frontal zone as the front becomes quasi-stationary over the Ohio Basin (figures 10C-D). The final rains over the Ohio are associated with the passage of a final deepening occluding Low which sweeps the front on out to sea (figure 11A). All of the foregoing is very typical for heavy Ohio Valley rains. The March 1913 storm is discussed in greater detail on pages 27-29 of Hydrometeorological Report No. 34.

Transition between storms

In figure 11B the hypothetical transition to the second storm begins. One essential factor is the development of an Arizona-New Mexico upper-level Low soon after the trough of low pressure with the first storm has moved off the East Coast of the United States into the Atlantic. The inception of this Low is depicted in figure 11B and becomes more fully developed in figure 11C. The Low in Arizona and Utah in figure 11B is interpreted as forming on the front moving in from the northeastern Pacific, shown on the preceding chart, figure 11A. (Some meteorologists reviewing this report have commented that the evolution of the Low from figure 11B and 11C is quite rapid in comparison with common experience. A more common method for evolution of the New Mexico-Arizona upper-level Low, but which would not fit in with the exact March 1913 weather map of figure 11A, is for a deeper trough along the Pacific Coast, most intense between Los Angeles and San Francisco, to move into the western United States, stall briefly, and for a surface Low to regenerate in the Arizona-New Mexico region.)

Other features of the transition and the final storm are that the polar High at the end of the first storm (figure 11B, eastern United States) moves to the Atlantic Coast and not strongly into the Gulf of Mexico. The southerly flow in the western Gulf is only temporarily weakened and at no time is fully displaced by northwest winds. This High stalls briefly on the Atlantic Coast (figure 11D) rather than moving farther into the Atlantic Ocean. Meanwhile, the Canadian High moves down into the eastern United States (figures 12B-C). This combination of Highs blocks the Lows in the Texas area and deflects the moist flow from across the Gulf to the Arkansas and adjacent basins (figures 12A, B, C). The eastern Pacific High maintains its strength and position, being reinforced by a new High cell from the west (figure 12C). The second storm in this hypothetical sequence, that of April 1927, is discussed in more detail in Hydrometeorological Report No. 34, pages 33-34.

Time interval between storms

Study of many Mississippi Valley rainstorms and their antecedents and sequels shows that in most parts of the Basin heavy precipitation can readily begin again in the same area and from approximately the same synoptic situation three days (72-hours) after the ending of a preceding storm in the same place. When the second storm is west of the first storm the time interval may be shortened. This would permit a heavy Arkansas rain in a new storm to follow rain in the Appalachians in two days. In the sequence depicted the time between rains in those regions (figures 11A and 11D) is placed at 3 days in view of the change in circulation types.

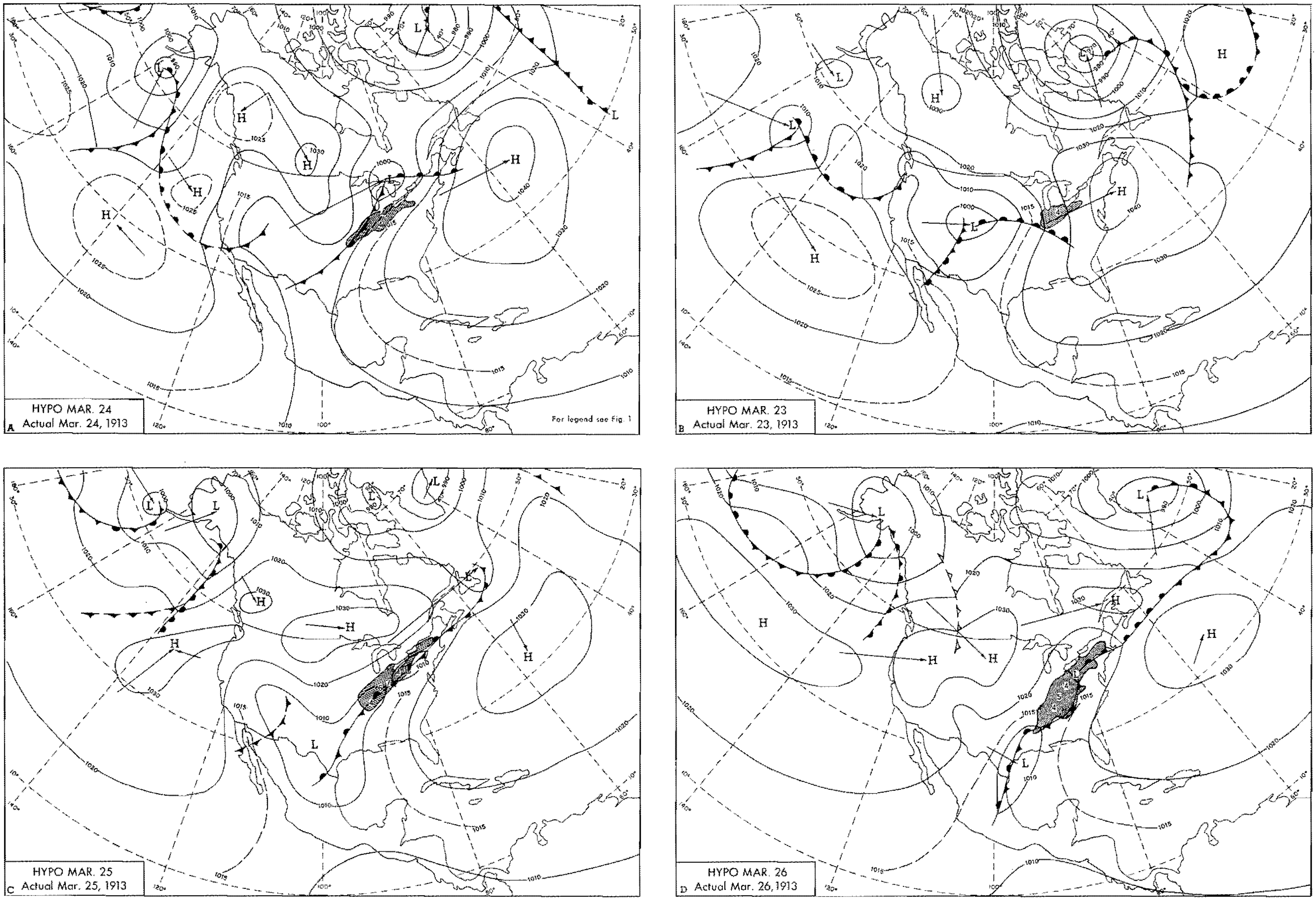


Figure 10. EARLY SPRING SEQUENCE (Hypo Flood No. 56)

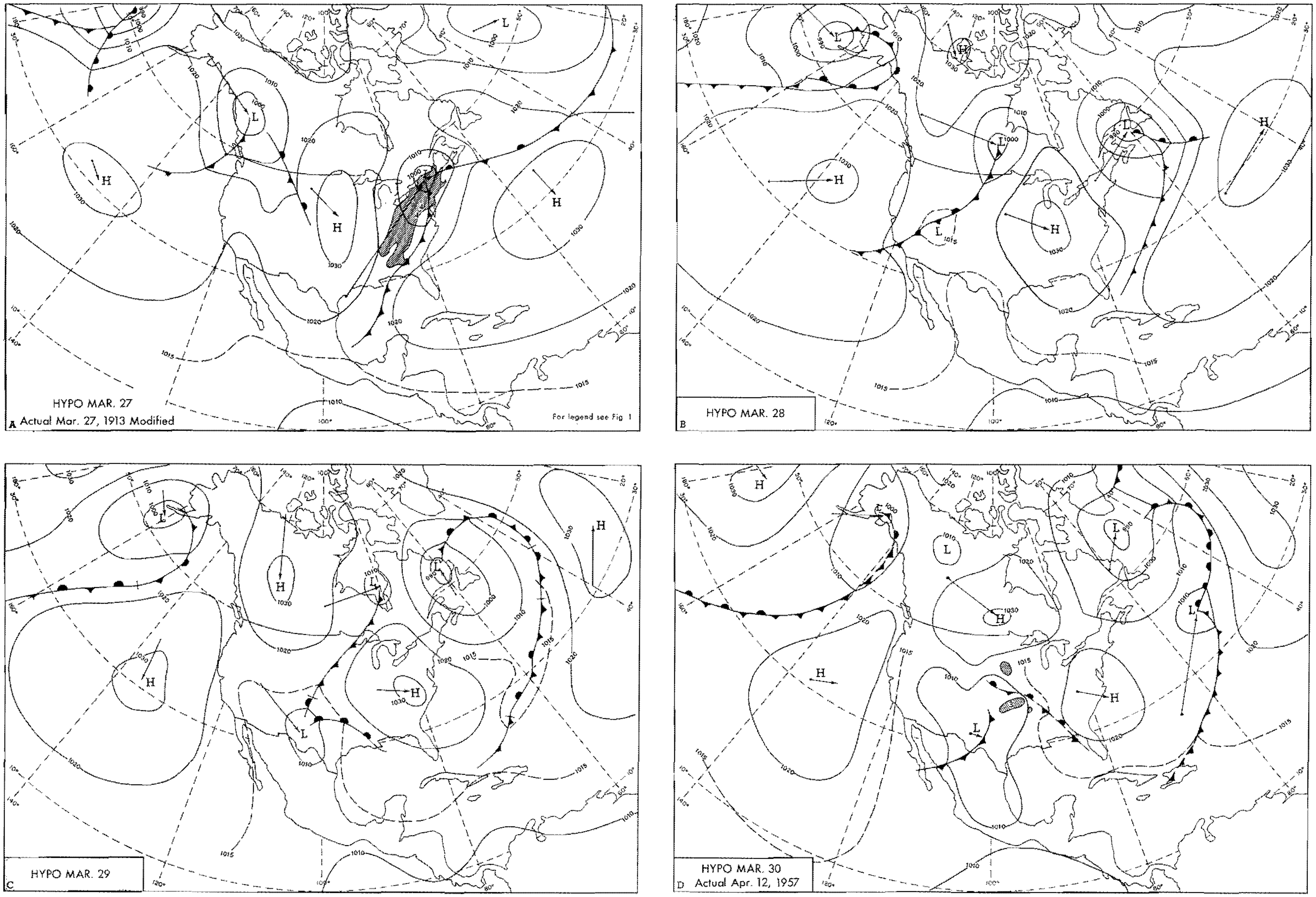


Figure 11. EARLY SPRING SEQUENCE (Hypo Flood No. 56)

