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DISCONTINUANCE OF CHART I—HYDROGRAPH OF SEVERAL PRINCIPAL RIVERS.

Beginning with this issue, the above-named chart will be permanently discontinued and the serial numbers of the remaining charts regularly published will each be advanced one number; thus the previous No. II will now be No. I, etc.

The information carried by this chart is published in tabular form, annually, in the volume Daily River Stages. Considerable inquiry shows that the purpose of the chart thus discontinued will be equally well served by the data of Daily River Stages.—EDITOR.

FORMATION AND MOVEMENT OF WEST INDIAN HURRICANES.

By EDWARD H. BOWIE, Meteorologist.

[Weather Bureau, Washington, D. C., May 3, 1922.]

SYNOPSIS.

The physical features of the hurricane are fairly well understood. The explanation of the process of formation of the hurricane remains in more or less dispute, there being two hypotheses that attempt to satisfactorily explain its origin. There are reasons for believing that countercurrents, having their origin in differences in temperature over large geographic areas, initiate the conditions that give rise to the system of gyrating winds; that the condensation of water vapor supplies the energy necessary to maintain them through considerable periods of time. The movement of the hurricane is generally attributed to the general drift of the air in the region of the hurricane. The daily synoptic weather charts and the observations of the free-air directions and speeds of the winds in regions contiguous to hurricanes appear to indicate that hurricanes are carried forward on the border of the major wind system (the northeast trade) of the tropics, and that as this wind system changes its direction the course followed by the hurricane is changed to correspond thereto.

The hurricane.—To the cyclone of the West Indies has been given the name *hurricane*, a vast system of gyrating aerial currents, surrounding a central small or relatively small and more or less circular region of calms known as the eye of the cyclone. The movement of the winds around this center is counterclockwise, with varying degrees of inclination and at speeds proportional to the steepness of the baric gradient. The physical features of the hurricane are fairly well understood. According to Bigelow and other writers, the approach of a hurricane is usually indicated, when the observer is in a position to make such observations, by a long swell on the ocean, propagated to great distances and forewarning the observer by two or three days in rare instances. A rise in the barometer at times occurs before the gradual fall sets in, which fall becomes very pronounced on the near approach of the center; fine wisps of cirrus clouds are first seen, which surround the center to a distance of 200 miles or more; the air is calm and sultry and the usual afternoon thundershowers are suppressed; this is gradually supplanted by a gentle breeze, and later the wind increases to a gale, the clouds become matted, the sea rough, rain falls, and the winds become gusty and dangerous as the vortex core comes on. Here is the indescribable tempest, dealing destruction, impressing the imagination with its wild exhibition of the forces of nature; the torrents of rain, the cooler air by reason o the falling rain, all the elements in an uproar, indicate the close approach of the center. In the midst of this turmoil there is a sudden pause, the winds almost cease, the sky clears, the waves, however, rage in great turbulence. This is the eye of the storm, the core of the vortex, and it is, perhaps, 20 miles or less in diameter, or one-thirtieth the diameter of the whole cyclone. The respite is brief and is soon followed by the abrupt renewal of the violent wind and rain, but now coming from the opposite direction, and the cyclone passes off with the several features following each other in the reverse order.

Region of first appearance.—The hurricane belt of the North Atlantic Ocean extends entirely across the ocean in low latitudes, but in so far as we are concerned it may be described and defined as that area extending from longitude 56° west to 95° west and from latitude 10° to approximately latitude 25°, or roughly the Caribbean Sea, the Gulf of Mexico, and the waters adjacent to the West Indian Islands. There are, of course, instances where hurricanes have entered this area from the eastward, but during a period of 35 years 90 per cent of the hurricanes of these waters according to Fassig, have had their origin within and not without this area. There is a well-marked belt of maximum frequency through the northern half of the Caribbean Sea, extending almost due west from the Windward Islands to Yucatan. During the greater part of the year this region and the water areas to the north and east are under the influence of the more or less permanent area of high barometer of higher latitudes, and the northeast trade flows entirely over it, but occasionally the northeast trade withdraws from this region and there is left a region of very slight baric gradient, more or less homogeneous temperature distribution in the horizontal, and feeble winds. It is during such times that hurricanes are likely to be found in these waters. Some years pass without hurricane formations; other years are notable for their frequency.

The formation of hurricanes.—We do not know all the facts which would permit an authoritative and unquestioned explanation of the origin of a hurricane. That remains one of a number of meteorological problems awaiting exact solution. Nevertheless, a number of hypotheses accounting for the origin of hurricanes are to be found in the literature having to do with this problem, but which is the correct one it is now difficult and next to impossible to say. Because opinion is more or less at variance, there follow brief summaries of the expressions by several writers on the subject of hurricanes, or, to use the more general name, tropical cyclones.

Ferrel, writing in the *Nashville Journal of Medicine and Surgery*[1] on "Winds and Currents of the Ocean," expressed the then prevalent idea that hurricanes are generally supposed to be produced by the meeting of adverse currents, which produce gyratory motions of the atmosphere at the place of meeting; that they may receive their origin and first impulse in this way seemed to him very probable, but that violent hurricanes, extending over a circular area of nearly 1,000 miles in diameter and continuing for 10 days, depend upon any primitive impulse alone, seemed to him very improbable. Later in the same paragraph (p. 13) he evidently gives his own conception of the causes which give rise to tropical and extratropical cyclones, for he says—

> For if even any part of the atmosphere should receive such an impulse as to produce a most violent hurricane, friction would soon destroy all motion and bring the atmosphere to rest. Besides, no gradually accelerated motion can depend upon a primitive impulse alone, even where there is no friction. Hurricanes, then, and all ordinary storms, must begin and gradually increase in violence by some constantly acting force, and when this force subsides friction brings the atmosphere to a state of rest.

Ferrel then definitely espouses Professor Espy's theory of cyclones and rains—viz, that all cyclones are produced by an ascending current of warmer air saturated with moisture and that this current is kept in motion by the continual rarefaction of the atmosphere above by means of the latent heat given out as the vapor is condensed when it ascends to the colder regions above.

In later years, particularly when engaged in the deliberate study of the motions of the atmosphere in the early eighties, while in the Signal Corps he postulated the conditions under which a cyclone might be generated. This will be found in a work which, unfortunately, has not received as wide distribution as could be wished; the work referred to is officially known as Appendix No. 71 to *Annual Report of the Chief Signal Officer, 1885*, but is better known as "Recent advances in meteorology."

During this period Ferrel found opportunity to make a careful review of the investigations of others and his own work had reached an advanced stage toward maturity. It is interesting, therefore, to note that he still attributes the origin of cyclones to thermal causes such as would give rise to interchanging motions between the interior and the exterior of a somewhat circular-shaped area of temperature abnormality. The motions thus initiated when coming under the deflective influence of the earth's rotation must take on cyclonic character.

Before passing to his most recent and final conclusions on the subject I wish to introduce two brief statements which show his state of mind with reference to the existence of ascending currents not clearly of convective origin. Speaking of the northeast trades of the Atlantic he says:[2]

> Before arriving at the calm belt they (the northeast trades) are deflected upward, and in the central part of the belt there is necessarily a vertical ascending current, *for all the air which comes in from both sides must ascend and return toward the poles as a countercurrent.* * * * As there is a constant pouring in of air nearly saturated with vapor from both sides of the calm belt, and an ascent there, there is almost a continuous and very abundant fall of rain every day.

[1] Later reprinted as *Professional Paper of the Sig. Ser.* No. XII.
[2] *Recent Advances*, pp. 226-227.

See also in this connection, C. E. P. Brooks and H. W. Braby: The clash of the Trades in the Pacific. *Quart. Jour. Royal Met. Soc., Jan., 1921;* abstract in Mo. WEATHER REV., March, 1921.

Ferrel in his recent and last work[3] begins the chapter on cyclones with a discussion of the general circulation of the atmosphere which would arise on an earth with a homogenous surface as a result of the temperature gradient between the Equator and the Poles. He then passes to a consideration of the disturbances in the general circulation on account of the nonhomogeneity of the earth's surface and to that class of temperature disturbances which give rise to monsoon winds. After this he takes up another class of temperature disturbances which extend over a comparatively small part of the earth's surface and are mostly neither fixed to any part of the earth's surface, nor do they continue generally for a great length of time and hence they are of a more local and temporary character than the others. In this class of disturbances there is a gyratory motion around some central point; hence the name cyclone.

Following his earlier conclusions he reaffirms his belief in the thermal origin of cyclones. He does not postulate a core of warm air in the cyclone which has passed the initial state and has moved many miles from its place of origin; hence the announcement that the center of the cyclone is cold as compared with the anticyclone does not necessarily affect the validity of Ferrel's conclusions, despite, however, the fact that there are no observations to prove that the center of the cyclone area at the time it is forming is warm. His fundamental assumption is that if the air over any portion of the earth's surface is warmer at all altitudes than that of the surrounding parts at the same levels it is lighter, and therefore forced to rise and flow out in all directions. This decreases the pressure at the earth's surface over this area, but increases it a little over the surrounding parts; and thus there arises a pressure gradient from the exterior to the interior below, which causes a flow of air in from all sides to supply the ascending current. Ferrel is careful to state, however, that this modification of his view seems to have been overlooked, that it is not necessary in order to have such a circulation, that all the strata of air from top to bottom shall be warmer than in the surrounding parts, but only that there shall be such a disturbance of the equality of temperature that the pressure of any part of the interior is less than that of the exterior part.

The above has reference to the initial conditions which are assumed to give rise to the cyclone, not to the conditions which may obtain after the cyclone has started on its path. The temperature of the air column will then be determined in a very large measure by one or more circumstances—first, its geographic position with reference to land and water surfaces; second, its remoteness from oceanic winds; third, the latitude and the general movement of the atmosphere of the region in which it exists; and, finally, by the temperature of the inflowing winds.

Studies of European investigators, Dines in particular, have shown that the central core of the European cyclone is cold as compared with the core of the anticylone. For the United States, or rather for that part for which observations are available, this view is not supported, for it is found that the eastern, or front, side of the cyclone is warm and the rear cold; accurately speaking the highest temperature is found not at the center, but a little to the east of the center in the regions east of the Rocky Mountains. No observations are available for the free air in cyclones entering the continent from the

[3] A Popular Treatise on the Winds, 1889.

Pacific Ocean, but surface observations would lead us to believe that the eastern side of the winter cyclone of our northwestern States and British Columbia is cold as compared with the western or rear side, or the opposite temperature distribution to that found elsewhere in the United States. In the Tropics, where the latitudinal temperature changes are small, we should expect a rather uniform temperature distribution around a cyclone. If it were true that all cyclonic centers are cold and anticyclonic centers warm to all altitudes, then we should expect to find the seat of maximum intensity in the cyclone at very high altitudes, and we might rightly say that the surface phenomena of the cyclone are to be likened to undertow.

Against the views of Professor Ferrel will be found objections by many cyclonologists. For example, a writer in the *Barometer Manual*[4] in discussing the convectional theory takes the view that—

The idea was that air heated at the surface became lighter than its environment, rose upward forming a core of warm air, the ascending air was replaced by air flowing in from all sides to fill up the vacant place, the inflowing air was diverted from its immediate object by the rotation of the earth, and so a cyclone was formed; and where on the other hand, cold air descends, an anticyclone. There is, unfortunately, no sufficient foundation of truth in this representation. First, the heated air rises truly enough, but in threads, not in masses, and a rising mass would lose temperature at the rate of 1° F. for 190 feet of ascent, and therefore the height it will rise depends, first, upon how much its temperature has been increased and, secondly, upon the rate at which the temperature of the environment falls off. If that air were of uniform temperature, the rising process would begin with the first increase of temperature, but soon cease, and the simple process of a column of rising air would never even begin. If, on the other hand, the temperature of the environment fell off at the maximum rate of 1° F. for 190, no sooner had the heating begun than the heated air would go off to the top of the atmosphere inevitably. Consequently the behavior of the heated air depends not so much upon its being heated as on the structure of the surrounding air, which is not given in the data. Secondly, the cyclone (or anticyclone) is not specially a surface phenomenon; its features are more pronounced and it reaches its best development away from the surface, where friction interferes, and when free of the surface the flow toward the core of the cyclone which was supposed to initiate the cyclone does not exist. Thirdly, the core of the cyclone is not warm compared with the core of the anticyclone, except occasionally in the surface layer, for the upper part of the anticyclone is the warm region and the upper part of the cyclone the cold. Fourthly, as we have already seen in the experiments with Dines' machine a vortex is not formed in air over a hot surface in the space through which the heated air rises. If the air is rising, the vortex is formed in the space underneath where convection begins. If there is a cyclone in the atmosphere and we want to find convection as a cause for it we ought to look for the source of the convection at the top and not at the bottom.

Davis[5] after describing in detail the evidence in support of the conclusion that tropical cyclones are essentially convectional phenomena on a large scale, remarks that—

They (tropical cyclones) occur in seasons and regions where high temperatures prevail; that they are most effectively aided by abundant condensation of water vapor from air at high temperatures; their circulation is in every way like that which we should expect would follow from a convectional process on a rotating earth. Yet it must be noted that the essential fact on which the belief in their convectional character should depend is not yet a matter of direct observation, for it has not yet been directly shown that the temperature of the cyclone mass is higher than that of the surrounding atmosphere at corresponding altitudes. If observations on mountain peaks should in the future show that the cyclonic mass is not warmer than the surrounding air, the convectional theory of tropical cyclones would have to be abandoned and some other theory devised to explain the phenomena.

Continuing, Davis says, that—

The student should therefore hold the convectional theory in mind as being well supported by reasonable evidence, and yet still lacking the final element of direct demonstration; he should remember the evidence that leads to the conclusion here regarded as the most probable one; he should not memorize the conclusion alone.

Now, as a matter of fact, observations in the free air in and around a tropical cyclone are not available, but the temperature observations at the surface of the area occupied by a tropical cyclone do not show readings above those of the surrounding regions. In the center of the cyclone—i. e., the eye of the cyclone—the observations are contradictory—in some cases there is a rise, in some no change, and in other cases a fall in temperature.

