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THE SOUTH-WEST MONSOON.

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IN India when we speak of "the monsoon" we almost invariably mean the rain which falls during the period from June to September. Thus we talk of a good or a bad monsoon according to whether the rainfall is in excess or defect. Technically, of course, this is wrong, for the name monsoon really applies to the wind, and was given by the Arabs to the winds over the Arabian Sea which blow for approximately six months from the North-East and for six months from the South-West, the word monsoon itself being derived from the Arabic name for a season. Sailors still use the word monsoon in this sense, and refer to the north-east and south-west monsoons, meaning only the steady winds which blow from these two directions: they have little interest in the rain, but the wind direction is of all-importance to them.

This application of the word monsoon to both the rain and the wind can lead to difficulties in expression; for a good monsoon, when applied to the rain, may not apply to the wind, for it does not follow that a year of good rain is necessarily a year with strong winds.

As we have no special word for the rain associated with the south-west monsoon, and as there is no rain in India associated with the north-east monsoon, I shall use the word monsoon in this lecture to signify the whole processes associated with the South-West winds which blow during June to September in the Indian region; whether the word is applied to the rain or to the winds will generally be quite clear from the context.

I believe that very few educated people would have any difficulty in giving an answer to the question—What is the cause of the monsoon? They would refer to the high temperature over the land compared with that over the surrounding sea, and would speak of ascending currents of air causing an indraft of sea-air towards and into the interior of the country. It is only when one points out that India is much hotter in

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May, before the monsoon sets in, than in July, when it is at its height, or draws attention to the fact that the hottest part of India—the north-west—gets no rain during the monsoon, or even shows by statistics that the average temperature is much greater in the years of bad rains than in years of good rains, that they begin to doubt whether they do know the real cause of the monsoon.

The monsoon is not the simple result of a single physical condition. It is produced by a combination of circumstances, involving consideration of temperature, pressure, humidity, geographical relationships between land and sea, the rotation of the earth, and lastly, but probably the most important, the distribution of mountain ranges. In preparing this lecture I have had the greatest difficulty in deciding how to place before you all the considerations involved, and how to draw attention to the difficulties which every assumption involves. The plan which I have decided to follow is to neglect fundamental causes at first. We will consider the conditions as they are found during July, the typical monsoon month, and try to explain why these conditions produce rain, and why some regions receive heavy rain while others obtain practically none.

We will then consider the conditions in May, and by discussing why the monsoon does not set in during that month we shall see the conditions which contribute most largely to the mechanism of the monsoon. We will then examine the conditions during typical periods of good and bad monsoon, and see what lessons they will teach us.

Fig. 1 shows the pressure and winds at 8 a.m. over the Indian area during July. It will be noticed that the lowest pressure is over the extreme north-west of India, and that the isobars over the Indian mainland run to the south-east and then take a northerly bend over the Bay of Bengal, running to the north or north-east over the extreme east of the area. The chief pressure gradient is over the Peninsula and the Bay, there being a region of very uniform pressure over Central and Northern India.

It should be noticed that the winds strike the west coast of India almost at right angles. The air streams across the Peninsula almost directly from the west to the east, but in the north of the Peninsula it is deflected slightly towards the north. The air which crosses the Kathiawar and Sind coasts breaks up into two streams, one moving towards the United Provinces and the other towards the Punjab.

The air motion over the Bay may be considered as a general sweep around a centre in Orissa, so that the air currents impinge on the South Burma coast almost at right angles, travel nearly parallel to the North Burma coast, and cross deltaic Bengal in a steady current from the south. The air which crosses the Bengal coast is deflected to the west soon after crossing, and extends as an Easterly or South-Easterly wind along the foot of the Himalayas right into the Punjab.

In Fig. 2 is shown the rainfall distribution during July. The following points should be noticed. There is a long narrow region of heavy rain along the west coast of the Peninsula. The coast of Burma is also a region of heavy rain, except over the delta of the Irrawaddy. Right in the centre of India proper there is a region of relatively heavy rain, in which the amount of rain rises to 20 inches locally. There are

three regions with very little rainfall—(a) in the extreme north-west, (b) in the south of the Peninsula, and (c) in Upper Burma.

Turning now to the distribution of temperature, we see from Fig. 3 that the mean temperature over the greater part of India during July is very uniform; the outstanding regions are, however, very significant. It will be seen that the regions of excessive rainfall on the coasts of the Peninsula and Burma are regions of relatively low temperature, while each of the regions of deficient rainfall in the north-west, in the south of the Peninsula, and in Upper Burma shows relatively high temperature.

In order to determine the cause of the heavy rainfall it is necessary

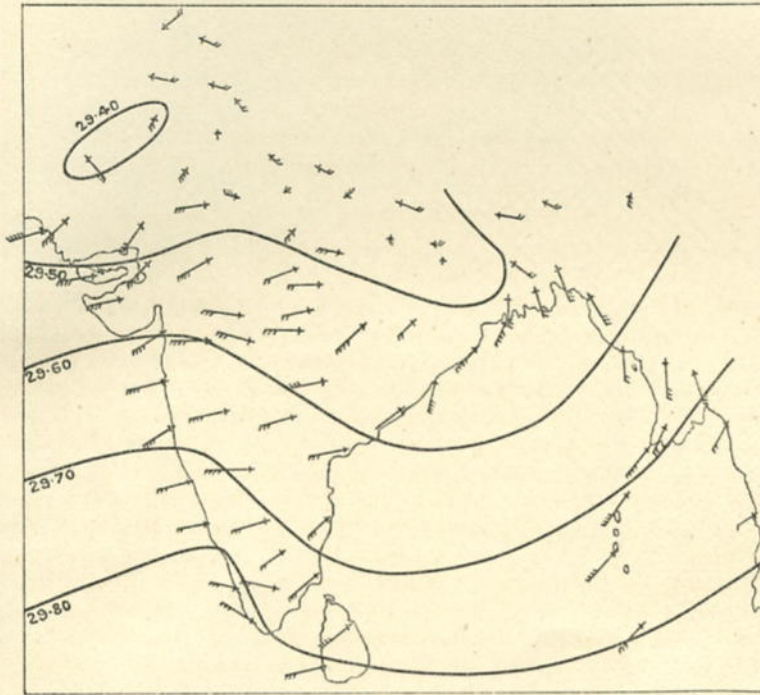


FIG. 1.—July Wind and Pressure.

to examine the air motion in relation to the hill ranges. For this purpose I have prepared the diagram shown as Fig. 4. In this the main lines of air motion have been represented as stream lines, while the hills over 3000 feet high have been shown by heavy black lines. The figure is only a diagram and is therefore not supposed to be correct in details; it has been designed to give a simple, clear idea of the general features of the air motion and the mountain ranges it meets.

The heavy thick line from A to B represents the high hills north of the Mekran coast, the average height of which is something like 5000 feet. From B to C we have the mountains of Baluchistan and Afghanistan, forming a wall nowhere less than 6000 feet above sea-level. From C to D is the main range of the Himalayas, which are

nowhere lower than 12,000 feet. D to E represents the chain of mountains in Burma running from the main Himalayan range due south to Tenasserim, the whole forming a barrier nowhere (except in insignificant gaps) less than 6000 feet. A range of mountains running along the Arakan coast, and then turning to the north-east to join the Himalayas to the east of Assam, is shown by the line GF. The Khasi Hills, in Assam, are represented by the short line HJ, running due east and west. The line running from K to L represents the Western Ghats, which are throughout the greater part of their length over 4000 feet high, and rise to still greater heights in the south of the Peninsula.