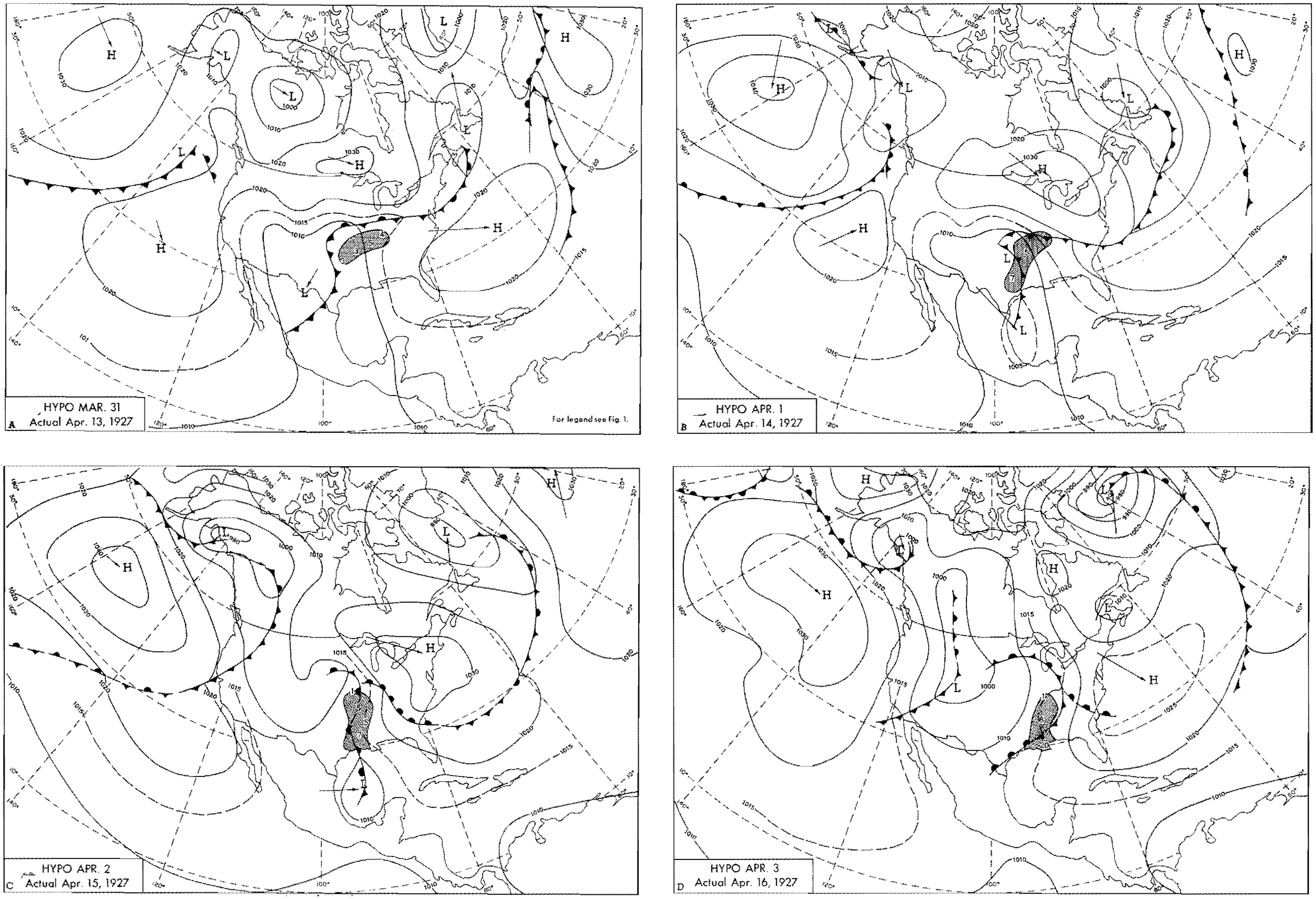


Figure 12. EARLY SPRING SEQUENCE (Hypo Flood No. 56)

VI. HYPOTHETICAL LATE SPRING FLOOD*

Selection of prototype storms

The most disastrous flood on record over the Lower Mississippi Basin was that of April 1927. Another phenomenal late spring storm over eastern Oklahoma, northern Arkansas, Missouri, and extending into Kansas and Illinois was from May 7 through May 20, 1943. A late spring flood threat to the Lower Mississippi is for storms similar to these historical storms to follow each other in a relatively short time. A model hypothetical flood series is formed by taking the heaviest burst of rain in the April 1927 storm, from April 12-16, and following it in turn by the rains of May 15-20, 1943, and May 7-12, 1943, respectively.

Seasonal progression

The seasonal progression of the major tributary flood threat in the Mississippi Basin from the eastern to the southwestern, and finally to more northerly, tributaries has been pointed out in earlier sections. The late spring hypothetical flood sequence described in this section is in harmony with this progression as compared with the early spring and winter hypothetical winter floods. The early summer hypothetical flood as described in the final section incorporates a sizable contribution of flood waters from the lower Missouri River. The Missouri makes no important contribution in any of the earlier floods and only a relatively small contribution in the flood sequences described in this section.

Storm types and transitions between storms

The weather maps for this hypothetical sequence are shown in figures 13 through 18. The features common to the three principal rain periods (figures 13A-14A, 14D-15D, and 17A-18A) are probably common to all major rainstorms over large areas in the region concerned. These include a well-developed High near the Atlantic Coast protruding into the eastern Gulf of Mexico, a well-developed closed cyclonic circulation in the southwestern United States at upper levels with the associated surface Low, isobars so aligned as to produce an airflow in the lower levels from the Caribbean Sea across the Gulf of Mexico into the southern United States, and a well-developed eastern Pacific High near the United States Coast.** The southerly

---

*Hypothetical Flood No. 63 in Corps of Engineers and Weather Bureau Interim Reports.

**The last feature, the Pacific High, is presumed in the May 1943 storms and in their counterparts in the hypothetical sequence. Meteorological data from the Pacific Ocean were not readily available in 1943 because of the war, and the map series being reconstructed by the Weather Bureau through the war years on a historical basis from many sources of information had not yet covered May 1943 at the time of preparation of this report.

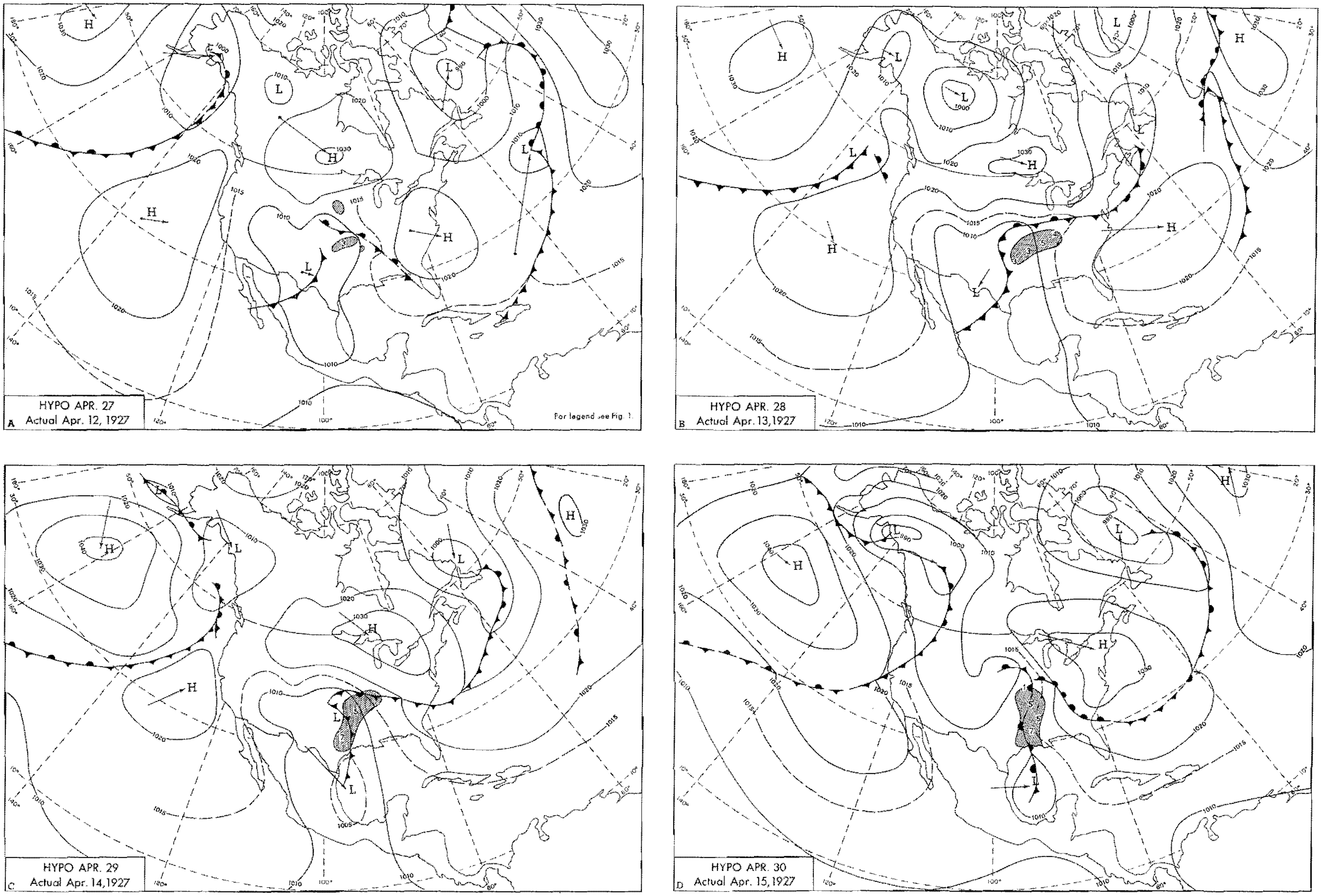
inflow from across the Gulf of Mexico does not have to be quite so intense as in winter storms since the warmer air can carry more moisture per unit volume.

