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Surface Wet Bulb Potential Temperatures in and near India - Normal values and a Study in Disturbed Weather

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ABSTRACT. In the extra-tropical latitudes, it has become customary to identify air masses by the temperature and occasionally humidity characters of the air streams. Though in India various entities like Dry Bulb, Wet Bulb, Maximum and Minimum and their anomalies have been plotted, there has been no critical examination of some concept which could be used. The temperatures obtained by the Radio-sonde observations are still very short of the requirements in the tropics where the space gradient of quantities is small. Surface observations are available over many more stations and over a much longer period that comparisons would be easier. The quantity envisaged is the Wet bulb Potential Temperature introduced by Normand obtained by surface observations. The larger number of observations that are available partly offsets the effect of nearness to the ground.

Normal Wet Bulb Temperature charts for the twelve months are given. During a pre-monsoon cyclonic storm of 1930, the field over India has been plotted for a number of days. From the latter charts, an interpretation is made to reason differing air masses entering into the storm field. Incidentally, it is also shown that secondaries of western disturbances show off as disconnected pools of air which seem to move in some Northeasterly direction. It is suggested that if 24 hour changes in the quantity are plotted, it would help identification of air masses.

A simple analysis is given so that the derivation between Normand's Wet Bulb Potential and Rossby's Equivalent or Equivalent Potential Temperatures is brought out and a nomogram connection can be drawn.

1. *Introduction.*

The question of different air streams entering into the problem of cyclonic depressions must have been in people's minds even before the science of meteorology was taken up seriously some generations ago. Hot air passing over a place, muggy air, cold easterly or westerly air, etc. are terms that have entered into the vocabulary of common folk and into their weather lore. In Indian meteorology, the early workers talked of the monsoon, of the dry streams and of their respective advances. This was possible as the Southwest Monsoon continued almost stationary over a longish period that one could associate definite characters to different streams and these formed a sort of basis of seasons over India. The real advance of air mass concept with its specific method of identification is due to Bjerknes. The further development of the ideas showed that a certain amount of invariability in the ever changing or fickle weather of the temperate latitudes existed and weather forecasting became simpler and more scientific and not entirely dependent on long experience.

In India and in the tropics in general, however, much remains to be done. There has been no general acceptance of a critically examined concept of entity like temperature which should naturally be extensible over the whole of the tropics. From the early years in Indian area, the directly observed temperature elements like dry bulb, wet bulb, maximum, minimum and the simpler derived quantities like the mean temperature, the changes in the above in 24 or sometimes 120 hrs. and the departures of the above from their normal values were plotted as a regular measure. Later, to minimise work, modifications were made by various forecasters by giving up one or more of these elements and by depending entirely on one element or the other. Recently, criteria based on the changes in two elements for detection of the incursion of fresh air masses were given : the departure of the mean temperature at a given place from its normal value for the particular epoch, and the percentage value of the diurnal variation of temperature with its normal value. If quantitative results are later expected, it might be hard to utilise these quantities especially the second criterion in the course of any simple work. The diurnal variation of temperature is a function of many quantities most of which are not easily determinable at present.

The crux of the question is what one should look for. The criteria that cannot stand a general test should be given up as quickly as possible so that fresh approach may be made. In the tropics, the differences in the temperature and other quantities between two air masses are so small that the effects of the diurnal variation, latitudinal convergence or divergence and radiation are so much mixed up that one is unable to draw definite conclusions. While trying to utilise the radio-sonde data from South China to India as evidence of the *Far Eastern Transitional air* (*Tr*) that enters into tropical cyclonic storms, it was found that the wet bulb potential temperature[2] at various levels was a useful criterion in addition to the structure of the dry bulb temperature-height curve.

The number of stations that have radio-sonde observations are few and the reliability to be placed on the observations is still unknown. The errors of observation are of the same order as the expected difference in temperature and humidity. A logical sequence was to utilise the surface wet bulb potential temperature. The number of surface observatories is large. The stations are near each other. Doubtful points can be checked up and observations can be followed day by day with a greater degree of confidence. In another recent paper on the mechanism of thunderstorms in the tropics, the wet bulb potential temperature at the surface was found useful for a study of the nor'westers[3].

2. *Normal Surface Wet Bulb Potential Temperatures.*

Before proceeding further, it is necessary to know the normal features in each season. Charts of surface wet bulb potential temperature based on the normals of pressure, temperature and humidity (in the morning at about 0800 hrs. L.T.) were prepared for the 12 months. In the following, all temperatures refer to wet bulb potential temperatures of Normand. (So long as the method of use of the various quantities is kept the same in all the derivations, a small deviation in actual method of derivation does not matter.)

The charts for normal surface wet bulb temperatures are shown in Figures 1 to 12 and show the following interesting features.

In winter, *December* and *January*, (Figs. 12 and 1) the gradient of wet bulb potential temperature is large across India and Pakistan; the extreme values over the region differ by as much as 36° F. The highest wet bulb potential temperature is over the South Bay of Bengal and over the Southeast Arabian Sea. These are the regions of the active Northeast Trades. Due to the effect of land, the lower wet bulb potential temperatures project or extend further south than over the sea, *e.g.*, west Ceylon and the extreme south Peninsula of India.

As winter changes to summer there is a general rise in the wet bulb potential temperature and a decrease in its gradient over the whole of *India and Pakistan* (Fig. 3).

In *April*, (Fig. 4) the wet bulb potential temperature is less than 76° F. in the South Bay of Bengal and in the Southeast Arabian sea while over the rest of the Bay of Bengal and in portions of the Southeast Arabian sea, the values are higher: 78°.3 F. in the Bay of Bengal and 79°.7 F. at Amini Devi in the Arabian sea. In the interior of west Pakistan and further northwest, the wet bulb potential temperature is less than 64° F.

The values of wet bulb potential temperature higher than 76° F. apparently correspond with the movement of the thermal and pressure equators northwards and the consequent displacement of the Northeast Trades.

In *May*, (Fig. 5) the highest value of wet bulb potential temperature is more than 80° F. and is found in the North Bay of Bengal. Across the land from south to north, in spite of the northern summer, the wet bulb potential temperature decreases northwards. The wet bulb potential temperatures of the more easterly regions of India and of eastern Pakistan is much greater than in the more westerly regions of India and of western Pakistan. The two correspond to the existence and incursion of *Tr* and the *Tropical Continental Air* (*Tc*). When a depression is forming, the tropical continental air has ultimately to be traced from a region west of the Northwest Frontier Province[4].

In *June*, (*Fig.* 6) the gradient of wet bulb potential temperature is weak. Its highest values, larger than 80° F. are in the neighbourhood of the North Bay of Bengal and of the North Arabian Sea. These high wet bulb potential temperatures correspond apparently to the existence or incursion of *Tr* or of displaced Northeast Trades. These high temperatures in northern summer are shown by the Northeast Trades only when they have blown over swampy land or over extensive sea. The isopleth for 76° F. is confined to more or less the Peninsula and corresponds to the frequent incursions of *Equatorial Maritime Air* (*Em*) from the south of the equator. In the extreme northwest regions of India and of west Pakistan, the wet bulb potential temperature is still lower than over the North Bay of Bengal.