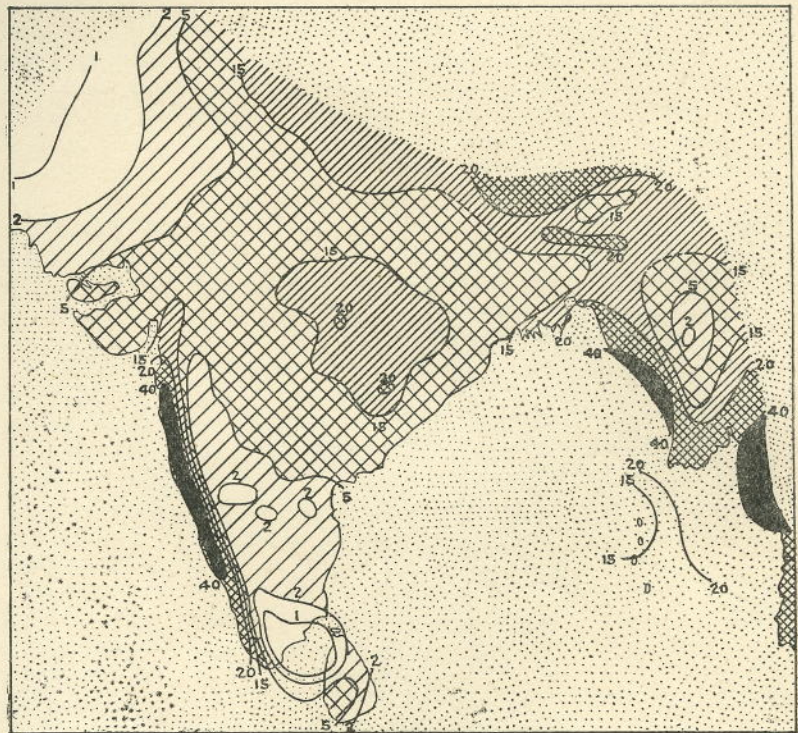


FIG. 2.—July Rainfall.

For the purposes of our examination the air motion may be represented by ten typical air streams numbered I to X on the diagram.

The first thing which strikes one on looking at this diagram is that the mountain ranges represented by the continuous line ABCDE are equivalent to the two sides of a box into which air streams through the other two sides. There are no openings through these two sides, and as the air pours in from the other sides it is clear that within the area shown the air must rise at least as high as the mountains. That is, the simple geographical relation of the mountains around India to the main air currents necessitates an ascensional movement of at least 6000 feet (the height of the wall of mountains in the east), while in reality it

is more nearly 20,000 feet. It is to this forced ascent that India owes its rainfall; the ascensional currents due to India being warm are absolutely insignificant in comparison.

Our diagram helps us to see at a glance the reason for the large variations in the distribution of the rainfall.

The wet area on the west coast.—The main air currents from the south of the Arabian Sea (represented by air streams I, II, and III) strike the Western Ghats practically at right angles and are forced to rise almost vertically 4000 feet. The air is warm and extremely humid, its temperature being 78° F. and humidity 90 per cent; it therefore

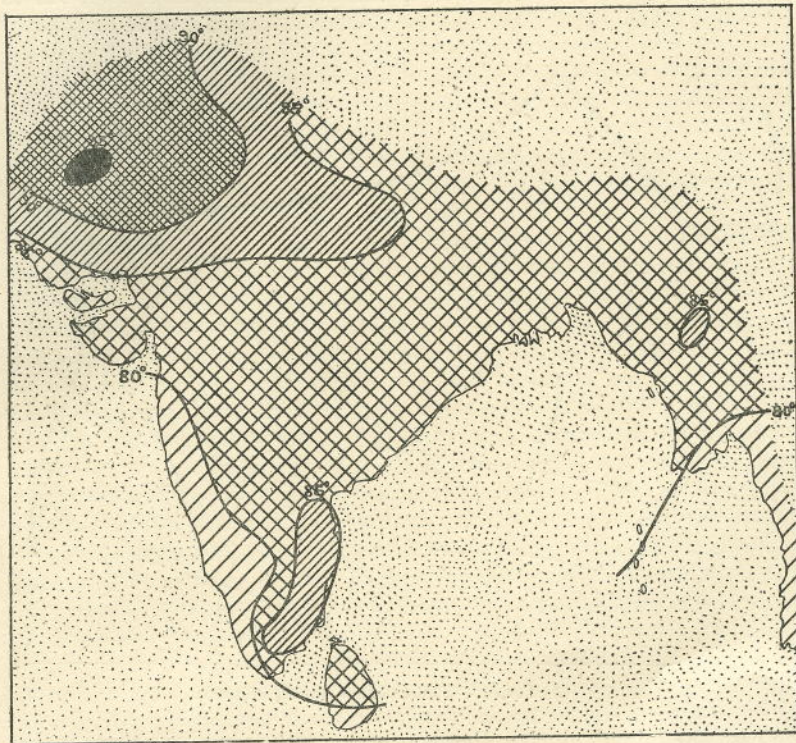


FIG. 3.—July Temperature.

contains much moisture. Condensation sets in at a height of about 500 feet, and during the remainder of its ascent condensation continues, giving rise to very heavy rain. The ascent is naturally most sudden in the middle of the range, while at the ends, where the air can escape round instead of going over the top, it is less rapid. The rainfall for July along the central parts of the range averages well over fifty inches, that is nearly two inches a day. It is clear that such heavy rainfall on such high mountains is a tremendous store of energy which has only been tapped to an infinitesimal extent by the great Tata Hydro-electric Works near Khandala.

The dry area in the Peninsula.—After the air stream has crossed over

the main ridge of the Ghats, it continues to the east, but now instead of rising it descends to the plains. A descending air current is warmed by adiabatic compression; this causes the rainfall to cease and the cloud particles to be rapidly evaporated. It should also be noticed that the air has lost a large proportion of its water in the rainfall on the west of the Ghats; hence when it descends to near sea-level on the east it is much drier than it was on reaching the west coast of India. For this reason the air streams I, II, and III are dry currents after passing the Ghats, and the whole of the south of the Peninsula receives very little rain during the south-west monsoon. During July the rainfall on the west of the Ghats varies between twenty inches and more than fifty, but on

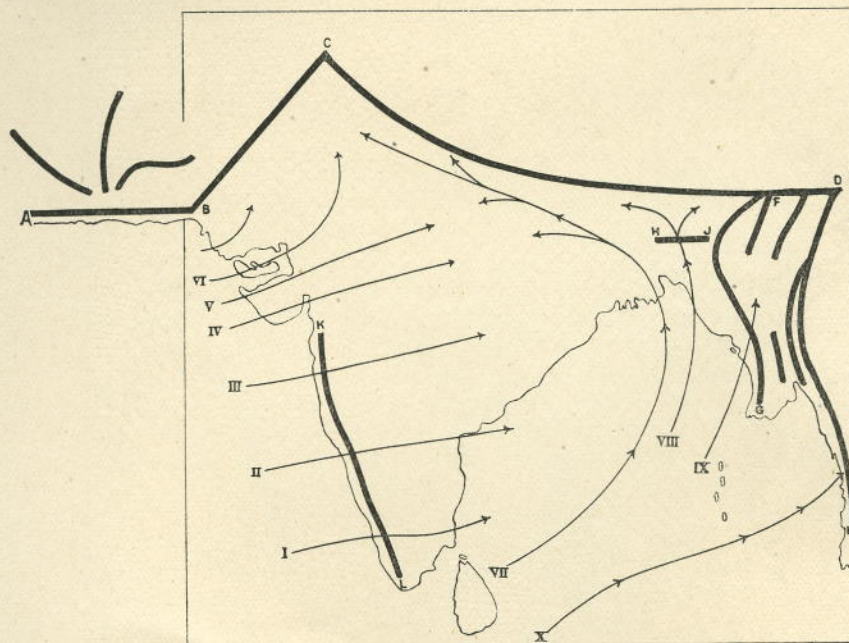


FIG. 4.—Stream Lines during Monsoon.

the east the rainfall during the month averages only about three inches, while there are isolated localities where it is as small as two inches, and in the extreme south as low as half an inch. The small rainfall in the latter region is due to the great height of the Ghats at their southern extremity, where they rise in the Nilgiris and the Cardamom Hills to well over 7000 feet.

