STUDIES ON THE CIRCULATION OF THE ATMOSPHERES OF THE SUN AND OF THE EARTH.

By Prof. FRANK H. BIGELOW.

V.—RESULTS OF THE NEPHOSCOPE OBSERVATIONS IN THE WEST INDIES DURING THE YEARS 1899-1903.

METHODS OF OBSERVATION AND REDUCTION.

The observers of the United States Weather Bureau occupied eleven stations in the West Indies during the years 1899–1903, and the opportunity was utilized to make a survey of the motions of the atmosphere in that region of the Tropics by means of nephoscopes.

The instruments were of the Marvin pattern, and the method of observation, to obtain the azimuth and velocity of motion, was identical with that described in the Report of the Chief of the Weather Bureau, 1898–99, Vol. II, chapter 2. The reductions were, however, carried out more perfectly than in any previous research of the kind in the following manner: (1) The three readings at each observation were reduced to a mean azimuth and velocity, for entry on the computing sheets. (2) Each vector V, φ was separated into its rectangular components, $+ S, + E$, where S is positive southward on the meridian, and E is positive eastward on the parallel of latitude. (3) The algebraic sum of each set of components was then taken from month to month, and the groups for corresponding months during the years 1899–1903 combined. (4) These sums were divided by the number of observations to obtain the mean velocity component per observation. The observations were taken for two years in the afternoon hours, and for the other two years in the forenoon hours, so that the diurnal variation was practically eliminated by putting the entire data for each of the twelve months in a single summation. (5) These mean ordinates were plotted month by month for the nine cloud levels, and average curves were drawn through them. In spite of the fact that the number of observations is large, when taken as a whole, yet, when subdivided among so many strata, there is more scattering of the ordinate points in certain levels than is desirable. The average curves approximate the normal components which would be derived from a very much more extensive series of observations. The full report will contain the observed ordinates and those obtained by graphical adjustment. (6) The resultant polar coordinates V, φ were then computed from the rectangular coordinates. Up to this point the numerical data had been carried forward in the number of millimeters passed over in twenty-five seconds on the scale of the nephoscope. (7) These numbers were now reduced to velocities in meters per second, by multiplying them by the factor $\frac{1}{5}H$, where H is the adopted height of the cloud stratum. The values of H were adopted from the Washington cloud heights, after considering the heights obtained at Manila during the same cloud year, 1896–97. These velocities and azimuths were transferred to charts, drawn to the scale, 1 millimeter = 1 meter per second. In preparing these charts for publication in the MONTHLY WEATHER REVIEW, the original scale has been reduced to 0.6 millimeter = 1 meter per second, as shown by the "velocity scale in meters per second" at the bottom of each chart of the sets Chart XII and XIII, the scale of Chart XIV being unchanged.

CHARTS OF THE RESULTING VELOCITIES AND DIRECTIONS OF MOTION FOR THE WEST INDIES.

The vectors (V, φ) have been plotted for each station, so that the mutual relations of the resulting motions can be properly compared and studied. There are several remarks to be made about the observations themselves. At Willemstad the observers have frequently misnamed the *cumulus* clouds as *cumulo-stratus*. This becomes apparent on plotting the vectors. The angles are correct, but the length of the arrows is too great. I have accordingly interpreted the values of V_1 and V under strato-cumulus as belonging to the cumulus level, and have used the reduction factor 0.5 instead of 0.9 in drawing the charts.

At Bridgetown the vector systems of the alto-stratus and the cirro-cumulus levels have apparently been interchanged. As they now stand at Bridgetown they are inconsistent with the flow of air as determined at Basseterre, Roseau, Port of Spain, and Willemstad; but if they are transposed, then there is harmony. The observation sheets indicate that the observers have an unusually large number of cirro-cumulus entries and comparatively few alto-stratus, so that apparently they were accustomed to name many alto-stratus clouds as cirro-cumulus clouds. It is not easy to secure identical estimates of cloud forms at so many independent stations as we have used, and these few instances of apparent discrepancies are gratifying evidence of the general excellence of the results in other respects.

