ON THE GENERAL CIRCULATION OF THE ATMOSPHERE IN MIDDLE AND HIGHER LATITUDES.

By W. N. SHAW, F. R. S., Secretary of the Meteorological Council. Received May 16; and read June 2, 1904, before the Royal Society, London, England.

In the course of an investigation into the trajectories, or actual paths of air, by means of synoptic charts, which is still in progress,[1] it became apparent that the paths of air taking part in cyclonic disturbances near the British Isles did not always originate, when traced backward, in anticyclonic areas, but followed a track skirting the neighboring high-pressure areas and traversing sometimes a very large part of a belt of the earth in a direction more or less parallel to a line of latitude; and, on the other hand, air moving in the neighborhood of a cyclonic depression did not invariably seek the nearest barometric minimum, but sometimes passed on, leaving the circulation of the depression on the left hand.

Two suggestions at once arise from these results: First, that the anticyclonic areas of the Atlantic take far less part as sources of air supply for traveling storms than is usually attributed to them, and, secondly, that the motion of air in middle latitudes is more of the nature of a passage around the pole in a general easterly direction, sometimes from northwest, sometimes from southwest, than is generally supposed.

The evidence in support of these suggestions will be considered when the results of the investigation referred to are presented, but it may be remarked here that the first suggestion, which would indicate that the anticyclonic areas are of the nature of stable, inert masses of air around which the winds circulate, rather than regions out of which winds blow, is not inconsistent with the phenomena of anticyclonic weather, and is borne out by the monthly wind charts of the South Atlantic recently prepared by the Meteorological Council and now in course of publication by the Hydrographic Office of the Admiralty; and, further, that the existence of a general circulation of the atmosphere from west to east along middle latitudes right around the earth, diverted to the northward along the eastern sides of the oceans and back again to the southward across the land areas, is supported by the recent summary of cloud observations by Hildebrandsson.[2] It is also supported by the isobaric distribution for the 4000-meter level computed by Teisserenc de Bort, with which the observed motions of the upper clouds are in agreement.

It is the second suggestion, the general circulation in middle latitudes around the pole, with which the present paper deals.

I propose to refer to certain representations of the average distribution of pressure and the corresponding average winds for January. It may be conceded at once that the motion of air represented by any synoptic chart of a considerable part of the earth's surface in middle or higher latitudes, including ocean areas, for any day in January, could not by any stretch of the imagination be regarded as a "steady" motion around the polar axis. The conspicuous features are large cyclonic systems traveling irregularly, and the actual motion is exceedingly complicated. The chart of mean isobars for the month, fig. 1, displays a large area of low pressure over the North Atlantic southeast of Greenland, the axis of which lies along the path frequently followed by centers of depressions, and indicates prevailing westerly winds on the southern side of the low pressure and prevailing easterly winds on the northern side.

But it is also well known that the cyclical distribution of isobars around local centers and corresponding rotary winds are specially characteristic of the surface as distinguished from the upper air. For a section taken at successively higher levels the pressure diminishes more rapidly over cold areas than over warm areas, because the air, to the weight of which the pressure at the base of the stratum is due, is denser in cold regions than in warm ones. The turbulent character of the motion is moderated as higher levels are reached, and the rotary character of the motion may be lost at a sufficient height.[3]

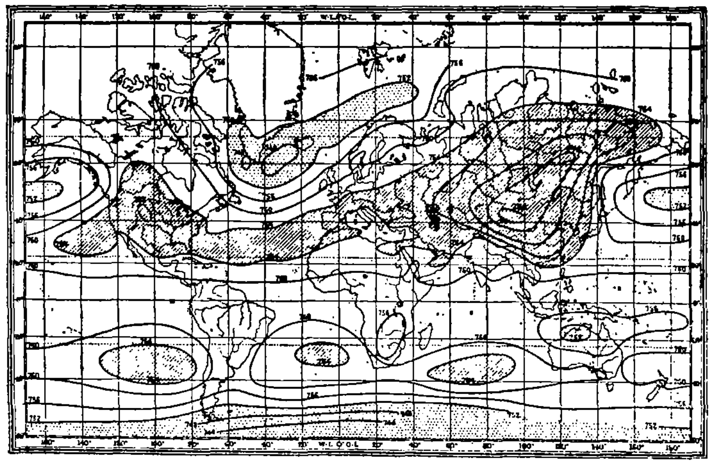

FIG. 1.—Surface isobars for January. Reproduced from Hann's "Meteorologie."