The wet regions on the coasts of Burma.—It will be seen that the air currents over the south of the Bay strike mountain ranges on or near the coasts of Burma. Stream line X impinges directly on to the hills of Tenasserim, while stream line IX strikes the hills behind the Arakan coast, both giving heavy rain where they meet the mountains.

The dry area in Upper Burma.—The low-lying region in Upper Burma is practically surrounded on all sides by high mountains, so that what little air reaches this region from the Bay of Bengal during the

monsoon has had to cross the hills. Upper Burma is similarly related to the monsoon currents as the Peninsula, and is therefore a dry area in the centre of which less than two inches of rain falls during July.

The heavy rain of Cherrapunji.—The most interesting case is that of stream line VIII. The air in this current leaves the Bay practically saturated; it then crosses deltaic Bengal, which at this time of year is practically one great swamp—in fact a continuation of the sea, except that its water is fresh. This air current strikes the Khasi Hills, in Assam, at right angles. These hills near Cherrapunji present almost a vertical face to the air current, which has to rise almost vertically for 4000 feet. Such a rapid rise through 4000 feet of a warm saturated air current blowing with a velocity of many miles an hour causes heavy deposition of water which falls on the top of the hills with great intensity. The annual rainfall of Cherrapunji is 424 inches, the greatest recorded rainfall on the face of the earth, although there may be places in the Western Ghats where the rainfall is locally heavier. Practically the whole of this great amount falls during the monsoon. The stream, after crossing the hills, descends into the valley of the Brahmaputra in Assam, where there is another relatively dry area.

The Gangetic Plain and the submontane regions to the north.—Stream line VII represents the main air flow over the west of the Bay of Bengal. This current arrives at the coast of Bengal heavily laden with moisture, but it meets no obstruction directly. On crossing the coast it is deflected to the west and passes right along the Gangetic Plain and reaches as far as the Punjab. It is, however, passing into a region from which there is no outlet, for air is flowing into the same region from the west and the south, and the great Himalayan barrier impedes its motion to the north. The current of air must rise, but it does not do so suddenly, but gradually, over the whole length of its passage from the Bay to the Punjab. Thus the rainfall is greatest in this stream near the coast of Bengal, and then decreases slowly in intensity as it penetrates Northern India. The average rainfall during July at stations along its path is 13 inches at Calcutta, 13 inches at Gaya, 12 inches at Lucknow, 8 inches at Delhi, and 3 inches at Khushab in the Punjab. The air motion is not in one continuous stream, but naturally spreads out on both sides. The air which goes towards the Himalayas is forced to rise rapidly, and this accounts for the relatively heavy rainfall in the submontane regions along the whole length of the Himalayas.

The relatively wet region in the central parts of the country.—Returning now to the Arabian Sea we will follow stream lines IV and V. These cross the Kathiawar coast and pass into Central India, thus the central parts of the country receive air from the Bay current and from the Arabian Sea current. It must therefore be the region of greatest ascent away from the mountains, thus accounting for the fact that the rainfall in the central parts of the country is greater than that over any other parts of the plains.

The dry region in the north-west.—We now have to consider the most interesting region in the whole of India. The north-west of India is during July one of the hottest regions on the face of the earth, it also has the lowest pressure in the world, and it is very near to the sea.

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On the theory of pure indraft this is just where one would expect to find the greatest rainfall, but it is the driest part of India! Even without this theory one finds difficulties. If this is the region of the lowest pressure, why does not the air flow into it, and rise there, giving heavy rain? That there is an appreciable flow of air into the north-west is clear from our diagram, for three air streams feed into it.

It is well known that owing to the rotation of the earth air does not flow directly from a region of high pressure to a region of low pressure, but circulates round the low pressure in an anti-clockwise direction in the northern hemisphere. The lowest pressure is over the desert between Multan and Jacobabad, *i.e.* well within the angle between the Himalayas and the hills of Afghanistan and Baluchistan. Thus air cannot flow in at ground-level to any appreciable extent from these sides. Air can only flow in from the east and south. The stream lines from these directions are shown on the figure. The amount of air which reaches the low-pressure area is small, for the gradients are slight and the main air stream which crosses the Sind coast subdivides and goes in part towards the central parts of the country. Still there would probably be enough ascensional movement to cause rain if it were not for two facts, (*a*) the great temperature and (*b*) the direction of the upper air currents. Throughout the monsoon the upper air over North-West India blows from the west and north-west off the high hills of Baluchistan and Afghanistan. This upper air current is warm and very dry. Observations made by Mr. Field in May at Karachi with the aid of kites showed that its humidity was as low as 20 per cent and that the dry air extended downwards to about 2500 feet above ground-level. The air near the ground has a high humidity as it crosses the Sind coast, but it warms up considerably as it passes inland—from 85° F. at Karachi to 95° F. at Jacobabad—so that its humidity decreases from 80 per cent to about 55 per cent. The air over the north-west of India would have to rise 3000 feet before condensation takes place, but before it reaches this height it has encountered the upper dry current from the west, and in consequence no cloud is formed over this region of low pressure. We have here a kind of vicious circle. The heat of the desert causes a low humidity of the air near the ground; this necessitates a high elevation before cloud can form; but a dry current from the west which is met before this height is reached prevents cloud formation; the clear sky permits of uninterrupted sunshine from a nearly vertical sun, which causes the high temperature at the surface; and so the circle is completed.

The cause of the dry region in the north-west is thus seen to be complex, and is made up of four factors, each of which depends on the other; they may be stated as:

- (*a*) The small amount of moist air which reaches the low-pressure area on account of its peculiar geographical position.
- (*b*) The dry wind from the west in the upper atmosphere.
- (*c*) The low humidity at the ground caused by the high temperature, which prevents condensation, as the air rises, below the level of the upper wind.
- (*d*) The high temperature caused by the absence of cloud and rain.

Similar conditions are met with wherever cloud and rain are prevented; thus the regions of small rainfall in the south of the Peninsula and Upper Burma are regions of high temperature, while the regions of heavy rainfall on the western coasts of the Peninsula and Burma are regions of low temperature.

We have now surveyed the whole field of the monsoon in India, and we have seen that the heavy rain is caused by the inflow of large quantities of damp warm air into a region where, on account of the peculiar distribution of mountain ranges, it is forced to ascend and in consequence to deposit its moisture as rain. We have seen that the actual temperature over the Indian land area is not directly responsible for the ascensional currents which cause the rain; on the contrary, in the regions where rainfall is prevented the temperature is abnormally high, while the greatest rainfall is accompanied by low temperatures.

So far we have left unexplained why there is such a remarkable flow of moist air into the Indian area, and it is now time to consider this question. Again we will look at the actual conditions and see if they will give us a clue. We must, however, now widen the field of our investigation and examine the conditions over a large part of the earth's surface surrounding India.

I have copied Fig. 5 from the maps of wind and pressure given in Buchan's *Atlas of Meteorology* (plate 12). I wish to call your attention to three main features of this diagram—(a) the region of low pressure over Asia, (b) the region of high pressure over the South Indian Ocean, and (c) the flow of air across the equator.

