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THE SIGNIFICANCE OF AIR MOVEMENTS ACROSS THE EQUATOR IN RELATION TO DEVELOPMENT AND EARLY MOVEMENT OF TROPICAL CYCLONES

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INTRODUCTION

The question of relationship between extensive air movements across the Equator and the development and early movement of tropical cyclones is considered from the standpoint of local observations on the Isthmus of Panama. Panama lies about 9° north of the Equator and is normally within the area of the northeast trades or near their southern edge during most of the year. But on comparatively rare occasions there are extensive air movements from the south that have all the characteristics of the trade winds. It is not possible from local observation alone to establish the fact that these winds are always extensions of the southeast trades of the Pacific, but this point is not necessarily important, as their direction of flow is continuous with the southeast trades and their effect on local weather is similar. All extensive air movements in this latitude can be classified as either "northerly" or "southerly" and are more or less definitely associated with the trade-wind systems of either the Northern or the Southern Hemisphere. In much the same way that "northers" and similar storms are associated with strong flows of air from the north, so also is the development of tropical cyclones in the west Caribbean associated with strong flows of air from the south. The question is: Are the winds noted in Panama what normally would be expected in the southerly quadrants of a developing cyclone, or do they possess a peculiar character of their own? In other words, are these winds more important than winds from any other direction in the processes that attend the development and early movement of Caribbean tropical cyclones?

In regard to the question as to why air movements across the Equator or winds having similar characteristics might be considered as worthy of special notice, it is desired to call attention to several points concerning tropical cyclones and the general air movements of the tropics.

Very little is known about the beginning of the destructive tropical cyclones in the Caribbean, except two things: First, a cyclonic center develops somewhere in the tropics; second, this center is transported in a direction having a positive component away from the Equator. Inasmuch as the deflective action of the earth's rotation on air movements increases with distance from the Equator, the poleward migration of the storm center is essential to its full development; and in the case of centers forming comparatively close to the Equator, is perhaps as important as the fact of original formation.

No matter what theory may be entertained regarding the details of cyclonic development, air movements of an extensive nature are necessarily involved. As it has been shown by observation that movements of tropical cyclones are controlled by the drift of the lower atmosphere surrounding them, it follows that air movements over an extensive area are associated both with their initial formation and their early movement (1). And it also follows that any atmospheric formation that fills the dual role of promoting cyclonic development and of providing the driving force necessary to carry the developing storm away from the Equator is favorable in the highest degree to the occurrence of tropical cyclones.

All air movements that may be associated with initial cyclonic development and also with the early movement of the storm fall in one of two groups; first, outflows from areas of increasing pressure; second, inflow toward an area of decreasing pressure. These two actions may appear identical to the observer, the only distinguishing characteristic being the nature of the pressure changes accompanying them.

Outflows from areas of increasing pressure are noted most frequently in the Tropics during the passage of anticyclonic areas in the Temperate Zones. The anticyclonic areas travel from west to east and usually follow a more or less pronounced barometric depression. As the general circulation of the lower atmosphere within the Tropics is from east to west, it follows that the initial overflow of air from an anticyclonic area may enter the Tropics at a considerable angle to the direction of the normal flow in this region. But as long as the air movement does not cross the Equator, its initial effectiveness as a disturbing factor tends to diminish, and, as the anticyclone travels toward the east, the direction of outflow more and more closely approaches the normal direction of the trades and eventually merges with them. But, when a strong flow of air crosses the Equator from one hemisphere to the other, its direction is changed by the deflective action of the earth's rotation, and, within reasonable time limits, it can never adjust itself to the circulation of the new hemisphere. While the normal circulation within the Tropics is from east to west, air-flows crossing the Equator tend to become more and more from west to east, and their direction to always remain at variance with that of surrounding air masses. Any storm formations that may occur, instead of being forced back toward the Equator, are carried farther away from it.