Some differences among the three principal precipitation regimes in the sequence are also evident. There was more of a blocking High in the northeastern United States during the first rainstorm than during the others. See, for example, figures 13B and C. The heaviest precipitation of this part of the sequence fell in a north-south frontal zone where there was strong convergence in the lower levels because of the particular configuration of curvature and shear in the windflow (figures 13C-14A). The later rain maps are more similar in appearance to typical winter heavy precipitation maps, with the principal isohyets stretched along a west-southwest - east-northeast quasi-stationary front. See, for example, figures 15B, 15C, 17C, and 17D.

The trend toward the summer type of regime in this sequence, as compared with the early spring and winter sequences, can be noted in the manner in which the heaviest rainbursts were terminated. During the colder season, a heavy rainburst or a series of heavy rainbursts is most frequently terminated by the formation of a deep, intense occluded cyclone, or Low, and its associated strong wind system which sweeps cold air across the rain area, resulting in an ensuing period of fair weather. In the late spring sequence described here, the termination of the rain is associated with the eastward drift of the various fronts and the dying-out of the principal convergence zones in the more typical summer fashion. No spectacular occluding Lows are formed. The re-establishment of a heavy rain regime, figures 14B-D and 16B-17A, is similar to the winter counterparts, but again with less marked isobars and configurations. Each of the two re-establishments is accomplished by the eastward drift of a moderate High which reinforces the Atlantic High and the intrusion into the western United States of a trough and Lows from the Pacific which undergo intensification east of the Rockies.

Transposition

The last part of the hypothetical flood sequence is based on a slight transposition of the actual storm of May 7-12, 1943. This is for a better fit of the isohyets to the Arkansas, White, and St. Francis Basins. The specific transition is to rotate the total storm isohyetal pattern 21° clockwise about the precipitation center at Warner, Okla., and move this rotated pattern 80 miles to the northwest. The combined rotation and transposition moves the bulk of the precipitation less than 80 miles. The isobars, fronts, and isohyets of figures 17 and 18 have been adjusted from their real counterparts to take this transposition into account. The portion of the rainfall over drainage above Cairo, Ill., as represented by the transposed isohyetal maps, was deleted from hydrologic computations. Rain in the earlier two storms in the sequence was used as it fell for hydrologic computations.



HYPO APR. 27
Actual Apr. 12, 1927

HYPO APR. 28
Actual Apr. 13, 1927

HYPO APR. 29
Actual Apr. 14, 1927

HYPO APR. 30
Actual Apr. 15, 1927

Figure 13. LATE SPRING SEQUENCE (Hypo Flood No. 63)

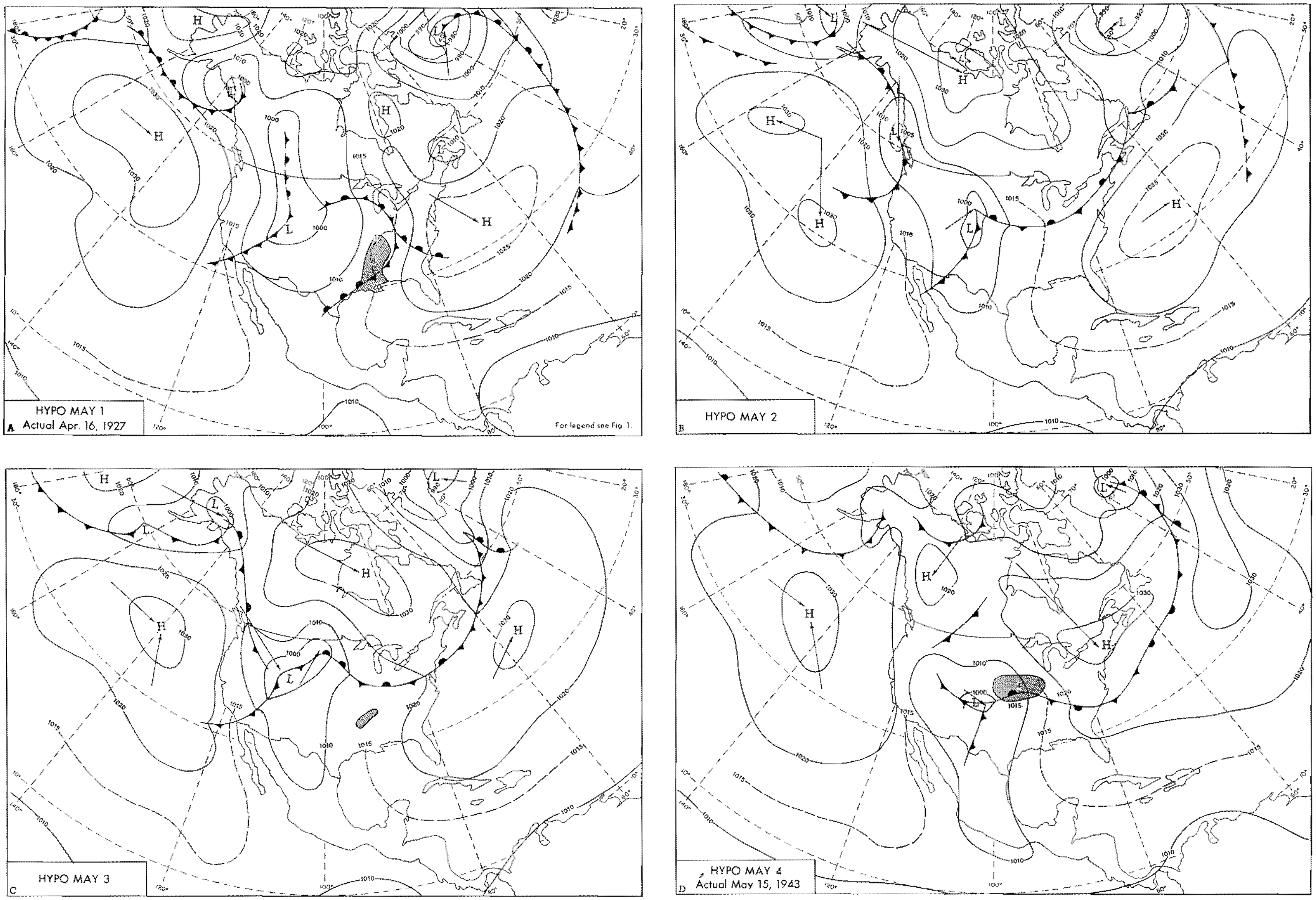


Figure 14. LATE SPRING SEQUENCE (Hypo Flood No. 63)

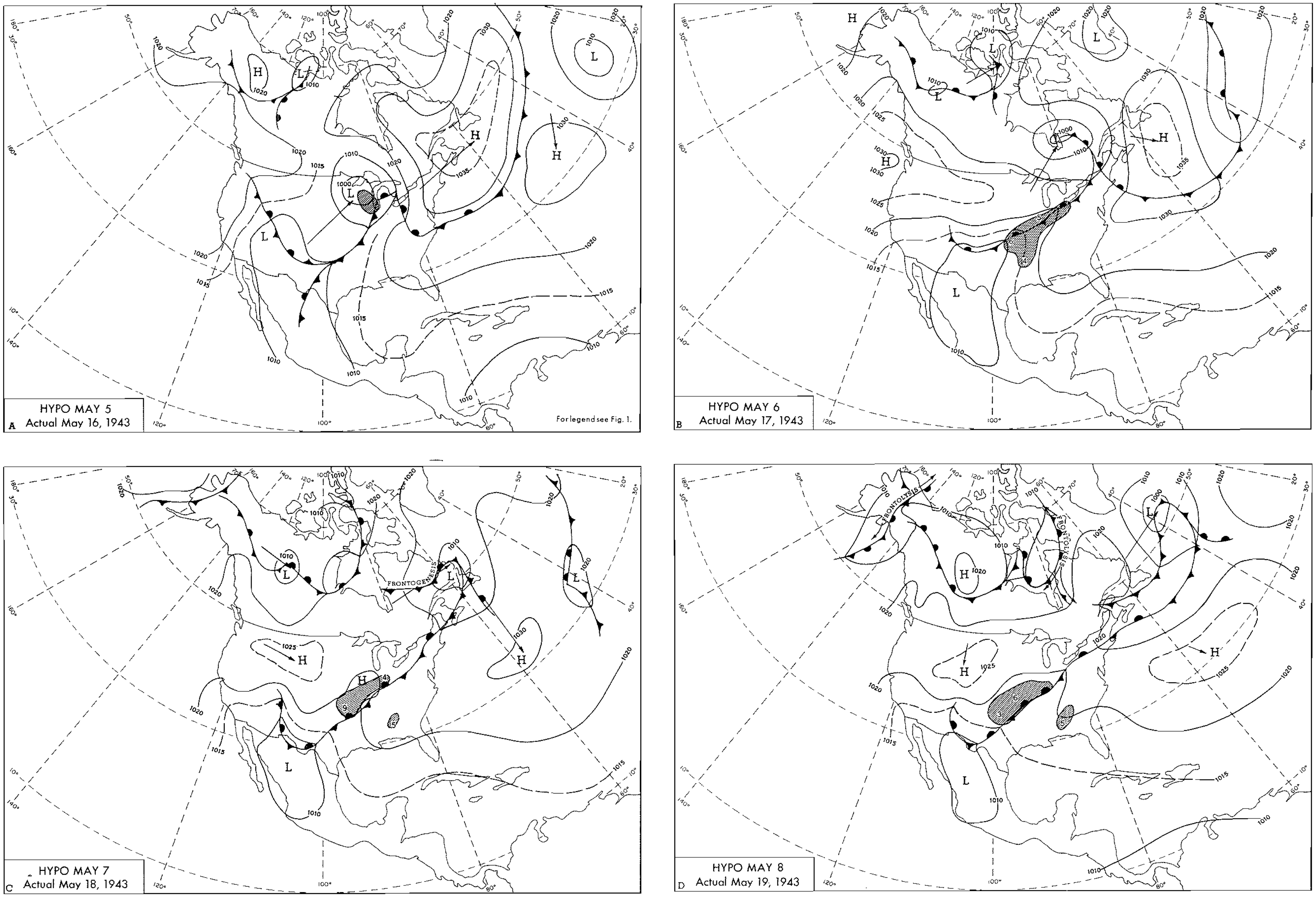


Figure 15. LATE SPRING SEQUENCE (Hypo Flood No. 63)