(a) *The region of low pressure over Asia.*—It will be seen that the isobars over Asia form closed circuits around the region of lowest pressure to the north-west of India, the whole being similar in many respects to a huge cyclone. In the northern hemisphere the winds circulate around a low-pressure area in an anti-clockwise direction, and it will be seen that the wind arrows shown on the diagram indicate such a general motion, disturbed, it is true, in places by local irregularities. The winds over India form only a part of this general whirl, from which it is clear that the monsoon in India does not owe its existence to the conditions over India itself.

To what is this low-pressure area over Asia due? One naturally replies, "To the abnormally high temperatures over great land masses during the summer." But if this is the complete explanation, why is the pressure so much higher over North Africa than over the centre of Asia, the temperature of the former being nearly 20° F. higher than that of the latter? The fact of the matter is that we are very prone to try to give short simple explanations of very complex questions. It is true that the primary cause of the low pressure over Asia is the relatively high temperature, but this is by no means the only factor to consider. Look for a moment at the isobar in our diagram for 29.80 inches and follow it right round its course, and it will be seen that in the south-west it passes over the Sahara desert and in the north-east practically reaches to the north polar circle: there is a difference of temperature between these two regions of approximately 35° F. and yet the pressure is the same! In other words, *in the same pressure system* we have the same pressure at two places with a difference of 35° F. in temperature.

The relationship between pressure and temperature is extremely complex and is affected by many geographical considerations, not the least being the fact that the earth is a rotating sphere. The low-pressure area over Asia is primarily due to differences of temperature, but its position and extent depend also on the distribution of land and

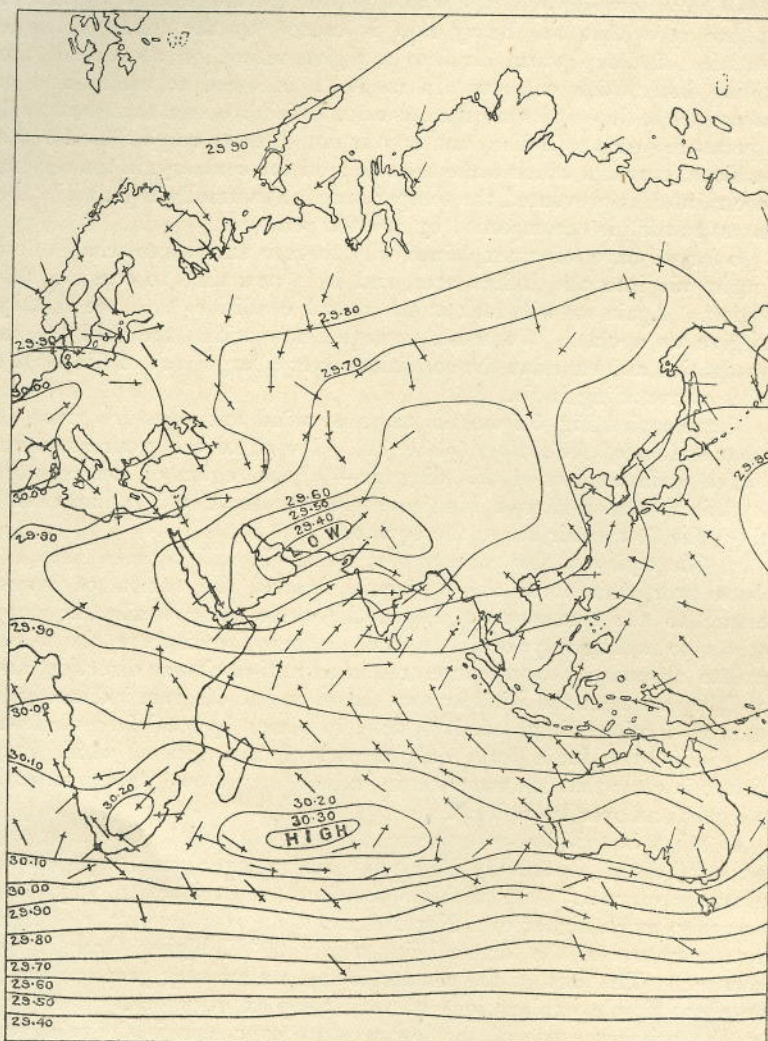


FIG. 5.—July Wind and Pressure.

water and on the earth's rotation. This pressure difference causes motion of the air, the air tending to circulate around the region of low pressure; but, chiefly on account of friction, there is a certain amount of motion towards the centre which necessitates ascending currents if the pressure distribution is to be maintained. But this is not the cause of the rainfall. In such a large pressure system the upward motion of the

air is insignificant; that this is so is clear from the fact that the interior of Asia, where the greatest amount of ascensional motion due to indraft takes place, is practically dry throughout the summer. The heavy rainfall in India is due to damp air circulating under the general pressure distribution, being forced to rise by the peculiar distribution of mountains in and surrounding India.

The high pressure over the South Indian Ocean.—There is a high-pressure system—a permanent anticyclone—over the South Indian Ocean throughout the year; it is, however, much more strongly developed during the northern summer. The wind circulation around this region is anti-clockwise, but with considerable outward motion. The consequence is that over the south of the Indian Ocean the winds blow steadily from the south-east and are called the "South-East trade winds." They cause a constant transfer of air from the south towards the equator.

Motion of air across the equator.—The South-East trades blow as far as the equator; while north of the equator the air takes part in the whirl about the cyclonic system over Asia, and therefore moves from the south-west. The two systems of air motion join up on the equator, so that there is one immense flow of air from the high pressure in the south towards the low pressure in the north. The air first moves to the north-west and then to the north-east, the consequence being that the air remains throughout its course over the ocean. Thus it will be noticed that the air which reaches the west coast of India has travelled more than 4000 miles over the ocean before arriving.

The change of direction on the equator, which is of course a consequence of the earth's rotation, is an important factor in the monsoon rainfall. If the motion did not change at the equator the air which reaches the west of India would have come from the continent of Africa and passed over only the Arabian Sea. That is, it would have started dry and passed over less than 2000 miles of ocean; it is clear, therefore, that such air would be much drier than air which starts over the ocean and travels twice as far over water. Owing to the happy coincidence that the direction of air motion changes at the equator on account of the earth's rotation, the air which reaches India during the south-west monsoon is extremely humid, through having travelled for such long distances over the ocean. We shall see later that this is a most important conclusion.

We are now in a position to state in a few sentences the main causes of the monsoon in India.