Normally, pressure conditions within the Tropics, including both the trade-wind areas and the doldrums, are very stable, in striking contrast to the Temperate Zones on either side where large pressure changes from day to day are a regular occurrence. Fundamentally the position of the doldrums and the attendant trade-wind belts are determined by the position of the heat equator. Variations normally arising within the Tropics

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are of a seasonal nature only, but short period variations frequently are produced by the influence of the rapid pressure changes in the Temperate Zones. Thus the doldrums, in addition to being a region of calms, is also an area of conflict, a no-man's land of advance and retreat between opposing forces. But at any particular time, the area of the doldrums represents a condition of equilibrium between the varying impulses of the opposing trade-wind systems on each side. Normally nothing can arise within the Tropics to materially disturb this condition of equilibrium, and when a cyclonic circulation develops it commonly forms 10° or more from the Equator.

To summarize, two ways have been mentioned in which air flows across the Equator, representing a continuous flow of the trade winds of one hemisphere into the other hemisphere, may aid the development and early movement of a tropical cyclone; first, as an outflow from an area of increasing pressure such winds may function materially in the initial formation of a cyclonic center and aid its early movement toward higher latitudes; second, as an inflow toward a developing storm center they may aid its later development and influence the further movement of the storm. These two forms of action may occur singly or the first may merge into the second during the formative period of the storm.

It is intended briefly to consider available data covering periods of southerly winds at Panama with particular attention to the question of the existence or nonexistence of the theoretical forms of action outlined above, and, if such forms of action are found to exist, to consider the question of their importance in relation to the formation and early movement of tropical cyclones.

SOUTHERLY WINDS AT PANAMA

In considering periods of general southerly air movement across the Isthmus of Panama, all days with constant southerly winds and a minimum daily mean velocity of 7 miles per hour at either Balboa or Cristobal have been tabulated. Balboa is on the Pacific side of the Isthmus of Panama and Cristobal on the Atlantic side, about 32 nautical miles distant. The record covers a period of 26 years, from 1908 to 1933, inclusive. The wind record was made by a four-cup anemometer from 1908 to 1929 and a three-cup anemometer from 1930 to 1933, with velocities uncorrected. The velocities given are derived from the sum of the winds from all southerly quadrants. The number of days recorded at each station during the 26-year period follows:

Number of days with constant southerly winds at the Isthmus of Panama—26-year period, 1908–33

	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Annual
Total days at Balboa	5	19	18	4	10	47	96	24	223
Total days at Cristobal	------	14	23	2	11	53	88	37	228
Total days common to both stations	------	6	13	1	5	33	66	17	141

The record shows 223 days at Balboa, of which 82 days were at Balboa only, and 228 days at Cristobal of which 87 days were at Cristobal only. This leaves 141 days common to both stations, or an annual average of less than 6 days. The occurrence of these days is confined to the hurricane season with a lesser maximum in June and a greater maximum in October. If days common to both stations only be considered, annual totals range from none in 1911 and 1914 to 18 in 1916 and 1933. Days with southerly winds are frequently grouped in periods several days in length. During the 26 years there were 142 such periods ranging in length from 1 day at one station only to a maximum of 9 consecutive days at both stations.

The record of surface winds alone does not furnish a complete index to the conditions attending these periods. When southerly winds become established at the surface with sufficient force to overcome the land-and-sea-breeze influence, it can be stated with reasonable certainty that the entire lower atmosphere is involved to a depth of a mile or more. Surface velocities for the 223 days at Balboa averaged 11.9 miles per hour, and for the 228 days at Cristobal 9.3 miles per hour. Mean daily velocities as high as 23 miles per hour have been attained at Balboa and 19 miles per hour at Cristobal during these periods. The maximum velocities occur just above the reach of frictional influence of the surface and may at times be twice as great as surface velocities. After the winds become well established the direction at the surface is steady southwest at Cape Mala (113 nautical miles almost due south of Cristobal), south at Balboa, and southeast at Cristobal. These differences represent local influences. Above the surface the direction varies with elevation from near south to near southwest. During periods of steady winds the air is comparatively clear and rainless. The temperature and humidity are both lower than the seasonal average. A comparison of mean values of temperature and 8 a. m. dew point, in degrees Fahrenheit, for days with constant northerly winds during the hurricane season and for days with constant southerly winds follows: The days used cover a period of 10 years.