From the viewpoint of the advocate of the convective origin of cyclones the causes that give rise to it should be looked for in the environment of the cyclone; that which takes place beyond the outer limits of the cyclone proper may be considered as having nothing to do in the genesis of these perturbations. The other school would have us look far beyond the immediate area of the cyclonic formation for its cause. In other words, look to the primary or general wind systems and their interactions for the cause of the local traveling cyclones and anticyclones and also for the cause of other unusual meteorological conditions as well. Hence we find in the literature on cyclones many references to and the parts played by the major winds currents. In fact it appears that the importance of these major air currents in the development of cyclones was the more or less commonly accepted view previous to the middle of the nineteenth century. Thus, we find, for example:[6]

The statement that in early times Dove spoke of the storms (cyclones) of the north temperate zone as occurring between two great currents of air, the northerly, or polar, and the southerly, or equatorial current, and many writers, rather prematurely, taught that great storms (cyclones) were generated in the region between these currents. To this idea two objections were made—namely, that, on the one hand, the polar and equatorial currents were too far apart and too feeble to have any such interaction on each other and generate such violent winds. On the other hand, if this were the sole cause of the hurricane, the latter would soon die away by reason of the resistances to the motion of the wind, and some regenerating process must be discovered in order to explain the generally steady increase in the intensity of such hurricanes up to the maximum before they begin to die away. After many years of discussion on these points it seems now to be generally admitted that a hurricane may begin in the space between opposing currents from the north and south quite as easily in a region where buoyant air is rising and cloud and rain being formed, because there is a slight diminution of the pressure between such opposing wind currents sliding past each other, a diminution sufficient to induce a slight indraft and the formation of a gentle whirl. As to the maintaining power, however, it still appears likely that the principal source for this must be found in the condensation of moisture, the evolution of latent heat, and the interception of sunshine by the cloud. But we must add to these the further consideration that if the air to the northward is abnormally cold or dry, or that to the southward abnormally warm and moist, then the centrifugal force of the earth's rotation will drive the northerly air toward the equator, while the lighter air, by its buoyancy, is driven northward. Just as centrifugal force acts in separating cream from milk in the separator used in the dairy, while gravity separates the cream from the milk by a slower process in the old-fashioned dairies, so in the earth's atmosphere the heavy air is drawn to the ground by gravity or driven to the equator by centrifugal force, while the lighter air is pushed upward or pushed northward, respectively. The general interchange of air between the polar and equatorial regions is due to differences of temperature, moisture, centrifugal force, and gravity, and is known as the general circulation of the atmosphere. We may therefore say that a whirl, when once started, develops into a hurricane under the combined favorable action of these forces—namely, the general circulation of the atmosphere, the absorption of solar heat by its own clouds, and the formation of cloud and rain with evolution of latent heat by its own internal currents and by the moisture of the air driven into it from without. The relative importance of these three depends upon latitude, and must vary from storm to storm, and from day to day.

[4] A Barometer Manual, M. O. 61, pp. 24-25, London, 1916—8th ed.

[5] *Elementary Meteorology*, p. 206.

[6] Prof. Cleveland Abbe in Mo. WEATHER REV., 32: 373.

Bigelow,[7] although having previously expressed the opinion to the effect that hurricanes were due solely to convective processes, as stated in the *Yearbook of the Department of Agriculture for 1898*, reached the conclusion from a careful study of the surface and upper air currents of the West Indies that a hurricane is built up on exactly the same mechanical principle as a tornado—namely, by the conflict of two currents flowing together from different directions and having different temperatures, only the hurricane is much deeper than the tornado, the hurricane forming a tube from 4 to 6 miles in height, while the tornado tube seldom exceeds 1 mile in height and that between them, the countercurrents, at the height of about 1 mile, a vortex tube is formed, which, by its gyratory action, extends downward through the lower strata, which latter must be in a more or less quiescent state or else drifting slowly eastward from top to bottom.

In the China Sea and the waters to the east-southeast the atmospheric environment is not dissimilar to that of the West Indies, and hence expressions concerning the formations of typhoons (cyclones) in these regions may be considered as applicable to the West Indies. Doberck[8] expresses the opinion that typhoons are generated by countercurrents, while Father Algué,[9] after reviewing the convective and countercurrent theories and quoting Prof. Julius Hann thereon, remarks on the supposition that the origin—that is to say, the primary factor of some cyclones—is precisely the action of opposing currents, originated by the thermal conditions of the atmosphere or by other causes, whose immediate effect is the whirl, from which comes the barometric depression and the consequent alteration of the atmospheric equilibrium which produces the convergent currents. He remarks that in such cases the convergent currents would subsist even though the opposing currents had disappeared, leaving the whirlwind thus formed by virtue of the general causes, just as if it had been formed by the condensation of aqueous vapor over a large area. This process, in his opinion, seems to account for the origin of many of the cyclones of the China Sea.

There has recently been given us a new conception of the part that these more than local wind systems play in the formation of cyclones as set forth by Dr. V. Bjerknes in his theory of the polar front. Of course this theory is made applicable to the extratropical cyclones, but nevertheless it is suggestive in connection with efforts to explain the genesis of the tropical cyclone. In the report of the proceedings of the seventh meeting of the International Commission for the Investigation of the Upper Air [10] he says that the analysis of the daily synoptic charts from the viewpoint of the "life history" of the different air masses has lead to the polar-front theory. According to this theory, the successive cyclones of the temperate zones are waves on the boundary surface between the cap of polar air and the surrounding warm air masses, the corresponding boundary line at the ground, "the polar front," accordingly traversing the centers of depressions around the pole. The extreme northern ends of the warm waves coincide with the centers of low pressure and the cold waves of polar air between them constitute the moving wedges of high pressure. He also says that an examination of depressions individually from their formation to their disappearance shows that young depressions correspond to slight waves with small excursions from the equilibrium state, and that later the amplitudes increase simultaneously with a deepening of the depression.

According to Dr. Anders Ångström:[11]

> The latest researches in regard to the constitution of the atmosphere in cyclones and anticyclones have more and more led to an increased realization of the importance of surfaces of discontinuity. The cold and warm currents, which seem to be general constituents and important agents in the cyclones, are separated by relatively sharp boundaries, characterized by sudden changes in temperature, humidity, and wind direction. The examination of the synoptic charts giving the conditions round the north European cyclones have in this point in general supported the ideas put forward by Dove, Bigelow, Margules, Exner, v. Ficker, and Bjerknes. * * * As in many fields of natural research, we are also in dynamic meteorology passing from the belief in the continuity of natural phenomena to an opposite view, where discontinuity prevails.

There have appeared from time to time in the literature on cyclones other than these two principal hypotheses—the convective and the countercurrent—but they have not been given more than passing attention. Now, from what has been stated it would seem that the cause of the origin of the tropical cyclone may be found in the countercurrent theory as to initiation of the cyclonic center, while the convective theory accounts for its maintenance after having started. This conclusion is reached after a consideration of what seems to be the facts in the case. We know that convection is going on more or less generally, but it appears that over the regions where convection is in operation the air does not rise *en masse*, but in filaments, and the visible result is the formation of cumulus clouds and their attendant phenomena, such as local showers, local thunderstorms, and local vortices of a small diameter. It is a common observation, as shown by the daily weather maps, that cyclones do not develop in these areas; moreover, regions of excessively high surface temperature are not places where cyclones are ordinarily formed, rather they form on the borders of such regions. Furthermore, it is difficult to visualize local superheating over the wide expanses of water where tropical cyclones form. Again, if convection were the primary cause of the origin of cyclones we should expect to find them of maximum frequency over the calm belts of the Tropics where there is a superabundance of water vapor and relatively high temperatures over large areas. We should not expect to find, if convection were the cause, the belt of maximum frequency of cyclones the world over in midwinter and along the border of the region of polar night. (See fig. 1.)

The diagram (on next page) has been prepared from the data of storm frequency shown by Chart 52, *Bulletin A*, Weather Bureau, a summary of international meteorological observations for the years 1878 to 1887, inclusive. Each column represents the number of cyclone centers observed at noon (Greenwich time) in the respective circumpolar belts of 5° in width. For example, between latitudes 45° and 50° there were observed during the period of 10 years cyclone centers to the number of 8,088. It is not to be inferred that no cyclones escaped detection during the 10-year period of observations, but it is to be assumed that the diagram represents the *relative latitudinal frequency* of cyclones for the Northern Hemisphere.

The temperature distribution, at least at the surface, in the tropical cyclone is seemingly one of but minor variations in the several quadrants of the cyclone, while

[7] Results of nephoscope observations in the West Indies during the years 1899-1903 Mo. WEATHER REV., April, 1904, pp. 166-169.
[8] The Law of Storms in the Eastern Seas. *Hongkong Observatory, No. 3*, Hongkong, 1898.
[9] *Cyclones of the Far East.*
[10] Publication of the Int. Met. Com. printed at Bergen, July, 1921.
[11] Forecasting of Dynamical Changes of Temperature. *Geografiska Annaler, 1921*, H. 3.

in the extratropical cyclone the temperature distribution appears to be different for different regions. In Europe the center, as previously stated, is found to be cold; in the United States east of the 95th meridian the eastern half is warm and the western half cold, while the surface temperature distribution of the cyclones of winter of the North Pacific coast strongly points to a cold front and a warm rear. From this we infer that the temperature distribution, inextratropical cyclones at least, is one purely dependent on whence came the air imported into the cyclonic area.

Now, with regard to the theory that cyclones arise from interactions between the currents arising from the general wind system, there seems to be much in its favor. Bigelow in his studies of the circulation of atmosphere over the West Indian waters, previously referred to, shows that such currents, which he has designated countercurrents, are commonly found. In fact, all regions of maximum frequency of tropical cyclones are bounded by oppositely directed currents of air, and, as stated by

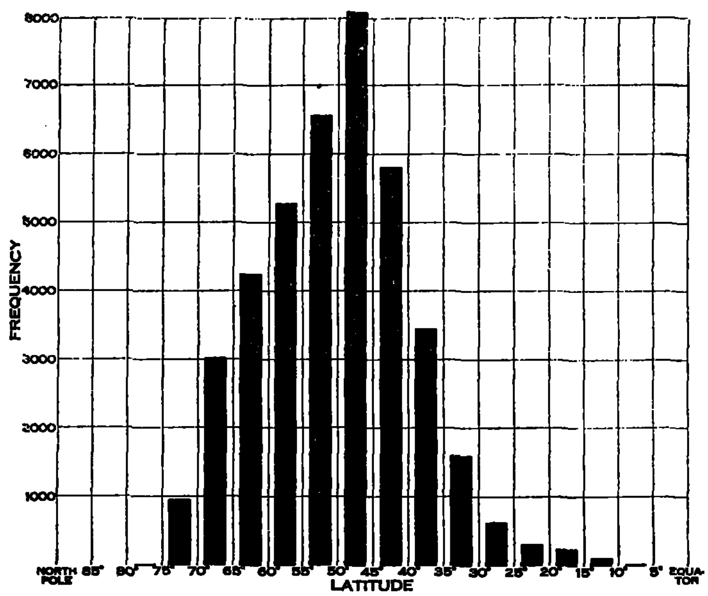


FIG. 1.—Latitudinal variation of cyclone frequency.

Abbe, Bigelow, Algué, Bjerknes, Meldrum, and other writers, it is reasonable to assume that they may have to do with the genesis of a cyclone.

The following by Sir Napier Shaw [12] is suggestive and points directly to the countercurrent theory as containing the explanation of the origin of cyclones and anticyclones:

> It is curious, but undeniable, that when a westerly current has an easterly current upon its southern side, the two show no disposition to mix, except possibly to produce fog; they keep an undisturbed anticyclonic region between them as a sort of buffer state. If the westerly current has an easterly current on its northern side, quite the opposite state of things results—the two currents engage one another forthwith, and a circular storm results. Doubtless the consequences are in accordance with the principles of circulation laid down by Prof. V. Bjerknes (MONTHLY WEATHER REVIEW, October, 1900), but to those unfamiliar with the reasonings of hydrodynamics they must seem rather mysterious.

It is altogether probable that these countercurrents obey the law of Buys Ballot to the effect that if one stands with his back to the wind the barometric pressure decreases toward his left and increases toward his right in the Northern Hemisphere, and the reverse in the Southern Hemisphere. This law is a necessary consequence of the influence of the earth's rotation, and it is generally accepted. Now, we can go further with this law as a basis and say without fear of contradiction that countercurrents will and must maintain a belt of high or relatively high barometer between them when they pass to the left of each other and a belt of low or relatively low barometric pressure between them when they pass to the right [13] of each other. The difference in barometric pressure from high to low will depend primarily on the width of the countercurrents, the velocity of flow, and the latitude. The only exception to this statement will be found in the equatorial region in the Middle Atlantic and Middle Pacific Oceans, where the northeast and southeast trades merge and flow onward as an easterly wind and without an intervening region of calms. In this case the combined system of winds is subjected to (1) the right-hand deflective influence of the earth's rotation of the Northern Hemisphere for that part of the current actually in the Northern Hemisphere and (2) the reverse for that part of the combined current flowing westward in the Southern Hemisphere. Hence we have the anomalous situation, found nowhere else, of a tendency toward low pressure in the midst of an onward flowing river of air.

Generally these countercurrents and the barometric gradients are in what may be considered to be perfect balance, but it requires no great stretch of the imagination to understand that this is not necessarily always so. If in the case of countercurrents passing to the right the balance is disturbed, we would expect in the case of countercurrents too strong for their gradients a further pulling apart, a diminution or rarefaction of the air aloft over the intervening belt of already low or relatively low pressure and calms, and a welling up of the stratum near the earth's surface. As the welling-up process goes on, the denser air from the contiguous regions flows inward toward the region over which the air has become rarefied, and gyratory motion will necessarily follow from the deflective influence of the earth's rotation. Moreover, the welling-up process will bring about condensation of water vapor and thus an added impetus will be given the incipient cyclonic formation, and as this condensation goes on as fresh vapor-laden air is brought into the cyclonic area energy for its maintenance will always be at hand.

THE MOVEMENT OF HURRICANES.

The student on examining the paths of hurricanes for a considerable number of years, for any given month, plotted on a single chart, must be impressed by the seeming indifference of hurricanes to follow any well-defined path or paths. The plotted paths show no inclination to converge on any given locality. No two hurricanes follow parallel paths throughout their courses from time of origin to time of disintegration. Tracks cross and recross and recurve here and there without seeming to obey any physical law. A considerable number of the plotted tracks show no recurve, and consequently these hurricanes did not pass into high latitudes; and, again, loops are noted in a few of the tracks where seemingly sudden and decided changes in the forces which propelled the hurricanes took place. From what has been stated it will be readily seen that a single track to represent an average path for a given month is of no particular value as an aid to the forecaster in determining the path a

[12] Shaw, Sir N.: *Forecasting the Weather*, p. 286.

[13] In the Northern Hemisphere the pressure is relatively low between east and west currents when the west current is south of the east.—*E. H. B.*

hurricane will follow. Moreover, a consideration of the plotted tracks unaccompanied by synoptic charts of pressure, winds and clouds will not be of material aid to the student in his endeavor to unravel and set forth the laws which control the movement of hurricanes. Synoptic charts of pressure, temperature, surface winds, free-air winds, and clouds over wide areas are essential to research problems associated with tropical cyclones. We must look beyond the immediate environs of the cyclone to determine the cause of its being as well as its direction and speed of progression.

Now while there may be considerable diversity of opinion as to exactly how the hurricane has its origin, there seems to be unanimity of opinion as to the cause which controls the hurricane in its movement along its track. The translation of the hurricane is commonly attributed to the general motion of the air over the region, in which the hurricane is found, but even here there is a difference of opinion as to the exact operation of the propelling winds. According to the late Dr. Julius von Hann [14] the influence that a prevailing general current of air exerts upon the progress of a whirlwind that has entered into it evidently consists in this, that the masses of air drawn into the whirlwind have to follow two impulses: One, that which is due to the whirl, and the other, that which is due to their original movements. Therefore, in the region of the trade winds and on the northwest side of a whirl, the motions are most accelerated, but on the opposite side most retarded, and thereby the whirl must receive a tendency to progress toward the northwest. "I believe," says he, "in its principal feature this agrees also with Lommel's theory of the recurving of the paths of cyclones on their leaving the trade-wind system."