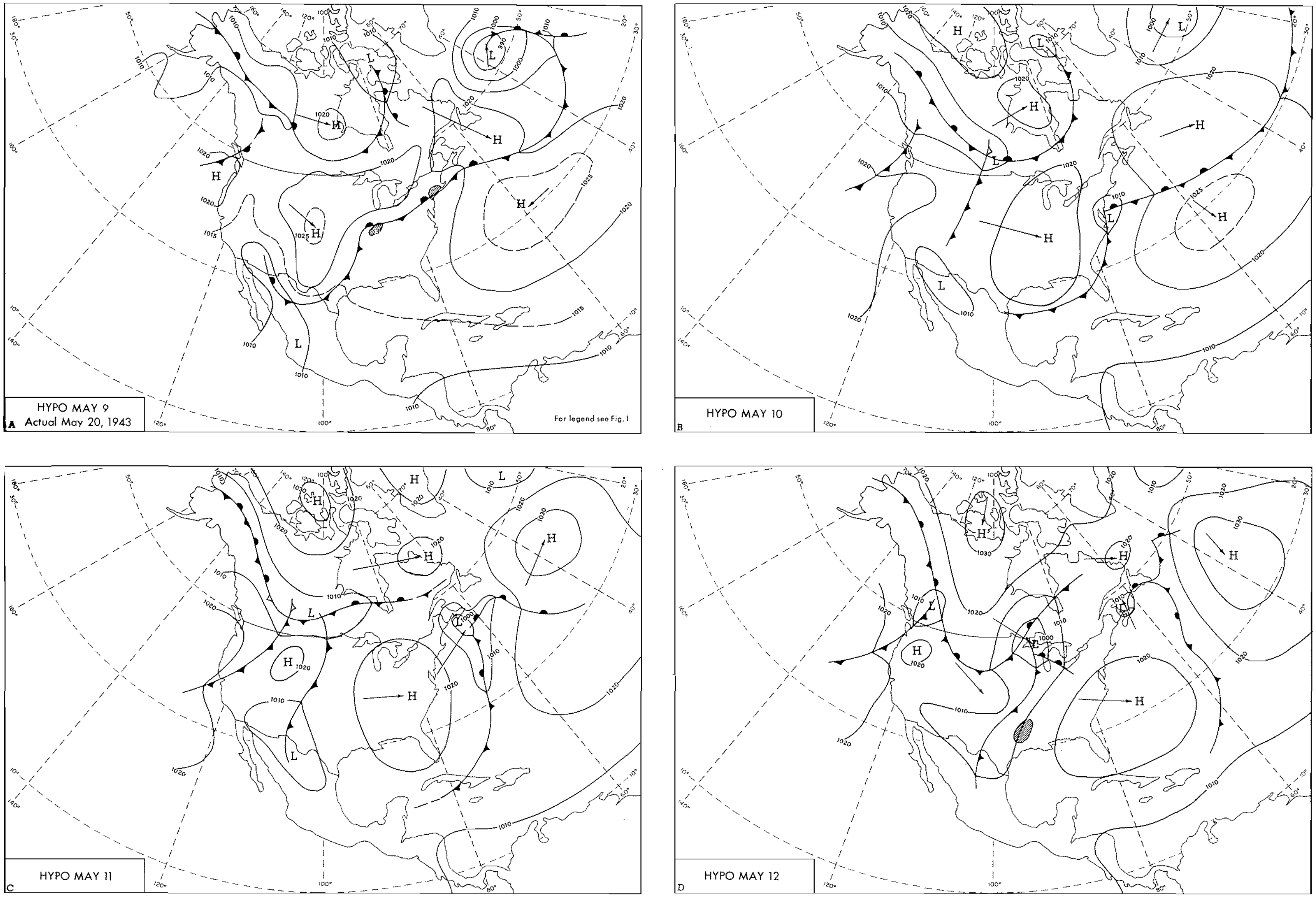
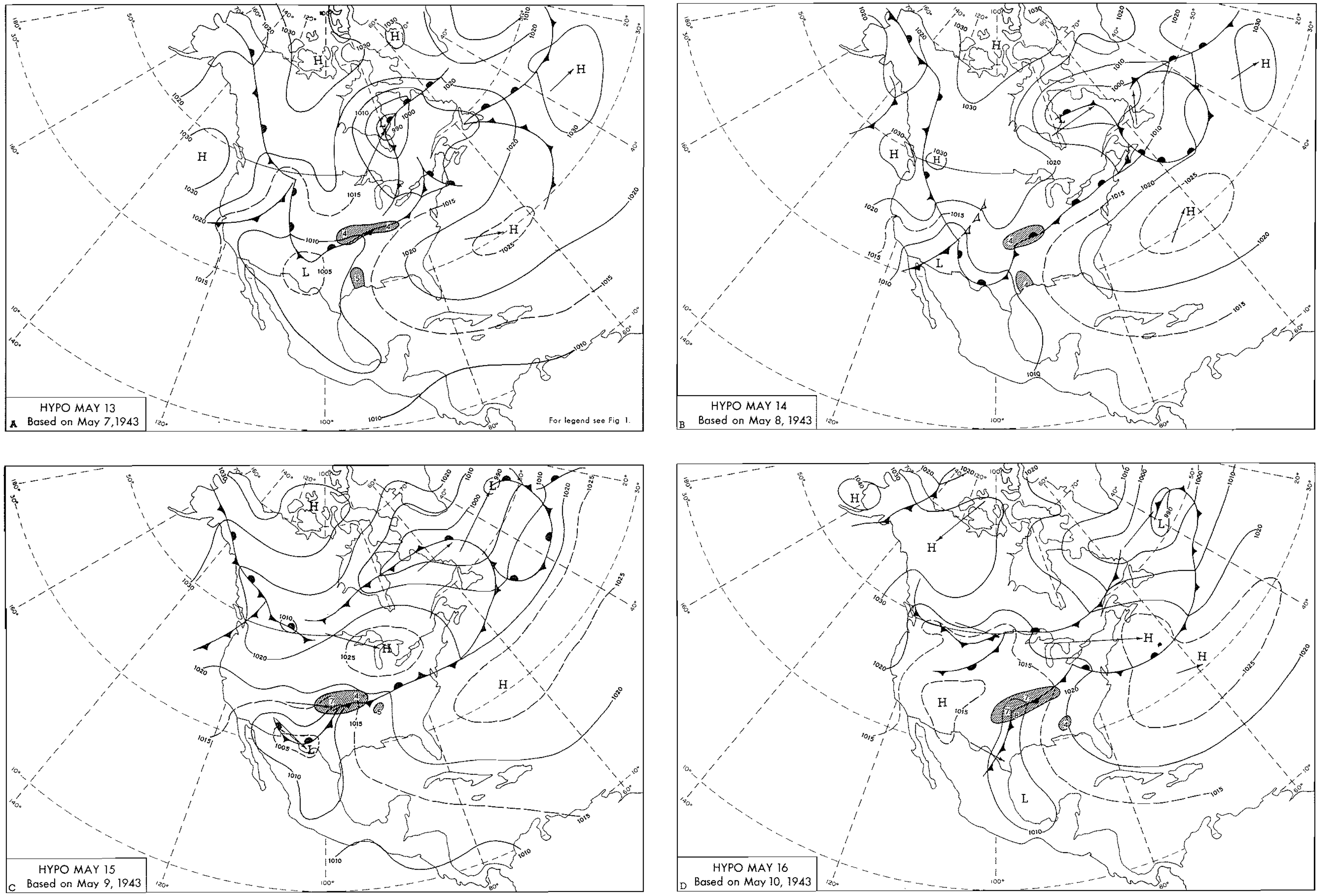


Figure 16. LATE SPRING SEQUENCE (Hypo Flood No. 63)