	Number of days	Cristobal (Atlantic)		Balboa (Pacific)	
		Temperature	Dew point	Temperature	Dew point
Northerly winds (Caribbean air)	104	82.9	76.5	80.9	74.1
Southerly winds (Pacific air)	75	80.0	73.2	78.4	73.2
Difference	------	2.9	3.3	2.5	1.9

The only significant barometer values during and preceding periods of southerly winds are relative pressure changes at two or more closely adjacent stations with accurate instruments. Absolute barometer values at one station do not constitute an index, as variations during periods are frequently exceeded at other times with no effect on local weather. The barometer values used here are daily means of bihourly values from the barograph trace checked by mercurial readings at 8 a. m. and 8 p. m. The seasonal mean barometer and values during these periods of southerly winds follow:

Barometer values during 142 periods of southerly winds

	June–November mean barometer	Average for second preceding day	Average for preceding day	Average for initial day	Low for any day	Greatest fall
Balboa	29.826	29.823	29.822	29.830	29.740	0.114
Cristobal	29.836	29.829	29.823	29.822	29.694	.115

The barometer on the initial day is very near the seasonal mean, but the normal pressure slope of 0.010 inch toward the south is reversed to 0.008 inch toward the north. During the 19-year period, 1915 to 1933, the mercurial barometers at Balboa and Cristobal are in suffi-

ciently close agreement to allow consideration of pressure differences. During this period there is an average of 20 days each year with a pressure slope toward the north showing a pressure difference in excess of 0.010 inch. Monthly frequencies are similar to frequencies of days with southerly winds. A pressure slope of this nature is usually associated with the occurrence of southerly winds.

The reversal in the pressure slope may be produced in two ways: First, by a rising barometer in which the relative rise at Balboa is the greater; second, by a falling barometer in which the relative fall at Cristobal is the greater. The character of the pressure changes on the initial days of periods of southerly winds follows:

Character of pressure change on initial days of periods of southerly winds

	Rising	Falling	Fluctuating	Total
Short periods (with less than 2 days at both stations)	52	28	21	101
Long periods (with 2 or more days at both stations)	15	18	8	41
Total periods	67	46	29	142

In most extended periods of southerly winds the initial phase merges into what may be called the second phase. This phase is always clearly marked by a falling barometer in which the relative fall in Cristobal is considerably greater than in Balboa, indicating the development of a low-pressure area somewhere to the northward. This is the period of lowest barometer, maximum mean daily wind velocities, and steady wind direction. No matter what the distance, direction, or intensity of the low pressure area may be, the wind-flow at Panama is as steady and unchanging as that of water through a pipe. Within a few days the wind dies down, the barometer rises, and normal conditions are restored.

The nature of the air-flow during periods of southerly winds is not always clearly indicated. Sometimes it is obviously an outflow from an area of increasing pressure to the southward. At other times it is equally clear that the controlling action lies in an area of decreasing pressure to the northward. Actions of each nature are frequently combined in one period. Local observation shows that a majority of the periods are preceded by a few days of mildly fluctuating pressure changes, unequal at locations a short distance apart, during which time the normal pressure slope is reversed. Southerly winds may be initiated by either a rising or a falling barometer. Following the initial phase, most of the longer periods develop positive characteristics indicating inflow toward an area of decreasing pressure to the northward. But there are a number of outstanding periods that are unquestionably begun and controlled throughout by a steady fall in pressure in the west Caribbean, with the air-flow from the south merely a drainage toward this area.