In *July*, (Fig. 7) the isopleth for 76° F. has extended further north. The high values of wet bulb potential temperature (80° F. or more) are found very near the northwest angle of the Bay of Bengal, near the United Provinces, over the west Punjab and upper Sind and near the north Arabian Sea. The high temperature over the United Provinces can be argued as due to the westward movement of the monsoon depressions, the *Tr* is taken over there from the more easterly longitudes. The United Provinces gets a good amount of rain and portions of it become swampy. The high temperatures over the west Punjab and its neighbourhood may be due to high dry bulb temperature in addition to a small incursion of *Tr* from the east. Further west of the Punjab, the value of wet bulb potential temperature is much lower. For the monsoon depressions, the source region of *Tc* may be found there.

In *August*, (Fig. 8) the isopleth for 80° F. breaks up into a number of closed curves or pools over north India and west Pakistan apart from the north Bay of Bengal and the north Arabian Sea. The isopleth for 76° F. which is connected with the one over the South Bay has moved further north than in July, showing the effect of incursions of *Em*. The difference between the extreme values of wet bulb potential temperatures over India and Pakistan is hardly 10° F. As the *Tc* with a low value of wet bulb potential temperature is only to be found beyond the northwest Frontier Province, it may explain partially why fewer full-fledged depressions form at the head of the Bay as a rule during the month.

The pattern tends to return to the winter type slowly.

In *September*, (Fig. 9) the isopleth for 80° F. hardly exists. The isopleth for even 76° F. is over the Arabian Sea and excepting the southwest Bay over the region east of 79° E. Elsewhere the values are much lower. The gradient of wet bulb potential temperature is already setting in over west Pakistan.

In *October*, (Fig. 10) the isopleth for 76° F. encloses the north and the southeast portions of the Bay of Bengal. Perhaps another isopleth of the same value encloses areas in the southeast Arabian Sea.

The values of wet bulb potential temperatures have considerably fallen over west Pakistan and in the adjoining portions of India. The difference between the extreme values in Baluchistan and in the southeast Arabian Sea exceeds 20° F.

In the next two months *November* and *December*, (Figs. 11 and 12) the general run tends to those of winter.

The above normal diagrams are interesting in the progression from summer to winter and back to summer. They give definitely a pattern for the active Northeast Trades or the easterly air. These Northeast Trades get displaced with the season and the character of the Northeast Trades depends on the locality and season. Over the sea or over a swamp on hot days the value of wet bulb potential temperature is equal to or more than 80° F. The low values of wet bulb potential temperature in the southern portions of the country in the summer and in the monsoon months can be explained as due to the frequent incursions of *Em* from the winter hemisphere. The incursion of cold continental air associated with its strong pressure and temperature gradients can happen from the northwestern regions.

Due to various reasons in the tropics, it is doubtful if the actual values of wet bulb potential temperature can be used directly for identification of air masses. Perhaps in mid-winter and sometimes in summer, this may be possible. But if the *changes* in the wet bulb potential temperature are taken say since the past 24 hrs. or since the last observation (corrected for diurnal effects) the incursion of fresh air masses or movement of disturbances must be easily detectable. There is a regularity in the movement of the changes.

3. *Wet Bulb Potential Temperature Charts for the Cyclonic Storm of May* 1930.

The field of surface wet bulb potential temperatures has been drawn for a pre-monsoon cyclonic storm of May 1930 for which ample surface data were available. [5] These are shown in Figures 13 to 27. The storm formed in the southwest Bay of Bengal. According to the above publication, the cyclonic storm was located as a depression on 5 May 1930, to the east of Hambantota, as a cyclonic storm on 6th to the northwest of the same place and on 7th was located very near Negapatam. It crossed coast at about 1100 hrs. I.S.T. of 7th. By the morning of the next day, it had weakened into a depression and was located about 50 miles to the south of Mysore and weakening further it lay about 50 miles to the east of Bangalore on the morning of 9th. This depression then moved northeastwards and was over south Circars and the adjoining regions of the Bay on the morning of 10th. By this time, the eastern end of the line of discontinuity had advanced northwards over the Bay, so that the line or front now ran in a northeasterly direction from the Madras coast and was indicated on the isobaric charts by a trough of low pressure. The depression then moved along this front, then redeveloping into the next storm of the season. "..........On the morning of 11th May, the residual depression left by the previous storm formed part of a trough of low pressure which extended from off the south Circars coast to the Chittagong coast ....By the morning of 12th, a deep depression was centred at 0800 hrs. near Lat. 18° N. and Long. 89° E. where the deficiency of pressure was about ¼″........Subsequently during this day, it intensified into a storm........By 3 hrs. next morning the storm had crossed coast about 40 miles south of Kyaukpyu and rapidly weakened into a depression. By the morning of 14th, depression had disappeared........"

The chief points to notice in these charts are the positions of Isopleths for 80° F. (on and after 9th May, 78° F.), for 76° F. and for 72° F. By drawing the patterns for nearly a week ahead of the cyclonic storm formation, the behaviour of the movement of the isopleths can be noticed.

On *3rd May*, (Fig. 17) along a line approximately NW to SE, one can suppose that a partition of *Em* and *Tr* existed. Across that partition, the gradient of wet bulb potential temperature is maximum. On *5th May*, (Fig. 19) the centre of the depression is found in the sector containing 76° F. isopleth. On *6th May* (Fig. 20), the 80°F. isopleth has had a shift towards the Coromandel and the north Madras coasts. On *7th May* (Fig. 21), the same isopleth has penetrated into the north Madras coast and over-runs parts of even southeast Hyderabad. On *8th May* (Fig. 22), when the cyclonic storm lay as a depression in Mysore, the 80° F. isopleth has been shifted northwards and its position over Orissa appears like a narrow tongue from the Bay of Bengal.

On *9th May* (*Fig.* 23) when the depression had recurved, the isopleths for 80° F. is practically in the northeast Bay of Bengal off the Arakan coast. The isopleth for 78° F. is quite similar to the above in the Bay of Bengal.

On *10th May* (Fig. 24), there is no isopleth for 80° F. in the Bay of Bengal. There is apparently a close isopleth for 78°F. in the Andaman Sea and another one east of Tennasserim showing apparently an incursion of fresh air from the east. The position of isopleth for 76° F. may be contrasted with the ones on the previous day and on the next day.

On *11th May* (Fig. 25), the isopleth for 78° F. in the Bay of Bengal has extended and covers most of the Central and South Bay of Bengal.

On *12th May* (Fig. 26), the isopleth for 78° F. covers the central parts of the north Bay of Bengal and southeast Andaman Sea. The isopleth for 80°F. covers portions of Orissa.

The onset of *Tr* before the formation of the cyclonic storm and the retracting of *Tr* at the stage of recurvature can be all noticed in the above series.