- (a) The *primary cause* of the monsoon is the difference of temperature over land and sea.
- (b) The relatively high temperature over the land in the northern hemisphere during the summer tends to lower the pressure there.
- (c) As the pressure falls over the land air motion results. The air motion is acted on by the rotation of the earth, it also modifies the original temperature distribution, which again modifies the original pressure. The result of all these interactions, each of which affects the others, is a closed low-pressure system over the whole of Asia and North Africa, with the

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- lowest pressure in the north-west of India. The pressure distribution in this final system bears no close relationship to the actual temperature in its different parts.
- (d) The air over the north of the Indian Ocean (including the Arabian Sea and the Bay of Bengal) takes part in the general motion set up by this huge pressure system. As this ocean is situated in the southern quadrant of the system the air motion over it is from the south-west.
 - (e) As the pressure falls over the land in the northern hemisphere the pressure rises over the ocean in the southern hemisphere. The resulting air motion, affected by the earth's rotation and the distribution of land in the southern hemisphere, modifies the pressure distribution, the final result being a closed high-pressure system in the south of the Indian Ocean.
 - (f) The air in the south of the Indian Ocean moves, under the influence of this pressure distribution and of the rotation of the earth, towards the north-west, as far as the equator.
 - (g) At the equator the air from the south is caught up in the circulation around the low-pressure system in the northern hemisphere, and moves towards the north-east.
 - (h) The south-west air motion over the north of the Indian Ocean is therefore a continuation of the south-east air motion over the south of the ocean.
 - (i) In consequence the air which reaches the Indian area has travelled for 4000 miles over the ocean, and is therefore highly charged with aqueous vapour.
 - (j) The south-west air current over the north of the Indian Ocean, which is impelled forward by forces extending over the whole region of its motion, is directed towards the high mountains of India, which are so arranged as to form a barrier to the north and to the east. The air is caught in a kind of trap, out of which there is no escape except by rising.
 - (k) The consequence of the forced ascensional motion is heavy rain over the Indian area.
 - (l) The actual distribution of the rain is determined by the ranges of mountains in and around India. The sides of mountains which directly meet the currents have heavy rainfall, while the regions behind the mountains are relatively dry.
 - (m) The dry region in the north-west of India is due to the arrangement of the neighbouring mountains, which prevents a large inflow of moist air into this region. A dry upper wind and the high temperature also help in preventing precipitation.

It has always been a source of difficulty to meteorologists to explain why the monsoon does not set in during May, for during that month the pressure distribution over India is very similar to that during June, and the temperature is very much higher. We will therefore examine the conditions during this month; for an explanation of the apparent difficulties will assist in confirming the explanations we have already given.

Fig. 6 shows the mean pressure and winds over India during May.

It will be seen that this diagram is very similar to the one for July. We have the low pressure as before over Northern India, and a similar system of air streams. There are, however, two important differences—(a) the pressure gradients are less in May than in July, the winds being in consequence less strong; (b) the isobars over the Peninsula run more from the north to the south in May than in July.

Turning now to Fig. 7, which shows the mean temperature for May, we see that the temperature over practically the whole of India is above 90° F., while in July only the extreme north-west has such high temperatures. As a matter of fact the mean temperature of the Indian

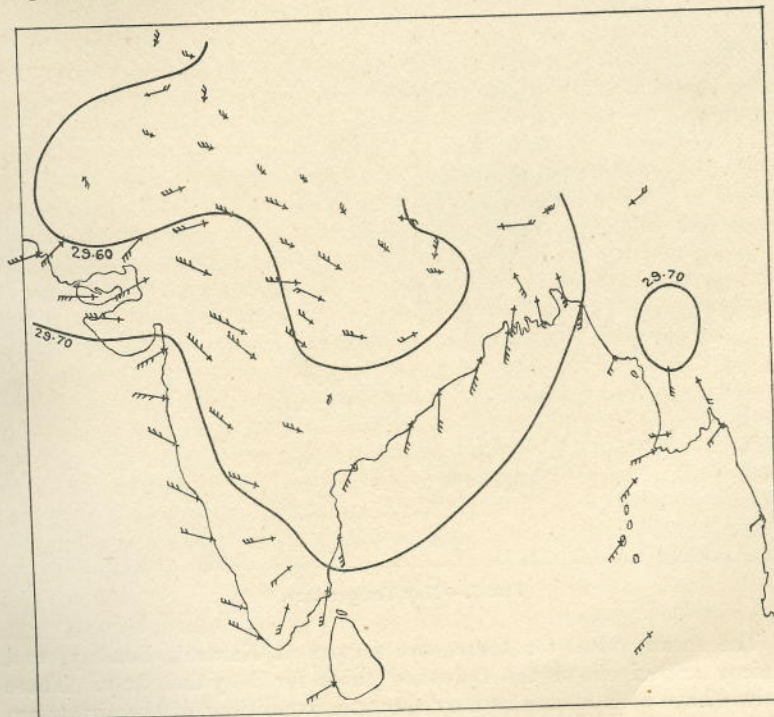


FIG. 6.—May Wind and Pressure.

land area is $88^{\circ}.7$ F. in May and only $83^{\circ}.5$ F. in July, a difference of over 5° in favour of May. The rainfall during May (Fig. 8) is extremely small, being less than two inches over the greater part of the mainland. The only regions where there is appreciable rain during the month are North-East India, Burma, and the south-west coast of the Peninsula.

We have now to determine the essential difference between the conditions in May and July.

It is clear that the high temperature cannot be a primary cause of the absence of rain, for if there were no rain in July the temperature would be still higher than in May. It is the absence of cloud and rain which produces the high temperatures in May, not *vice versa*.

The direction of the air motion is very similar in May and July: in

both months we have air from the oceans passing into the Indian area, where it must rise.

We are left with two factors to examine—(a) the amount of wind and (b) its humidity.

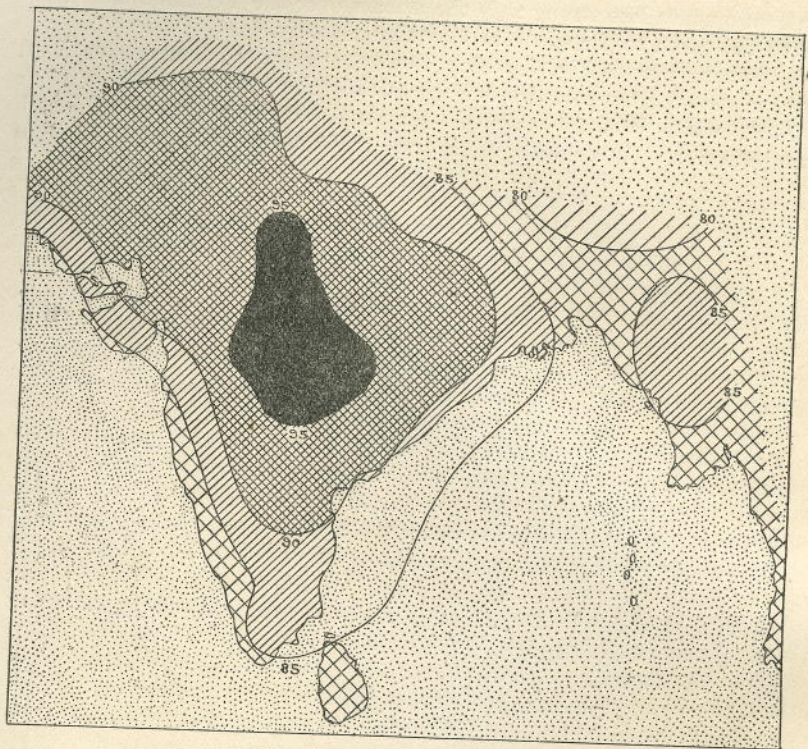


FIG. 7.—May Temperature.

The mean value for these two factors at Karachi, Bombay, and Minicoy are given in the following table for May and July. These stations have been chosen as they show the conditions of the air stream as it reaches India from the Arabian Sea.

STATION.	Mean Wind Velocity. Miles per Hour.		Mean Relative Humidity. Per cent.	
	May.	July.	May.	July.
Karachi	5.8	12.6	76	80
Bombay	7.4	14.2	74	86
Minicoy	7.4	12.4	77	82

We see from this table that not only is the amount of air flowing into the Indian area less in May than in July, but the air is also appreciably drier. The latter is an important fact, for it means that the air has to rise higher in May before condensation sets in than in July. We have

during May over the whole of India the same vicious circle as in North-West India during the monsoon. The air which enters is small in amount and relatively dry; it is warmed up by the high temperature prevailing over India, and there is, therefore, little cloud formation. The clear sky allows of a still further warming up, and so the circle goes round. It is only when later on more air enters with a greater humidity that sufficient cloud and rain are produced to lower the temperature and so remove this bar to further precipitation.