On comparing the charts here presented with those published by Prof. H. H. Hildebrandsson for the international committee, it appears that he has computed only the angle of the azimuth of motion without the velocity, and that the same schematic velocity is entered throughout the year. Apparently the actual velocities have not been computed for that report at any station. The importance of having the velocity as well as the direction of motion is evident, and this is emphasized by examining the great variations between the summer and the winter velocities and between those at the different cloud levels of each station of the West Indies. Comparing the Hildebrandsson and the Bigelow results for Havana (Plate VII, International Report), with fig. 22, Chart XII A, the azimuth directions are not in agreement in the autumn; comparing those for the Antilles (Plate III, International Report), with figs. 28, 29, 30, Charts XII B, and XII C, Basseterre, Roseau, and Bridgetown, the legend "Nuages superieurs" should apparently be changed to "Nuages intermediaries" or "Nuages inferieurs."

The vectors of the West Indian stations have been plotted in three forms: The first, Charts XII A, XII B, XII C, figs. 22 to 32, wherein the vectors of the same month throughout the nine levels terminate on the same vertical line; the second, Charts XIII A, XIII B, XIII C, figs, 33 to 43, wherein the vectors for June terminate on the same vertical line and the others in succession, so as to form a continuous broken line; the third, Charts XIV A, XIV B, XIV C, figs. 44 to 61, showing approximate normal vectors for winter and summer. The first enables us to study the movements simultaneously occurring in a given month from the surface wind to the cirrus level, and from this many important conclusions can be drawn. The second makes more distinct the general course of the movement in the several strata throughout the year, and especially the nature of the currents that depend upon the forces producing the westward drift of the lower levels and the eastward drift of the upper levels, together with the transition levels between them. The third system of charts is a composite of the mean winter and the mean summer systems, respectively, some of the minor irregularities being rectified in the adopted vectors. January and February constitute the middle of the winter group, while July and August are at the middle of the summer group. In adopting these vectors regard was had to the most probable balanced system which is indicated by the entire set of vectors. If the reader has doubts as to the accuracy of these final results, the original material of the third set of charts is to be found in the first and second sets, or in tables from which all the charts have been plotted, which will appear in the full report. Numerous studies in the dynamic meteorology of the Tropics are now practicable for the first time, but as it will require much careful labor to execute them, only some general remarks are required in this place.

THE ARCH SPANNING THE TROPICS, WHICH DIVIDES THE EASTWARD DRIFT FROM THE WESTWARD DRIFT OF THE GENERAL CIRCULATION.

The general theory of the circulation of the atmosphere shows that in the temperate zones of the Northern and the Southern hemispheres there is a strong prevailing eastward component producing an eastward drift, while in the Tropics there is a prevailing westward component causing a westward drift. The tropical westward drift is, however, limited in altitude, and at a certain elevation the drift reverses from a westward to an eastward direction. The position of the curve which separates the eastward from the westward drift varies with the season of the year. When the sun is far to the south and the northern winter prevails, the arched curve must be skewed to the south, and when the sun is far to the north and the northern summer prevails the arch is skewed toward the north. This is on the assumption that the foot of the arch rests on nearly the same latitude in winter and summer at any given region of the earth. The high pressure belt, which fixes the position of the arch on the surface of the earth, for the eastern portion of the United States lies somewhere between +30° and +35° north latitude, and crosses the Atlantic coast at about Florida and South Carolina. It is desirable to determine from our observations its exact location, but as this is of subordinate importance for our immediate purpose it can be passed over in this connection. Further accounts of the mathematical significance of the tropical discontinuous surface between the prevailing eastward and westward drifts may be found by consulting the full report, and my paper in the MONTHLY WEATHER REVIEW, January, 1904, Vol. XXXII, p. 15.

One special purpose of the West Indian nephoscope survey for 1899–1903 was to determine this surface of separation in the higher levels, and its variation with the season of the year. The velocities and direction of motion on either side of it, and the numerous meteorological inferences that can be drawn from these conditions, made the work of primary importance in the development of the dynamics of the atmosphere. The series of Charts, XII A to XIV C, figs. 22 to 61, are now available for this purpose. The twelve months, as observed, may be taken in two groups, of which the winter group is distributed about January and February as the central months, and the summer group about July and August. If there had been simultaneous observations in the Southern Hemisphere at latitudes corresponding to those that were occupied by the West Indian stations in the Northern Hemisphere, we should then have the data applying simultaneously to the entire tropic zone. The same result can be closely approximated by treating the winter group as representing the north tropical zone, and the summer group as representing the south tropical zone, during the northern winter. Hence, by using the results from November to April in the northern latitudes, and assuming that during this period the conditions observed for the northern latitudes during May to October then prevailed in the southern latitudes, the synchronous action of the circulation can be found for the northern winter throughout the Tropics. By reversing this process the corresponding results for the northern summer are obtained.