In general accordance with the obliteration of cyclical motion at great height the system of isobars computed by Teisserenc de Bort for the 4000-meter level, fig. 2, shows no isolated low-pressure areas, and the lines suggest a circumpolar circulation instead of the system of local cyclonic circulations. The isobars are deflected in certain parts from the lines of latitude, but they form complete circumpolar rings. It is not unreasonable, therefore, to regard the actual motion at that level on any day as the result of disturbances of "steady" motion; the steady motion, about which the actual motion fluctuates, being represented by flow along the mean monthly isobars.

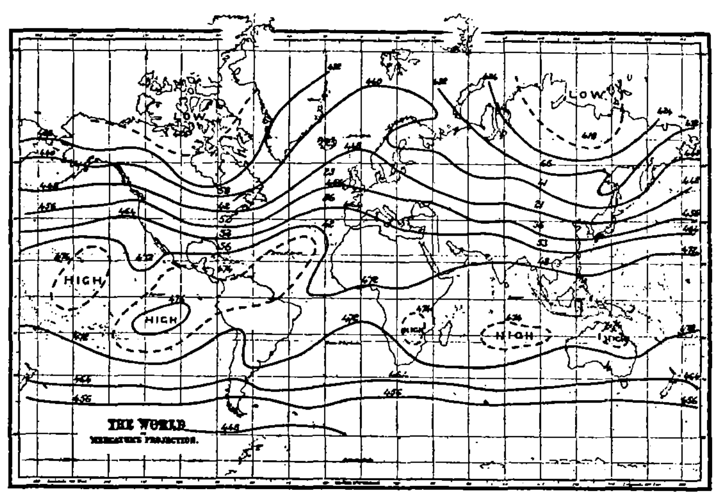

FIG. 2.—Isobars at the level of 4000 meters for January. (From Hann's reproduction of the original diagram by Teisserenc de Bort.) With velocities in miles per hour, corresponding to the acceleration for different gradients resulting from the earth's rotation.

Since two consecutive isobars are not, strictly speaking, parallel to each other throughout their course, but diverge in some regions and converge in others, the velocity is different at different points of an isobar. Upon the principles of hydro-

[1] Some of the results of this investigation have been already published. Quarterly Journal Roy. Met. Soc., vol. 29, p. 233, and vol. 30, p. 57: Monthly Pilot Chart of the North Atlantic and Mediterranean, February, 1904.

[2] Rapport sur les Observations Internationales des Nuages au Comité International Météorologique; also Brit. Assoc. Report, Southport meeting, 1903.

[3] See Hann, Meteorologie, p. 538, and Teisserenc de Bort, Brit. Assoc. Report, 1903.

dynamics, the change of velocity, in the absence of any impressed force to produce such a change, implies an alteration of pressure; hence, where the isobars are widening, the flow of air must diverge from strict parallelism with the isobar toward the region of higher pressure, and vice versa. The angle of divergence at any point would be, however, too small to affect the considerations put forward in this paper.

Neglecting the effect of frictional resistance, the condition of persistent motion along parallel isobars is that the force due to the distribution of pressure, i. e., the pressure gradient, shall supply the acceleration which is necessary to keep a particle of air in its path; this condition is expressed by the relation between the pressure gradient γ, expressed in inches of mercury per degree (60 nautical miles), and the velocity V of the moving air in statute miles per hour, as follows:—

$$\gamma = D\,(V^2 \cot \rho \times 0.000016 + V \sin \lambda \times 0.033),$$

where λ is the latitude, ρ the angular radius of the small circle osculating the path, and D the density of the moving air.

Of these two terms, that containing ρ depends upon the curvature of the path and, from the magnitude of the numerical coefficient, it is clearly insignificant unless the velocity of the wind is very great or the radius of curvature of the path very small. It becomes very important in the case of revolving storms of small diameter. The other term is that depending upon the rotation of the earth, and represents $2\omega V \sin \lambda$, where ω is the angular velocity of the earth's rotation.[4] Omitting the first term, we get for the condition of steady motion

$$\gamma = DV \sin \lambda \times 0.033 \text{ inch per degree of 60 nautical miles.}$$

On fig. 2 the gradient is already indicated by the separation of the isobars; the wind velocity which is necessary for steady motion, assuming, for the purpose of computing D, a fixed vertical temperature gradient, and neglecting the effect of the divergence or convergence of the isobars, is given in figures in various parts of the diagram. The velocities here indicated refer to the air at the 4000-meter level, but it may be noticed that since the pressure gradient for a given velocity is proportional to the air density, and the pressure is due to the weight of the superincumbent air, steady motion along parallel isobaric lines with the same velocity at all altitudes would result, if the run of the isobaric lines were the same at every altitude. That condition would be satisfied if at each altitude the isobars were also isothermal lines.