But why are the winds less and the air drier in May than in July?

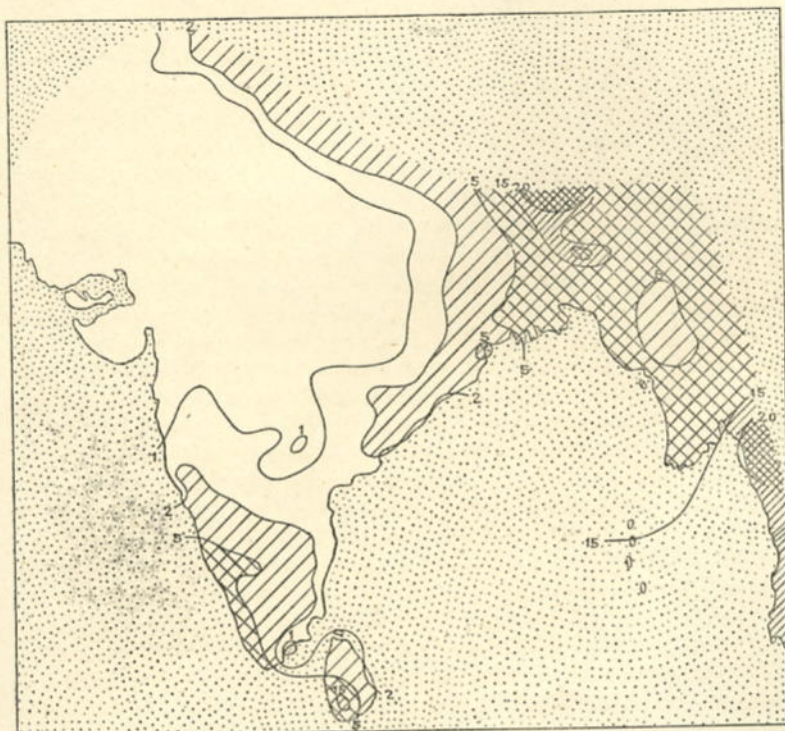
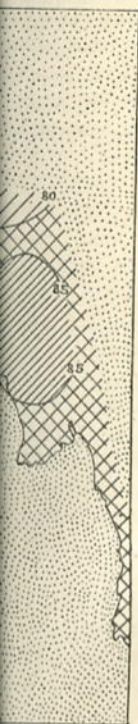


FIG. 8.—May Rainfall.

The reason is clearly shown in Fig. 9, which gives the pressure and wind over the same area as we studied in Fig. 5.

The low-pressure system over Asia has not developed so far in May as in July, and on account of the relatively high temperature of India during May the isobars over India and the Arabian Sea have a different shape—they run more from the north to the south—in consequence of which light Northerly winds prevail over the centre of the Arabian Sea. It will also be noticed that the southern high-pressure system is only partially developed and the South-East trades do not feed into the Arabian Sea. They extend as far as the equator, where they are met by the Northerly winds from the Arabian Sea, and ascensional motion takes place there. Thus the moisture which the trade winds later in the year deposit over India is, during May, lost near to the equator. The winds

the Indian area,
amount of wind



ombay, and
July. These
the air stream

Humidity.
July.
80
86
82

flowing into
appreciably
the air has to
. We have

are relatively lighter and drier in May because the two pressure systems are not so well developed and the air motions caused by them are not joined up over the equator. It is only when the pressure changes have proceeded further, and air passes straight from the South-East trades

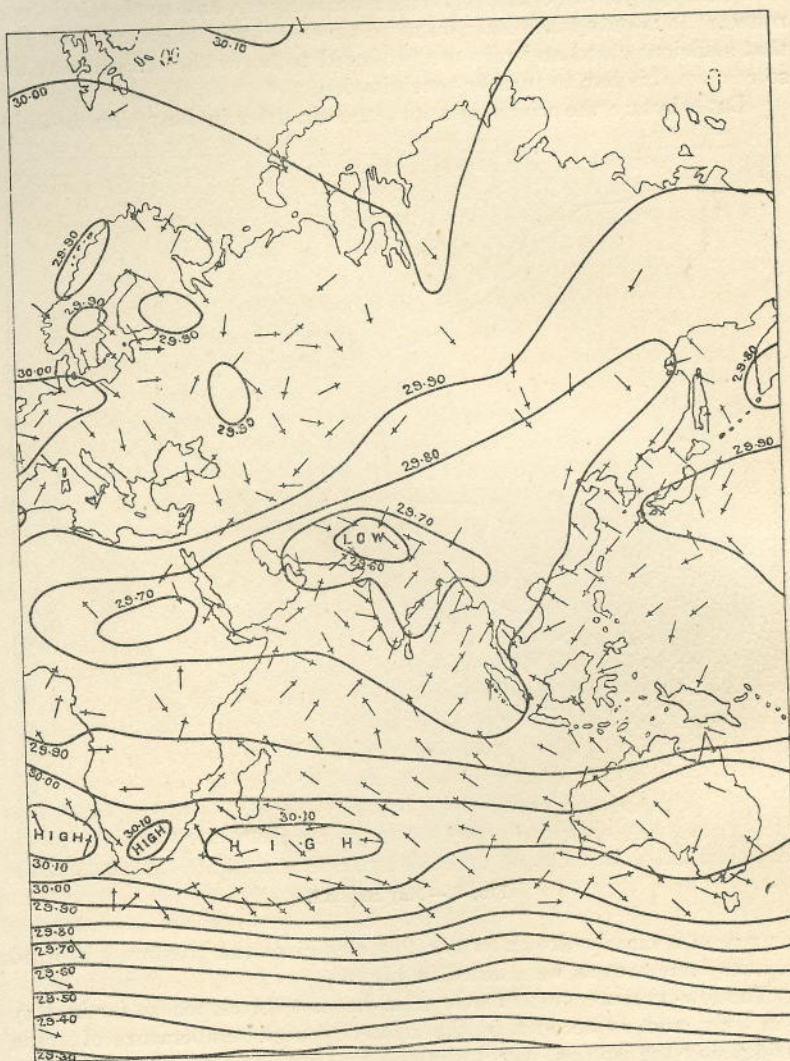


FIG. 9.—May Wind and Pressure.

into the circulation around the Asian low-pressure system, and enough damp air reaches India to cause sufficient cloud and rain to overcome the high temperature, that the monsoon can become established.

Although the monsoon is not established during May, there is a large inflow of air into the Indian area from the seas, which is warmed up by the prevailing high temperatures; this gives a very unstable state, and

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violent ascending currents are formed locally, which on account of the contained water vapour have much energy. May is therefore a month of many thunderstorms, especially in Burma, Assam, and Bengal, which receive much moisture from the Bay. Similarly during breaks in the monsoon, the total inflow of moist air is not cut off, while the temperature begins to rise in consequence of the reduction in cloud and rain; thunderstorms are characteristic of these periods also.

We have now seen, from several different points of view, that the processes which give rise to the monsoon in India are very complex and highly inter-related; any disturbance in one factor affects all the others, and it is impossible to state which is cause and which is effect. Suppose, for instance, that through some unknown cause the South-East trades find difficulty in crossing the equator. The consequence is that the Arabian Sea does not receive its supply of moist air from the south; this in its turn affects the humidity of the air reaching India. Clouds have difficulty in forming and there is less rain; in consequence the temperature rises over India, causing relatively low pressure over the land surface. This in its turn causes the isobars over the east of the Arabian Sea to run more from the north to the south than usual, and the winds over the Sea have a marked Northerly component as far south as the equator. Any one examining a weather map on such an occasion would see the high temperature and low pressure over India, with the isobars running from north to south and Northerly winds over the east of the Arabian Sea. He would naturally conclude that it was the latter which were preventing the South-East trades from crossing the equator. Thus the failure of the trades to cross the equator would be judged to be the effect and not the primary cause.