As the wet bulb potential temperatures have been plotted on the above series of synoptic charts for May 1930 over a wide area *i.e.*, India, Burma and Pakistan, a few further observations can also be noticed. It has been stated elsewhere[4,6,7] that a western disturbance has to be broken up into a number of distinct secondaries, that each of these secondaries travels in an eastnortheasterly direction and that each secondary has its own 'cold front' or cold pool of air at its rear[8,9]. The regular travel of distinct cold air pools in an almost northeasterly direction at the rate of approximately 400-500 miles a day can be easily noticed in northwest India and west Pakistan. The cold pool of air due to a western disturbance in the Punjab is distinct from that due to the secondary over Kathiawar or Gujarat (see for example the temperatures near Veraval) which again is distinct from the cold pool of air over the Deccan (as shown by the temperatures near Poona). On 4th May, a pool of cold air was near south Kathiawar and on the next day it was over southwest United Provinces. The cold pool of air near Poona on 30th April had moved by the next day to the neighbourhood of north Central Provinces. The two instances have only been cited as examples though a larger number of instances can actually be noticed.

4. *Concluding remarks.*

It is a natural question whether it is not sufficient to plot the wet bulb temperatures at the surface of the ground. Quite a large part of India and Pakistan is covered by hills or is a plateau. All the observations of wet bulb temperatures taken at these places would at best reproduce the orographic features more prominently than the air masses (see the diagrams of Doraiswamy Iyer[10]) The whole of the Deccan plateau across which the winds associated with the southwest Monsoon blow goes out of the picture. The Burma observations also cannot be fully utilised. It has been pointed out[11] that unless one follows the air masses from a sufficiently great distance and from a sufficiently earlier epoch, the proof of the existence and establishment of different air masses in the tropical depressions becomes difficult. Hence there must be some reduced level to which all the measurements can be referred to. The use of wet bulb potential temperature which is a quantity reduced to 1000 mb level will, therefore, be logical.

As another argument, the wet bulb potential temperature increases if the dry bulb temperature increases or if the humidity or wet bulb temperature increases. It may happen that the changes in the dry and wet bulb temperatures are not concordant. There are four distinct possibilities. In an extra-tropical depression one deals essentially with cold dry air and with hot or warm moist air. The changes in the D.B. and W.B. thermometers are in the same direction and the change in the wet bulb potential temperature will also have the same tendency. Hence for qualitative work, in those latitudes, it may be sufficient to either plot D.B. or W.B. changes (dew point changes). But in India, the southwest Monsoon air is cold and moist. The continental air in summer is dry and hot. Hence the changes in the D.B. or W.B. will not be concordant with the onset of these two air streams. The change in the wet bulb potential temperature is a complicated function of the changes in the D.B. and W.B. thermometers.

Even in the height of summer, secondaries of extra-tropical depressions pass over the northern regions of west Pakistan and of India causing some weather. In early winter (November to January) tropical depressions form in the Bay of Bengal and occasionally in the Arabian Sea. As such it is necessary, for a major part of the year, to deal with cold moist *Em*, cold or hot and dry *Tc* or *Tcm* and with the variable *Tr* when extensive charts covering India, Burma, Pakistan and their neighbourhood are dealt with. A quasi-conservative and instructive element that should be plotted becomes the surface wet bulb potential temperature. If small charts over northwest India and west Pakistan are taken, it is quite possible in winter that the changes in W.B. temperatures may just suffice.

The question of reporting observations will naturally arise. Most of the International bodies being in the temperate latitudes, use dry bulb and dew point temperatures (the latter is similar to wet bulb temperatures). If T_dT_d the dew point temperature, a derived quantity, can be reported by an observer, it may the worth considering whether in and near the tropics (particularly round India) wet bulb potential temperatures should not be reported instead of or along with the dew point temperatures.

5. *Acknowledgements.*

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APPENDIX

In connection with a memoir by Sohoni and Paranjpe[12] on latent instability, the author prepared a short note deriving in essentials the value of Normand's wet bulb potential temperature in relation to Rossby's equivalent potential temperature[13] using Rossby's equations and suggested the use of a nomogram connecting the two potential temperatures and also the partial potential temperature. The nomogram may be useful for rapid work and the arguments are reproduced below.

Let us consider a definite amount of unsaturated air ; T, p, e are the actual values of temperature, pressure and of vapour pressure respectively. $(p-e) = p_d$ is the partial pressure of dry air. w is the mixing ratio equal to $0.622e/(p-e)$. θ_d is the partial potential temperature of dry air. c_p is the specific heat of air at constant pressure.

Let the air be cooled adiabatically to T_o so that the air gets saturated ; then,

$$Tp_d^{-k} = \theta_d P^{-k} = T_o p_{do}^{-k}$$

where $k = \dfrac{R}{m_d c_p}$. P is a standard pressure say 1000 mb. and R/m_d is the gas constant per unit mass of dry air.

Now the air is taken along the pseudo-adiabatic curve or compressed so that it always remains saturated until it attains the given pressure P. Let θ_N be the temperature at that stage.

The equation for the pseudo-adiabatic stage is[13]

$$\frac{dT}{T} - \frac{kdp_d}{p_d} + \frac{0.622}{c_p}\, d\left(\frac{Le_m}{Tp_d}\right) = O$$

where $e_m(T)$ is the maximum vapour pressure (saturation vapour pressure) at temperature T and L is the latent heat corresponding to temperature T ; L_o corresponds to T_o and L_N to θ_N.

The equation may also be written as

$$Tp_d^{-k}\, e^{\frac{0.622 L e_m}{c_p p_d T}} = \text{constant.}$$

Hence,

$$\theta_N \left\{P - e_m(\theta_N)\right\}^{-k} e^{\frac{0.622 L_N e_m(\theta_N)}{c_p \theta_N \left[P - e_m(\theta_N)\right]}}$$

$$= T_o p_{do}^{-k}\, e^{\frac{0.622 L_o e_m(T_o)}{c_p T_o p_{do}}}$$

$$= \theta_d P^{-k}\, e^{\frac{0.622 L_o e_m(T_o)}{c_p T_o p_{do}}}$$

where p_{do} is the value of p_d at temperature T_o.

Hence

$$\theta_N \left\{\frac{P}{P - e_m(\theta_N)}\right\}^k e^{\frac{0.622 L_N e_m(\theta_N)}{c_p \theta_N \left[P - e_m(\theta_N)\right]}}$$

$$= \theta_d\, e^{\frac{0.622 L_o e_m(T_o)}{c_p T_o p_{do}}} = \theta_E$$

$$= \theta_d\, e^{\frac{0.622 L_o e}{c_p T_o p_d}}$$

as $\dfrac{e_m(T_o)}{p_{do}} = \dfrac{e}{p_d}$, being proportional to the mixing ratio remains constant in the unsaturated stage. θ_E is Rossby's equivalent potential temperature.

If the air is not unsaturated initially the equation is

$$\theta_N \left\{\frac{P}{P - e_m(\theta_N)}\right\}^k e^{\frac{0.622 L_N e_m(\theta_N)}{c_p \theta_N \left[P - e_m(\theta_N)\right]}}$$

$$= \theta_E = \theta_d\, e^{\frac{0.622 L e}{c_p T p_d}}$$

In Rossby's tables $\Delta\theta_E = \theta_E - \theta_d$ can be found for a given value of $0.622e/p_d$. But $e_m(\theta_N)/\left\{P - e_m(h_N)\right\}$ is a definite one valued function of θ_N and the exponential function is uniquely determined if the value of the standard pressure P and the mixing ratio are given. The same series of tables can be used for finding

$$\theta_N \left\{\frac{P}{P - e_m(\theta_N)}\right\}^k.$$

Of course it is the reverse process, *i.e.*, given the θ_d and w, θ_E is found from the squares of the tables. But in the present case θ_E is known and θ_N and w_N are unknown. For a first approximation we may take

$$\theta_N \left\{\frac{P}{P - e_m(\theta_N)}\right\}^k = \theta_d$$

and the corresponding value of θ_N is found by means of a graph connecting θ_N and

$$\theta_N \left\{\frac{P}{P - e_m(\theta_N)}\right\}^k$$

Then the value of $\frac{0.622\ e_m(\theta)}{P-e_m(\theta)}$ is determined.