The recurve of storms in the West Indies, and over the Gulf of Mexico, according to Weather Bureau *Bulletin A*, is dependent upon general meteorological conditions, and more especially upon the distribution of atmospheric pressure. The anticyclone or high-pressure area of the North Atlantic Ocean lies northeast of the West Indies, and causes east to northeast winds over the southern part of the ocean and the Caribbean Sea. The storms (hurricanes) which develop in the region east of the West Indies, and also those of a more westerly origin, have a tendency to follow the course of the main equatorial current over the Caribbean Sea. This course is doubtless largely influenced by the general drift of the atmosphere in that region, and following the anticyclonic circulation of the winds the hurricanes skirt the western quadrants of the Atlantic high area, and, carried by the general drift of the atmosphere, follow paths which recurve north and northeastward near the southeastern coasts of the United States. As a majority of the hurricanes traced followed the course indicated, it may be considered the usual course of West Indian storms when the average meteorological conditions obtain over the southern and southwestern North Atlantic Ocean and the eastern part of the United States. Some of the more important storms that originate near the West Indies do not recurve, but move westward over the Gulf of Mexico and dissipate over Mexico or the Southwestern States. In such cases high barometric pressure apparently prevents a recurve.

Garriott [15] in his study of tropical storms of the Gulf of Mexico and Atlantic Ocean, in September, says it may be assumed that with a nearly normal distribution and movement of atmospheric pressure September cyclones will recurve near longitude west 80° and between latitudes north 25 and 28°. He also says that when a cyclone is central east of Cuba and an area of high pressure is advancing eastward over the Gulf and South Atlantic States, the cylcone will probably recurve east of the Bahamas; when the cyclones reaches central Cuba or longitude west 80°, and an area of high pressure is advancing over the west Gulf and Southwestern States, the cyclone will probably recurve over Florida or the east Gulf; when the cyclone reaches the 75th meridian and an area of high pressure is overspreading the interior and eastern districts of the United States with stationary or falling barometer over the west Gulf and the Southwestern States, the cyclone will probably advance westward over the Gulf of Mexico.

Maxwell Hall [16] states that no cyclone is an isolated phenomenon; it is always related to the general distribution of pressure in the latitudes where it is generated, and that the concentric circles, which are usually drawn to represent a cyclone, ignore the fact that a cyclone is always connected with and controlled by some adjacent area of high pressure.

It is a generally recognized principle in weather forecasting that in the Northern Hemisphere a cyclone moves so as to keep the area of high barometer to the right of its course. In what has been said concerning the influence of areas of high barometer in determining the course or path of a cyclone or hurricane, I believe it should be understood that the writers had in mind the currents of air associated with anticyclones and not the actual differences in barometric pressure from cyclone center to anticyclone center, and this is believed to be true despite the fact that the author several years ago [17] in a paper on the movement of cyclones used the actual differences in pressure, but then only in the absence of data concerning the free-air winds over the regions adjacent to the cyclone. It is, too, generally recognized that the position of an anticyclone in relation to the cyclone has a decided bearing not only on the direction of movement but also on the speed of movement of the cyclone.

Assuming that meteorologists generally are in accord as to the influence of the general drift of the major wind currents and the lesser wind currents associated with traveling anticyclones in determining the movements of cyclones or hurricanes, it is essential that the forecaster of such phenomena as attend them should have a clear concept of how this is brought about.

There are printed in connection with this paper Charts 1 to 6, showing the general distribution of pressure attending the movement of the hurricane of August 14 to 17, 1915, across the Gulf of Mexico. It will be noted that the regions of barometric pressure above 30 inches have been shaded to emphasize the relation of the anticyclone to the course of the hurricane. It will also be observed that the path followed by the center of the hurricane was such that high barometric pressure was always to the right of the course the hurricane center followed on any given day. This hurricane was one of unusual intensity during the time it was crossing the Gulf of Mexico, but after crossing the coast line into the interior of Texas its intensity and speed of progression diminished quite rapidly. A further inspection of these charts will show that the center of the hurricane was always on the border of the area of high barometric pressure to the northward, and that as the position of

[14] Hann, J., Über die Beziehungen zwischen den Luftdruckdifferenzen und der Windgeschwindigkeit nach den Theoren von Ferrel und Colding-Zeitschrift der *Oster. Gesell. für Meteorologie,* Marz, 1875, Nr. 6 s. 6.

[15] MONTHLY WEATHER REVIEW, May, 1895, p. 167.

[16] West Indies Hurricanes as Observed in Jamaica, MO. WEATHER REV., 45: 578.

[17] MO. WEATHER REV., 34: 61.

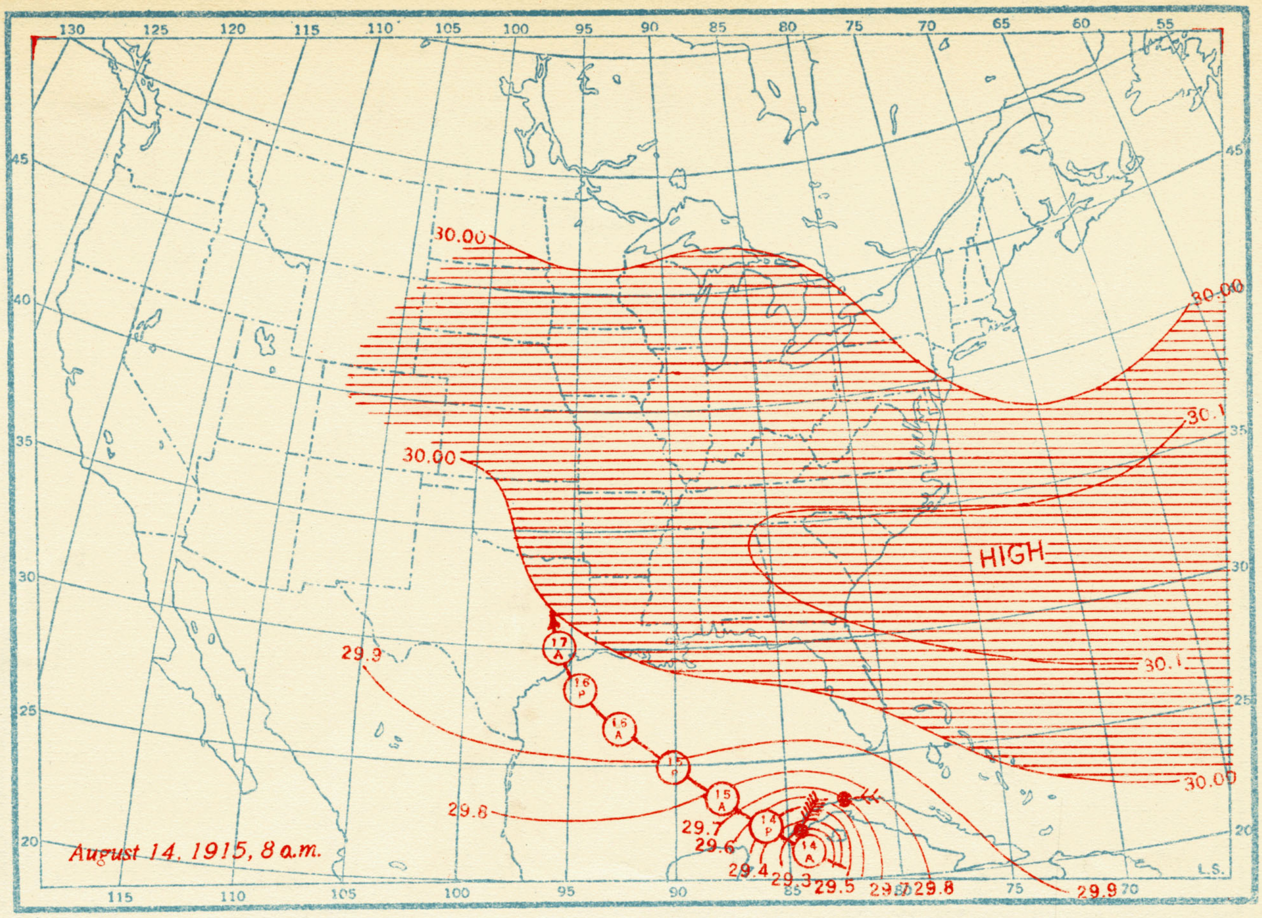
the center of the anticyclone and the general trend of its system of isobars changed these changes were followed by the course of the hurricane. Now the question is: How was this disturbance carried along its track? Disregarding the internal mechanism of the hurricane, are we to assume that the "general drift of the atmosphere" which carried the hurricane onward prevailed over the entire area occupied by the hurricane? Or are we led to assume that the right semicircle of the hurricane was involved in the major wind system flowing along the isobaric system of the adjacent area of high barometric pressure to the northward, and that it was this wind system that carried the hurricane along its course. I rather think this was the case, for it is difficult for me to visualize an eddy of the nature of a hurricane existing in and carried forward in, say, midstream of a wide and deep onward flowing aerial current such as the northeast trades. If we assume that the right semicircle of the hurricane is involved in this major wind system the problem becomes simplified, and at once the source of the power which carries the hurricane onward is seen; also, an explanation is offered of why the winds of the greatest speed are to be found in that semicircle of the hurricane before recurve, where there is a compounding of the cyclonic and anticyclonic wind systems. Where the hurricane is involved in two major wind systems—i. e., when it comes under the influence of the wind system of a traveling anticyclone in addition to the more or less constant wind system of the trades—the resultant of these two systems—considering both their directions and speeds—will presumably determine the direction and speed of movement of the hurricane center.

There are also printed in connection with this paper Charts 7 to 14 of the hurricane of September 7–14, 1919, and Charts 15 to 22 of the hurricane of September 25–28, 1917. Both of these hurricanes were of marked intensity. It will be observed that a reconstruction of the isobars in the immediate vicinity of the hurricane on each of these charts has been attempted—i. e., dotted isobars have been drawn to indicate the probable trend of the isobars had the hurricane not been in existence. Long heavy arrows, marked A, indicate the probable direction of the major wind system along the reconstructed or hypothetical isobars to the northward of the hurricane center. The inner closed isobar indicates the position of the hurricane and the small arrow with broken shaft indicates the movement of the hurricane center in successive periods of 24 hours in the case of the 1919 hurricane and 12 hours in the case of the faster moving hurricane of 1917.

At the time of the occurrence of the hurricane of September, 1919, pilot balloon stations for making upper-air observations of the direction and speed of the wind were in operation at a few points in the South Atlantic and Gulf States. The wind directions observed in the free air above these stations during the 7th to 14th of September, 1919, are indicated, marked B, on these charts. The base arrow indicates the surface direction, the second arrow the direction of the wind at the 1,000-meter level, the third arrow the direction at the 2,000-meter level, and so on to the 4,000-meter level if that was reached. It will be noted that these upper-air wind directions conform to the hypothetical directions of the wind when they are shown for the same regions. The reader should refer to the MONTHLY WEATHER REVIEW of October, 1919, where he will find a detailed account of the sounding observations made in the Southern States while this hurricane was crossing the Gulf of Mexico. The paper is by Mr. R. Hanson Weightman.

Moreover, the pilot balloon observations made at San Juan, Porto Rico, during and after the approach of the hurricane of September, 1921, show the existence of this wind system, and it was in evidence again in October, 1921, at the Key West, Fla., station when a hurricane passed northward through the Yucatan Channel and thence northeastward to the vicinity of Tampa, Fla. Moreover, the hypothesis explains why in the vicinity of Habana, Cuba, as observed by Father Viñes, when the vortex of a hurricane lies to the south-southeast, the cirrus clouds move from south-southeast, the cirro-cumulus from the southeast, the dense cirrus-veil from the east-southeast, the alto-stratus from the east, the low clouds from the east-northeast, and the wind from the northeast. Here we have the turning to the right as height increases; it seems probable that between 3,000 and 4,000 meters in the right front will be found the wind system that corresponds with the direction of advance of the hurricane center. It is believed that the hurricane, half embedded in the trade-wind system, is carried onward by reason of its being thus situated, and that meteorologists in forecasting the movement of a hurricane must consider this a reasonably well established fact, but when two exterior wind systems—i. e., the trade system and that of a traveling anticyclone—pass through the hurricane area the problem becomes more complicated, but it is believed that under these conditions, the direction and the rate of movement of the hurricane center will become the resultant of the two. In the case of a single area of high barometric pressure, fixed in position and magnitude, there is reason to believe that the course of a hurricane would be a simple one—viz, its center would follow the outer isobar with the speed of the wind system then prevalent.