ASSOCIATION OF SOUTHERLY WINDS AND TROPICAL CYCLONES

During the 26-year period, 1908 to 1933, 45 storms forming in the west Caribbean have been classified as tropical cyclones and so published. Thirty-five of these storms have been closely associated with periods of southerly winds at Panama, and 10 storms have not been closely so related. During the same 26-year period, there have been 142 periods of southerly winds at Panama. Thirty-nine of these periods have been associated with cyclone development, and 103 have not been so associated, although many of the latter have been accompanied by lesser storm developments. Included in the 39 periods are 4 associated with cyclone formation outside the west Caribbean but within a distance of 1,000 miles. The direct relationship in these cases is problematical although within the range of possibility. The association of cyclone formation and periods of southerly winds classified as to length and initial pressure characteristics follows:

Character of pressure change on initial day

	Rising	Falling	Fluctuating	Total
Total short periods	52	28	21	101
Number associated with cyclone formation	(6)	(8)	(2)	(16)
Total long periods	15	18	8	41
Number associated with cyclone formation	(7)	(12)	(4)	(23)
Total periods	67	46	29	142
Number associated with cyclone formation	(13)	(20)	(6)	(39)

More than half of the long periods are associated with cyclone formation but only about one-sixth of the short periods. The character of the pressure change on the initial day seems to have little significance in regard to possibility of cyclone formation, although it does furnish an index to the nature of the development.

Periods of southerly winds are associated with the initial formation and early movement of cyclones only. Many storms of east Atlantic origin have crossed the Caribbean Sea south of Cuba within the last 26 years with no effect whatever upon the air circulation at the Isthmus of Panama. But if a storm of any intensity develops in exactly the same area, it is almost sure to be associated with strong air movements at Panama. There has been one exception to this rule, the storm of November 1932, and this was really a case of redevelopment.

The association between southerly winds and cyclones seems to apply to both the initial formation and the early movement. Of the 39 periods associated with formation and movement of cyclones, 26 show southerly winds at Panama 1 or more days preceding published date of formation, and 13 show southerly winds beginning on the same day or after published date of formation. There are 14 periods of southerly winds lasting 3 days or longer at both stations that are associated with cyclone formation and movement. Among these periods, there are 3 in which southerly winds at Panama stopped with the storm center less than 500 miles distant, 7 in which the southerly winds stopped with the storm center between 500 and 1,000 miles distant, and 4 in which the southerly winds persisted after the storm center had attained a distance of 1,000 miles.

It is intended to consider in detail eight typical periods of southerly winds at Panama, using daily mean values of wind movement and pressure at Balboa and Cristobal for a 15-day period preceding, during, and following the period of southerly winds. A ninth period is also considered in which a wind record at Cape Mala is available. These periods may be classified in three types on the basis of their initial action in association with the accompanying cyclonic development; first, those periods in which the dominant feature appears to be a frontal advance from the south, and in which air-flow from the north appears to be nonexistent or to play a purely passive role in the storm development; second, those periods in which strong air-flows from both the north and the south are evident in the local record, but in which the air-flow from the south appears dominant for a short time after the initial cyclonic development; third, those periods

whose dominant feature appears to be a slowly developing low-pressure area in the west Caribbean, and the local air-flow a part of the drainage toward this low-pressure area.

Four of the nine periods considered have to be classified under the first type, whose dominant characteristic is a frontal advance from the south. All of these periods occurred during the month of October, in the years 1921, 1923, 1924, and 1926. The period in October 1910 also partakes of the same nature but will be discussed later. During October 1923 southerly winds obtained at Balboa on the 11th and again at both stations on the 16th to 19th. Following the single day at Balboa, a cyclone formed in the Gulf of Tehuantepec, about 800 miles distant, on the 13th. Following the 4-day period, a cyclone formed north of eastern Cuba, about 1,000 miles distant, on the 22d. The relationship in these cases is problematical. During the following week, from the 21st to 27th, the Isthmus of Panama experienced the heaviest general rainstorm on record.

During October 1924 there was a 6-day period of southerly winds from the 13th to the 18th. A cyclone formed in the Gulf of Honduras, about 600 miles distant, on the 16th, the fourth day of southerly winds at Panama.