The corresponding value of next approximation for θ_N is then obtained. The new value of θ_N is now used for the next approximation of θ_N and so on to the required degree of accuracy.

There is also a second method of getting θ_N. For any given value of P and θ_N

$$\theta_N \left\{ \frac{P}{P-e_m(\theta_N)} \right\}^k e^{\frac{0.622\ L_N e_m(\theta_N)}{c_p\ \theta_N \left[P-e_m(\theta_N)\right]}}$$

is a unique function. We can draw a graph or nomogram connecting this function and θ_N and one can directly read off θ_N for any given value of the function which is equivalent to θ_E which is Rossby's equivalent potential temperature.

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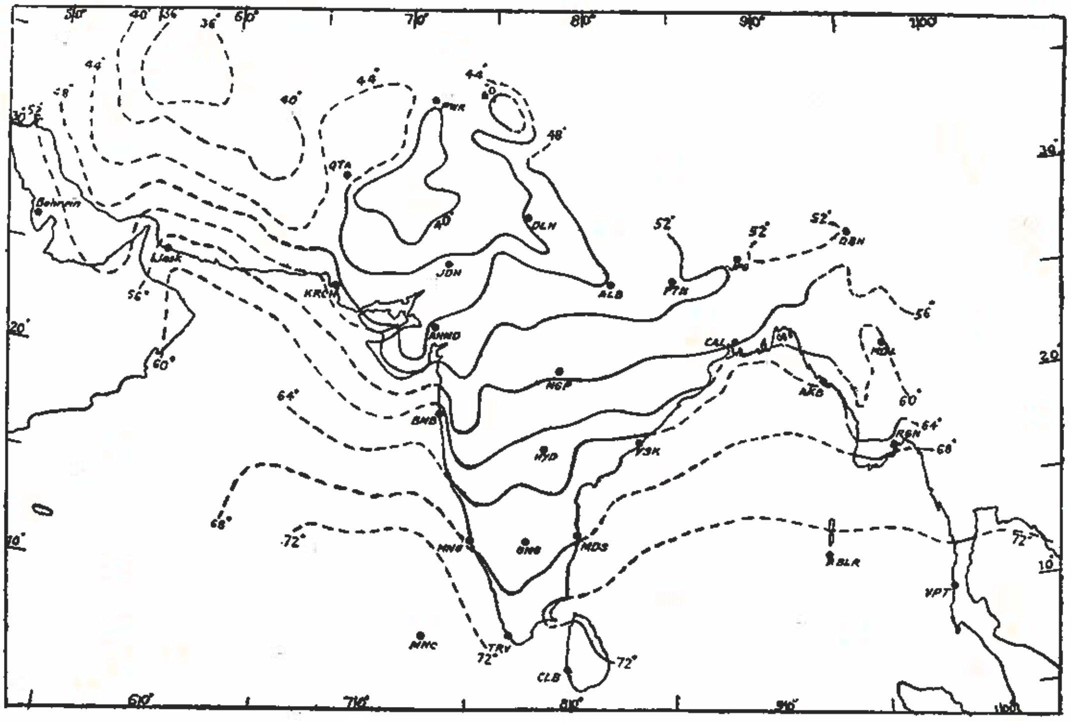