Now reverting to the statements made concerning the endless variety of shapes of hurricane tracks and their seeming disregard of all physical laws, it would appear that these tracks are not haphazard but conform to the changes that take place in the positions and magnitudes of the areas of high barometer and their attendant wind systems. Hence the endless variety of tracks is but a reflection of the endless variety of the changes in the isobaric systems of these high barometric areas at the times the hurricanes were in progress.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29.4
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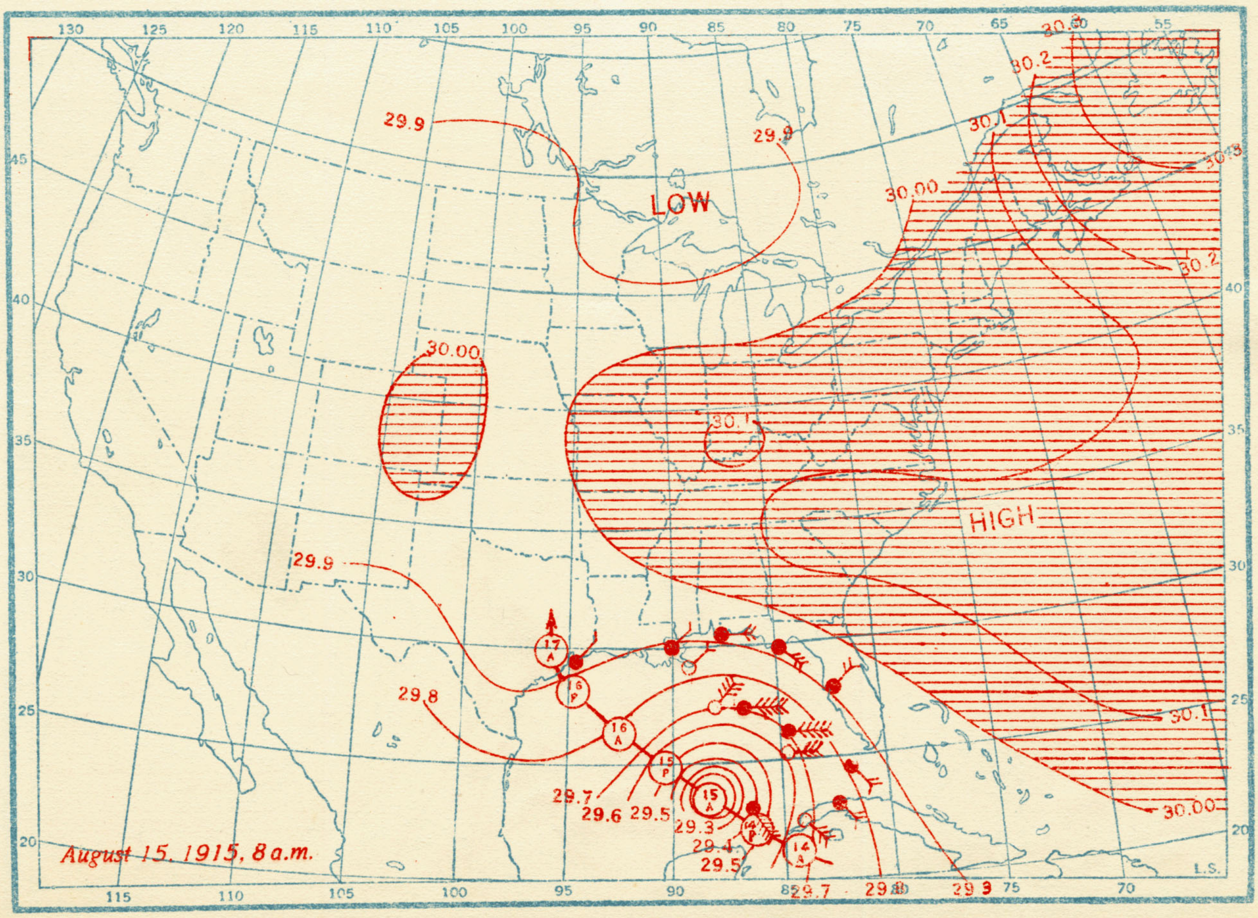
29.5
29.8
August 14, 1915, 8 a.m.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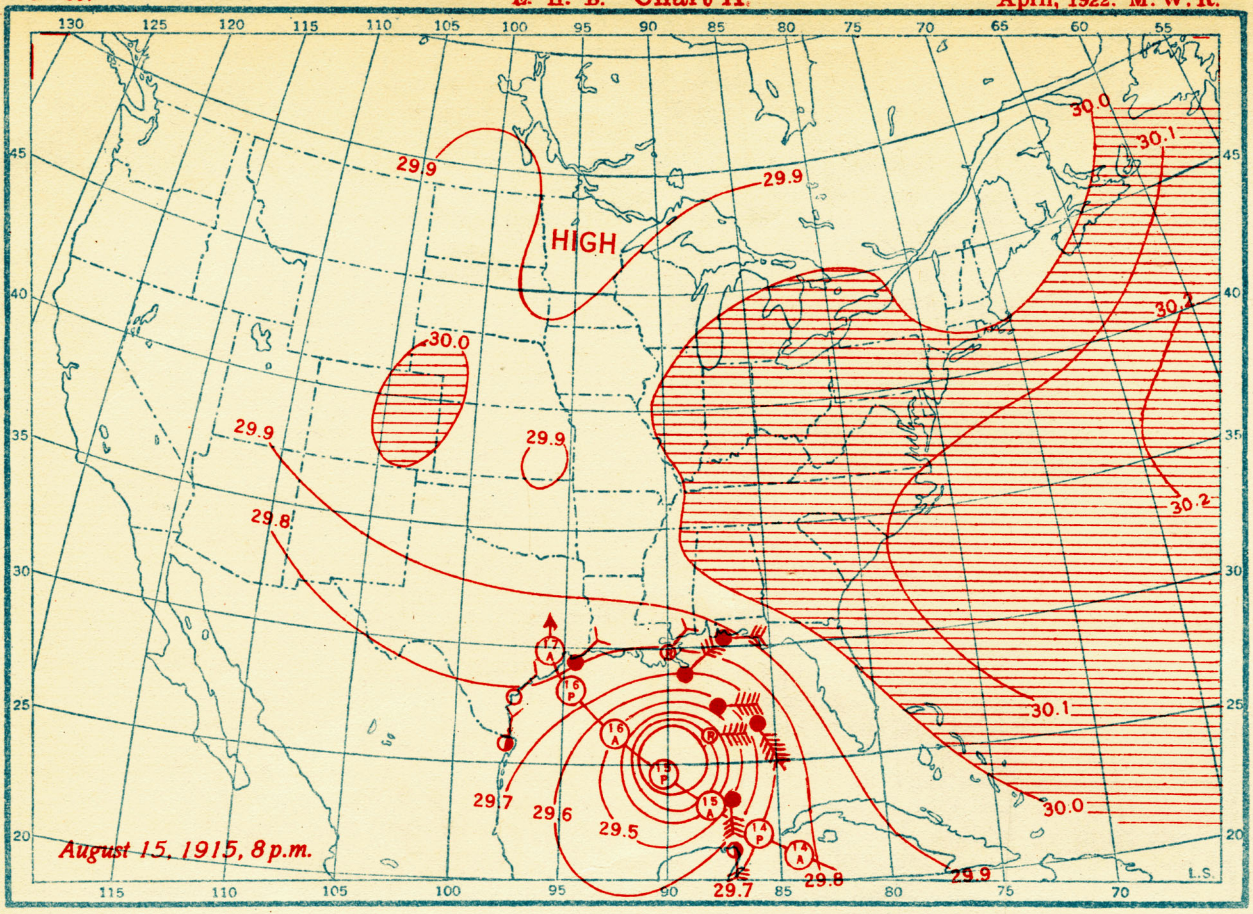
29.3
29.4
August 15, 1915, 8 a.m.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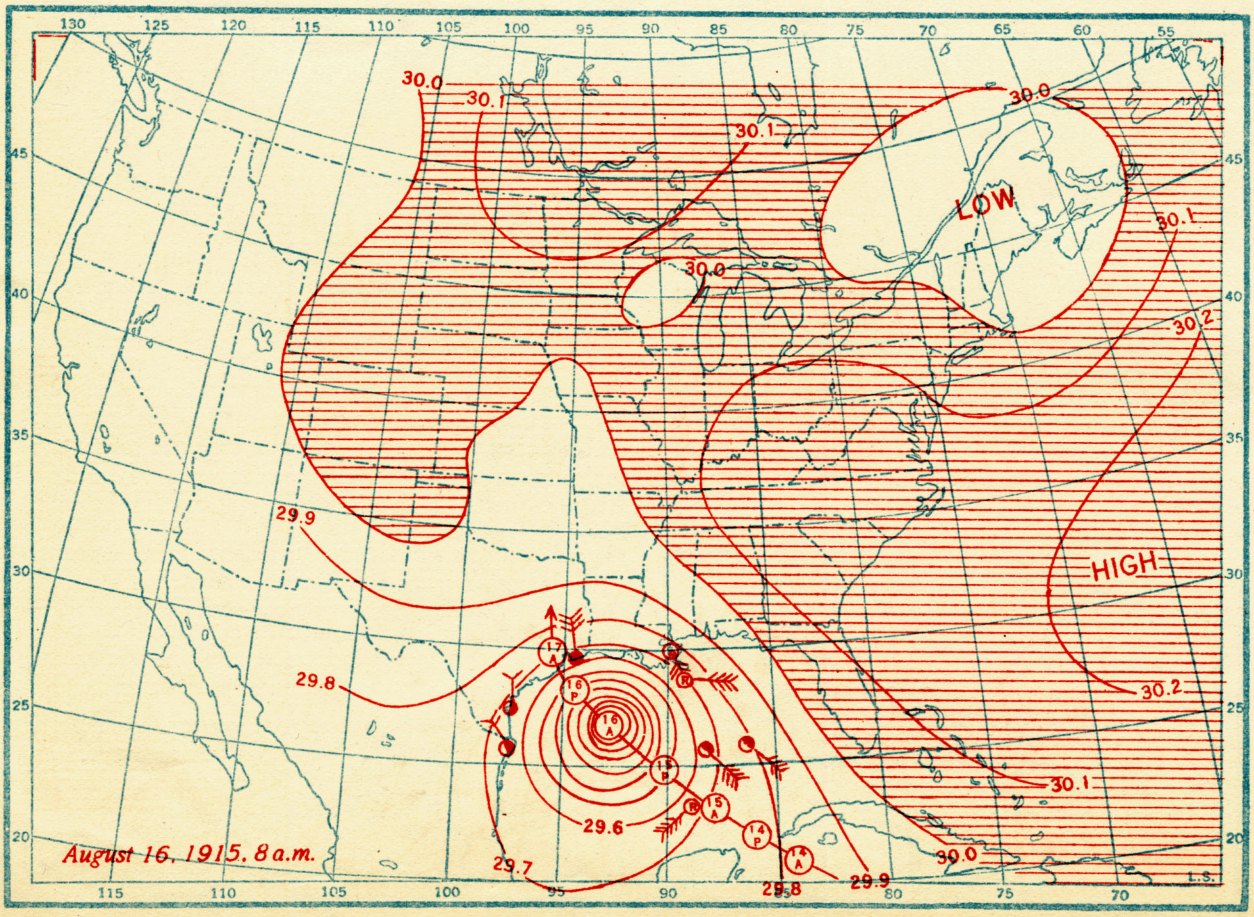
29.6
29.5
L.S.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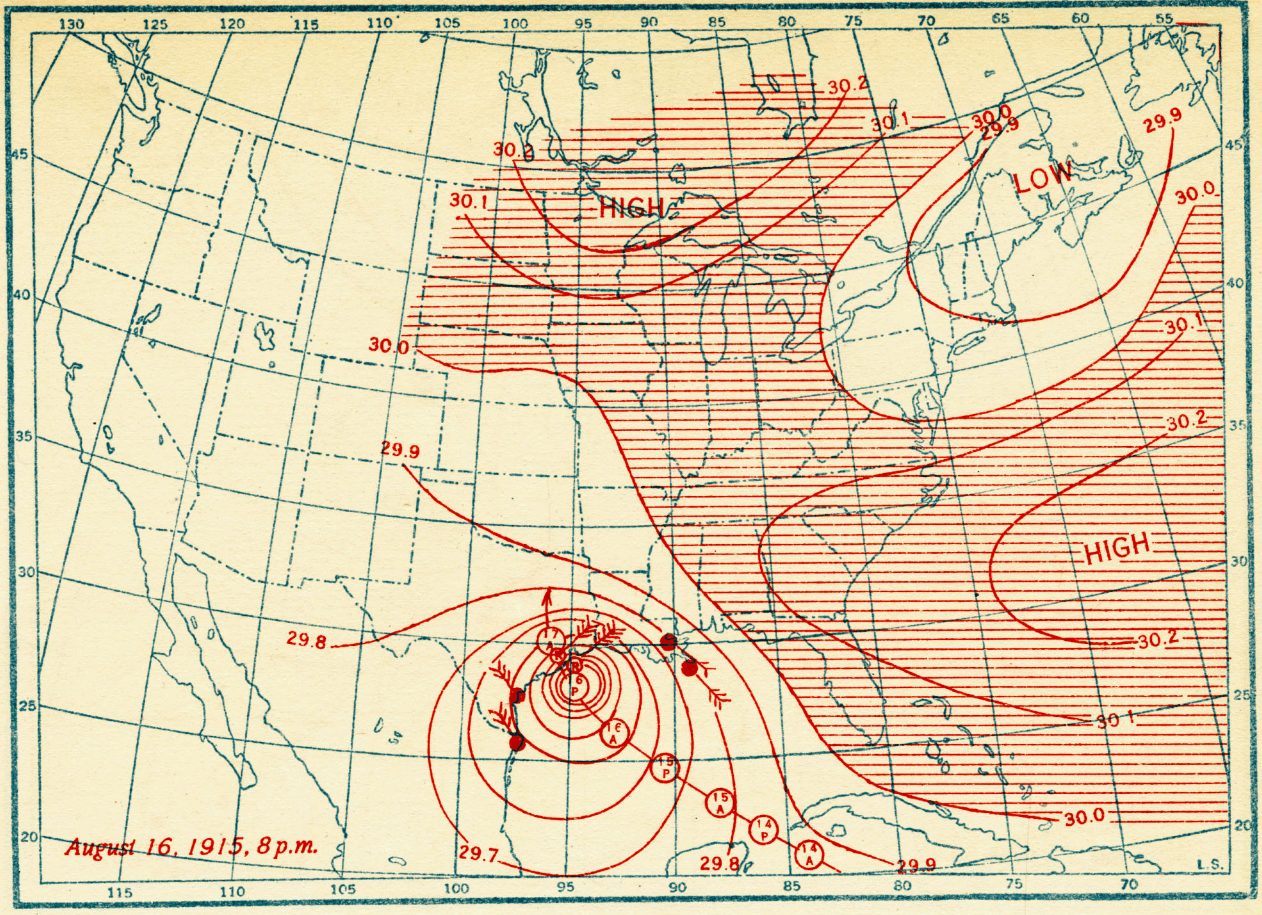
29.7
29.6
L.S.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LOW
HIGH
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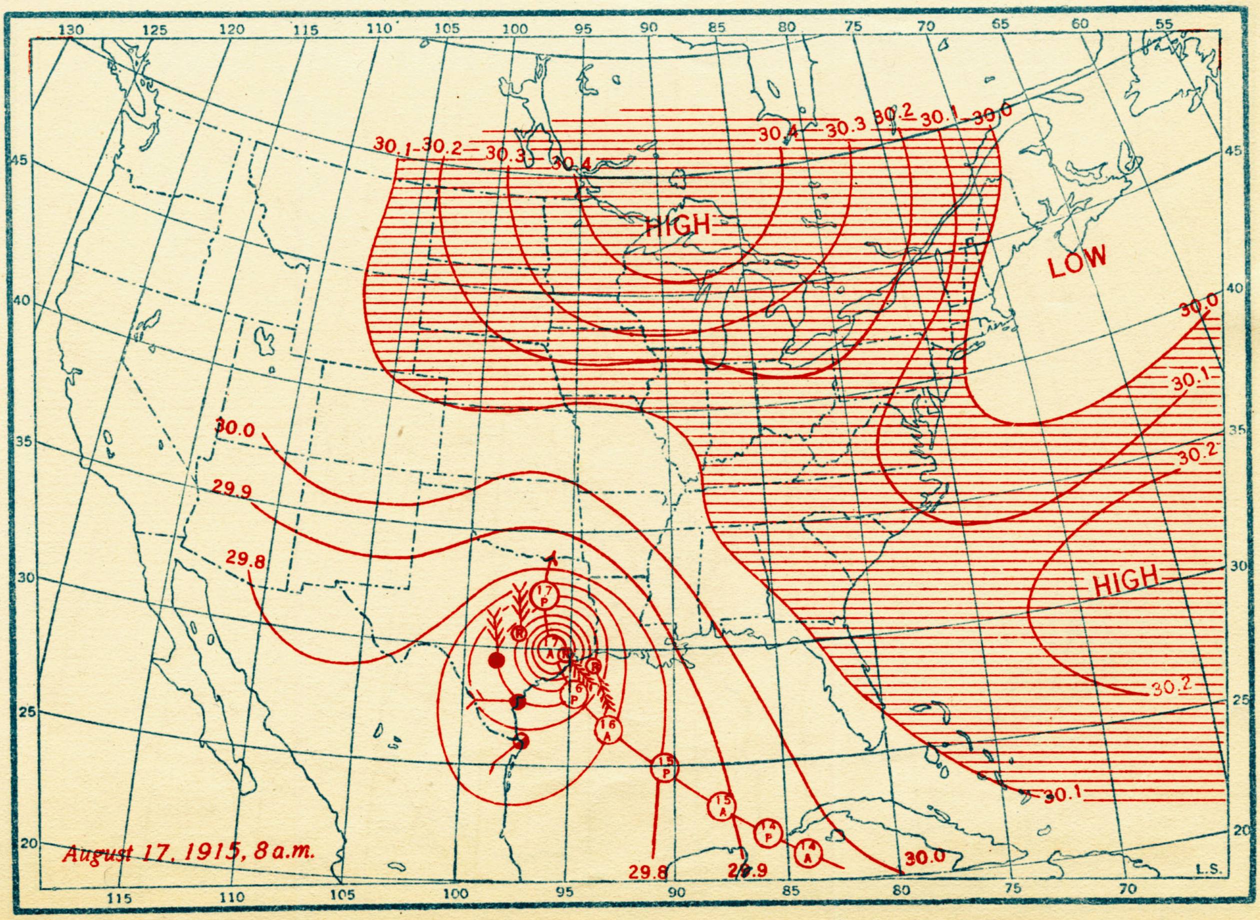
29.7
L.S.
August 16, 1915, 8 p.m.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LOW
HIGH
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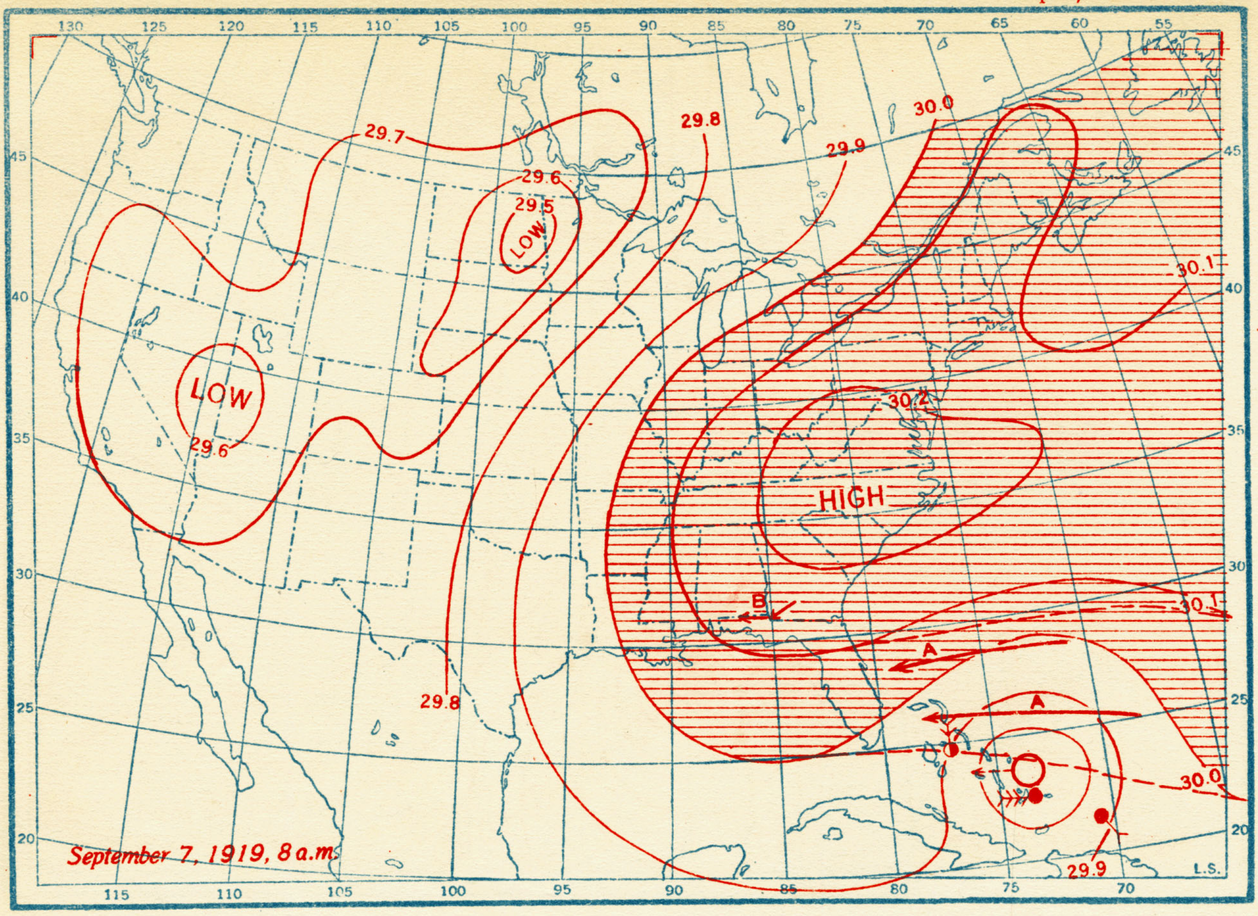
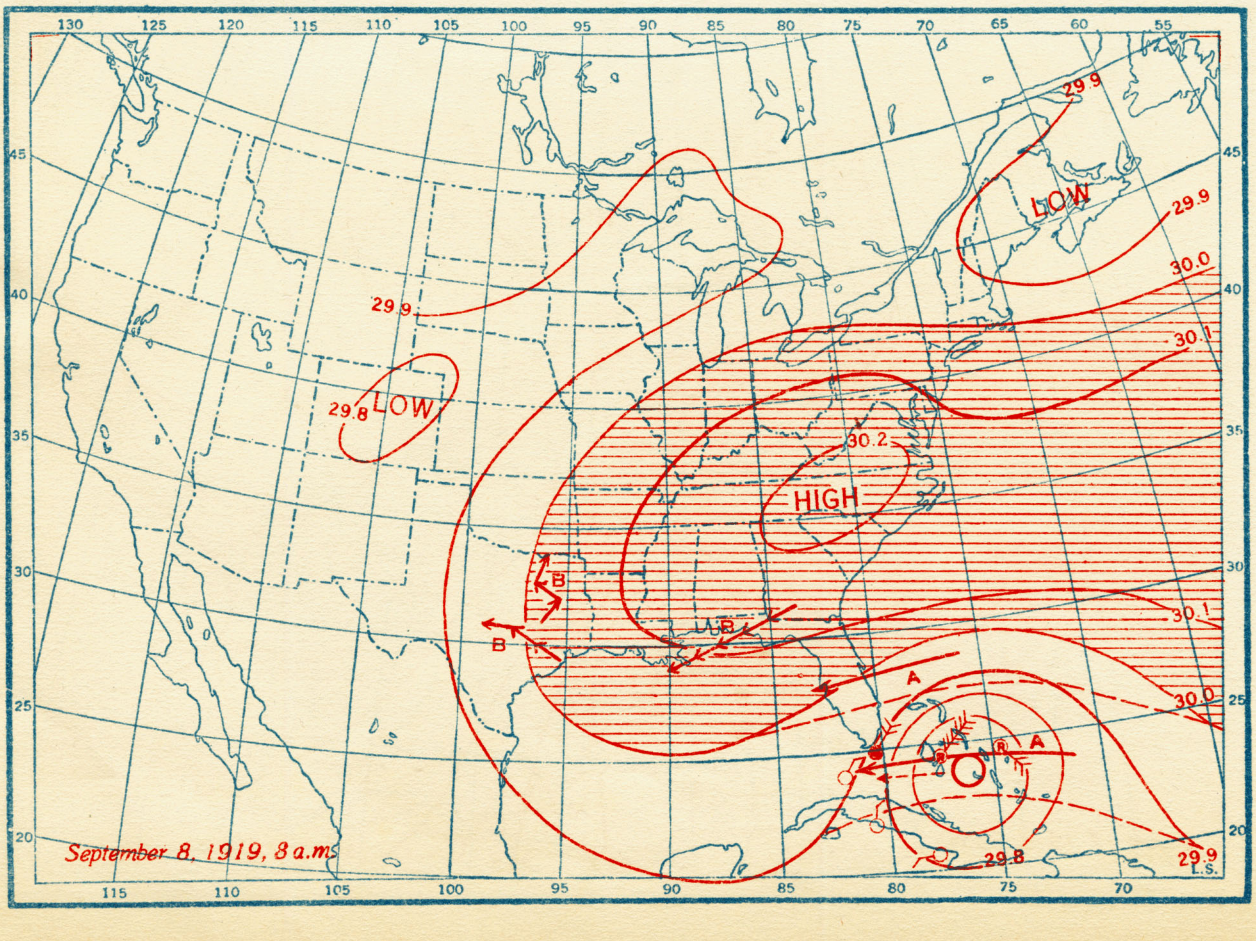
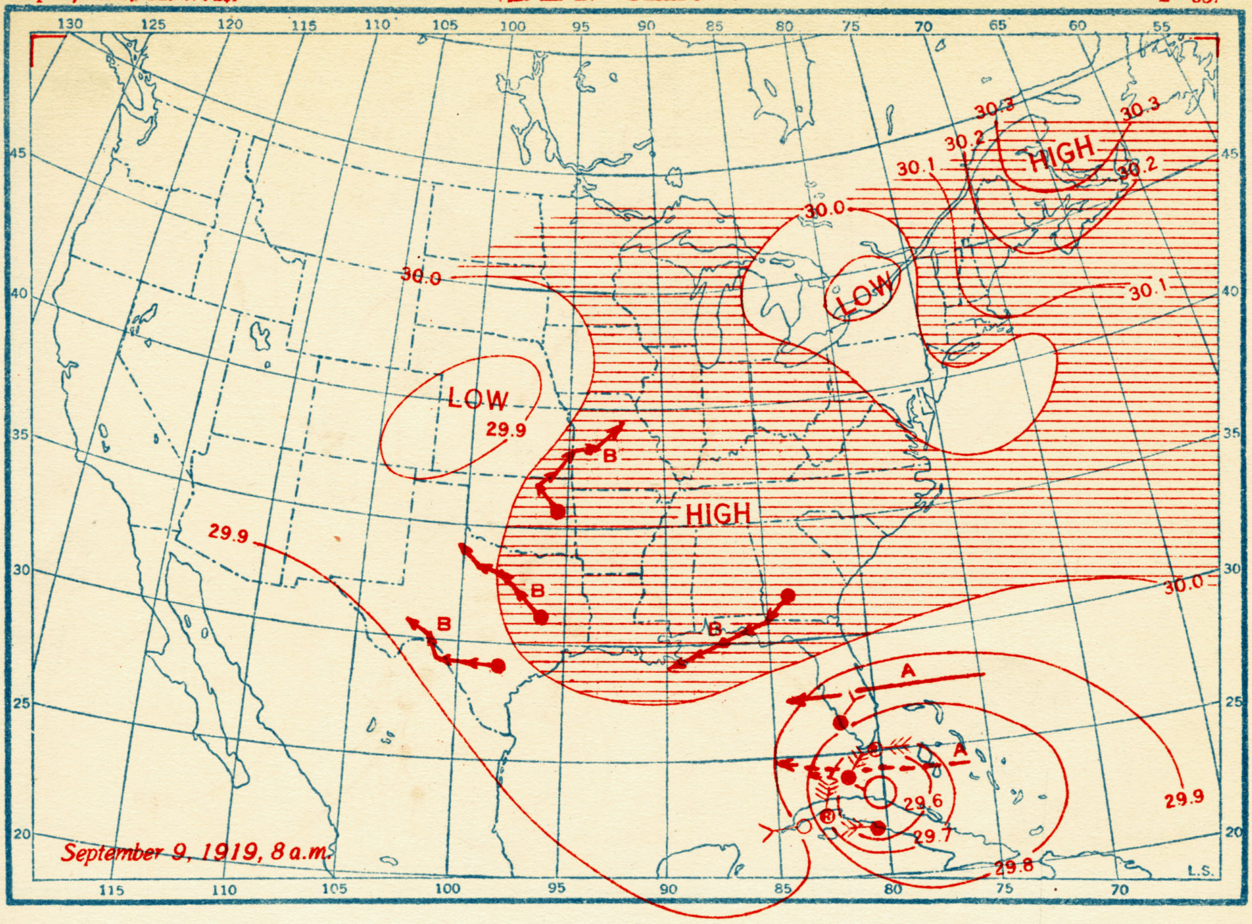
29.8
L.S.
August 17, 1915, 8 a.m.

