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ANNUAL RAINFALL VARIABILITY MAPS OF THE UNITED STATES

By EARL E. LACKEY

[University of Nebraska, Lincoln, Nebr., November 1938]

The series of rainfall maps herewith described involve the weather records of 2,077 stations in the United States. Only a few records were used that were not up to date, and none which included fewer than 20 consecutive years. A small number of records ran to more than 100 years.

In some rugged areas where stations were scarce and where a real distribution of rainfall was very uneven, a few stations with broken records or records shorter than 20 years were used.

In comparatively level areas the placing of isohyets was an easy task, but in areas of great relief a resort to inference and interpolation was imperative.

The five maps were constructed on the basis of quartile deviations. In order to do this the numerical record by years for each station was arranged in an ascending sequence and then the 0-, 25-, 50-, 75-, and 100-percentile points in the distribution were computed in inches.

In the distribution for any station the 100-percentile point indicates that the precipitation was equal to or more than the given amount 100 percent of the time. This value represents the least rainfall the station ever has received; that is, the minimum. When the minimum figures for each of the 2,077 stations were written on a map of the United States and isohyets drawn connecting points of equal amounts, a *map of the minimum annual rainfall of the United States* (figure 1) was obtained.

The 0-percentile values in the distribution represent maximum rainfall; that is, the precipitation was more than the designated amount 0 percent of the time. Stated in another way, this value represents the most rainfall the station has received during the time of record. When the maximum values for the 2,077 stations were placed on a map and the isohyets drawn, a *map of the maximum annual rainfall of the United States* (figure 5) was obtained.

In a similar manner, the 3d quartile (75 percent), median (2d quartile, 50 percent), and 1st quartile (25 percent) values in each of the 2,077 distributions were represented on maps of the United States; these are reproduced here as figures 2, 3, and 4, respectively.

When the five maps of annual rainfall variability are consulted, it is found that Baltimore has always received 21.6 inches or more (minimum);[1] that 75 percent (¾) of the time the precipitation was equal to or more than 34.4 inches; 50 percent (½) of the time, equal to or more than 40.6 inches; 25 percent (¼) of the time, equal to or more than 46.7 inches; and 0 percent of the time, more than 62.4 inches (maximum).

[1] The figures given here were taken from the computed distribution. However, readings from the maps should not depart far from these values.

THERMAL ASPECTS OF THE HIGH-LEVEL ANTICYCLONE

By THOMAS R. REED

[Weather Bureau Office, San Francisco, Calif., September 1938]

The warm-season phenomenon of an anticyclone in the upper air over the North American continent was pointed out a number of years ago by the writer [1] and he assumed at the time that it was thermally induced.[2] High temperatures at the surface were believed to be the principal cause, the inference being that when the lower atmospheric strata became warmed, due to the high surface temperatures prevailing over the western highlands in midsummer, the ensuing expansion produced a convexity in the higher isobarometric surfaces, which in turn set up an anticyclonic flow of winds around the high level "dome" thus created. The clockwise flow was revealed by synoptic studies of resultant winds at levels of 3,000 m. and higher, the circulation of which was found to conform with a fair degree of consistency to an anticyclonic pattern, centered in a majority of cases over the southern Rocky Mountains.

But while the statistical existence of the high-level cell seemed well supported by theory and observation, there was, initially, no direct evidence of its thermal structure. Subsequently, however, such evidence has become available. The data from airplane soundings which have accumulated in recent years have supplied it, and the purpose of the present paper is to set forth some of this information and show its relation to the phenomenon in question.

First, in support of the assertion that the high-level anticyclone is essentially a thermal phenomenon, let us examine the pattern of mean free-air isotherms in the midsummer months. (Figures 1 and 2). Free-air temperatures for July and August alone are considered, because the high-level "cell" is fully established only in those months, although it may be, and frequently is, in evidence in other months when surface temperatures are abnormally high and the prevailing westerlies relatively

[1] Thomas R. Reed, The North American High Level Anticyclone, MONTHLY WEATHER REVIEW, Nov. 1933, vol. 61, 321.