Fig. 1. Normal Wet Bulb Potential Temperature — JANUARY

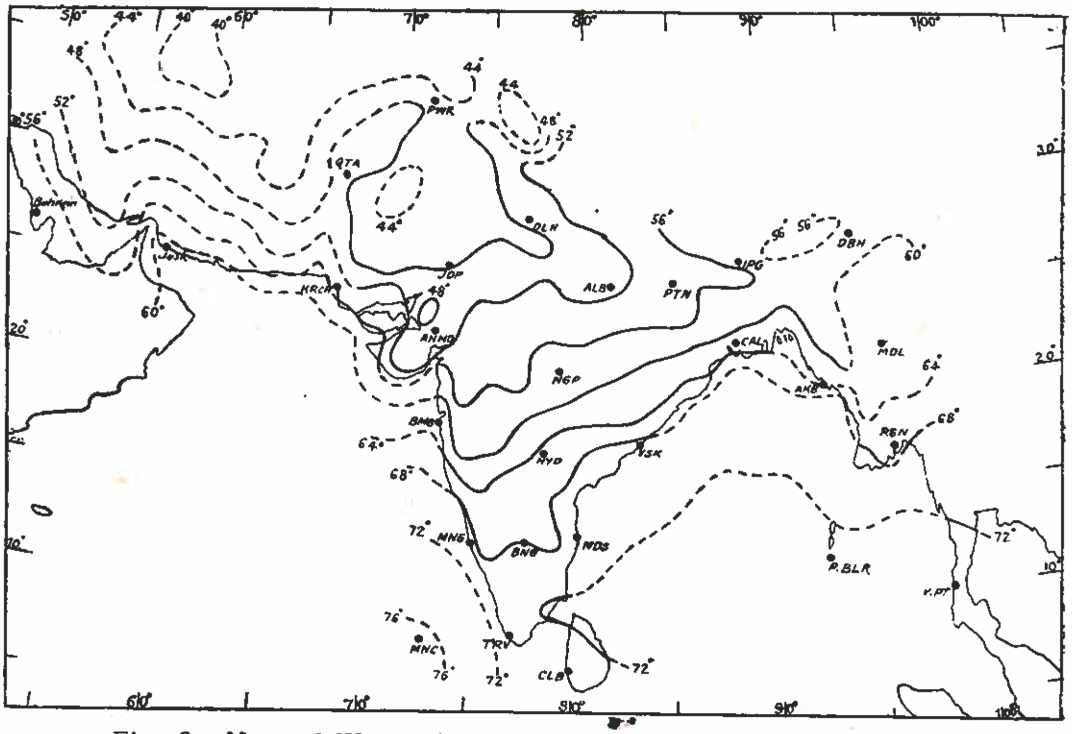


Fig. 2. Normal Wet Bulb Potential Temperature — FEBRUARY

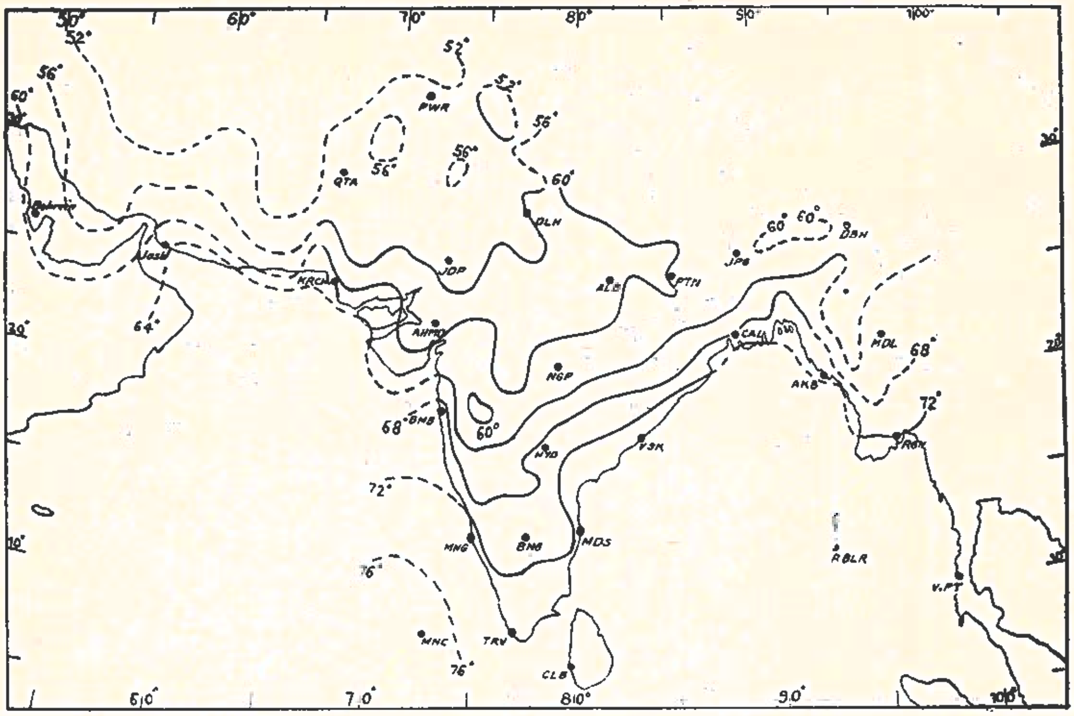


Fig. 3. Normal Wet Bulb Potential Temperature — MARCH

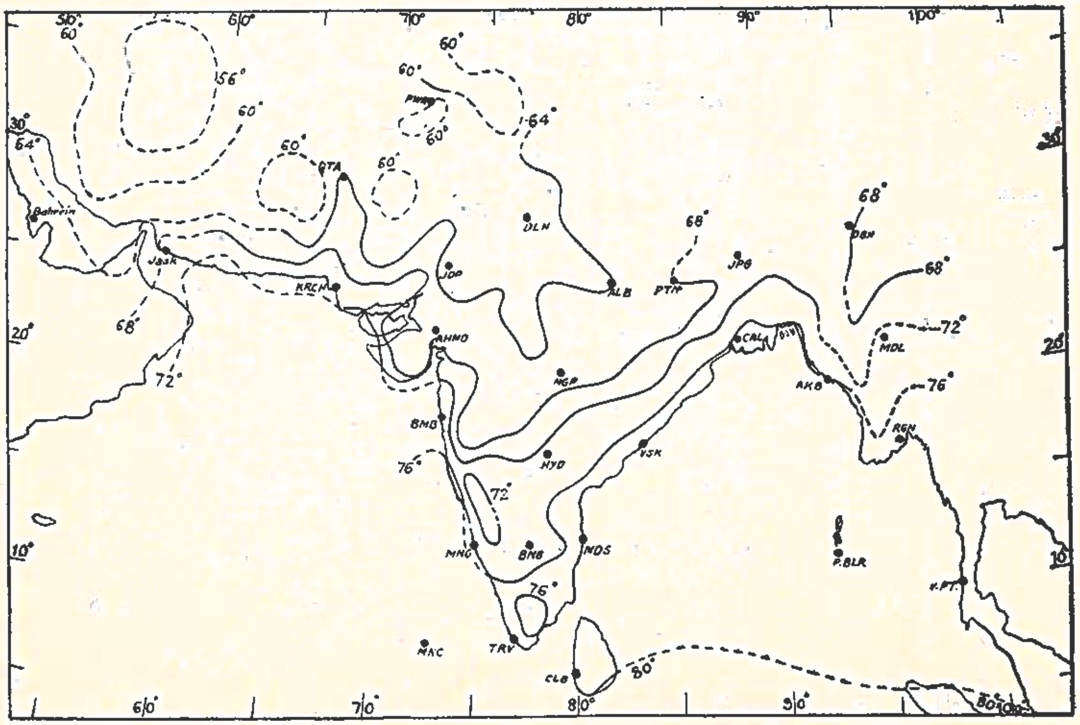


Fig. 4. Normal Wet Bulb Potential Temperature— APRIL