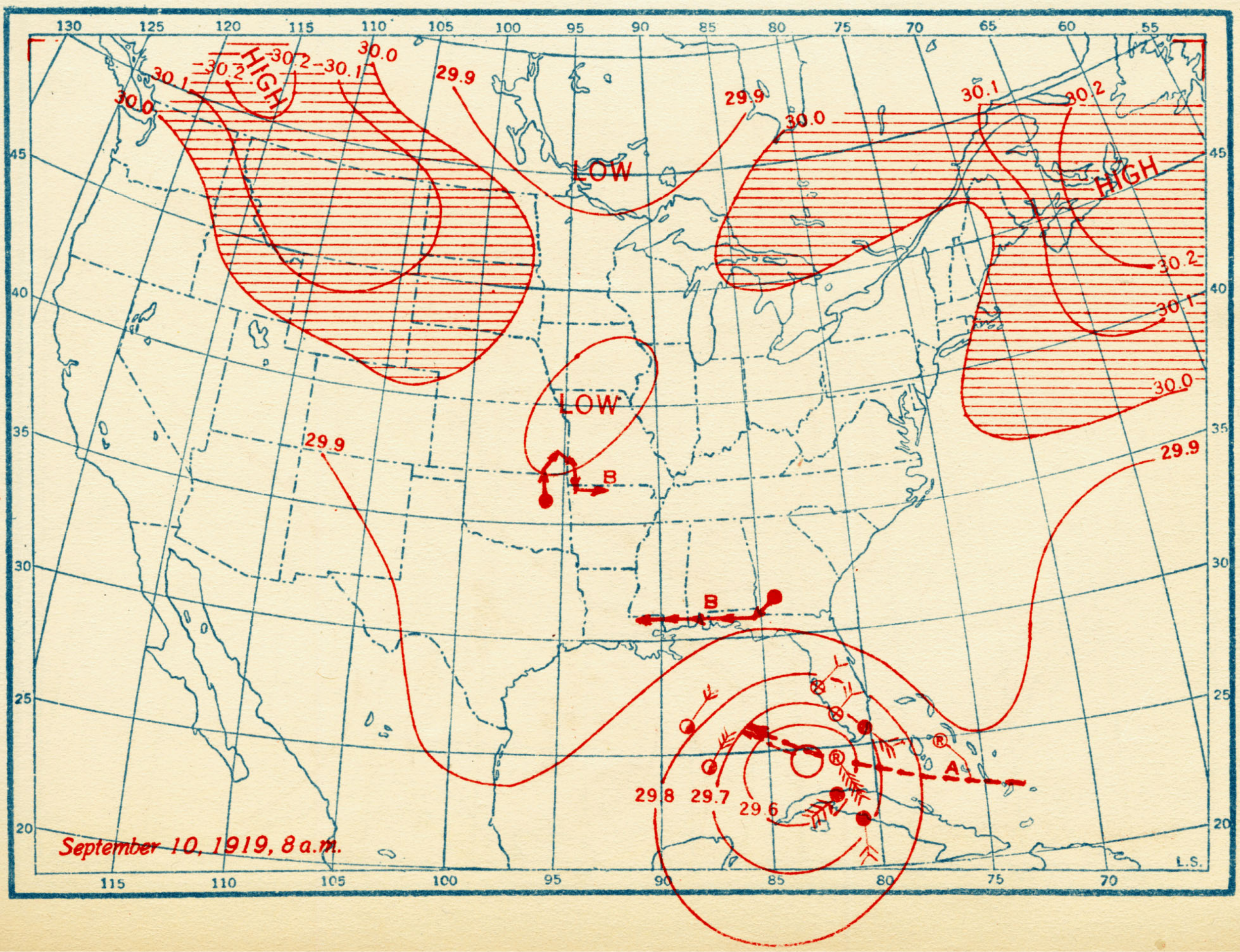


September 7, 1919, 8 a.m.