A HYPO MAY 13 Based on May 7,1943

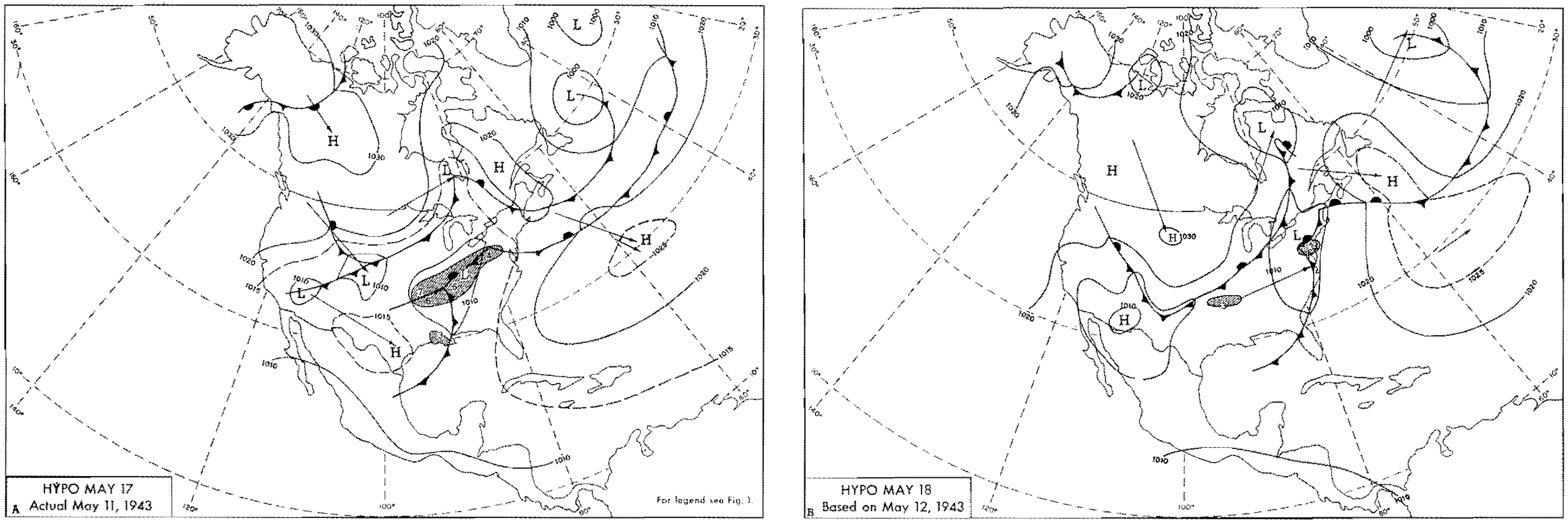
For legend see Fig 1.

B HYPO MAY 14 Based on May 8, 1943

C HYPO MAY 15 Based on May 9, 1943

D HYPO MAY 16 Based on May 10, 1943

Figure 17. LATE SPRING SEQUENCE (Hypo Flood No. 63)



A HYPO MAY 17 Actual May 11, 1943

For legend see Fig. 1.

B HYPO MAY 18 Based on May 12, 1943

Figure 18. LATE SPRING SEQUENCE (Hypo Flood No. 63)

VII. HYPOTHETICAL EARLY SUMMER FLOOD*

Greatest summer floods of record

By early summer the storm potential over the Missouri and Upper Mississippi Rivers is very much greater than in winter and early spring. A major flood threat to the Lower Mississippi at this season is a flood such as the record flood of 1844, coupled with a moderate flood on the lower Ohio. The peak of the rain in the 1844 flood was on June 12-13 over northern Missouri, Kansas, Nebraska, and Iowa.** Hydrologic data from the 1844 flood are insufficient for that historical event to be a practical quantitative prototype for a hypothetical flood sequence.

Substitute for greatest flood of record in sequence

To circumvent the paucity of data in the 1844 flood, two great modern rainstorms, which were synoptically similar to the 1844 storm at its height, were substituted in developing a hypothetical early summer flood sequence. These are the same two storms used at the end of the late spring sequence, those of May 7-10, 1943, and May 15-20, 1943. The first is transposed in place and season, toward the place and time of the 1844 flood rain. The second is used in actual location.

Transposition of May 7-10, 1943 storm

The storm of May 7-10, 1943, was postulated to occur in the hypothetical sequence 25 days later in the season than its actual date of occurrence and about 425 miles farther north. Specifically, the isohyetal pattern was rotated 14-1/2° clockwise about the Warner, Okla., center and was moved so that this center lay 120 miles west of Des Moines, Iowa. This transition was tested meteorologically as described below.

First, the general synoptic type of the May 7-10, 1943 storm in its simplest aspects -- quasi-stationary front with the isobars at sea level in a pattern of inverted "V's" at the front -- can occur almost anywhere in the United States where orography is not significant, as can be confirmed by reviewing series of weather maps. However, this fact does not remove the need to investigate whether the intensity and pattern of the circulation observed in the actual storm would produce comparable rainfall if transposed northward. Would the transposed circulation direct an adequate flow from the Gulf, and would the Rocky Mountains interfere with the necessary Low in the Southwest?

---

*Hypothetical Flood No. 52A in Corps of Engineers and Weather Bureau Interim Reports.

**Surface weather maps for 1844 storm are shown in Weather Bureau Technical Paper No. 17, "Kansas-Missouri Floods of June-July 1951", page 104, July 1952.

To transpose the circulation in a manner that was both reasonable and objective, the following procedure was followed: Departures from the normal May sea-level pressures and 700-mb heights (about 10,000 feet) were computed for the entire United States for May 10, 1943, the day of the most intense rain. The fields of departure from normal were then shifted the distance and in the direction of the transposition. The transposed departures from normal were then added algebraically to normal June pressure and height, thus obtaining transposed charts of pressure and height that are consistent with the change in place and season and with usual seasonal changes in atmospheric flow. Figure 19 shows the observed surface chart for 0030 CST May 10, and the 700-mb chart for 2230 CST, May 9, as well as the transposed charts. The latter are reasonable in appearance, show a strong flow from the Gulf toward the proposed rain area, and depict the Low to the southwest of the rain at a place where it is climatologically reasonable for such a Low to occur and where the Rockies will not interfere with the associated low-level flow.

As a final check on the transposed charts, mean temperatures between Sea level and 700 mb (the mean temperature is fixed if the sea-level pressure and the 700-mb height are given) were computed and found to be consistent with known temperature distributions for major rainstorms and within the observed range of temperatures for the season. The reasonableness of the transposition for this day having been confirmed, maps for the other days of this prototype storm were assumed to be similarly transposable and were subjectively re-sketched in their transposed positions.

Reduction of May 7-10, 1943 storm for transposition

In strong flows of air from the south, as on the transposed map of May 10, 1943, there is nearly always a decrease in the dewpoint within the current with increased distance from the coast. It is established hydrometeorological procedure in northward transposition of storms to reduce the precipitation volume to allow for the lessened availability of moisture. On the other hand, a storm like this one, in which the intensity of the temperature gradients both immediately across the front and on a larger scale are related to the precipitation, may be expected to be more intense in a northward location for a given moisture volume reaching the rain area. Various techniques and assumptions for estimating appropriate reduction factors yield results ranging from 0.70 to 0.95. In view of the short climatological record on which the basic data are based and the uncertainty of some of the assumptions, use of a reduction factor as low as 0.70 would appear risky. Adjustment factors from about 0.80 to about 0.95 are meteorologically reasonable, with selection of the exact value to be used depending upon the degree of rism to be accepted in design. The more conservative figure of 0.95 was used in the hydrologic computation of the flood sequence described in this section.

Occurrence of May 15-20, 1943 storm later in season

The prototype storm of May 15-20, 1943, was used in its exact place of occurrence but 25 days later in season in the hypothetical flood series. The general synoptic type -- occluding cyclone followed by quasi-stationary front with inverted-V trough -- can occur at any season. Precipitation experience, however, indicates a general tendency for large-area storms to be more intense in the Oklahoma-Missouri-Kansas region at the date of occurrence, around May 15-20, than at the transposed date, 25 days later. Therefore, the reasonableness of this transposition in time, at the full intensity of the storm, was particularly subjected to scrutiny.

A fundamental characteristic of the storm was the strong temperature gradient from the warm to the cold air. The seasonal progression of this temperature gradient was investigated. The intensity of all cold fronts passing through Oklahoma, Arkansas, Missouri, and Illinois during the years 1899-1939, during May and June, was measured with an index value and plotted on a seasonal chart, figure 20. The index of intensity was the maximum difference in temperature between surface stations located 350 miles apart, on the once-a-day historical Northern Hemisphere weather maps, and in the warm and cold air, respectively, on the two sides of the front. It was permissible to measure the 350 miles in any direction. The index was intended as a combination of the immediate gradient at the frontal surface and also the broader scale temperature gradient. Only the maximum one-day intensity of a particular frontal passage was plotted on figure 20 for fronts that required several days for transit through the area. Curves enveloping 100%, 90%, and 50% of the temperature index values are shown in the figure. The maximum temperature index value for the May 15-20, 1943 storm is plotted on the figure both at the observed date and the transposed date. It can be noted that both points lie close to the 100% envelope. (The 100% envelope was drawn in by the analyst before plotting these two comparative points.) Possibly with a greater amount of data the 100% curve might slope down slightly with the advancing season as does the 50% curve. It is clear, however, that almost as great a temperature gradient may be experienced in mid-June as at the date of occurrence in mid-May, and the greater availability of moisture in June would offset this slight postulated decrease in temperature gradient. The conclusion, therefore, is that it is entirely reasonable for a storm of the type and volume of the May 15-20, 1943 storm to occur on June 10-15.

Hypothetical flood sequence

The final hypothetical early summer flood sequence consisted of a progression of storms downstream as follows: the storm of May 7-10, 1943, transposed to the time and near the place where the 1844 flood storm was probably centered; the May 15-20, 1943 storm in the place of occurrence; and finally a burst over the extreme lower Ohio patterned after a portion of the isohyetal map for June 28-30, 1928. The weather maps for this sequence are depicted in figures 21-25. They consist of the actual maps of

May 7-12, 1943, with the United States part transposed, the maps of May 13-20, 1943, as observed, and three final maps which are progressive modifications of the real maps for May 21-23, 1943. The modification serves to show a more intense trough moving into the central United States from the West and greater cyclonic development in Texas. The modified maps are somewhat similar to the real maps of June 26-28, 1928.