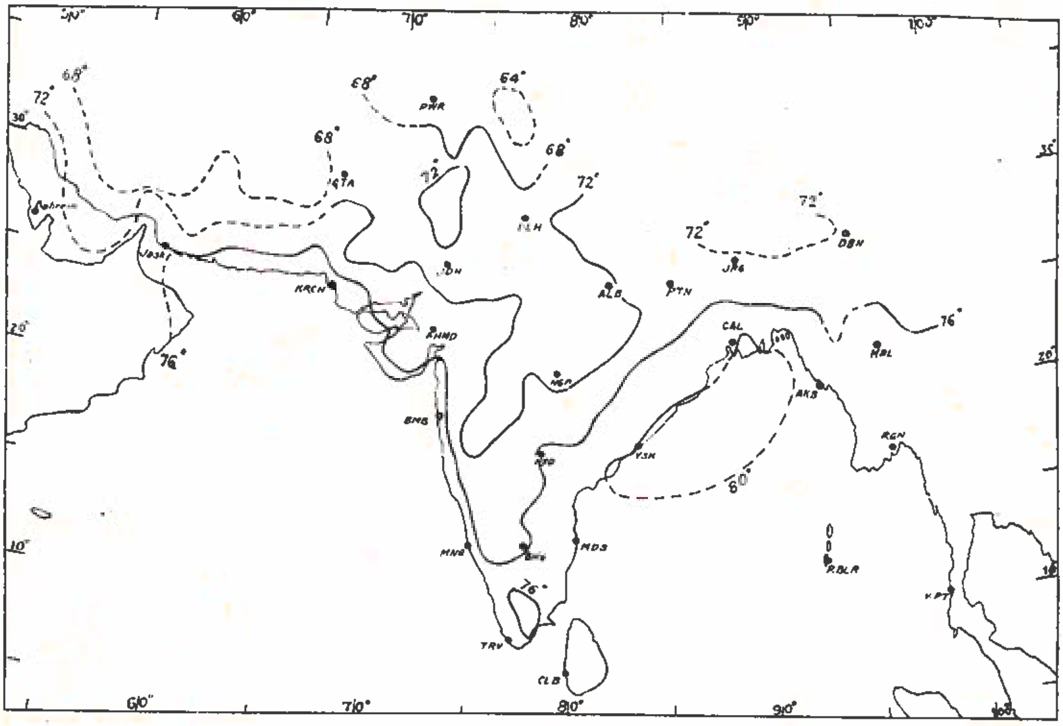


Fig. 5. Normal Wet Bulb Potential Temperature — MAY

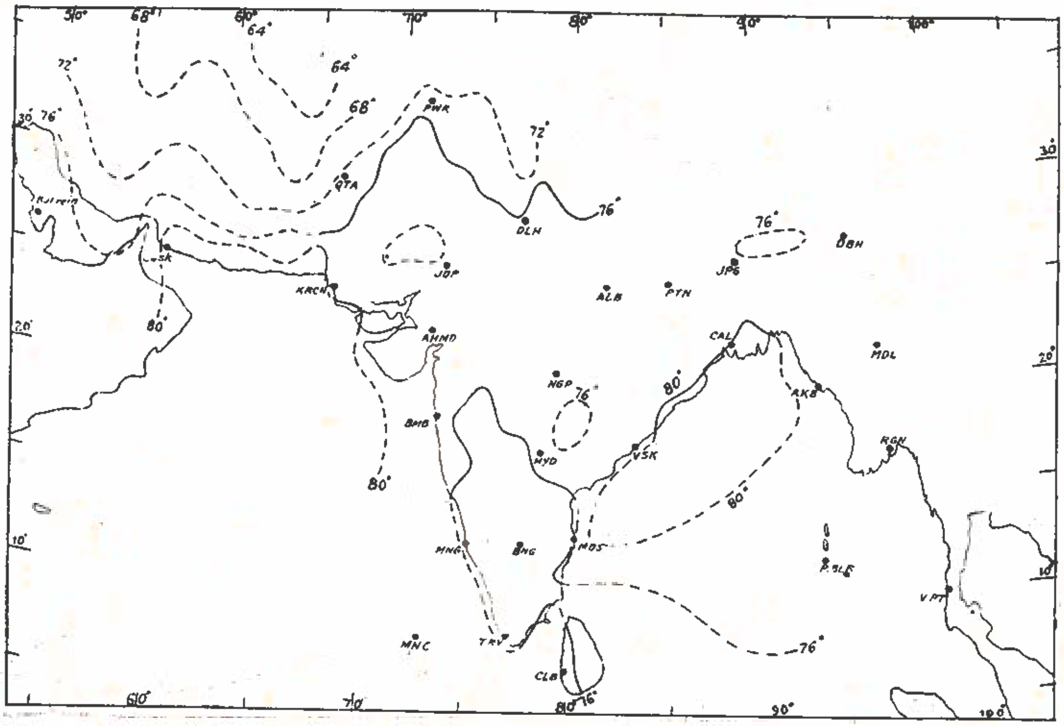


Fig. 6. Normal Wet Bulb Potential Temperature — JUNE

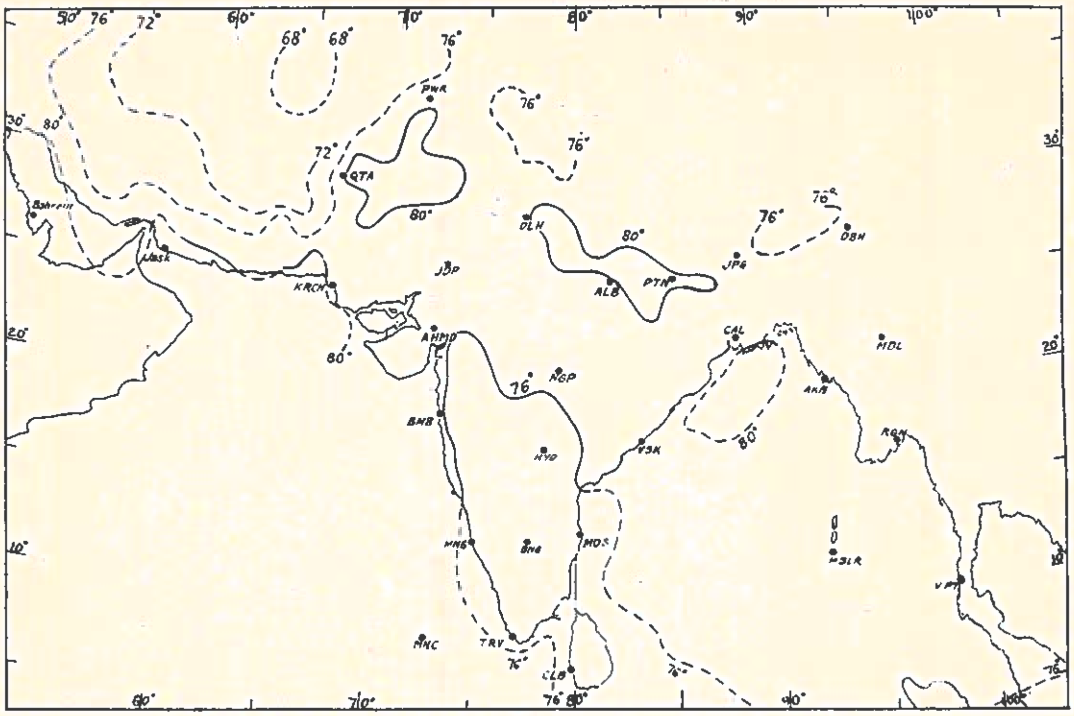


Fig. 7. Normal Wet Bulb Potential Temperature — JULY

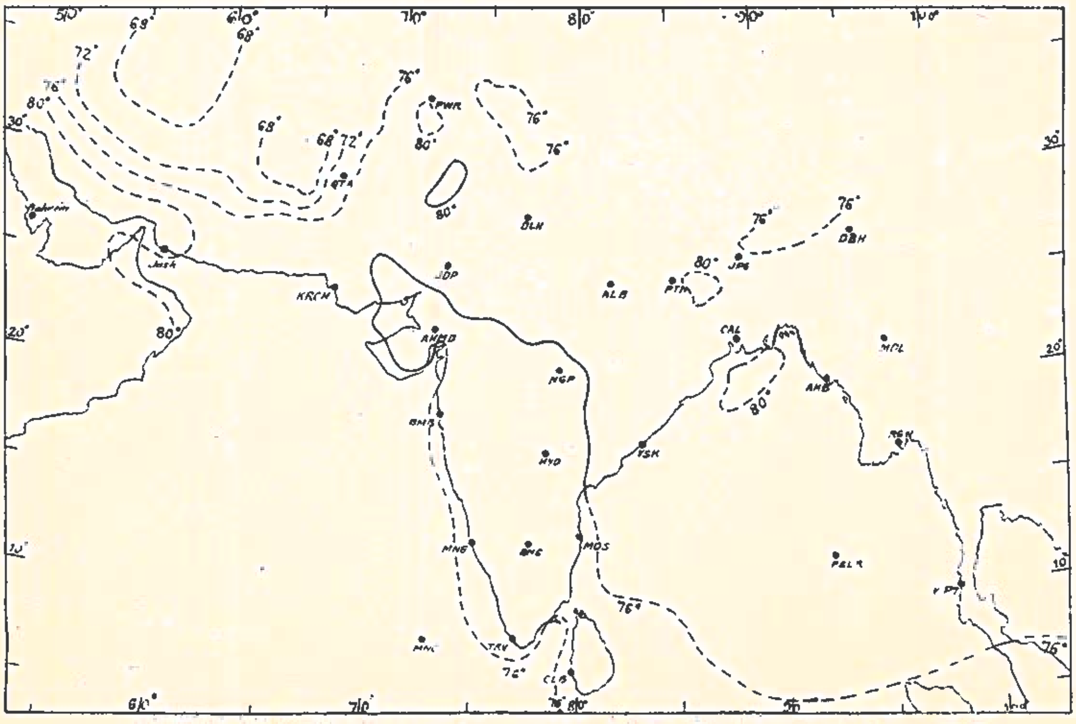