September 8, 1919, 8 a.m.


HIGH
LOW
LOW
HIGH
30.3
30.2
30.1
30.0
29.9
29.8
29.7
29.6
A
B
L.S.
September 9, 1919, 8 a.m.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LOW
LOW
HIGH
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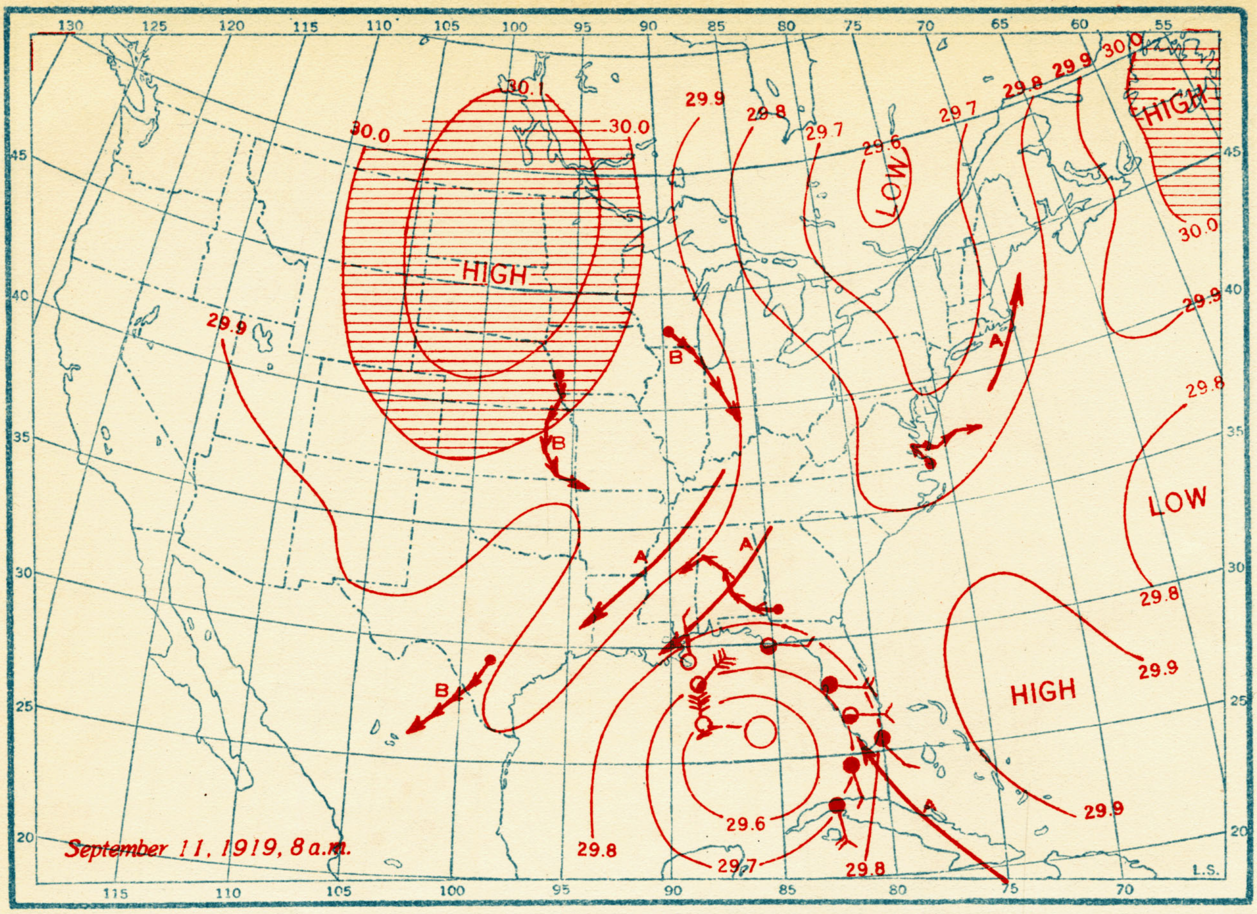
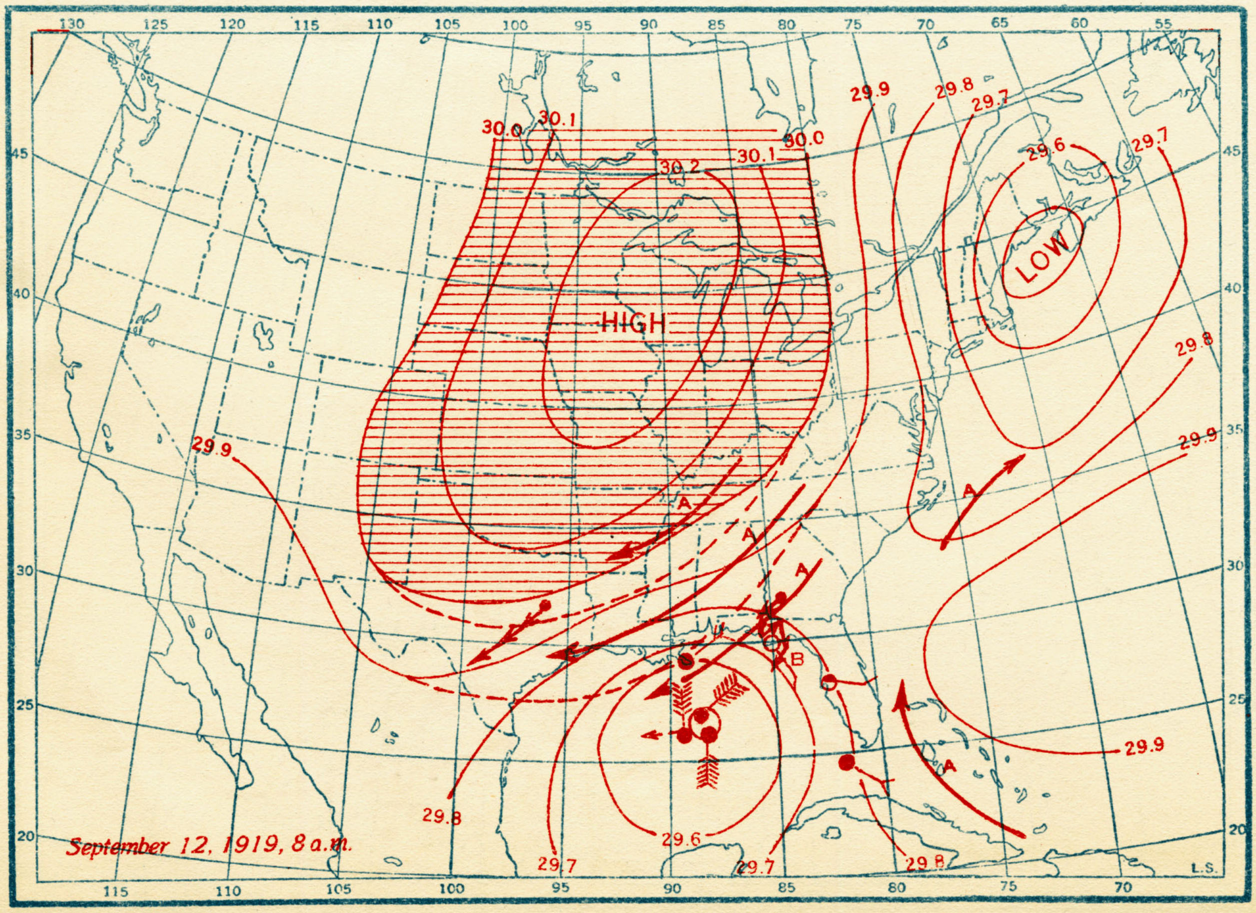
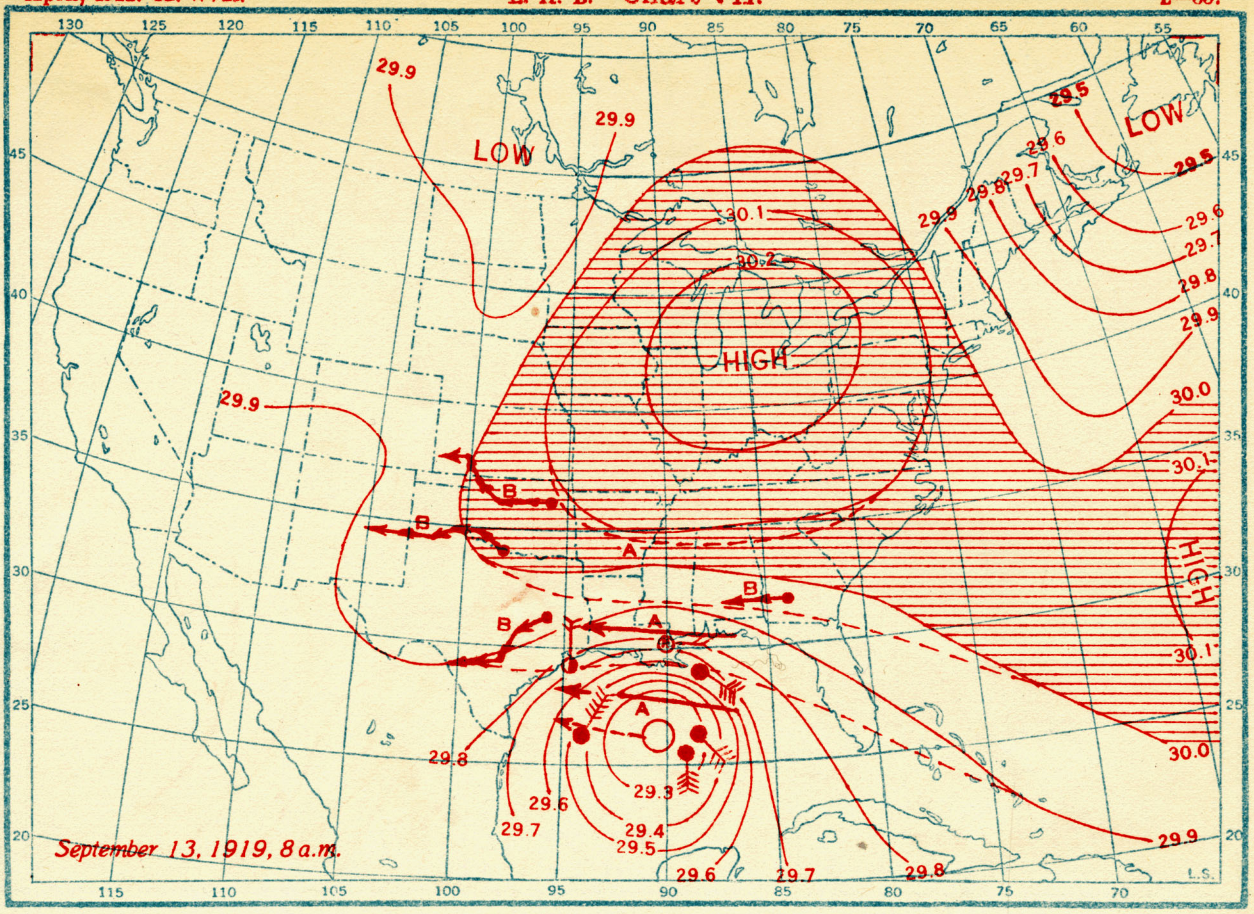
30.0
29.9
29.8
29.7
29.6
A
B
L.S.
September 10, 1919, 8 a.m.



September 11, 1919, 8 a.m.