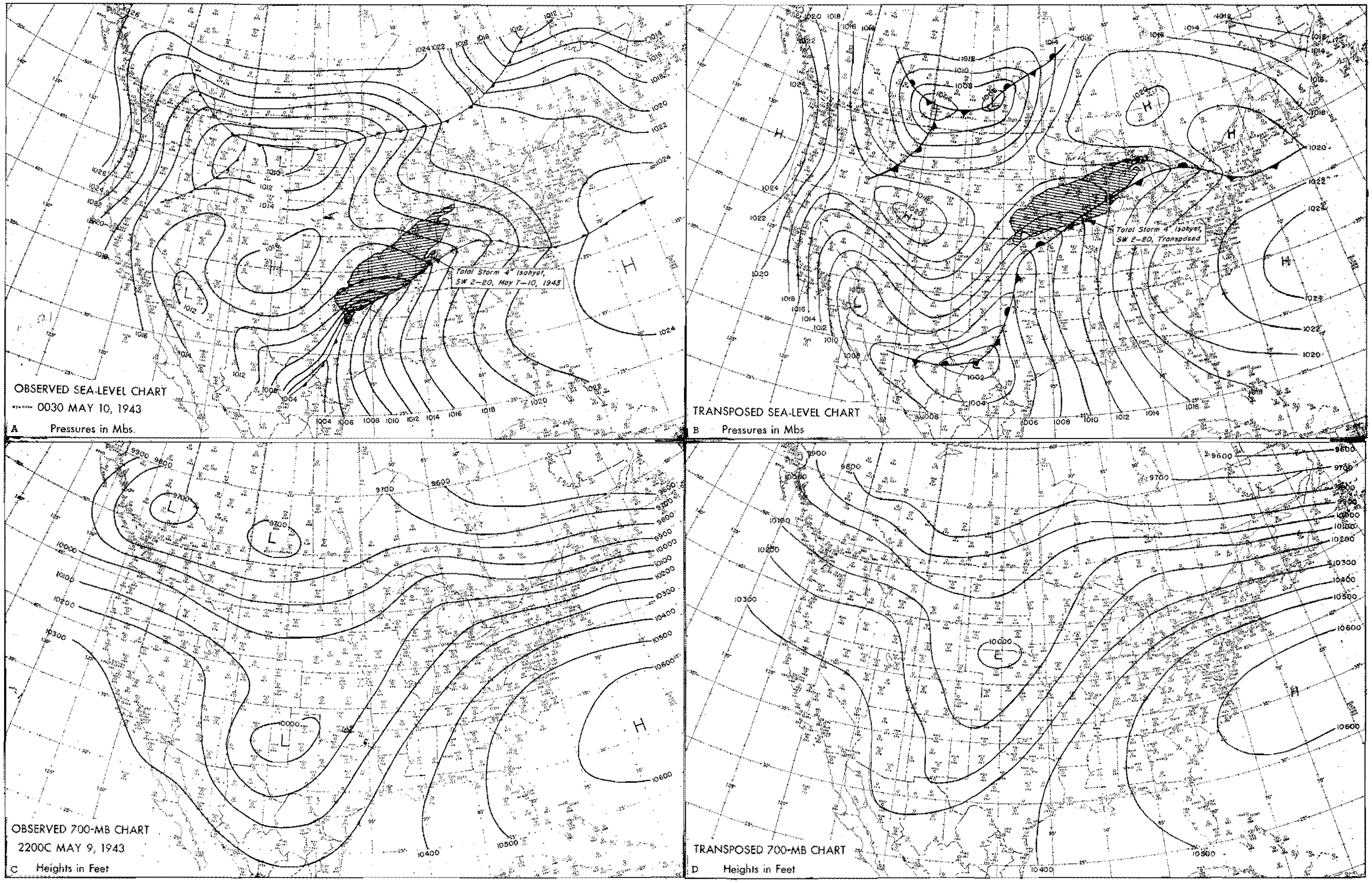
SUMMARY

Hypothetical floods were derived by combining historical floods to be used as design floods for levees in the Mississippi River system and other associated engineering purposes. These are not probable maximum floods and were not developed from the probable maximum concept. The meteorological reasonableness of the hypothetical combinations was examined by constructing hypothetical map sequences. These sequences are also illustrative of the trends of weather events that could occur in many combinations to produce floods. The time intervals between prototype rainbursts were set on meteorological grounds. The hypothetical flood sequences shown in this report are the most severe of a larger number of such sequences that were originally determined.

ACKNOWLEDGMENTS

This report is the product of collaboration with the Corps of Engineers. Particular mention is appropriate of the great amount of painstaking time given by Mr. Dwight E. Nunn of the Office of Chief of Engineers to developing the hypothetical sequences.

The project leader in the Hydrometeorological Section for this part of the study, under Dr. Charles S. Gilman, Chief of Section, was Vance A. Myers. Other meteorologists taking part in the construction of the hypothetical sequences were Roger R. Watkins, Nelson M Kauffman, and W. W. Swayne. The report was edited by Lillian K. Rubin, and the copy was typed by Edna Grooms.



A OBSERVED SEA-LEVEL CHART 0030 MAY 10, 1943 Pressures in Mbs.

B TRANSPOSED SEA-LEVEL CHART Pressures in Mbs

C OBSERVED 700-MB CHART 2200C MAY 9, 1943 Heights in Feet

D TRANSPOSED 700-MB CHART Heights in Feet

Figure 19. EARLY SUMMER SEQUENCE TRANSPOSITION TEST (Hypo Flood No. 52 A)

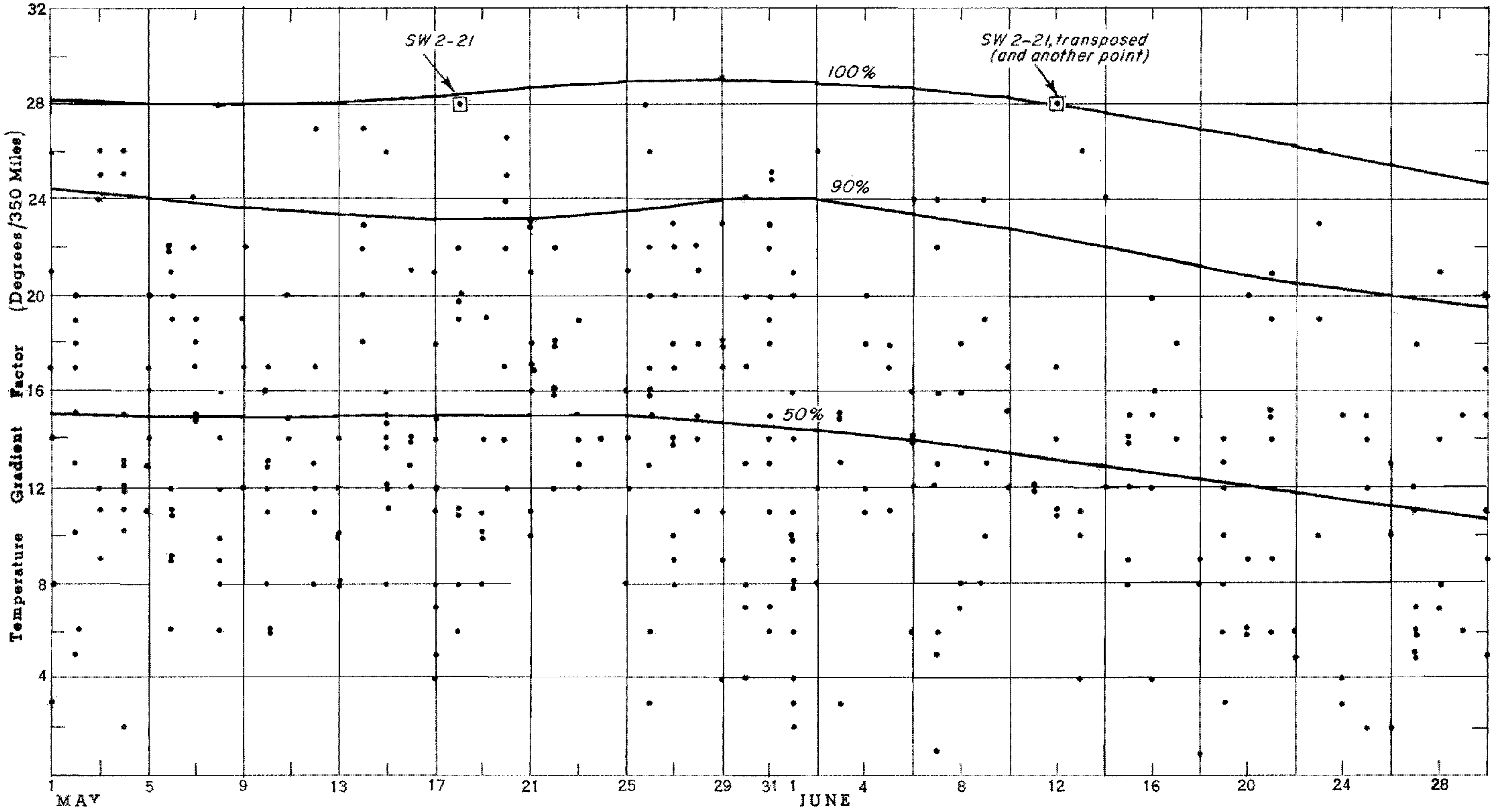
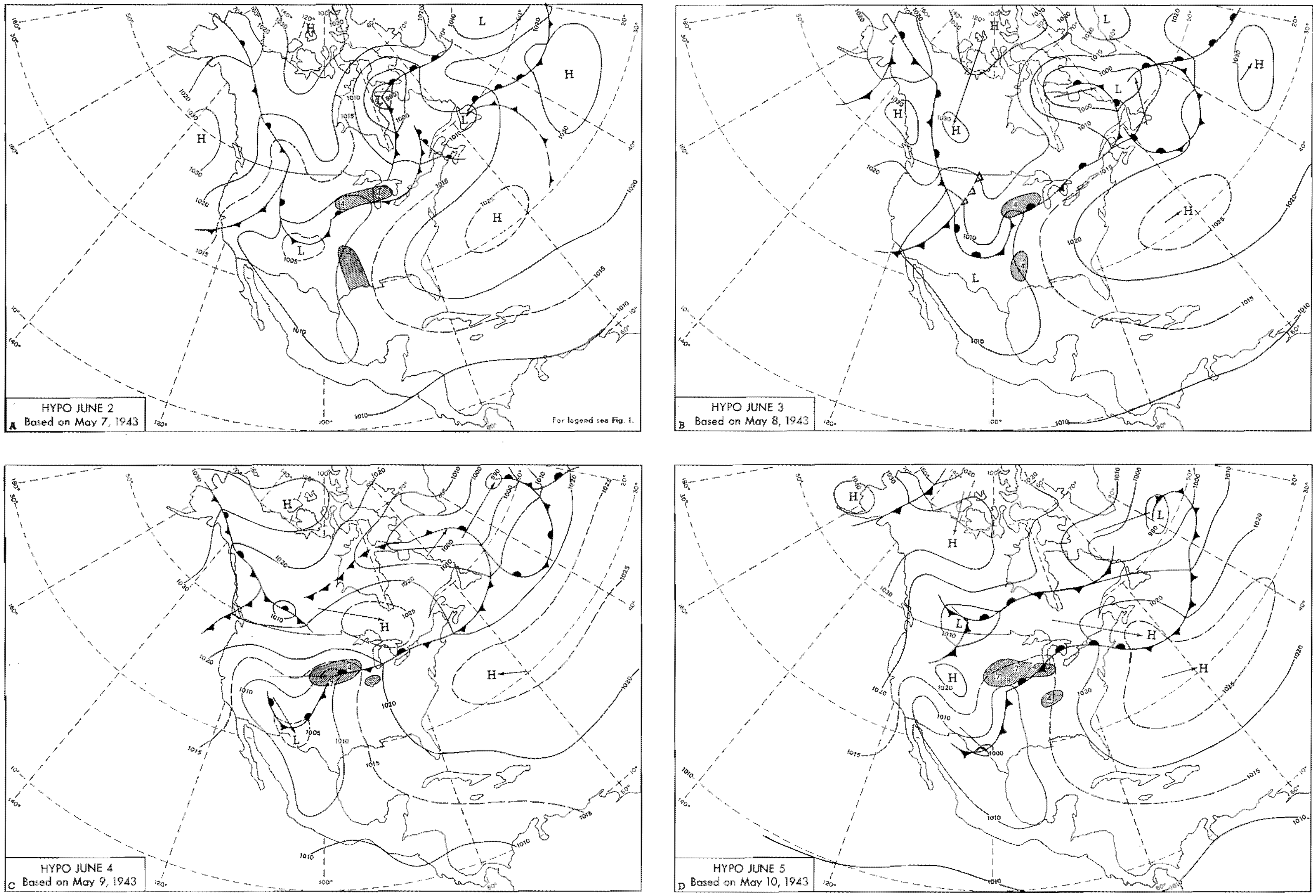