[2] Recently in an admirable contribution to the subject, Rossby has sought to account for the existence of this and similar anticyclones as dynamically, rather than thermally, induced eddies; and Namias has illustrated the application of the theory by an exegesis of isentropic movements associated with examples of the current systems involve. No doubt both factors play a part, but in the anticyclone under discussion the thermal factor seems to the writer paramount. Unfortunately this aspect is not yet susceptible of adequate isentropic treatment for two reasons: (1) the fewness of upper air sounding stations west of the 100th meridian and (2) the altitude of the available soundings, their height not being sufficiently great to permit the construction of isentropic charts at effective levels in the free air. For discussion of the dynamical theory see Rossby, Namias, and Simmers: Fluid Mechanics Applied to the Study of Atmospheric Circulations, Papers in Physical Oceanography and Meteorology, Vol. VII, No. 1, published by Massachusetts Institute of Technology, Cambridge, Mass., 1938.

weak. Note that the mean free-air isotherms instead of traversing the country from west to east as in other months, form a series of roughly concentric contours over the western half of the United States, with the central isotherm of highest temperature embracing Colorado and parts of the adjoining states. The pattern is approximately the same for isotherms at 3,000, 4,000, and 5,000 meters above sea level. The highest mean temperature at the 3,000- and 4,000-meter levels is found over Cheyenne, Wyo.; and at the 5,000-meter level over San Diego. Presumably, if more aerographic data were available the

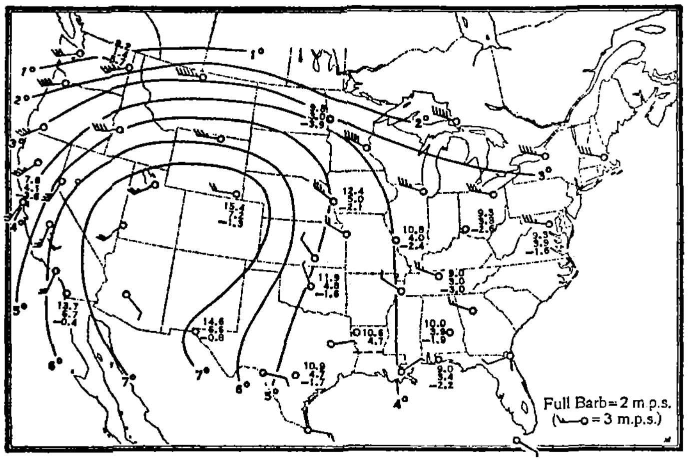

FIGURE 1.—Normal temperatures (°C.), and resultant winds in July at 4,000 m. Numbers reading from top to bottom, indicate normal temperatures at 3, 4, and 5 km., respectively.

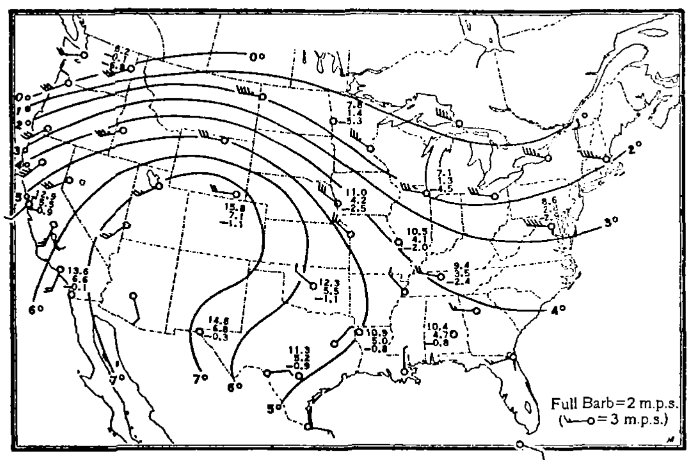

FIGURE 2.—Normal temperatures (°C.), and resultant winds in August at 4,000 m. Numbers, reading from top to bottom, indicate the normal temperatures at 3, 4, and 5 km., respectively.

maximum would be found somewhere within the triangle formed by Cheyenne, San Diego, and El Paso, as this area embraces not only a region of very high temperatures in midsummer but also a region in which the altitude of the surface of insolation is high. The upward bulging of the surfaces of isobarometric pressure associated with these free-air temperatures necessarily results in an effective dome of relatively high pressure at high levels over the region specified, and consequently in an anticyclonic circulation around the center of maximum pressure. Examination of free air resultant winds for the 3,000-, 4,000-, and 5,000-meter levels confirms this assumption and shows them to be in agreement with the thermal gradient, the wind arrows being approximately tangent to the isotherms. Thus the winds aloft are southeast to south over the south Pacific slope, south to southwest over the north Pacific slope, westerly over the northern Rocky Mountain region, northwest over the Missouri Valley, and north to east over the west Gulf States.