The wind velocity near the surface is diminished by surface friction, but it follows from this relation between gradient and velocity that beyond the range of appreciable surface friction the velocity does not increase with height in an atmosphere in which the distribution of isobaric lines is similar at all heights.

The velocities entered upon the diagram lie between 20 and 66 miles per hour, and these are not inconsistent with observed cloud velocities, so that a steady motion with the velocities indicated is a reasonable representation of the average conditions so far as they are known. As regards the direction of the slope of pressure, that direction is determined by the relation of the direction of motion of the air to the direction of rotation of the earth. Whatever be the direction of motion of the air, the horizontal acceleration arising from the earth's rotation is along the normal to the path, and to the left, in the Northern Hemisphere. On that side, therefore, the low pressure must lie. For motion along a parallel of latitude the slope of pressure will be "downward" toward the pole for motion from west to east, and for motion from east to west "downward" toward the equator.

Hence, we may conclude that the distribution of pressure at the 4000-meter level is favorable for a steady circulation of air around the polar axis, with an average velocity of about 50 miles per hour. The direction of the motion is from west to east, with divergence in the Northern Hemisphere toward the north over the Pacific and Atlantic oceans, and back again to the south over the continental land areas. In the Southern Hemisphere the motion follows the lines of latitude more closely and the deflections are less marked, though the influences of the land projections are similar.

Below the 4000-meter level is a region of cyclonic depressions with rotary motion, lying between the tropical high-pressure belt and other anticyclonic regions to be found in the far north. The motion near the surface level corresponds with the surface distribution of pressure, which is made up of the distribution at the 4000-meter level, transmitted to the surface, and the pressure due to the weight of the stratum below the 4000-meter level. I now exhibit, fig. 3, the distribution of this remainder of the surface pressure when the distribution at the 4000-meter level has been deducted. It has been obtained by plotting the difference between the surface distribution of fig. 1, and Teisserene de Bort's distribution at the 4000-meter level, fig. 2.

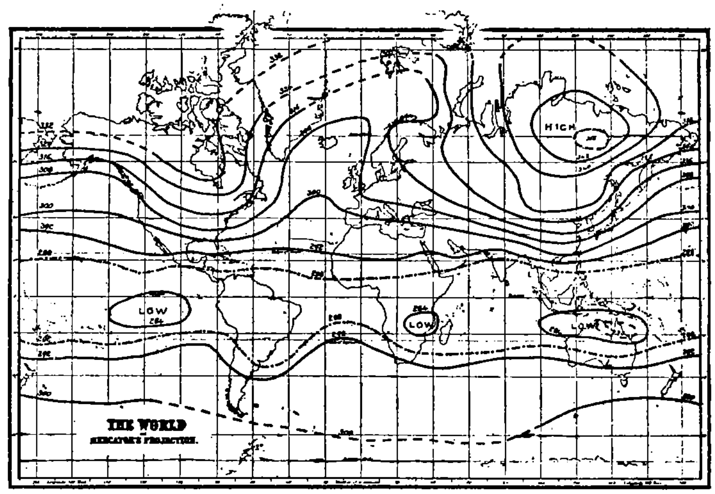

FIG. 3.—Mean pressure due to the weight of the stratum of the atmosphere below 4000 meters, for the month of January. Computed from figs. 1 and 2. Pressures are given in millimeters.

The result is very remarkable. A comparison of figs. 2 and 3 shows at once the general trend of the lines is very similar to that for the upper air, but the *direction of the gradient is reversed*. This is in accord with the theoretical calculation of the direction of the gradient, because the direction of motion for such a pressure distribution is the reverse of that represented in fig. 2. *The result of the pressure distribution due to the lower stratum alone would be a circulation around the polar axis from east to west along lines almost identical with the lines of flow for the upper air, but in the reverse direction.*

I now refer to fig. 4, showing the average distribution of surface temperature for the same month, January. Again the similarity of the trend of the lines to those of figs. 2 and 3 is obvious. It is, of course, not in any way remarkable that figs. 3 and 4 should show similar lines, for fig. 3 shows the amount of barometric pressure to be deducted from the surface pressure for a layer of air 4000 meters thick, and the calculations of the deductions have been based upon the surface temperatures. The diminution of pressure for a given height is the same at all points of an isothermal line, assuming the vertical temperature gradient to be the same at all points along the line; but that the remainders representing the pressure