Fig. 8. Normal Wet Bulb Potential Temperature — AUGUST

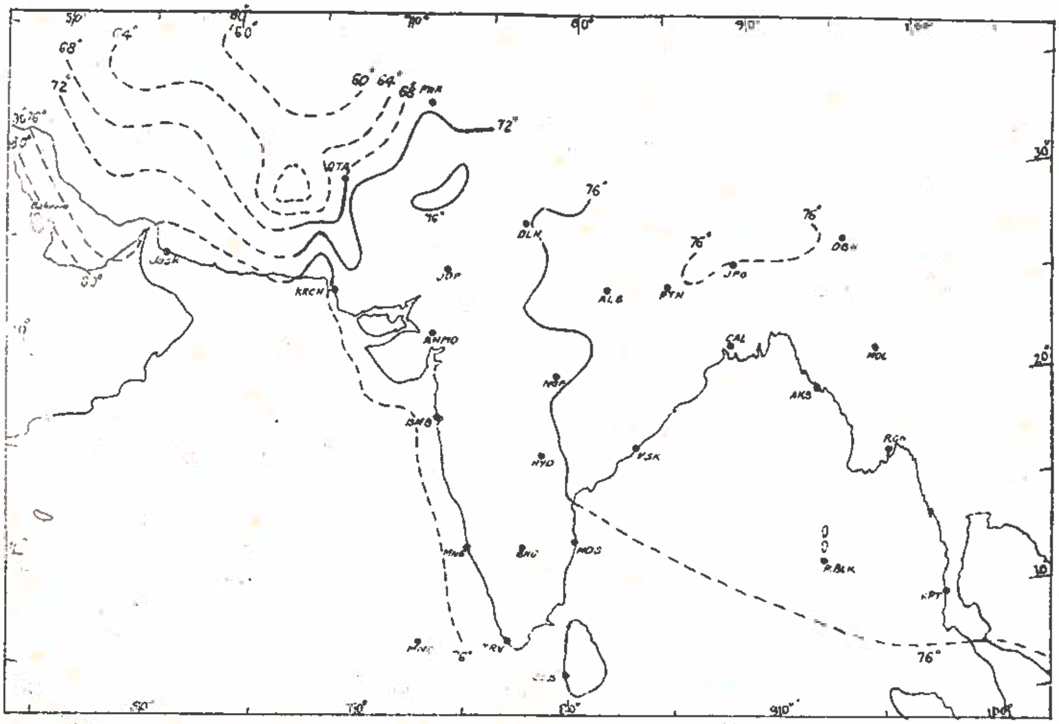


Fig. 9. Normal Wet Bulb Potential Temperature — SEPTEMBER

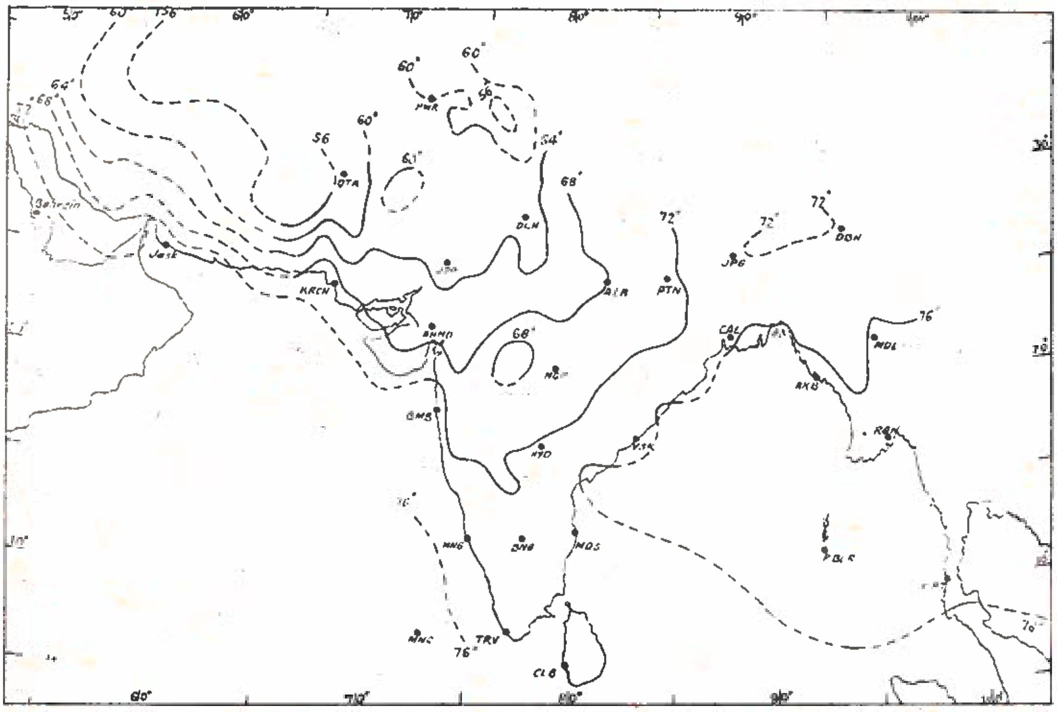


Fig. 10. Normal Wet Bulb Potential Temperature — OCTOBER

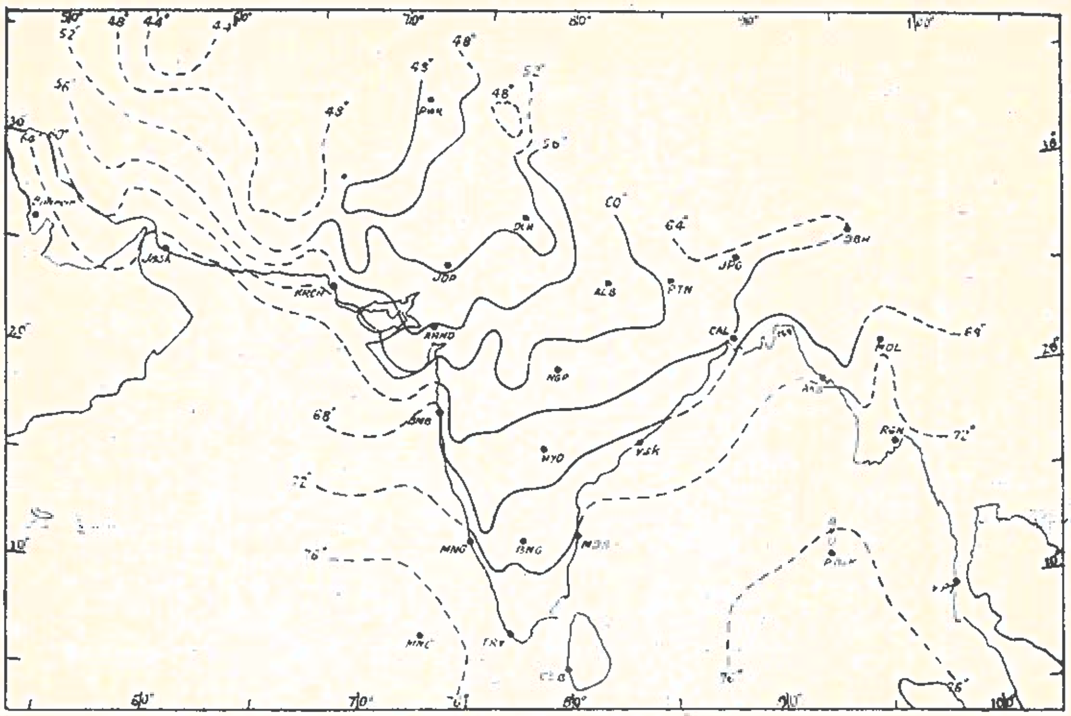


Fig. 11. Normal Wet Bulb Potential Temperature — NOVEMBER