The fact of high mean temperatures in the free air over the western highlands in midsummer is not the only feature of note. The fact of high specific humidity is of equal interest. The mean values for this element are higher over the area under consideration than anywhere else over the continent at like levels, and approximate closely the specific humidities observed at similar levels over Coco Solo, in the Panama Canal Zone. As an example of these relationships the reader is referred to figure 3 which shows the mean specific humidities at the 3 and 4 kilometer levels in July 1937—a typical month. Note that the highest mean values are found over El Paso, Tex. (although very little higher than those over Salt Lake City), while the lowest values are found over San Francisco, Calif.

Thus, normally over Colorado and contiguous regions to the south and west there is in midsummer a condition not only of high temperature, but of high humidity as

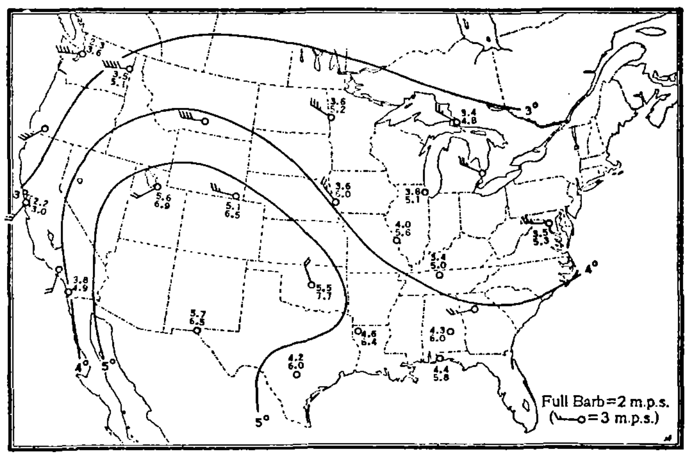

FIGURE 3.—July 1937. Specific humidity at 4,000 m (upper value), and 3,000 m. (lower value).

well. Moreover, as might be expected in an anticyclonic cell, there is likewise a condition of characteristically weak and variable winds. This, however, is true only of the central region within the high-level cell: the peripheral region, as has been already said, is one of anticyclonic gyration, and it is to this anticyclonic gyration and the various types of air embraced in it that the central region owes its importance as a climatic factor. In this respect the high-level cell may be considered a "center of action" in that it becomes an agency for initiating and maintaining a circulation that operates to bring both Tropical Atlantic and Tropical Pacific air masses into regions where they might not otherwise be found.

Thus it seems to effect a transport of TA air from the Atlantic high-pressure cell and of TP air from the Pacific high-pressure cell northward over the Pacific Slope, eastward over the northern Rocky Mountain States, and then southward over the Missouri and Mississippi Valleys. These air streams are easily identifiable if mean monthly values for equivalent potential temperature (Θ_E) are plotted for various levels from 3,000 meters up. (See figures 4 to 7) L. P. Harrison, in his summary of aerological observations in the August 1937 issue of the MONTHLY WEATHER REVIEW, made the following comment:

> The mean maximum free-air values of (specific humidities and equivalent potential temperatures) were found to be centralized over the southeastern portion of the Western Plateau region and contiguous areas to the east. Study of the patterns shown by the

monthly resultant winds, and the lines of constant value of these two elements constructed on charts for the various levels, discloses striking evidence of the probable existence, statistically at least, of a high-level anticyclone over the territory specified above. The three types of data referred to appear most consistent with this conclusion for levels from 3 to 5 kilometers above sea level, if it is assumed that the equivalent potential temperatures and the specific humidities undergo little change on the average in air masses transported along anticyclonic trajectories over the regions in question.