[4] See Hann's Meteorologie, p. 421. [This term was first deduced by Poisson as applied to projectiles and by Ferrel as applied to the atmosphere: See Ferrel "Motions of fluids and solids on the surface of the earth," in Runkle's Mathematical Monthly, 1858-1860. The expressions given by Hadley, 1735, Tracy, 1843, Coiding, 1871, Reye, 1872, and Waltenhofen, 1875 are imperfect; those by Poisson, 1837, Ferrel, 1860, Sprung, 1879 and 1881, Finger, 1877, Hann, 1875, Ekholm, 1894, and Cottier, 1897 are correct.—*C. A.*].

of the upper atmosphere at 4000 meters should also be very similar in shape, is indeed remarkable, especially when one considers that *the gradient is in the reverse direction* from that of the pressure values for the lower stratum.

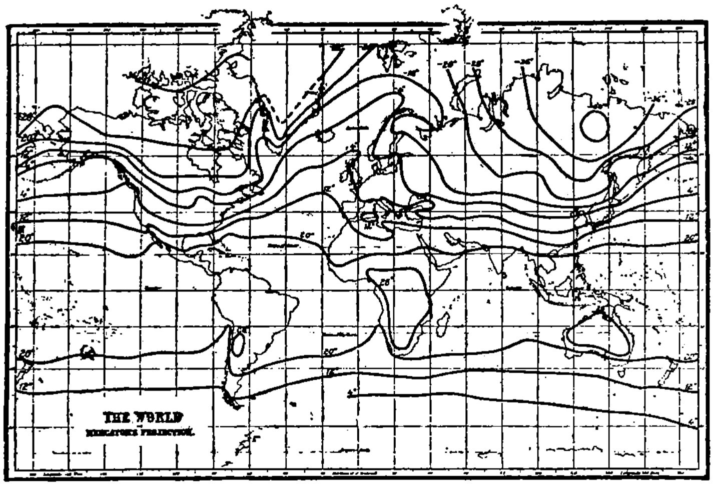

FIG. 4.—Mean temperature at the earth's surface, for the month of January, in centigrade degrees.

It is unnecessary to call special attention to the points of similarity even in detail between the shapes of the "partial" isobars for the lower stratum, fig. 3, and the upper stratum, fig. 2, with reversed gradient. The isolated minima in fig. 3 about the equator, corresponding to isolated maxima in the same regions in fig. 2, are very striking, but one point of difference may be noted. In fig. 2 the circulation indicated is approximately about the geographical pole, where in consequence a minimum of pressure is indicated. In fig. 3, the circulation is clearly around a pole of extreme cold in northeast Siberia, where there is a maximum of pressure for the lower air.

It thus appears that the forces represented by the average distribution of pressure for the month of January may be divided into two parts, viz:

A, that due to the upper atmosphere, above 4000 meters, which would, if it acted alone, correspond with a steady motion from west to east along paths following closely the lines of the average isotherms; and *B*, that due to the lower stratum of the atmosphere, which, if it acted alone, would correspond with a steady motion, also approximately along the isotherms but from east to west.

The actual distribution is represented by the superposition of *A* and *B*. Since pressure gradient and velocity are both vector quantities, and are related to each other in simple proportionality, the superposition of force distribution corresponds with the composition of the velocities due to the separate distributions. Hence, in the combination of the two distributions of force at the surface where *A* is predominant, i. e., in the middle latitudes on either side of the equator, there is a resultant circulation from west to east; where *B* is predominant, i. e., in higher latitudes, there is a resultant circulation from east to west.

The superposition of the two systems gives a line of minimum pressures, with a westerly flow of air on the equatorial side, and an easterly flow of air on the polar side. It is very irregularly marked in the Northern Hemisphere, owing to the distance of the pole of cold from the geographical pole; in the Southern Hemisphere the arrangement is probably much more symmetrical, owing to the coincidence of the pole of cold with the geographical pole.