An inspection of the vectors of motion in the winter months shows that for Havana, Cienfuegos, and Santiago, Cuba, with mean latitude 22°, the reversal is about midway between the cumulo-stratus and alto-cumulus levels, or at approximately 3500 meters above the sea level. At Kingston, Santo Domingo, San Juan, Basseterre, Roseau, and Bridgetown, having the mean latitude of 17°, the reversal is apparently in or above the alto-stratus level, or about 6400 meters elevation. At Willemstad and Port of Spain, with mean latitude of 12°, the reversal is in the cirro-cumulus level, at about 8000 meters elevation. This is shown on the northern winter branch of fig. 62, "Mean altitudes at which the westward drift reverses to the eastward drift in the Tropics."

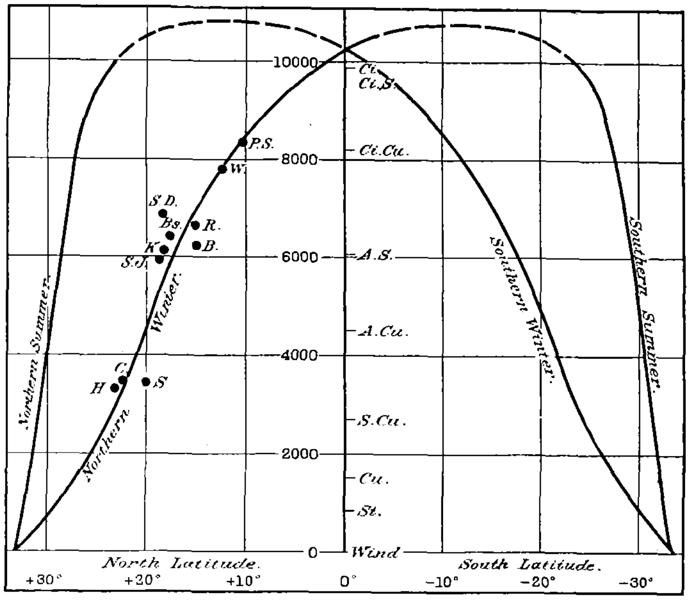

FIG. 62.—Mean altitudes at which the westward drift reverses to the eastward drift in the Tropics.

An examination of the vectors for the summer group of months indicates that generally there is a tendency to reversal in the cirrus and cirro-stratus levels, at about 10,000 meters elevation. This, however, is not definitive, and I have indicated the probable top of the arch in a broken line rather than to positively assign the limit. The summer westward circulation is very feeble throughout the column from the sea level at least to the 10,000-meter level, and it may be that it extends even to a higher level over the effective thermal equator, which lags about forty-five days behind the position of the sun in latitude. In the very complex circulation actually existing in the Tropics it is not possible to make very exact statements regarding such a loosely defined boundary as that which really separates the eastward and westward currents of the atmosphere underneath the sun. The calms of the thermal equator move northward and southward with the sun, and apparently the westward drift extends upward unbroken to about six miles, though at that level there are evidences that the eastward drift is making itself felt. The east and west currents play against each other at these high levels in a somewhat irregular manner.

THE LEVELS OF MAXIMUM HORIZONTAL VELOCITY.