FIG. 20 VARIATION OF FRONTAL TEMPERATURE GRADIENTS IN NEBRASKA, OKLAHOMA, ARKANSAS, MISSOURI, IOWA, AND ILLINOIS.



A HYPO JUNE 2 Based on May 7, 1943

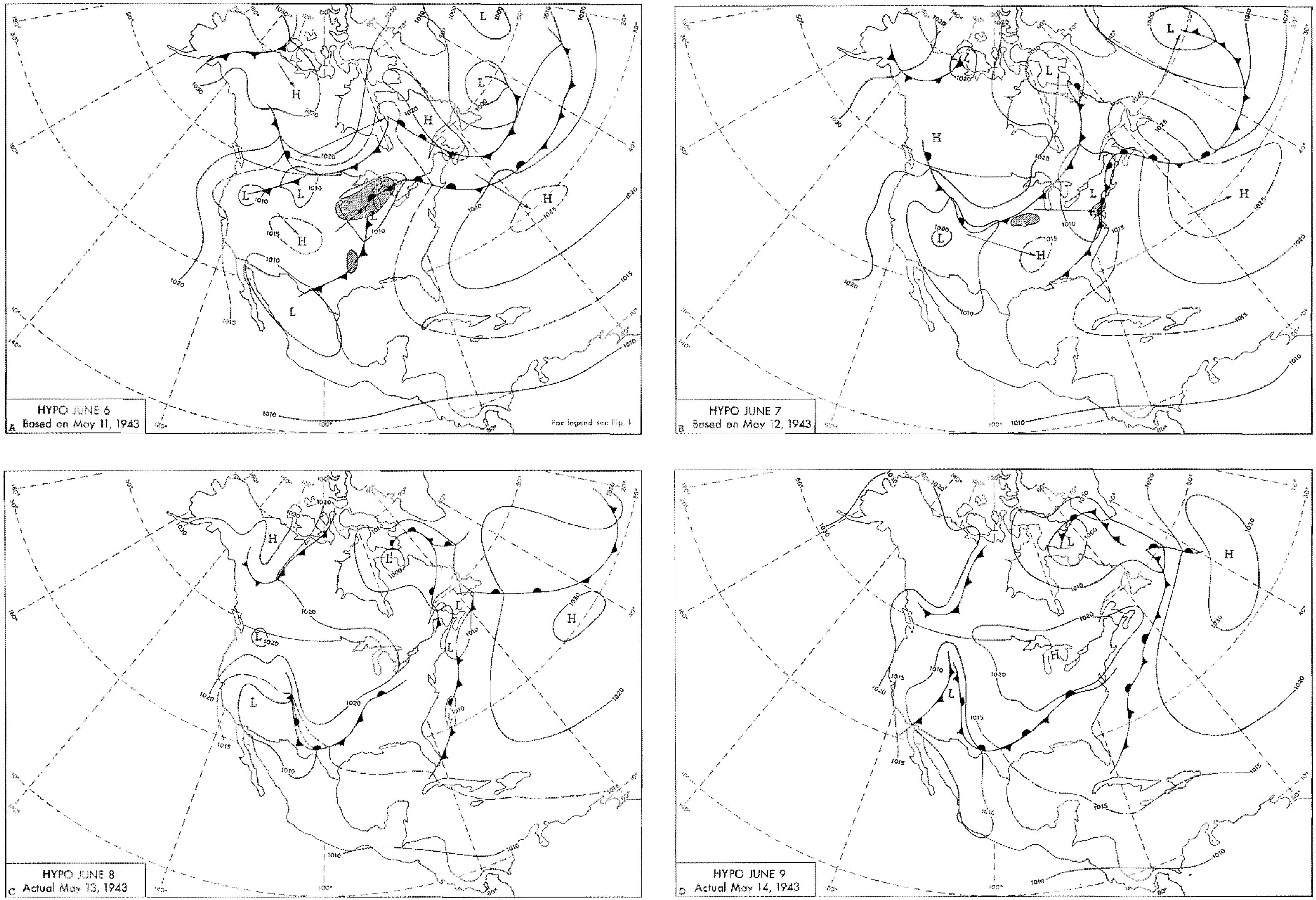
For legend see Fig. 1.

B HYPO JUNE 3 Based on May 8, 1943

C HYPO JUNE 4 Based on May 9, 1943

D HYPO JUNE 5 Based on May 10, 1943

Figure 21. EARLY SUMMER SEQUENCE (Hypo Flood No. 52 A)



A HYPO JUNE 6
Based on May 11, 1943

B HYPO JUNE 7
Based on May 12, 1943

C HYPO JUNE 8
Actual May 13, 1943

D HYPO JUNE 9
Actual May 14, 1943

Figure 22. EARLY SUMMER SEQUENCE (Hypo Flood No. 52 A)