During October 1926 there were 4 days of southerly winds at each station from the 15th to the 19th. A cyclone formed about 100 miles north of Cristobal on the 16th. The center of the developing storm on this date was so close as to cause variable winds and squalls at Cristobal. The Panama data in connection with this storm have been thoroughly discussed by Tingley and Hurd (2) (3). Southerly winds persisted at Cristobal until the 19th, when the storm center was about 700 miles distant.

The period of southerly winds in October 1921 has been given special attention here because an automatic wind record is available at Cape Mala, which extends the comparative wind values to three stations along a north-south line about 113 nautical miles in length. Daily mean values of wind movement, pressure, and rainfall for a 40-day period, September 25 to November 3, were examined. No general wind movement from the north is evident during this period prior to November 1. Northerly winds were purely local, due to thunderstorms and land and sea breezes. Constant southerly winds occurred at Balboa and Cristobal on 7 days at each station during the 40-day period, 1 day on September 28, 1 day on October 5, and 5 days on October 18 to 23. Constant southerly winds occurred at Cape Mala on 15 days during the same period. In general the southerly winds were associated with a rising barometer, with the relative rise in Balboa the greater. The lowest barometer occurred on October 17, followed by a general upward trend for 10 days. A tropical cyclone formed about 300 miles north of Cristobal on October 21,[1] which may be considered the fourth day of general southerly air movement across the Isthmus.

In a development like this, heavy rainfall and the highest momentary wind velocities are nearly always found in what may be termed the squall area, which may extend for a considerable distance in front of the steady winds. Most of the rainfall during this 40-day period occurred during the 10 days preceding the 20th of October. The latter part of the month was practically rainless at all stations. During the 3-day period, October 17 to 19, the Gulf of Panama represented by the Cape Mala and the Balboa stations lay in a squall area. Winds approaching gale force would blow for a short period and then die down to almost calm. The nature of the winds is suggested by the strong gale on the 19th. The wind averaged 36 miles per hour at Cape Mala for the hour ending at 10 a. m. This gale reached Balboa at noon with the wind averaging 25 miles per hour for the 2 hours ending at 2 p. m.

The steady winds became established at Balboa about midnight of the 19th and 20th, and at Cristobal during the afternoon of the 20th. The maximum wind velocity at Cristobal occurred on the afternoon of the 21st, after the storm was already in existence and under way. After these winds become well established, they are unchanging in direction. The wind at Cape Mala blew steadily from the southwest for 147 hours, at Balboa it blew from the south for 52 hours, and at Cristobal it blew from the southeast for 69 hours. After the storm developed, constant southerly winds continued to blow at Cape Mala until the 29th, but had become light and variable at Balboa and Cristobal by the 24th.

Two of the nine periods of southerly winds considered can be classified under the second type, in which strong air-flows from both the north and south are evident near the time of cyclone development. During November 1912, there were 3 days of southerly winds on the 12th to 14th. A tropical cyclone formed on the 11th about 150 miles north of Cristobal. Air-flow from the north was evident on the 10th, immediately preceding the cyclone development, and was resumed on the 17th, reaching the force of an intensified trade on the 18th, with a mean daily velocity at Cristobal of 21 miles per hour. Storms of this type usually occur near the end of the hurricane season, when the northeast trades are advancing toward the south and the southeast trades of the Pacific have not begun their seasonal retreat. Such storms usually follow a short abnormal path.

The period of southerly winds on June 28 to July 1, 1916, was immediately preceded by a moderate air-flow from the north on the 26th, represented locally at Cristobal by west and northwest winds. A cyclone formed about 150 miles northwest of Cristobal on the 29th. This is not exactly the same type as the November storms, as the northeast trades are retreating rather than advancing at this season. But the local record of barometer and wind suggests the possibility that opposing air-flows may have established close contact near the time of initial storm development. A sharp reversal of the pressure slope is centered on the 28th, marking the change in control from northerly to southerly movement.