Especially significant are the mean values for equivalent potential temperature at the 3-, 4-, and 5-kilometer levels

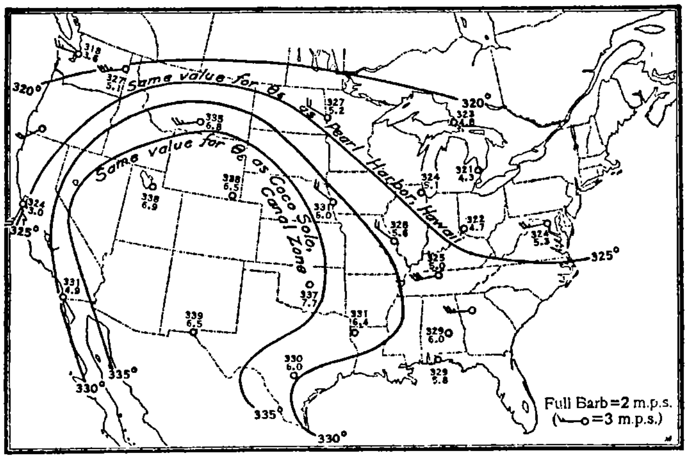

FIGURE 4.—July 1937. Equivalent potential temperature, specific humidity, and resultant winds at 3,000 m.

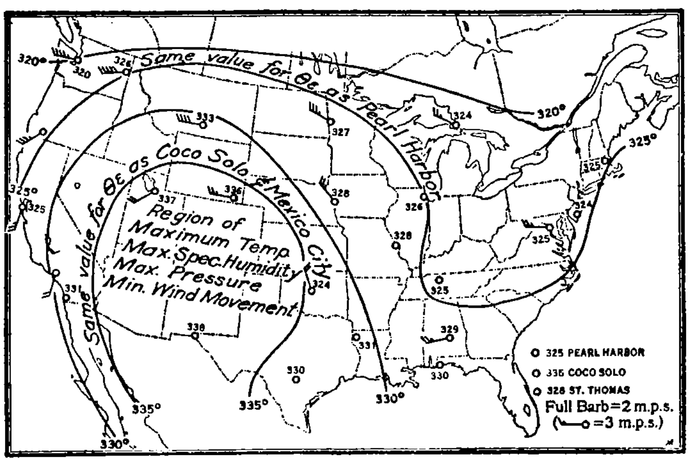

FIGURE 5.—July 1937. Equivalent potential temperatures at 4,000 m., and resultant winds at same level.

within the high-level cell. They are higher within the cell than anywhere else at like levels either over the continent or in the tropics. In order to find as high values outside the anticyclonic cell it is necessary to look for them at lower levels. Thus in July 1937, the mean value 339° for θ_E found at the 4,000-meter level over Cheyenne, cannot be found anywhere above the 1,000-meter level at either Kelly Field, Tex., or Pensacola, Fla. The same relationships hold good in August, also. Moreover, the high values for θ_E within the cell are not restricted to the air over Cheyenne, but are found over Salt Lake City and El Paso, likewise.

This fact lends credence to the view that the high thermal energy content of the high-level cell has its source in strata of lower origin, being associated with air fed into the region of the cell below and lifted to the level of the cell by convection. Such an inference would account (partially, at least) for the higher values of θ_E within the cell than are to be found at like levels beyond its periphery. It also accommodates itself to the fact that like values for θ_E are found at comparatively low levels on the coast of the Gulf of Mexico. It is, furthermore, a fact of importance to consider in connection with the phenomenon of thunderstorms activity in the region normally occupied by the high-level cell, viz, the southern Rocky Mountains. Reference to Alexander's thunderstorm charts [3] shows this to be the region of greatest thunderstorm frequency in our country in midsummer outside of the east Gulf States.