The line of minimum average pressure forms the storm track of the circular storms, resulting from the merging of the two circulations. It is evident that such merging must take place. If circumstances were so adjusted that there was an equilibrium condition along any level, the difference of density of air at different temperatures would cause a departure from equilibrium conditions, in one direction above the prescribed level, and in the opposite direction below it. And to this primary cause of disturbance of the steady motions corresponding to the two separate distributions of pressure, must be added the instability that is due to the condensation of water vapor. The region of minimum pressure becomes, therefore, the scene of great changes of energy, cyclonic circulations, and variable winds. It may, indeed, be noticed that increase of entropy when mixing takes place is represented by $\frac{H(T-T')}{2TT'}$ (supposing $T-T'$ to be small compared with T or T'), where H is the quantity of heat transferred in mixing, and T and T' are the absolute temperatures of the amounts of air, supposed equal, which mix. Hence, the entropy change is greatest where there is the greatest temperature difference, but, for the same temperature difference, where temperatures are lowest.

To sum up the result that has been arrived at, the average distribution of pressure can be divided into two parts, neither of which shows the characteristics of local cyclonic distribution; one part, due to the upper atmosphere, favors a westerly circulation; the other, due to the lower atmosphere, favors an easterly circulation; and both circulations follow roughly the lines of the average isotherms.

This result leads to many suggestions of considerable importance. The second component of the distribution is obviously directly dependent upon surface temperature, and must be changed when surface temperature changes; the first may also be regarded as depending ultimately upon surface temperature, for its lines follow those of surface temperature on the average, but the connection must be less direct. It may possibly indicate differences of thickness of the atmospheric layer as distinguished from differences of density in a layer of uniform thickness. The first effect of a change in the distribution of surface temperature will be to change the character of the second component, leaving the first component unchanged, except in so far as expansion of air in the lower strata alters the pressure at a given level in the upper strata. The study of the effects of recognized changes of temperature distribution upon the second component, which are easily calculable, may have very important consequences in relation to classifying the facts within our knowledge of weather changes in middle latitudes. It seems to follow directly that easterly winds are, as a rule, winds of relatively speaking low altitudes, due to surface temperature, and that local areas of high pressure, with an anticyclonic circulation, may lie underneath regions of general westerly flow in the upper air.

Another conclusion that follows directly from this method of analysis of the distribution of forces corresponding to the surface circulation is the confirmation that it affords of the suggestion of the existence of a high-pressure area over the Antarctic Continent, made by Sir J. Murray in the discussion of the *Challenger* observations. Such indications of the results of antarctic explorations as have been already received are consistent with the suggestion,[5] and the detailed results of the recent expeditions must furnish very valuable additions to the material for study of this interesting question. It is clear that the effect of the component, due to the lower atmosphere in the southern latitudes, will become intensified where the intensity of the low temperatures becomes effective; and the pole of extreme cold, which in the Southern Hemisphere must be nearly coincident with the geographical pole, will

[5] See Mr. Bernacchi's paper on "Winds and temperature at Cape Adare" in "Magnetic and meteorological observations made by the *Southern Cross* Antartic Expedition." Roy. Soc., pp. 40 and 49.

have associated with it a component distribution for easterly circulation similar to the low temperature pole of northeast Siberia, in the Northern Hemisphere. The intensity of the cold in the south polar regions is undoubted, and the existence of the distribution for an easterly circulation round a high-pressure center, due to the weight of the lower air, follows directly therefrom.

A third effect of the distribution of pressure in lower regions of the atmosphere, and the corresponding air circulation, may perhaps be traced in the series of wind charts of the South Atlantic already referred to, where there is obvious evidence of a tendency of the winds to run tangentially to the coast line. The coast line is equally obviously a line of separation between regions of different surface temperature distribution, and hence a locality of steep temperature gradient. Thence follows a steep pressure gradient for the lower atmosphere, and associated therewith a distribution favorable for the flow of air in opposite senses on the two coast lines for the same latitude.

The division of the atmosphere into an upper and a lower stratum at the 4000-meter level is perfectly arbitrary, and that level is chosen only because M. Tiesserenc de Bort selected it for constructing his charts of mean isobars of the upper air eighteen years ago.[6] It is in the region of the clouds of intermediate height and probably does not correspond with any specific discontinuity in the atmospheric layer. It is accordingly remarkable that the separation of the surface, or resultant distribution, into two distributions of opposite type should be so complete when the level of 4000 meters is taken as the surface of separation. It is not desirable to follow out the consequences of small differences that might be found, because the calculation of the isobaric distribution at high levels is itself as yet not susceptible of very great accuracy, and indeed the distribution of pressure at sea level even in the Northern Hemisphere is not entirely free from uncertainty, owing to the uncertainty of the reduction for altitude.