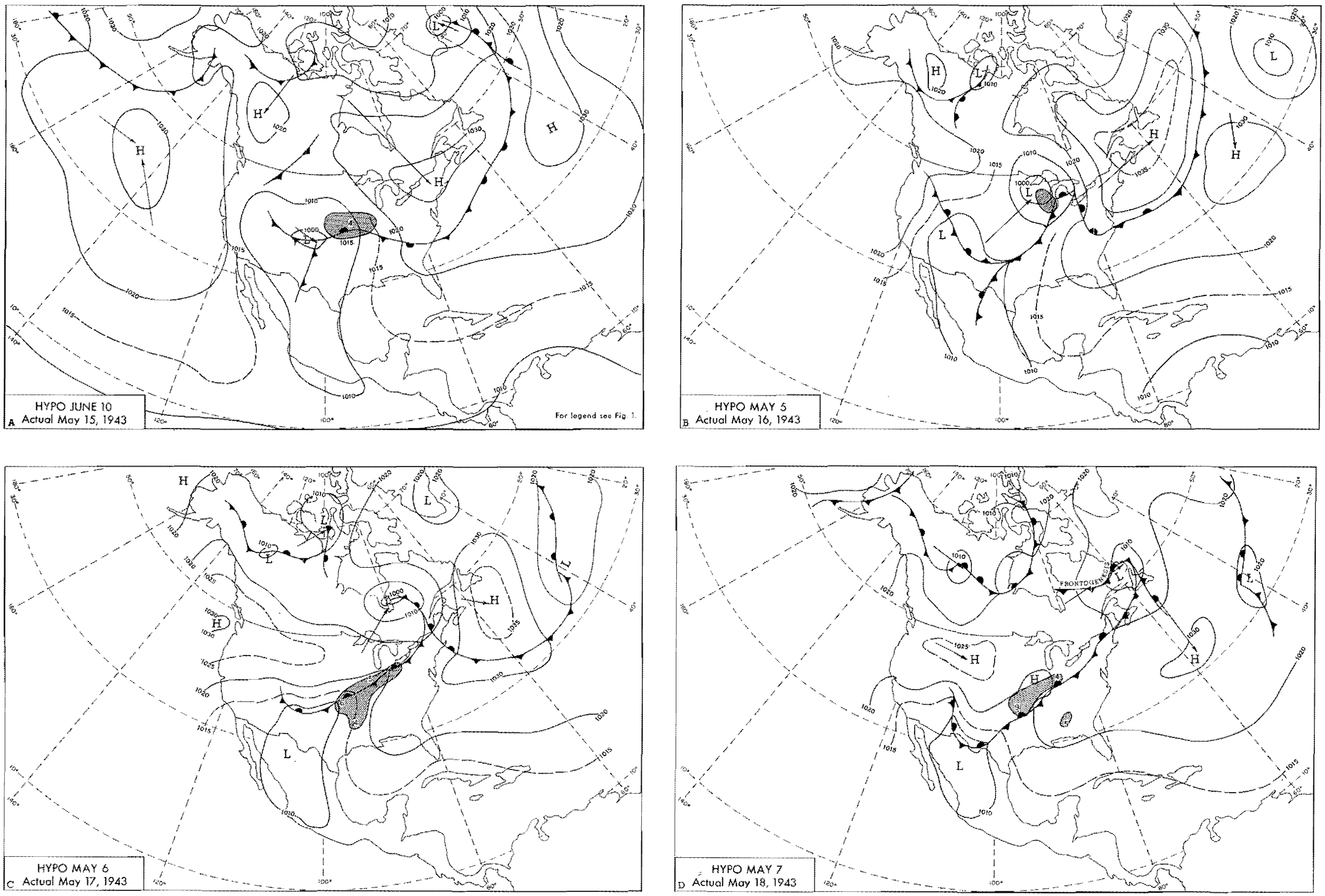


Figure 23. EARLY SUMMER SEQUENCE (Hypo Flood No. 52 A)

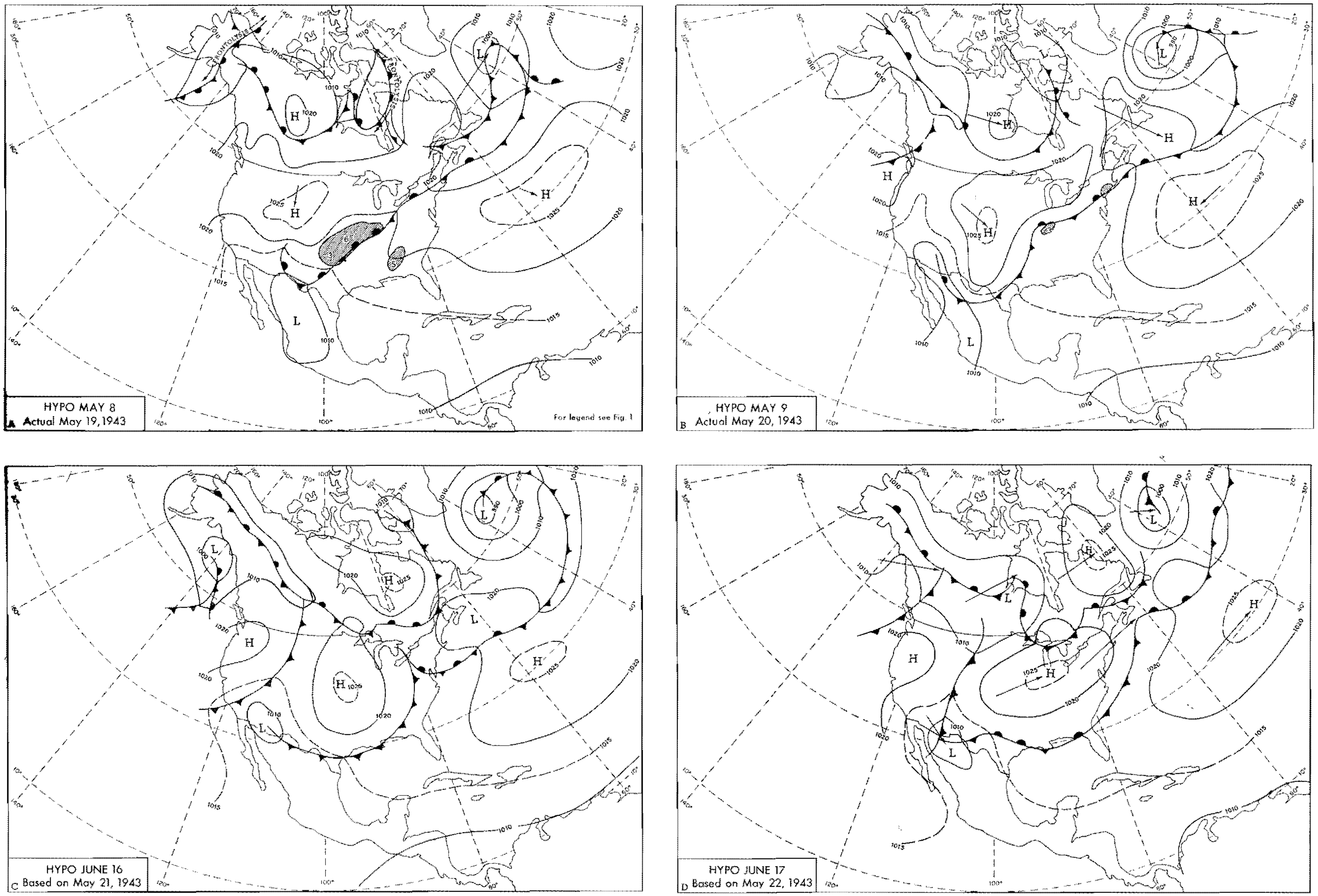


Figure 24. EARLY SUMMER SEQUENCE (Hypo Flood No. 52A)

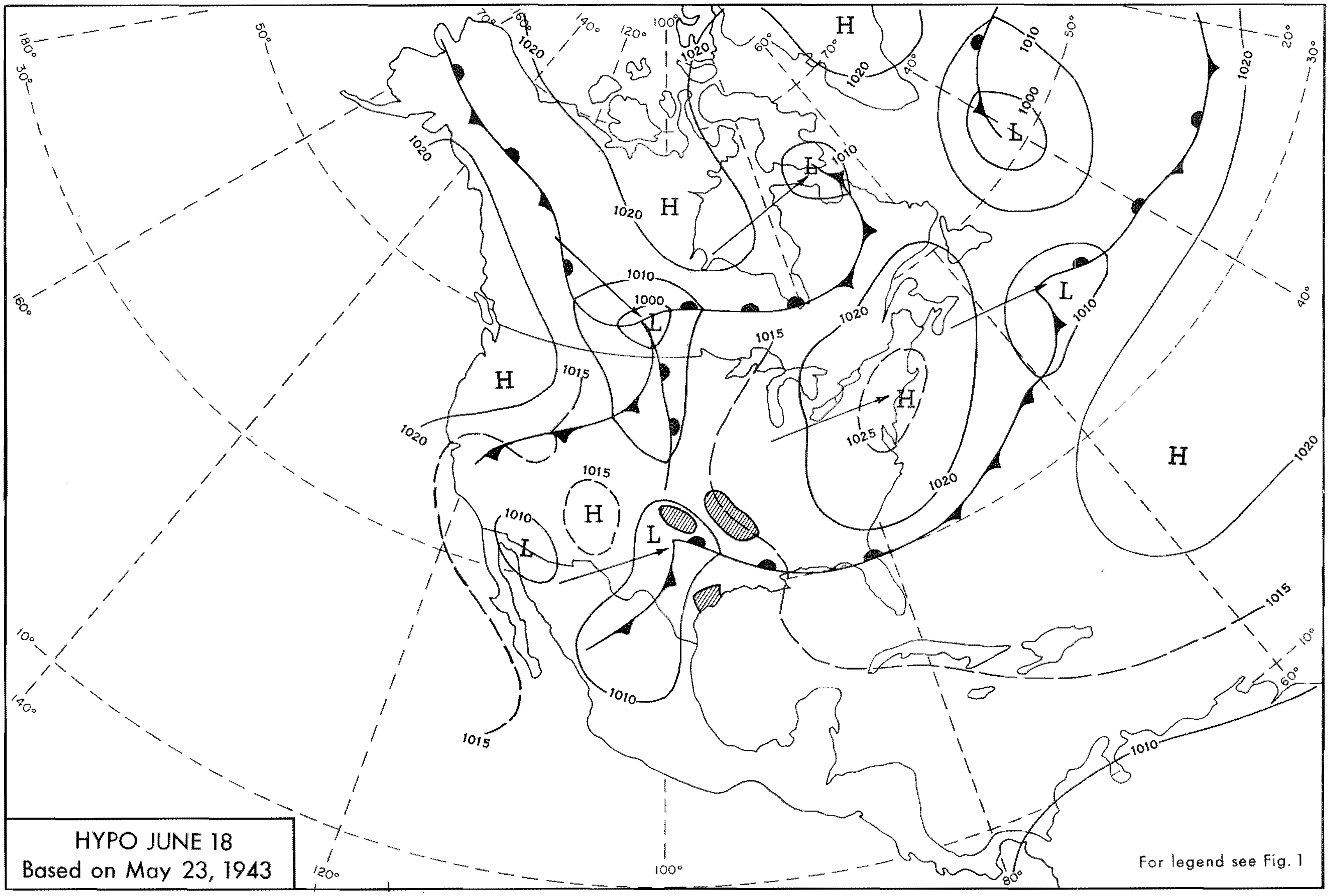


Figure 25. EARLY SUMMER SEQUENCE (Hypo Flood No. 52 A)

☆U. S. GOVERNMENT PRINTING OFFICE : 1960 O - 536669