An examination of Charts XIII A, XIII B, XIII C, figs. 33 to 43, brings out clearly the levels of the maximum horizontal currents. The circulation generally increases in westward velocity from the surface to the strato-cumulus level, then falls off to a minimum in the alto-stratus level, where the direction is irregular, and then increases to a maximum eastward velocity in the cirrus level. The stations of Cienfuegos and Santiago, Cuba, together with Kingston and Santo Domingo, give relatively small resultant velocities in the lower levels, from wind to cumulus, as compared with Havana, San Juan, and the southeastern group, Basseterre, Roseau, Bridgetown, Port of Spain, and Willemstad. The former group of stations develop greater irregularity in their azimuth directions than do the latter group, and consequently their resultants are much diminished in magnitude. This probably indicates some action of the continental mass of North America in disturbing the westward drift, which prevails steadily in the Windward Islands, and in changing its general direction from the southeast, which is the natural flow from the trades, to the northeast in that region. The strato-cumulus level in the more eastern stations has a powerful westward current, which falls off decidedly in the vicinity of Cuba. On the other hand the northeastward or eastward velocity in the three upper levels—cirro-cumulus, cirro-stratus, and cirrus—is at a maximum over the Cuban stations, and tends to diminish toward the southeast; that is, from the Antilles to Port of Spain. The trade from the southeast holds quite uniformly in the lower levels of the eastern group of stations, and the northeastward upper trade prevails in the upper levels of the western group. Between the lower and the upper levels there is a region of transition whose nature is quite clearly indicated. At Port of Spain the southeast trade prevails throughout the year with maximum in the cumulo-stratus level, diminishing and partially reversing in the cirro-stratus and cirrus levels. At Willemstad, Bridgetown, and Roseau there is an exclusively northern component in the alto-cumulus and alto-stratus levels. At Basseterre and San Juan this component becomes northwestward or shows signs of reversing. At Kingston and Santiago the azimuths are irregular and the velocities small, and at Cienfugos and Havana the eastward drift practically dominates. Beyond these statements it is not very safe to go at present. The circulation is complex and depends largely upon the relation of the Atlantic high area, belonging to the general high pressure belt of the Northern Hemisphere, to the adjacent continents. The normal system seems to be like that of Willemstad, Bridgetown as corrected, and Roseau, where the movements from the southeast in the lower levels change to movements from the south in the middle levels and from the southwest in the higher levels. The southwest antitrades are conspicuous over Cuba, but they become west and even northwest antitrades over San Juan and the Windward Islands. One is surprised to find that the southeast trades prevail so steadily in the northern zone, winter and summer, even up to latitude $+17^\circ$, including Port of Spain, Willemstad, Bridgetown, Roseau, Basseterre, and San Juan. It is evidently of primary importance that meteorologists should extend this nephoscope survey to the Azores, Ascension Island, St. Helena, the South American Continent, Central America, and Mexico. The entire circulation of the atmosphere can thus be carefully determined by means of the method here illustrated.

THE WINTER AND THE SUMMER CIRCULATIONS.

At a glance the great contrast between the motions of the air in winter and summer is apparent. Over Havana the northeastward velocities are above 30 meters per second in winter, and in the summer they become about five meters per second and are directed westward. The summer vectors on Chart XIII A, XIII B, and XIII C form an irregular broken line which in some cases become a very good loop. This looping or tangle in the line is quite characteristic of the summer vectors in the middle levels at Havana, Cienfuegos, Santiago, Kingston, San Juan, Basseterre, and of the vectors in the high levels at Roseau, Bridgetown, Port of Spain, and Willemstad. These loops and tangles sometimes make it difficult to determine from the original observations what is the true mean curve to be drawn, because the ordinates are quite scattering and irregular in the middle cloud levels. In the lower and higher levels there was little difficulty experienced from this cause in drawing the mean lines. As a general principle none of the broad statements which meteorologists have been accustomed to make regarding the trade-wind system seems to hold over a very large region. The changes from one locality to another are numerous and important, showing that the circulation of the Tropics is really very much localized. There exists no system of cyclones and anticyclones to disturb the general circulation, but this circulation is itself much more complicated than it is in the temperate zone. The dynamics of the two systems are very different, and depend upon a complex distribution of temperatures and pressures. Every effort should be made to determine what these are before resorting to analytic discussions, which will be of little permanent value until all the principal facts are known.

THE CAUSE OF THE WEST INDIAN HURRICANES.