Two of the nine periods of southerly winds considered can be classified as belonging to the third type, whose dominant feature appears to be a slowly developing low-pressure area in the west Caribbean. A 4-day period of constant southerly winds occurred on November 5 to 8, 1932. The storm associated with these winds represents the only instance in a 26-year record in which a storm of east Atlantic origin has materially influenced the air circulation at the Isthmus of Panama. This storm was first noted near the island of Guadeloupe on October 30. For 4 days it was driven in a southwesterly direction across the eastern two-thirds of the Caribbean Sea. But on November 5, after clearing the north coast of Colombia, it tapped the reservoir of the southeast trades of the Pacific across the Isthmus of Panama, and redeveloped on an immense scale, involving the winds of the entire western Caribbean and southward into the Pacific. The barometer at Panama was marked by a steady fall from November 1 to 7 and then by a steady rise until the 12th.

[1] This storm was located by Bowie on the p. m. map of October 20. See MO. WEA. REVIEW, October 1921, vol. 49, pp. 567-569.

The mean pressure at Cristobal on November 7 was 29.694 inches, the lowest on record during any period of southerly winds.

The longest period of southerly winds ever recorded at Panama occurred on September 28 to October 6, 1933, a total of 9 consecutive days at each station. The associated local pressure record was similar to that of the storm of the preceding year, with the minimum barometer on September 30. A cyclone center was identified about 450 miles north of Cristobal on October 2.[2] This is perhaps the outstanding example of the slow development of a low-pressure area in the west Caribbean. While the winds at Balboa and Cristobal were much the same as in many other periods, reports from the southward in the Pacific at the time show no marked wind movement.

The period of southerly winds in October 1910 is of special interest in that it combines the first and third types of development under the classification here used. This is characteristic of many storms of the first type, but one type of development usually merges into the other without a break in local winds. In this case a definite break in southerly winds occurred between the original storm development on October 11 and 12, associated with a frontal advance from the south, and its redevelopment on October 16 and 17 associated with slowly falling pressure in the west Caribbean. According to Mitchell, a tropical cyclone formed about 250 miles north of Cristobal on October 11. It then moved northward to near the western end of Cuba, where it remained nearly stationary for 3 days, from the 14th to 17th, and then resumed its northward course (1). Southerly winds obtained across the Isthmus of Panama on October 12 and 13, associated with a rising barometer, with the relative rise at Balboa the greater. This was followed by a definite break in southerly winds on the 14th and 15th, and their resumption on the 16th and 17th, with a falling barometer, with the relative fall at Cristobal the greater. The storm center was about 900 miles distant at the time of the second appearance of southerly winds.

DISCUSSION

Observations of southerly winds at the Isthmus of Panama would seem to warrant the conclusion that they cover an extensive area and may be considered as continuous with the trade wind system of the Southern Hemisphere. The outstanding pressure characteristic during periods of these winds is a reversal of the normal pressure slope, indicating a change in the location of the controlling low-pressure center from south of Panama in the Pacific to north of Panama in the Caribbean. Local pressure changes show that these winds may be either outflow from an area of increasing pressure to the southward, or inflow toward an area of decreasing pressure to the northward. Action of both natures is associated with cyclone occurrence to the northward in the west Caribbean.

The constancy in direction of these winds and their distance from the attending storm center seems to show with reasonable certainty that they are not an integral part of the cyclonic circulation itself, but that they represent independent action in the general circulation. On the other hand, the fact that these winds many times precede and are closely associated with cyclone formation and movement argues that they may play an important role in the initial development of these storms. And the fact that periods of southerly winds are intensified and prolonged when accompanied by storm formations argues that the existence or movement of a cyclonic circulation in turn influences these air movements materially. The association between air movements across the Equator from one hemisphere to the other and the development and early movement of tropical cyclones as observed at Panama seems close enough to warrant the conclusion that definite relationships exist, but of such a complex nature, that without more extensive and detailed observations, the exact function and relative importance of these air movements cannot be defined.