September 12, 1919, 8 a.m.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HIGH
LOW
HIGH
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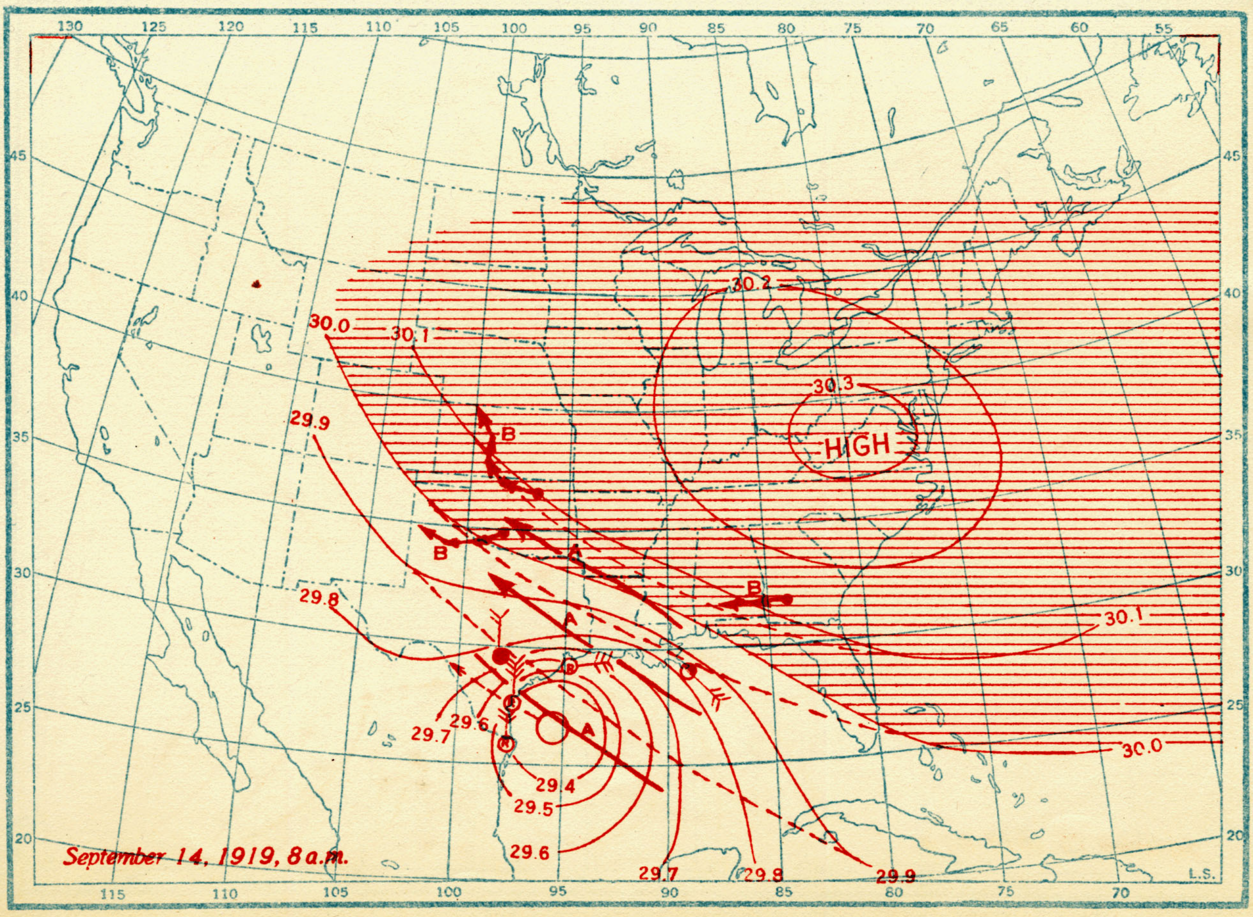
29.6
29.5
29.4
29.3
A
B
L.S.
September 13, 1919, 8 a.m.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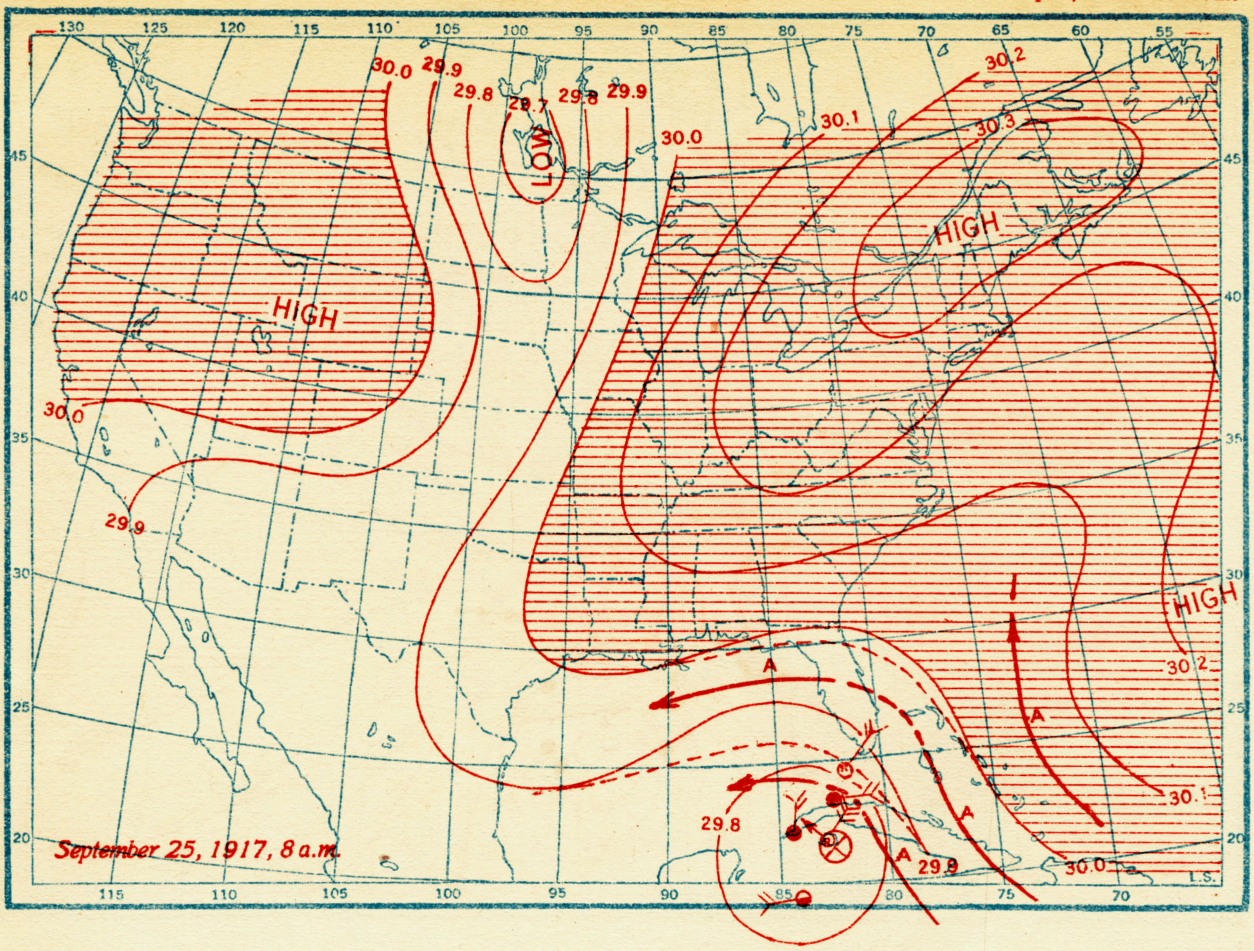
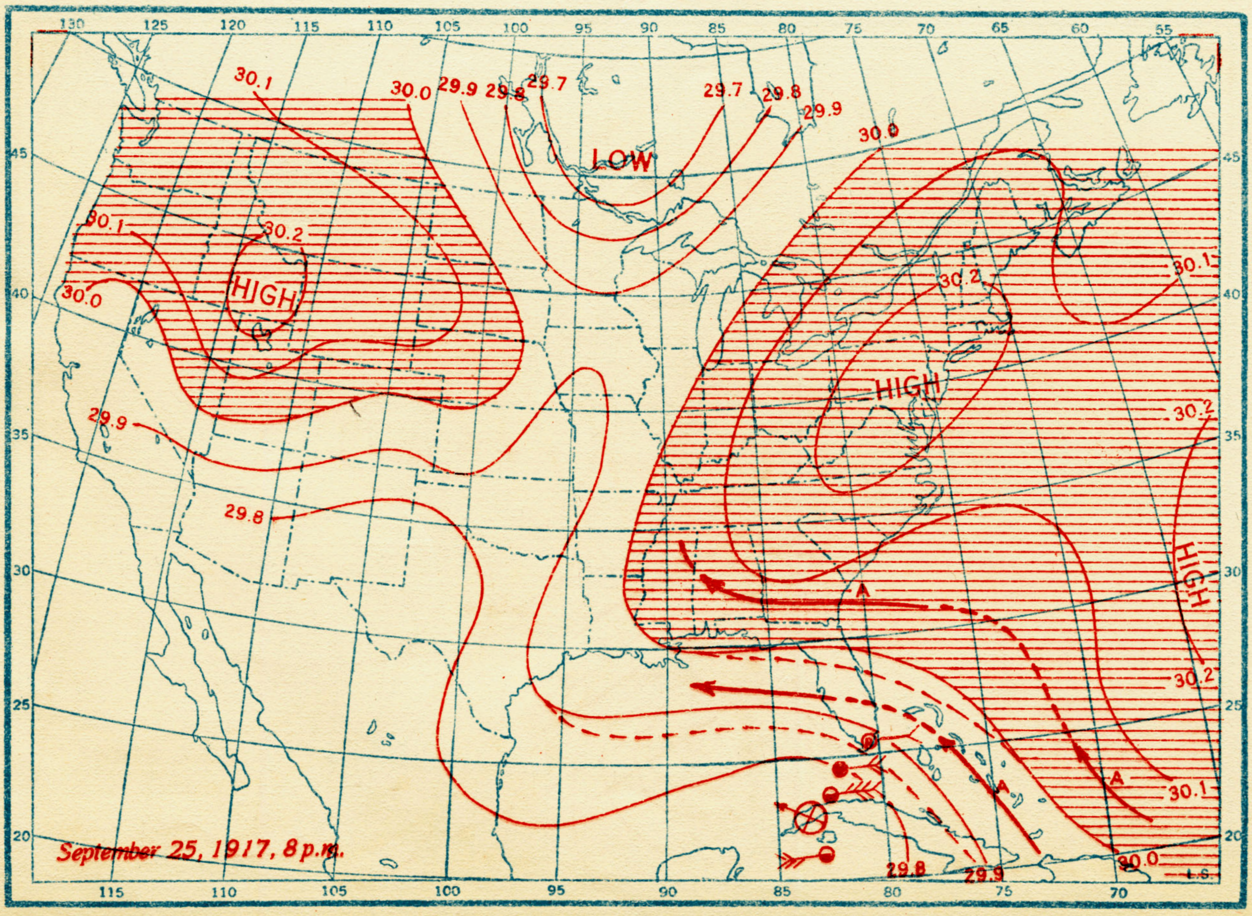
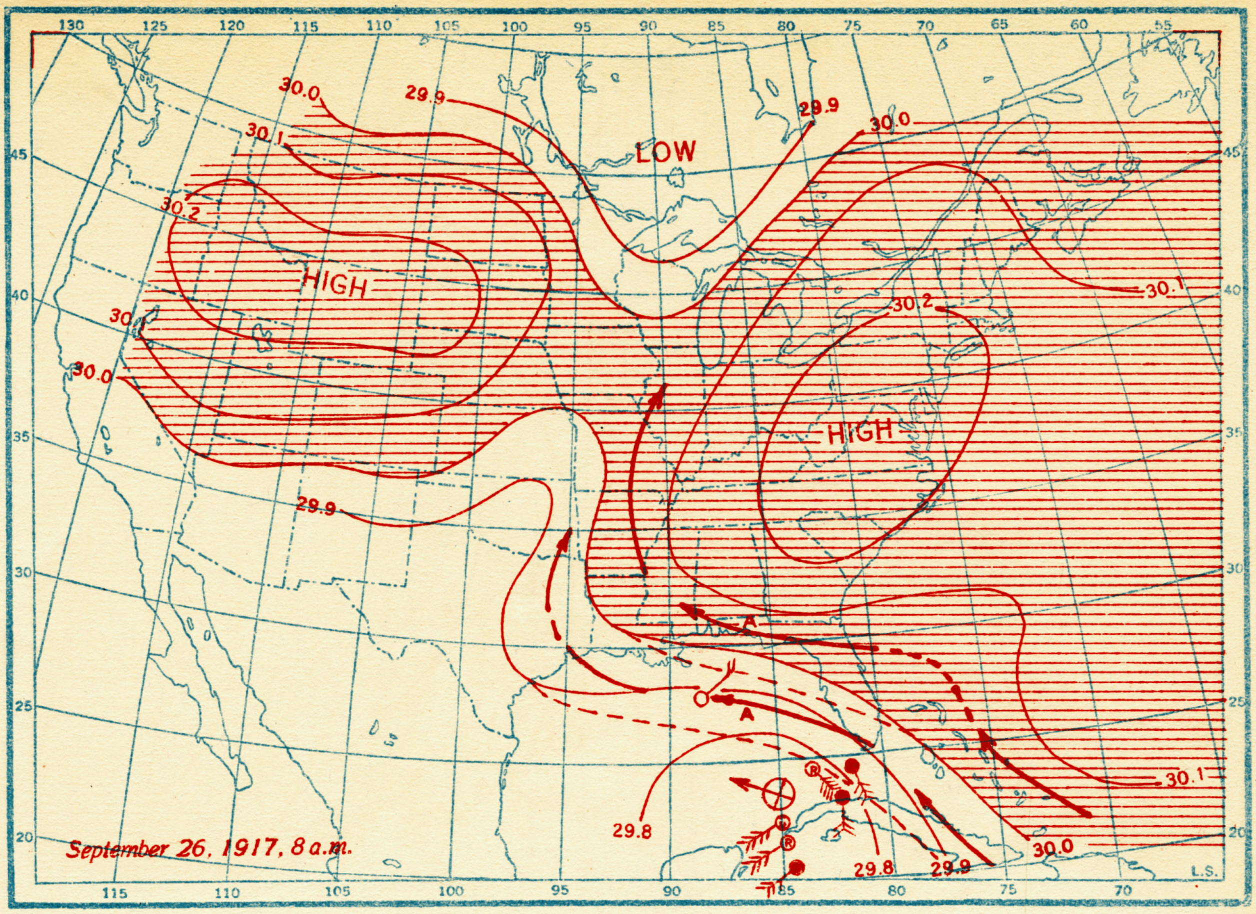
29.4
A
B
L.S.
September 14, 1919, 8 a.m.



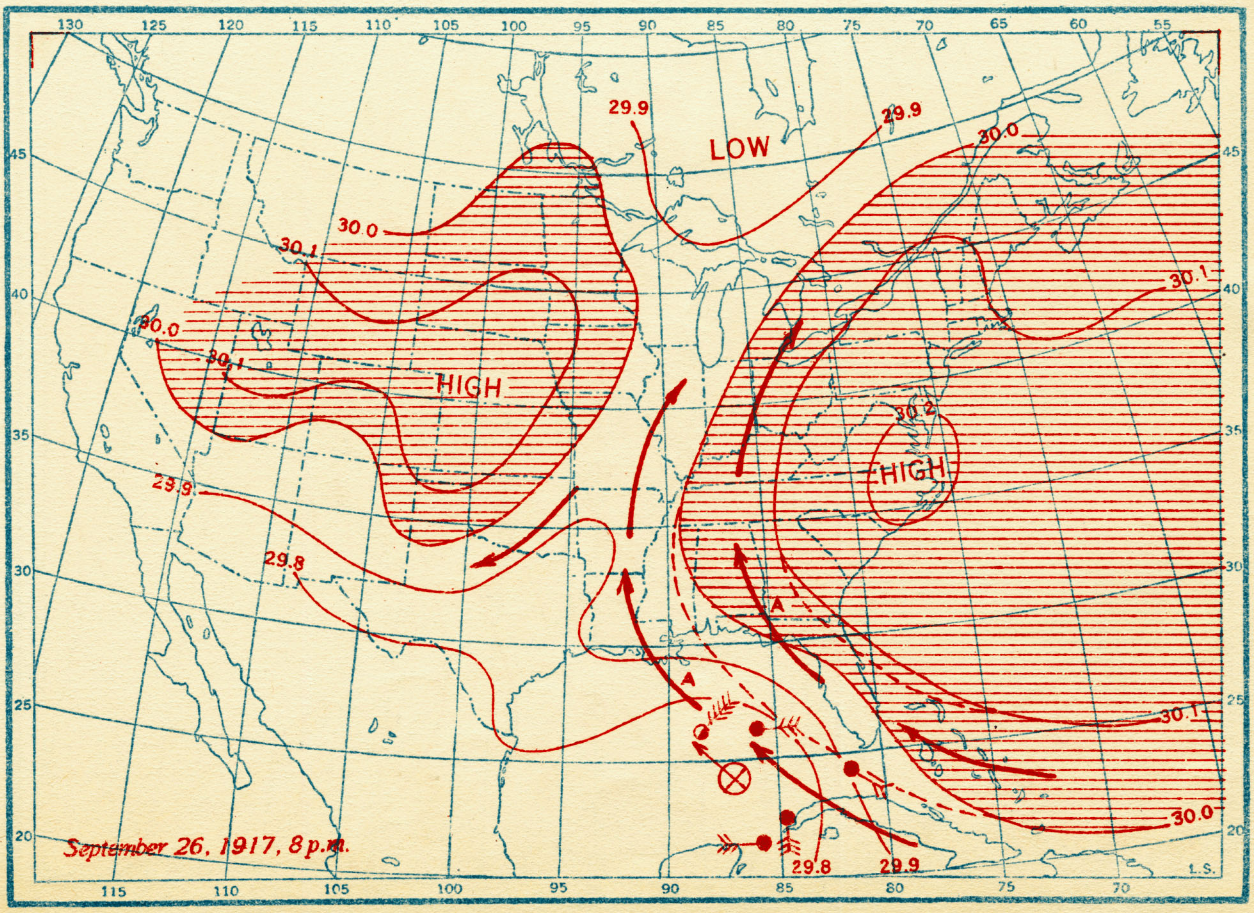
September 25, 1917, 8 a.m.