The hurricanes which devastate the southeastern districts of the United States in the months from July to October originate in the West Indian region, and, as much conjectural writing has been published in order to account for them, it is important to throw what light is possible upon the subject. In the complex circulation shown to exist over the Carribean Sea, it is easy to suppose that gyratory local circulations can be set up which will develop into cyclonic action. The summer circulation is irregular, as befits a belt of calms such as prevail in the doldrums, or it has a feeble westward direction. In the winter this motion has become powerfully eastward in the upper levels, in consequence of the overspreading of the cold sheet of air from the temperate zone, which is controlled by the eastward drift of higher latitudes. In the autumn, especially in September, a marked change takes place, by which the stagnant or westward moving air is sharply propelled eastward. This is seen by examining the months of August, September, and October, in the alto-stratus and the higher levels on Charts XIII A, XIII B, XIII C, figs. 33, 34, 35, 38, 39, 40, and 41, for Havana, Cienfuegos, Santiago, San Juan, Basseterre, Roseau, and Bridgetown. This indicates the locality where hurricanes are especially generated, and agrees with otherwise well known facts. They seldom occur as far south as Port of Spain and Willemstad, but at these stations there is no indication of a sharp reversal in the cloud region. *The levels from alto-stratus to cirrus, from four to six miles high, are those chiefly concerned in causing the hurricane formation.* The lower levels do not have the same reversal currents, but their vectors are very steadily directed from the southeast to the northwest throughout this season of the year. 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 four to six miles long, while the tornado tube seldom exceeds one mile in length. In the tornadoes of the United States the cool wind from the northwest flows against and over the warm current from the south or southeast as they meet in the central valleys. Between them, at the height of about one 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 forward from top to bottom. In the case of the hurricane in the high levels we have the cool eastward drift of autumn strengthening and spreading into the tropic zone, with a northeastward or eastward current, as shown at Havana, Cienfuegos, Santiago, San Juan, Basseterre, Roseau, and Bridgetown, Charts XIII A, XIII B, and XIII C. This meets the southeast trade with currents moving northwestward, as shown at Willemstad and Port of Spain, Charts XIII C, figs. 42 and 43, and between them a gyration is set up which penetrates downward four to six miles, and so produces a vortex tube of large dimensions and great power at the surface, such as hurricanes exhibit. This conclusion is an exact agreement with the results obtained in the Report of the Chief of the Weather Bureau, 1898–99, vol. 2, as given on chart 35 for the tropical hurricane and described on page 457. It was there shown that the vectors of motion in the cirrus level require the existence of a vortex tube at least five miles long. The usual drift of hurricanes from the place of generation is at first westward or northwestward, and this is because they are carried along with the prevailing currents in the lower and middle levels. It seems then that hurricanes build up in the higher levels by the counterflow of currents there prevailing, that they penetrate through four to six miles of lower strata to the surface, and are borne along westward by entanglement in the lower currents through which they penetrate. When these change their direction to the northward and northeastward the hurricane track recurves with them. On the other hand the hurricane itself disappears in higher latitudes and is transformed into a shallow cyclone, because there the countercurrent flow in the higher levels ceases. These conclusions can be further illustrated by reference to Charts XIV A, XIV B, and XIV C, mentioned above.

APPROXIMATE NORMAL CIRCULATION IN THE WEST INDIES DURING THE WINTER AND SUMMER, RESPECTIVELY.

On Charts XIV A, XIV B, XIV C, figs. 44 to 61, which show the average normal circulation in the West Indian district of the Tropics, special attention is directed to the vectors in the four upper levels—alto-stratus, cirro-cumulus, cirro-stratus, and cirrus—for the summer months, figs. 44 to 52. These charts were drawn by inspecting all the available data from the eleven stations and carefully determining the most probable mean vectors that would make a natural, well-balanced system, wherein irregularities due to imperfect observations would be rectified. A comparison with the vectors of Charts XII A, XII B, and XII C, shows that the changes which have been introduced are all of a minor nature, and it is supposed that a larger number of observations with the nephoscopes would produce a system of vectors very closely approximating those here adopted. In the lower levels, from the surface wind up to and including the alto-cumulus level, the currents are similar, except that in the strato-cumulus level the velocity is at a maximum. From this level it diminishes both upward and downward.

It should be remembered that in discussing the nephoscope observations of 1896–97 for the strictly cyclonic and anticyclonic components in the circulation of the middle latitudes, we reached the same result regarding the prevailing level of maximum velocity, namely, that the maximum velocity is in the strato-cumulus level. Compare chart 68, page 625, Report of the Chief of the Weather Bureau, 1898–99, Vol. II.