But a number of interesting points are suggested. For one thing, it would appear that tropical cyclones may develop in a variety of ways, and, if there is any secret in the formation of these storms, it would seem to lie in unusual combinations of simple weather processes and atmospheric action, rather than in any one simple process alone. Strong air-flows across the Equator from one hemisphere to the other may be a special form of atmospheric action that plays an important role in these peculiar combinations of conditions.

One interesting feature in the action of these winds seems to be in connection with what may be termed "frontal formations." This type of action is well represented by the storm development of October 1921. Very similar characteristics are noted in connection with the "northers" of the southwest Caribbean, as distinguished from overflow northers. These storms are marked by a continuous succession of heavy wind and rain squalls, and are followed by an extended period of steady northerly winds. In this squall area are found the highest winds of the whole formation. There are no distinctive pressure characteristics. A norther may start with either a falling, stationary, or rising barometer, but there is usually a marked rise in pressure following them and accompanying the steady winds. The essential feature seems to be that the high winds and squalls occur around a slight barometric depression that must be produced in some way by mechanical action attending the frontal advance. Action of this kind may occur along a front hundreds of miles in length. A norther in the Gulf of Tehuantepec is frequently accompanied by an intensified trade in Panama or vice versa. In much the same way, when strong air movements from the south approach the Pacific coast of Panama and Central America, heavy rains and violent local storms frequently appear at widely distributed locations along the coast. Hurd (4), in discussing the cyclones of the eastern North Pacific cites instances where a cyclone may appear at one point along the Mexican coast and violent southerly gales simultaneously hundreds of miles distant.

The direction of early movement of a cyclonic development, especially when located in low latitudes, may be as important in the life history of the storm as the fact of formation itself. Cyclones forming near the Isthmus of Panama in the Caribbean move almost straight north for the first 500 miles or more of their course. If they do not, their chance of ever appearing in any published list of tropical cyclones is slight. In the southwest Caribbean, southerly gales of much the same character as those observed at Panama are the most noticeable feature of these developments. Cline (5), in his study of cyclones in the latitude of the Gulf of Mexico, shows that the highest wind velocities occur in the rear quadrants of the storm, pointing in the direction the storm is traveling. It may be difficult from observation of mature storms in high latitudes to distinguish cause and effect, but near

[2] A center was located on Oct. 1. See MO. WEA. REVIEW, October 1933, vol. 61, p. 308.

the time of formation, the early movement of the storm is most certainly determined by the action of the air masses surrounding it, and, a controlling air-flow from the direction of the Equator providing the first impulse may determine its entire future life history. Mitchell (1) has shown that tropical cyclones rarely, if ever, form in the eastern two-thirds of the Caribbean Sea. How is this fact to be interpreted? Is it because dominant air-flows from the direction of the Equator are effectively blocked by the South American continent?

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MONTHLY AND SEASONAL DISTRIBUTION OF SNOWFALL [1] IN CALIFORNIA

By MALCOLM SPRAGUE

[Weather Bureau, San Francisco, Calif., June 1934]

California, because of its great extent from north to south and its diversified physical features, is a region where the climatic elements have an exceptionally wide range. This is especially true of snowfall. On the extreme southern coast, snow has not fallen within the last 84 years, while the western slopes of the middle and northern Sierra Nevada include several localities where the annual mean snowfall approaches the record for the United States. The total fall is influenced more by altitude, proximity to the Pacific Ocean, shape and steepness of mountain slopes and their direction in relation to moisture-bearing winds, and by local topography, than by latitude. Topographical contrasts are especially noticeable in southern California, where semi-tropical fruits may be seen ripening near the bases of snow-covered mountain peaks. As an example of latitudinal influence, Imperial, near the southern border of the State, has an annual mean snowfall of 0.2 inch, while the coastal station of Crescent City (near), located some 620 miles farther north, has a mean of less than 2 inches. In contrast to this small south to north increase, modified by ocean influence, is the large increase within short distances west to east in the district adjacent to the line of the transcontinental railway which crosses the crest of the Sierra Nevada near Summit, Placer County. Within this area Colfax, elevation 2,421 feet, has an average annual snowfall of 25 inches; Blue Canyon, located 18 miles farther northeastward, elevation 4,695 feet, 203 inches; and Soda Springs, 19 miles east-northeast of Blue Canyon, elevation 6,752 feet, 410 inches.