So far, we have based the whole of our discussion on the normal monthly charts, and it is always dangerous to trust to these alone, for the actual daily conditions may vary widely from the mean monthly values.

For the period 1893 to 1899 the Indian Meteorological Department collected observations taken on the ships in the Indian Ocean as far south as 8° S. latitude, and from these prepared daily weather maps over the whole area. The observations on any given day were not many, and left much to be desired as regards barometric readings, but from these charts a very good general view of the conditions is obtainable. A rapid survey of the published charts shows that the conditions on the different days seldom vary essentially from the scheme which we have deduced from the monthly means. These charts are worthy of the closest study, but that is impossible in a lecture. I have, however, chosen three days, typical of three different sets of conditions, and we must spare the time to examine these. The conditions chosen are (a) a typical day during May 1894 before the monsoon had reached India, (b) a day in August 1894 when the monsoon was firmly established, and (c) a day in August 1899 during the disastrous break in the rains which occurred in that year.

In Fig. 10 the conditions on May 19, 1894, the first of these typical days, are shown. In the upper half of the figure we have the pressure, wind, and rainfall over India, while in the lower half the conditions over the wider region are shown.

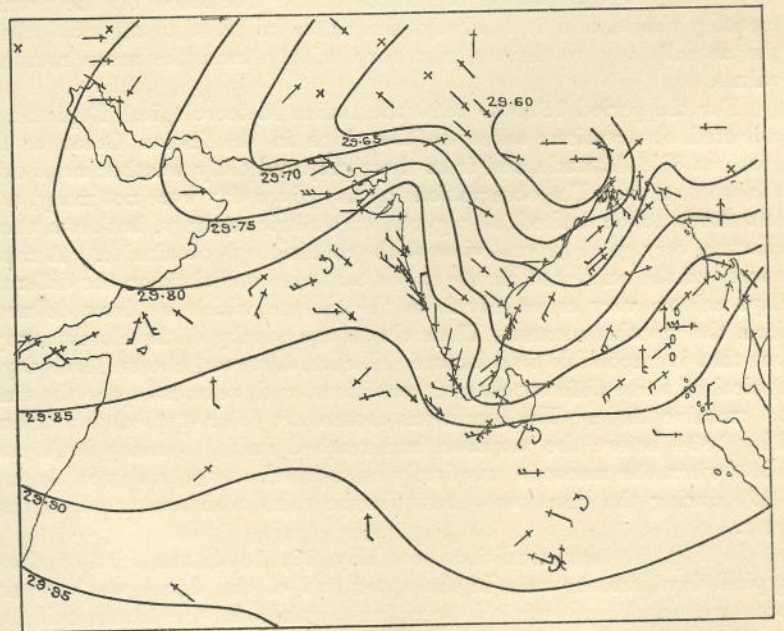
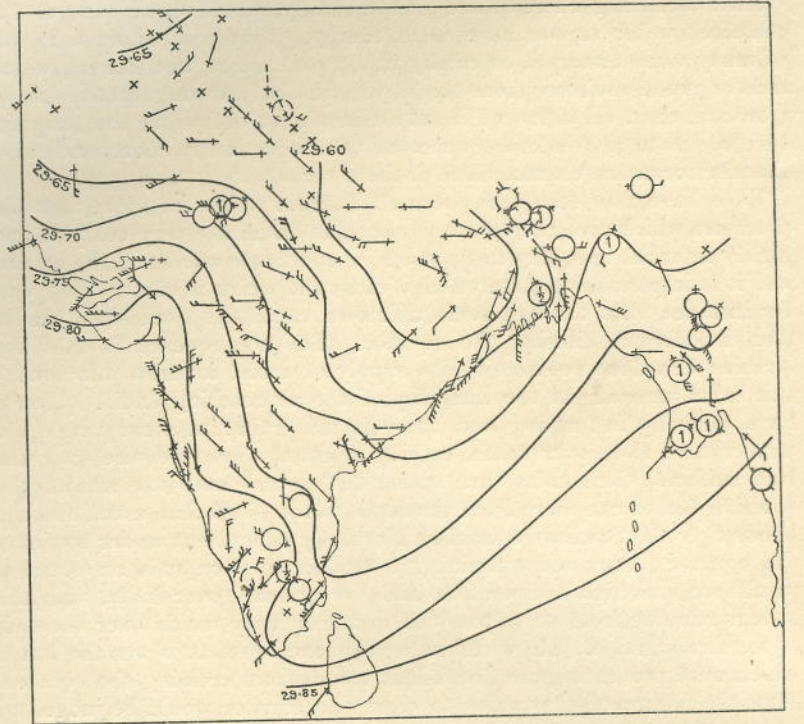


FIG. 10.—May 19, 1894.

From the upper map we see that there is a considerable pressure gradient over India, but little rain¹ except the usual scattered thunderstorms, chiefly in Burma and North-East India. The general run of the isobars from north to south over India proper will be noticed. From this map alone it is difficult to see why there should be so much inflow of moist air with so little rain.

Turning now to the lower map, we see from the few observations south of the equator that the South-East trades were in existence, but not very strong. Over the Arabian Sea the winds were light, and over the east of the Sea were blowing from some northerly direction. This map shows clearly that there was no steady flow of air from the south of the Indian Ocean into the Arabian Sea, and thence into India. Under such conditions the air which is forced into the Indian area, where it must rise, is warmed up by the high temperature prevailing to such an extent that condensation does not take place except in local thunderstorms.

The pressure distribution over India, shown in Fig. 11, for August 4, 1894, is not widely different from that shown in Fig. 10, but there is rainfall in all parts of the country. The pressure over the Indian Ocean is, however, very different. Here we have a pronounced pressure gradient from the south to the north, and there are no Northerly winds in the Arabian Sea.

The South-East trades have connected up with the winds over the Arabian Sea and large quantities of moist air are passing over the coast of India. Previous cloud and rain have already lowered the temperature over India, and the forced ascent of such large quantities of air, highly charged with aqueous vapour, cannot help but produce rain. These are typical monsoon conditions.

Our third example, Fig. 12, August 18, 1899, is typical of a break in the monsoon. It will be seen that although the period is later than the middle of August the conditions are nearly those of May. There is little pressure gradient over the south of the Indian Ocean, and the winds in the south-east of the Arabian Sea are blowing against the South-East trades. In consequence the weather is cloudy and rainy over the equator, and the supply of moist air is cut off from the Arabian Sea and the west of India. A certain amount of moist air passes into the Bay and thence into Burma and North-East India, where there is moderate rainfall, but the weather is dry and hot over the rest of the country. Why the conditions were like this in August 1899, and remained so throughout July, August, and September, is a problem not yet solved. Looking at the map we see that the pressure gradient between the south of the Indian Ocean and the Arabian Sea is small, and that the high-pressure area in the south is badly developed. It would appear at first sight as if this were due to the pressure being less than usual over the Southern Indian Ocean, but as a matter of fact the pressure in the south was much above the normal. The small gradient was caused not by a deficiency of pressure in the south, but by an excess in the north. One of the most frequent causes of breaks in the monsoon is the establishment of an area of relatively high pressure over Western India.

In this lecture I have laid great stress on the part played by the

¹ Rainfall is shown on the map by circles, the amount of rain in inches during 24 hours being given.