In the upper levels of the Tropics, on the other hand, a new circulation is prevailing, which is peculiarly interesting in connection with the causes that generate hurricanes. Instead of one single westward drift, as in the five lower levels, there exist two countercurrents in the four upper levels. The western group of stations—Havana, Cienfuegos, Santiago, and Kingston—have their vectors pointing southward; the eastern group of stations—that is, Santo Domingo, San Juan, Basseterre, Roseau, Bridgetown, Port of Spain, and Willemstad—have vectors pointing generally northward. Between them there is a distinct region of counterflow, and, consequently, an area of low pressure. If we assume that in the upper strata, where the mechanical friction is a very small quantity, and where the internal mixing from local minor cyclones is negligible, the vectors are directed nearly parallel to the isobars, then we can easily construct their configuration, though we can not assign numerical values to them without further investigations. On the eastern side there is a high area, which is a portion of the western end of the prevailing Atlantic high pressure. On the western side there is another high pressure area, whose origin is not so easy to understand. Over the North American Continent in summer the heated surface conditions produce a general low pressure area in the lower strata, and simultaneously a high pressure area in the upper strata. It is very likely that the western high pressure in the upper strata over the West Indies is really the southern extension of the continental high pressure area prevailing in summer over the United States. Some further computations on our nephoscope observations in the United States will be required to determine the exact facts.

Between these two high pressure areas in the West Indies there exists a low pressure area, with countercurrents on either side, so that all the conditions are present that are needed to produce a *cyclone in the upper strata.* If the prevailing pressures and currents become intensified at any time, the high-level cyclone is strengthened, and it then penetrates with its large vortex tube to the surface as a regular hurricane. The entire circulating structure is borne along northwestward in the prevailing drift of the *lower* levels till it recurves in the southeastern part of the United States. It is evident that the locality of the formation of the center of cyclonic motion may shift eastward and westward over the West Indian region, depending upon the state of the atmosphere at the time, the position of the two great high pressure areas, and the conflicting currents in action. The normal type here produced is in reality made up of numerous fluctuations on either side of the mean. In forecasting for hurricane conditions it becomes necessary to watch carefully the motions of the four upper cloud levels, in order to learn the practical signs foreshadowing such a hurricane condition.

On Charts XIV B, XIV C, figs. 53 to 61, "Normal vectors for winter," the interest is of a different character from that explained in connection with the summer type. Here it is the reversal from the westward drift of the lower strata to the eastward drift of the upper strata. From the surface up to and including the strato-cumulus level the configuration is generally the same throughout the West Indian region, Then the reversal vectors first set in at the western stations, Havana, Cienfuegos, Santiago, in the alto-cumulus and alto-stratus levels; the other stations become involved later in the higher cirro-cumulus, cirro-stratus, and cirrus levels, where the regular antitrades prevail. The azimuths of the higher vectors show that the northward component nearly vanishes in the cirrus level over the eastern stations. It will be necessary for meteorologists to outline the eastern portions of the Atlantic high area in the levels up to 6 miles before executing conclusive discussions of the important dynamic problems suggested by these vectors.

THE MEASUREMENT AND UTILIZATION OF FOG.

By PERCY LEONARD, dated Point Loma Homestead, San Diego, Cal., April 12, 1904.

Seeing that the prevalence of fog here in the early summer is a very great help to vegetation, but that only a very small part of this gets into the rain gage, it seems a pity that our climate does not get the credit of this moisture in the precipitation records. Why should not an instrument be made, to imitate, to some extent at least, the action of the leaves and twigs of trees, and arrest the passing fog particles and make them render an account of themselves in the measuring tube?

I would suggest a wire framework of the same area as the rain gage, and say one foot high and made to fit on the rain gage. This wire-work cylinder to be crossed and recrossed with some durable filaments (e. g. horsehair) dividing up the cubic content into cubes of one-half an inch or less.

From a day of drifting fog I am convinced a great deal of water would be intercepted and deposited in the measuring tube.

Perhaps it might not answer to make the fog depositor a permanent extension of the rain gage, as it might interfere with its function as a measurer of legitimate rainfall. In this case perhaps it might form a separate instrument and its data be entered in a column by themselves.

A simple cylinder of very fine meshed wire gage of the same diameter as the rain gage to fit on the top might be better than the horsehair-crossed space, because I imagine that this would not interfere at all with its functions as a rain gage pure and simple.

If such fog depositors were used throughout the country the comparison of the returns would be interesting, and this much abused "arid section" so called, would make a very respectable showing of fog deposit that would level up to an appreciable degree its total precipitation to that of districts with a larger rainfall.

It must occur to everyone who reads the above article that