September 25, 1917, 8 p.m.



September 26, 1917, 8 a.m.



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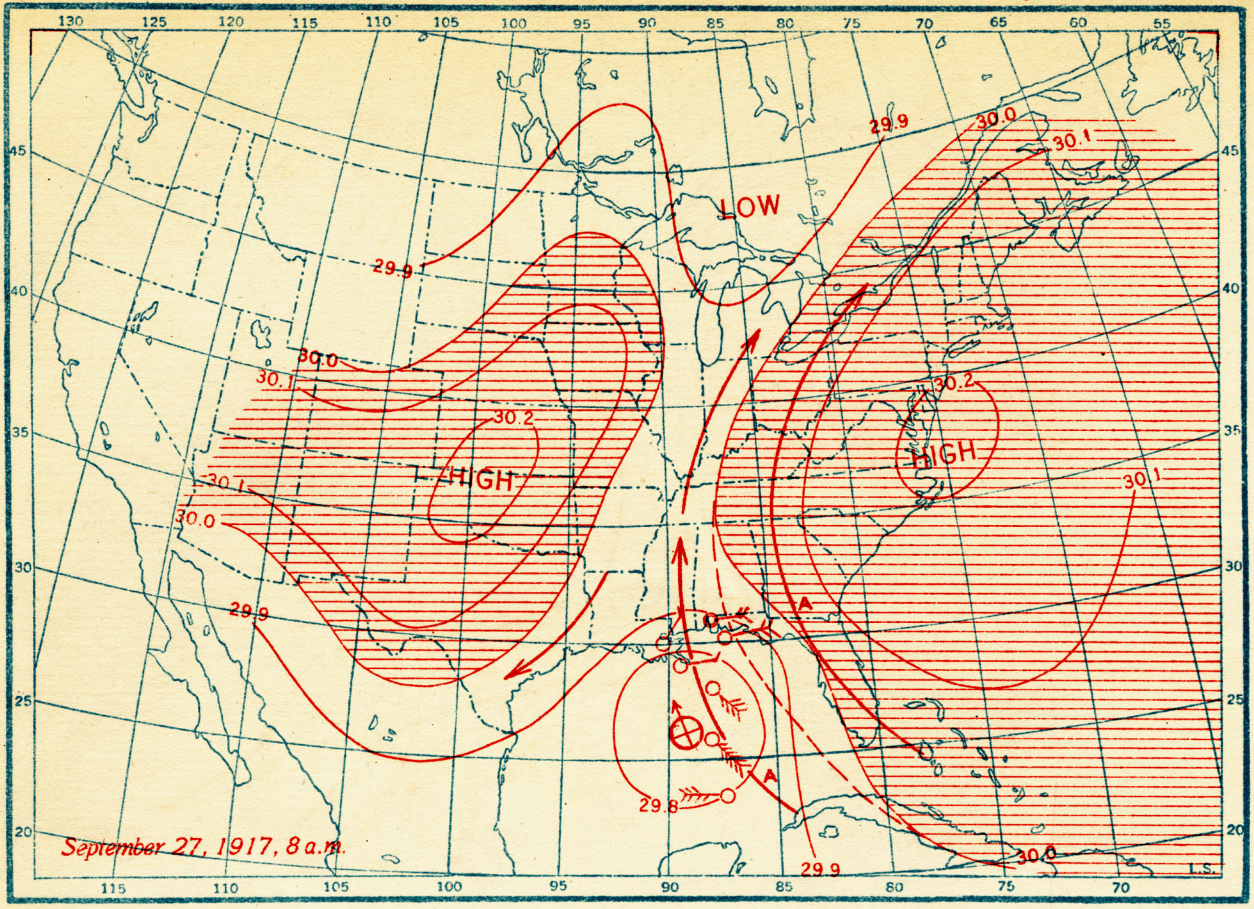

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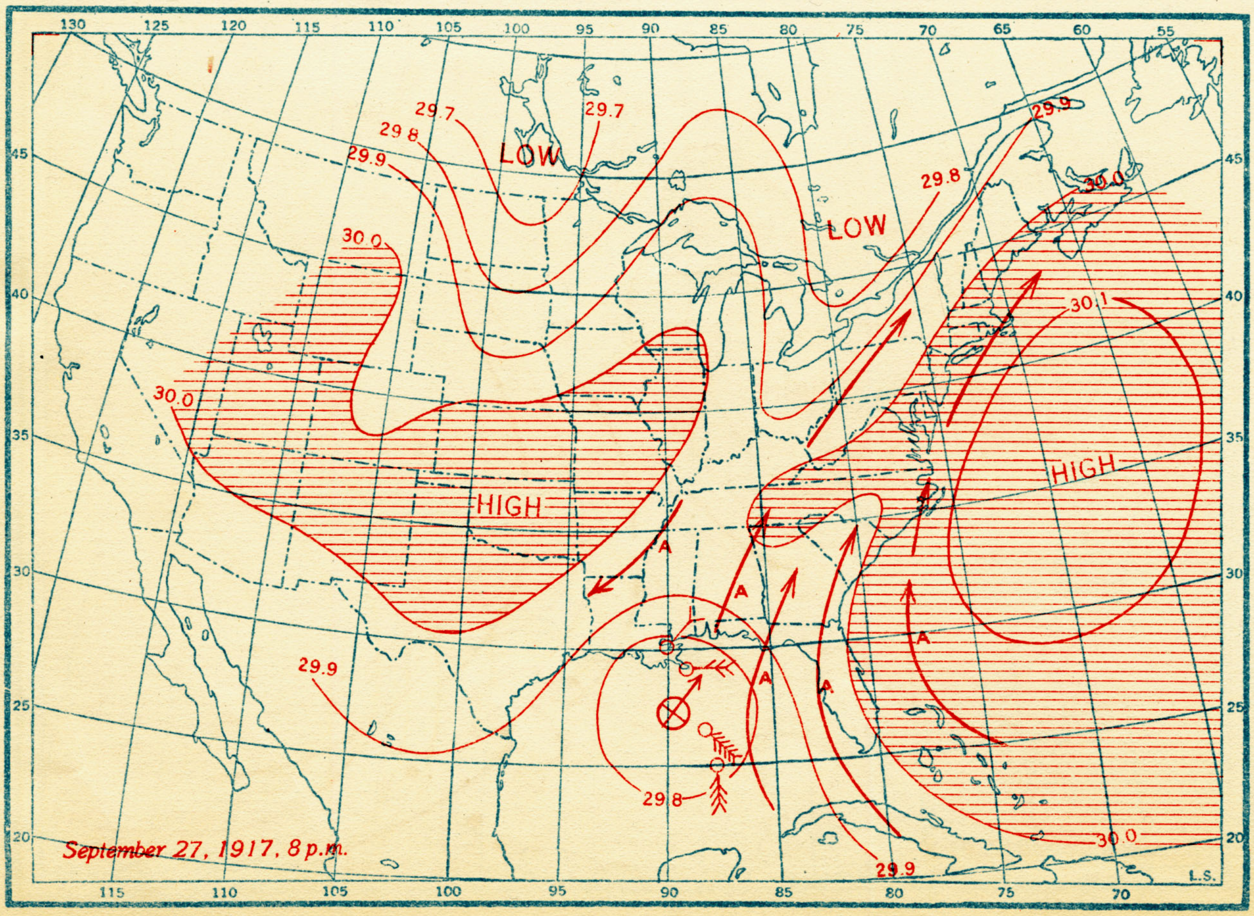

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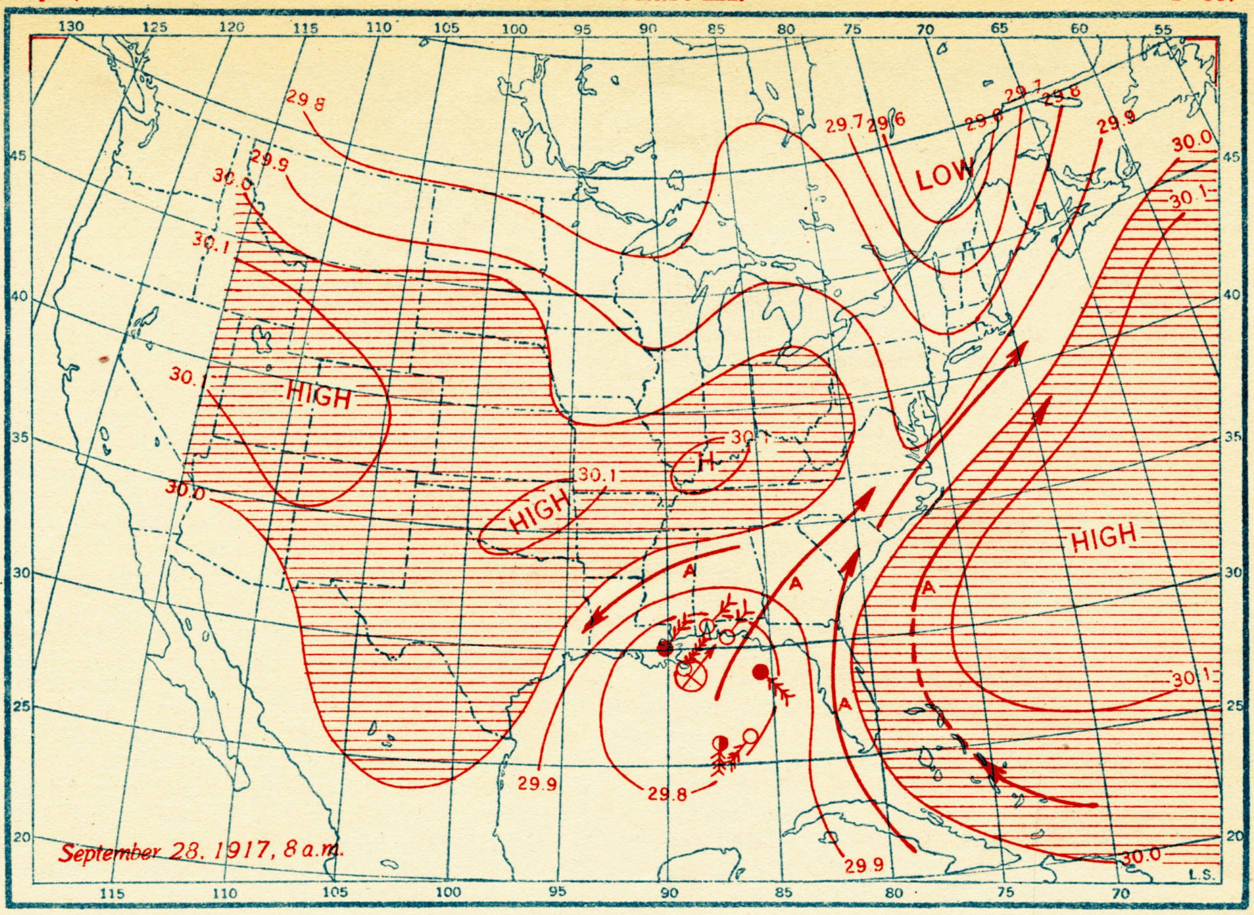
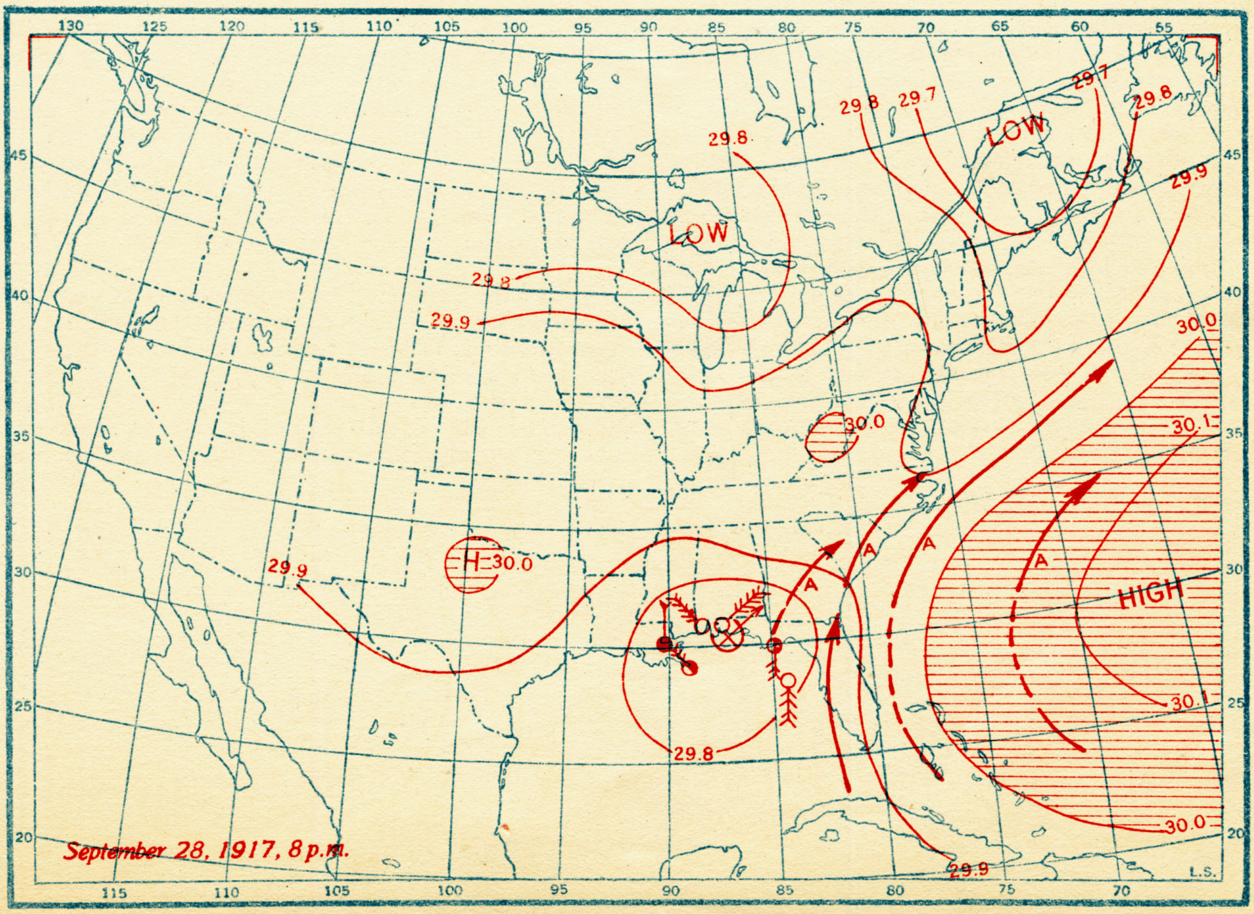

HIGH
HIGH
HIGH
LOW
H
29.8
29.9
30.0
30.1
29.7
29.6
September 28, 1917, 8 a.m.
L.S.


LOW
LOW
HIGH
H
29.7
29.8
29.9
30.0
30.1
September 28, 1917, 8 p.m.
L.S.