The precipitation received in the form of snow, while consequential over only about half of the State, is a vital factor in all of the more important activities in California, providing a water reserve for navigation, mining operations, hydroelectric projects, and domestic and municipal consumption, and making possible many minor activities that depend on the others for their prosperity. The California snow-fields also have a recreational value and their use for winter sports has increased greatly during recent years.

SNOWFALL DISTRIBUTION BY MONTHS

Snow has fallen over the "High Sierra" in all months of the year, but over the valley floors and much of the coastal area, only occasionally during the winter and spring months. Daily amounts generally are inconsequential over the lowlands and drier portions of the State, and increase with increase in seasonal precipitation and in altitude up to 7,000 feet, reaching a maximum over the western slopes of the middle Sierra Nevada. The heaviest 24-hour snowfall of record in California was 60 inches at Giant Forest, Tulare County, on January 19, 1933, and the next heaviest was 59 inches at Summit on December 23, 1916.

The distribution by months for the State as a whole in percent of average seasonal amount is as follows: January, 26; February, 20; December, 18; March, 17; April, 8; November, 7; and October and May, 2 each. The total fall for the other 4 months is less than 1 percent of the seasonal average. This average distribution is fairly representative. However, in the warmer portions of northern and central California the midwinter months have a somewhat higher percentage than like months for the State as a whole. Similarly in the colder portions, especially over the eastern slopes of the southern Sierra Nevada, higher percentages occur in the spring months. The distribution over the southern slopes of the mountains of southern California is similar to that over the southern slopes of the southern Sierra Nevada. The monthly distribution for four groups of stations is illustrated in figure 1. Reading down from the left, the first group represents the Coast Range Mountains; the second the western, and the third the eastern, slopes of the Sierra Nevada; and the fourth, the mountains of southern California.

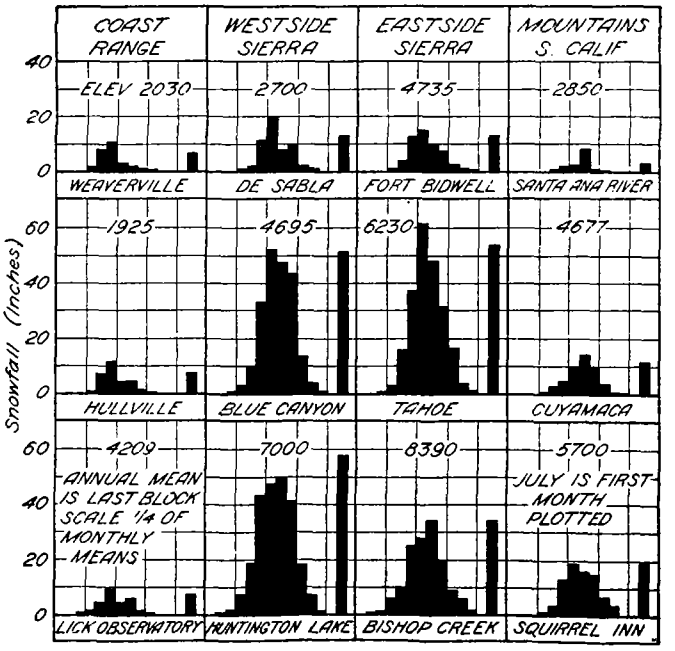

FIGURE 1.—Mean monthly snowfall distribution.

[1] Presented at the American Meteorological Society at Berkeley, Calif., June 21, 1934.