In conclusion it may be worth while to point out the apparent relation that exists between surface temperature abnormalities and the position of the high-level cell. The latter is usually found over or to the south of the region of pronounced plus departures from normal temperature at the surface. Figures 8 and 9 illustrative of these obser-

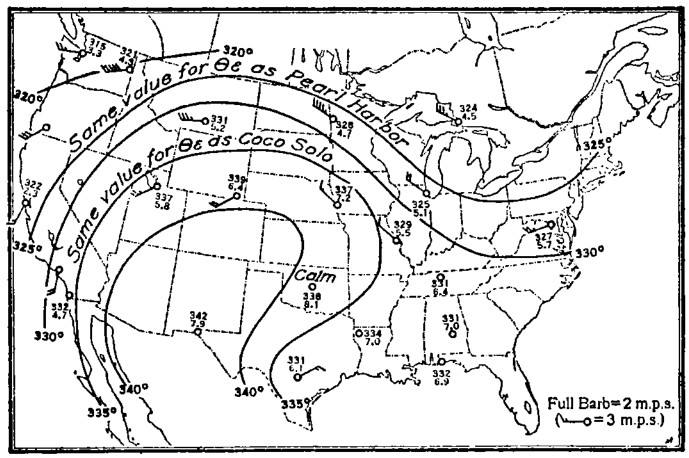

FIGURE 6.—August 1937. Equivalent potential temperatures, specific humidity, and resultant winds at 3,000 m.

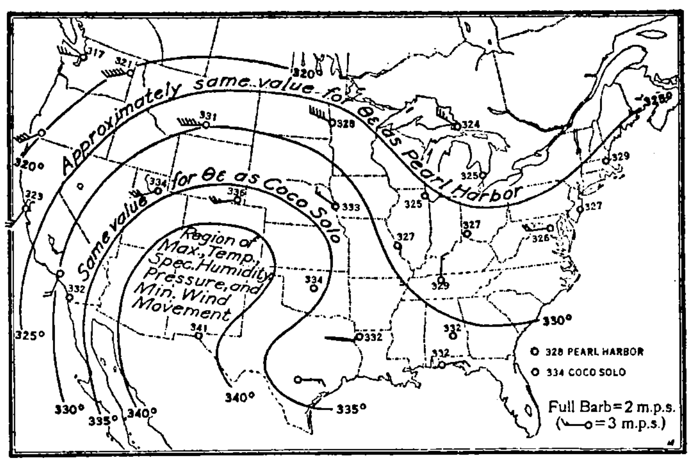

FIGURE 7.—August 1937. Equivalent potential temperatures and resultant winds at 4,000 m.

vations show the mean isotherms and resultant winds at 4,000 meters in July and August 1936—a summer of memorable heat and drought in the Middle West. It will be noted that in July the region of greatest abnormality in surface temperatures was in the Dakotas, and the center of the high-level cell was just south of it. On the other hand, in August the region of largest temperature de-

[3] W. H. Alexander. "The Distribution of Thunderstorms in the United States," MONTHLY WEATHER REVIEW, Vol. 63, May 1935, p. 157-158.

parture was in Kansas, and the high-level cell was almost directly overhead.

Maj. E. H. Bowie has drawn my attention to an article by George Reeder which appeared in the MONTHLY WEATHER REVIEW of October 1919, entitled "The Relationship between Cirrus Movements from Easterly Points, and the Occurrence of Severe Droughts," in which the author showed that during severe droughts in summer in Missouri, and preceding them, "the cirriform clouds show a persistent though very sluggish movement from easterly points." Lacking free-air data, Mr. Reeder endeavored to account for this abnormal cloud movement by a study of surface pressures. It is quite likely that had he possessed the information which we now have regarding air circulation at high levels he would have attributed the phenomenon to other causes, for the easterly winds over Missouri could occur only when the high-level anticycline was far north and east of its normal position. Figures 8 and 9, just considered, may be taken as an example of an air structure probably approximating situations of the kind he described. It will be noted that in each case there was a northwest resultant wind over the upper Mississippi Valley, countered further south by a southeast resultant wind over Oklahoma. Note, too, the close agreement between resultant winds and isotherms, and how the high-level circulation has apparently maintained an air mass of abnormal warmth far eastward over the Mississippi Basin, and hence an atmospheric structure hostile to convection.