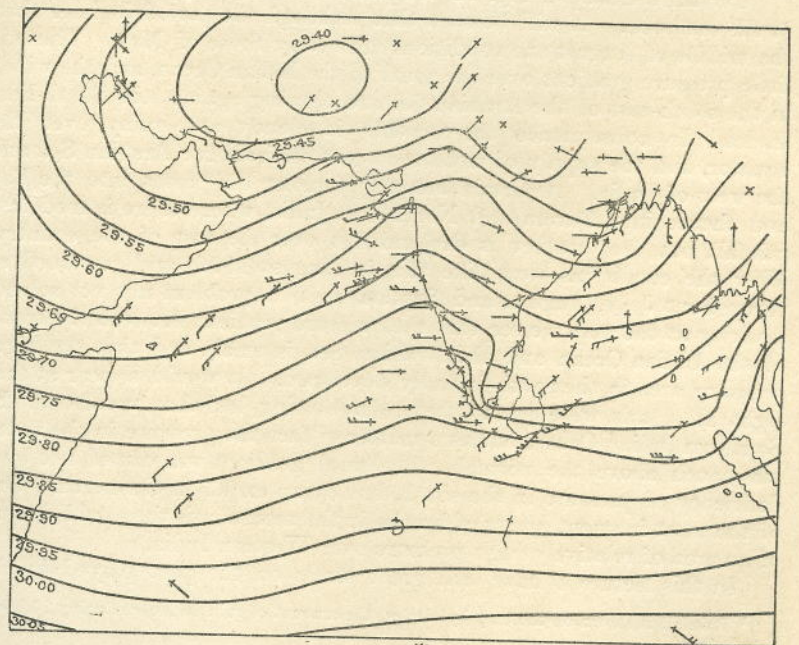
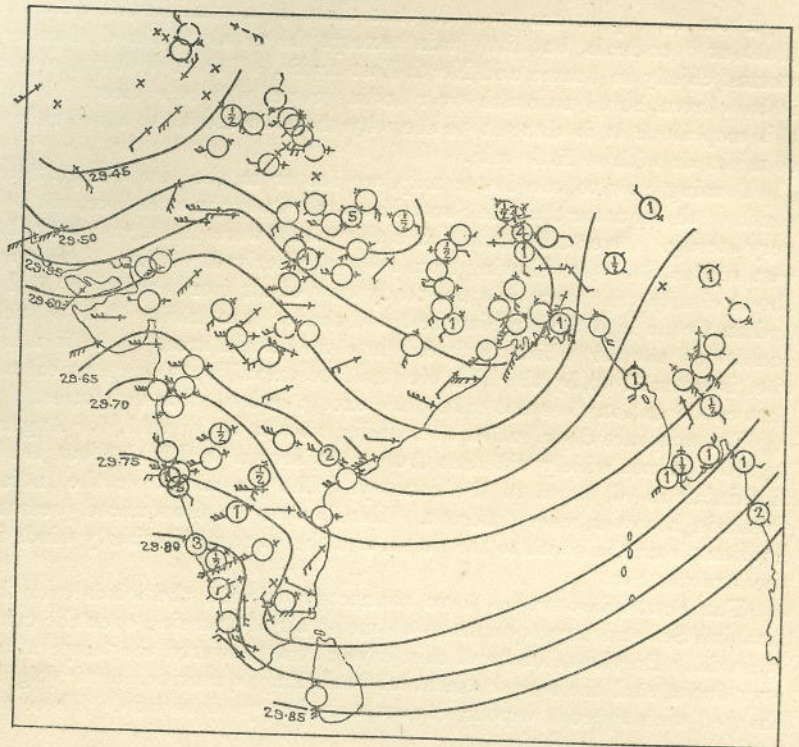


FIG. 11.—August 4, 1894.

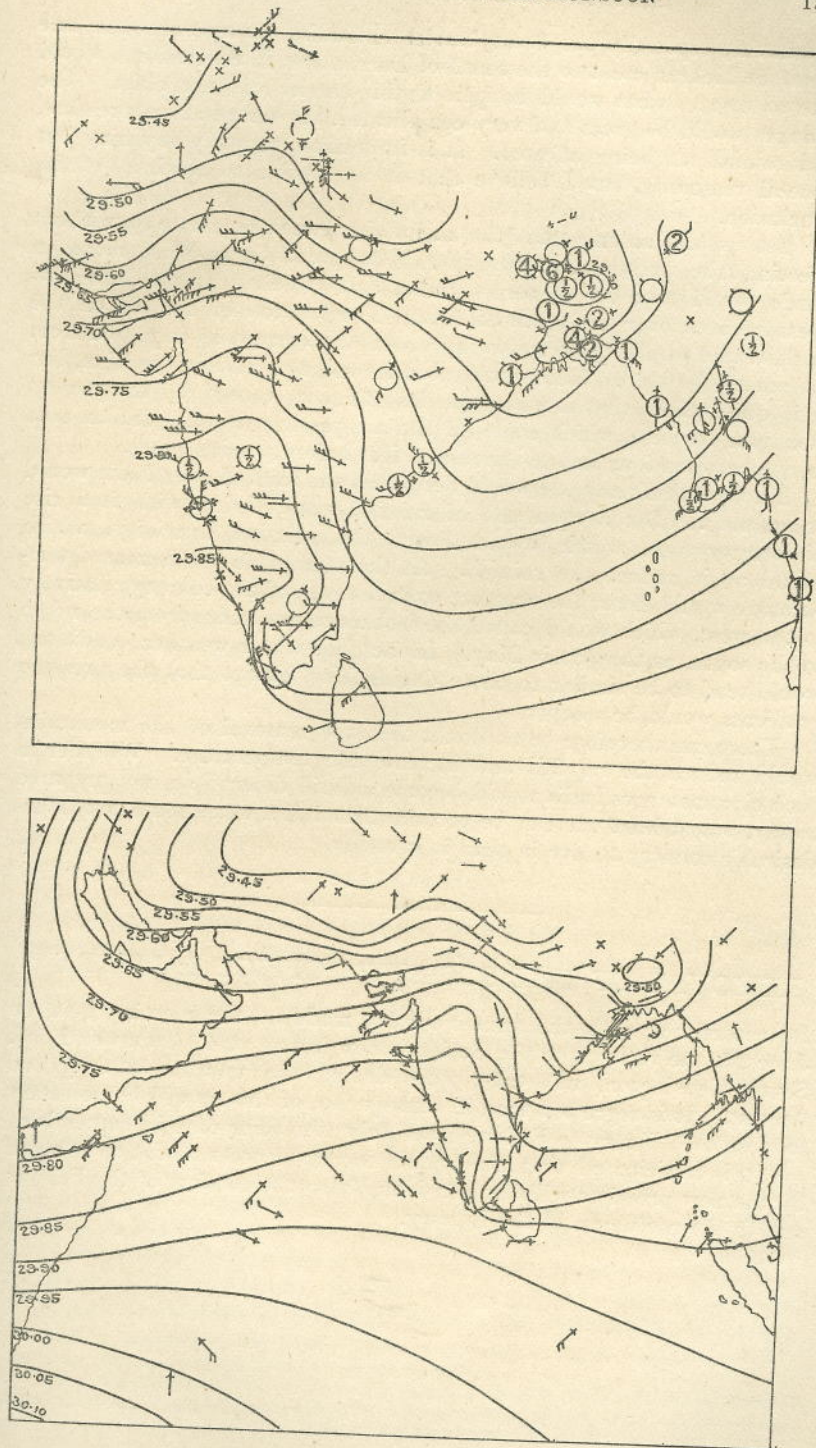


FIG. 12.—August 18, 1899.