The remarks in this paper refer to the circulation in middle and higher latitudes, because the determining force for steady motion is assumed to be dependent upon the velocity of motion of the air and rotation of the earth. The acceleration computed from these elements contains sin λ as a factor, and it is therefore without serious influence in the equatorial regions.

It is fortunate that this is so, because the drift of upper air over the equator is generally accepted as being from east to west, and about 80 miles per hour may be assigned as the rate of this drift. From the results of Sir J. Eliot's work on the cloud observations of India,[7] it appears that at Simla, in latitude 31° north, the westerly current in the upper air is extraordinarily steady throughout the year, whereas at Madras the upper current shows considerable variation with the season. Between the westerly current at Simla and the easterly equatorial upper current there must be a region where the conditions in the upper air are in many ways similar to the surface conditions in temperate latitudes, that is to say, steady motion would involve the existence of two oppositely directed streams of air at the same level, but in not far distant latitudes. It would appear that for rotary storms originating in that region the gradient must depend only upon local centrifugal action and the velocities for given barometric variations must be correspondingly great. I am not sufficiently well acquainted with the sequence of events in a tropical hurricane to be able to follow out the suggestion that those phenomena have their origin in the upper air; I hope to be able on a subsequent occasion to cite examples to show that storms in the region of the minimum pressure in temperate latitudes may arise from special *surface conditions*, and there is at least some evidence for the correlative origin of tropical hurricanes.

I have made no comparison of the first results of this method of analysis of the average barometric distribution with the conclusions arrived at by Thomson and Ferrel, for the general circulation of the atmosphere, nor with those more recently obtained by Bigelow, because the method of treatment is in some respects novel, and it seems desirable to wait for its further application before making any such comparison. I may remark, however, with regard to the theories of the two authors first mentioned, that a steady circulation around the polar regions requires only the supply of the comparatively small amount of energy necessary to make up the loss occasioned by surface friction, and consequently no great transference of energy from the equatorial regions to middle or higher latitudes in the form of heat or otherwise is demanded for the maintenance of the circulation.

Moreover, I have confined my observations to the barometric distributions for the month of January. So far as I have examined the distributions for July, the conclusions to be drawn from them are in many respects similar, but the separation of the pressure component for easterly circulation from that for westerly is not complete at the 4000-meter level as it is in the case of January.

In conclusion, I desire to acknowledge the assistance I have received from Mr. G. T. Bennett, M. A., of Emmanuel College, Cambridge, with whom I have discussed especially the dynamical questions involved, and from Mr. R. G. K. Lempfert, M. A., and other members of the staff of the Meteorological Office, who have supplied me with much of the material upon which the general conclusions set out in this paper have been based.

[6] Annales du Bureau Central Météorologique de France, 1887, Part I, p. C. 1.

[7] Indian Meteorological Memoirs, vol. 15, Part I, 1903.

HOURLY CLIMATIC RECORDS ON THE ISTHMUS OF PANAMA.

By Gen. H. L. ABBOT, U. S. A., retired. Dated June 4, 1904.

Appreciating the value of the most precise information attainable as to the climatic conditions existing upon the Isthmus, the engineers of the New Company, before resuming canal operations upon a large scale, inaugurated, in July, 1899, a series of automatically recorded, continuous observations at Alhajuela on the upper Chagres River and at La Boca on the Bay of Panama. The early records, which appeared in the MONTHLY WEATHER REVIEW for May, 1899, and March, 1903, have given a good general idea of these conditions, but it is only by a long continued hourly study that many important details can be made known. When the canal property was transferred to the United States, in April, 1904, these records of the company covered five years for eight of the months, four years for three of the months, and three years for May. This present paper discusses the data collected.

The two localities are well suited to develop any characteristic differences between the climate of the interior, where the largest works must be executed, and that on the Pacific coast, where is found the largest population. Table 1 presents a general summary of the data collected relative to temperature. It is apparent from the figures not only that the monthly variation is extremely small during the entire year, but also that there is no sensible difference in mean monthly temperatures between the interior and the Pacific coast. There are, however, important differences in the daily range between extremes, which increase from about 9° F. at La Boca to 13° F. at Alhajuela, and also in the critical hours, especially that of extreme heat, which is always earlier in the interior than on the Pacific, and later in the dry than in the rainy season. Figure 1 exhibits these differences to the eye.

During these five years the rainfall was rather less than that indicated for other and longer periods. As there is an intimate relation between rainfall and temperature, Table 2 is added to facilitate comparisons; it should be considered in connection with a similar consolidated table, covering a wider district and many more years, which appeared in the MONTHLY