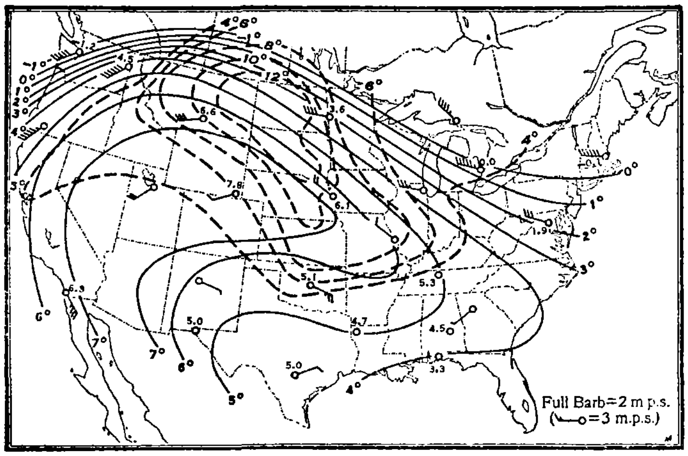

FIGURE 8.—July 1936. A month of unusual heat and drought in the Middle West Solid lines indicate isotherms at 4,000 m., °C.; broken lines, departures from normal temperature at surface, °F.; resultant winds at 4,000 m.

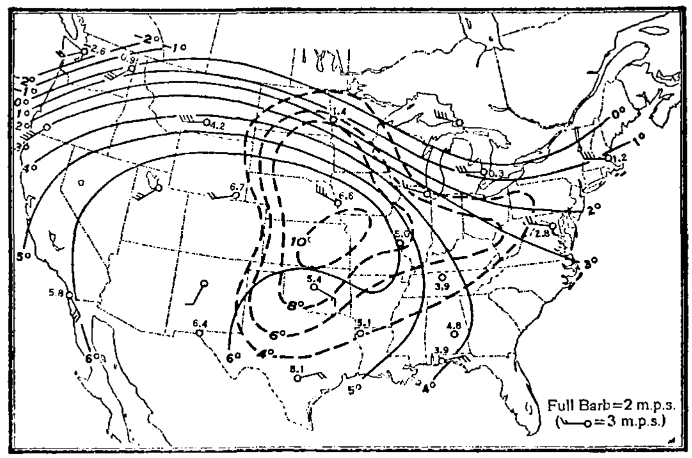

FIGURE 9.—August 1936. A month of unusual heat and drought east of the Rocky Mountains. Solid lines indicate isotherms °C. at 4,000 m.; broken lines, departures from normal temperature at surface °F; resultant winds at 4,000 m.

Special thanks are due Messrs. Little and Samuels of the Aerological Division of the Weather Bureau for help in providing data for some of the charts herewith.

FURTHER STUDIES OF AMERICAN AIR-MASS PROPERTIES

By ALBERT K. SHOWALTER

[Weather Bureau, Washington, June 1939]

These studies originally were undertaken for the purpose of bringing up to date the mean values of the characteristic air-mass properties of North America as first given by Willett (*1*). This seemed desirable in view of the large mass of airplane sounding data obtained since the publication of Willett's paper, which was based principally on kite observations. A preliminary analysis of the new data indicated that some minor changes in Willett's classification of air masses might be necessary. A more thorough study, however, based also on certain synoptic considerations, led to the abandonment of the absolute system of classifications, for reason that will be stated later; and the conclusion was reached that Bergeron's differential classification, which was used by Willett as an alternative system, forms a better basis for air-mass definitions.

The relation between the two classifications can be seen by listing and comparing them as follows:

Absolute classification (adapted from Willett)

PC—Polar continental air which, after becoming modified, is called NPC (transitional polar continental).

PP—Polar Pacific, and the modified form NPP.

PA—Polar Atlantic, which, when modified, becomes NPA.

TA—Tropical Atlantic, which in the charts and cross sections used for this study, included both the TA and TG (tropical Gulf) masses of Willett's classification, since both of the air masses come out of the subtropical anticyclone cell of the Atlantic.

TP—Tropical Pacific.

TM—Tropical maritime, a designation used when it is impossible to determine whether the air mass is of Atlantic or Pacific origin or when the two are mixed.

S—Superior, which includes all air masses which appear warm and very dry because, principally, of subsidence and divergence. S includes the type of air mass labeled TC (tropical continental) in Willett's original publication and TS (tropical superior) in later treatises by the same author (*2*).

NP—Modified polar, which is air definitely of polar origin but of doubtful continental or maritime origin, or a mixture of continental and maritime polar air. This type of air mass, which was not definitely classified by Willett, forms the predominant polar air mass of summer.