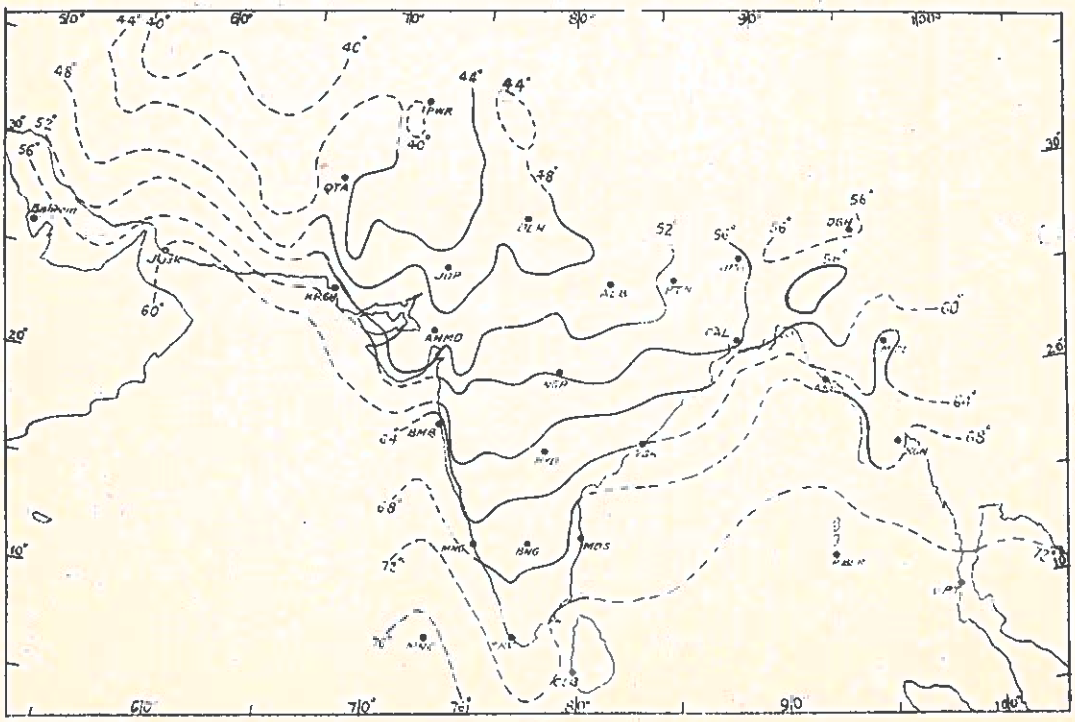


Fig. 12. Normal Wet Bulb Potential Temperature — DECEMBER

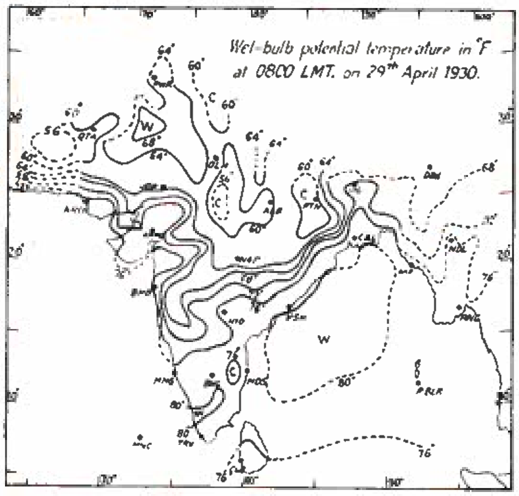


Fig. 13.

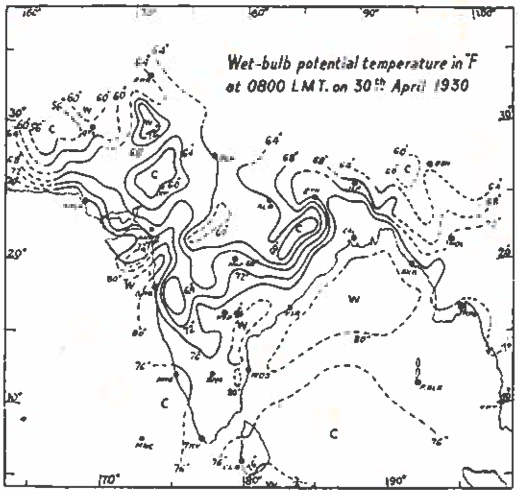


Fig. 14.

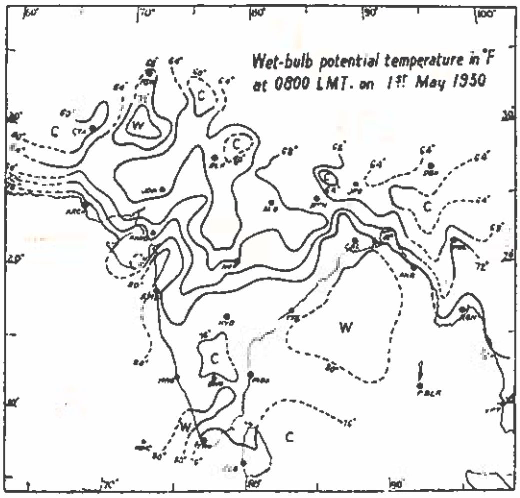


Fig. 15.

Fig 16.

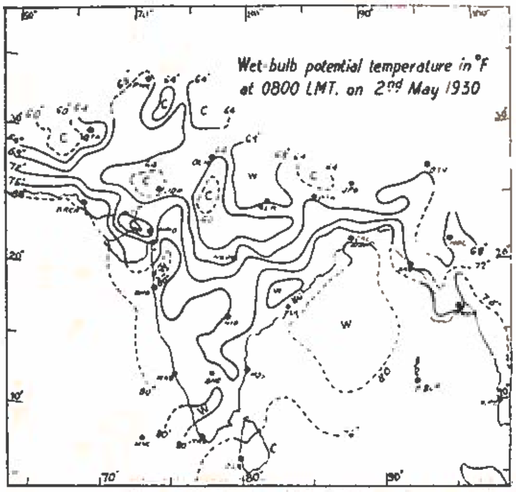
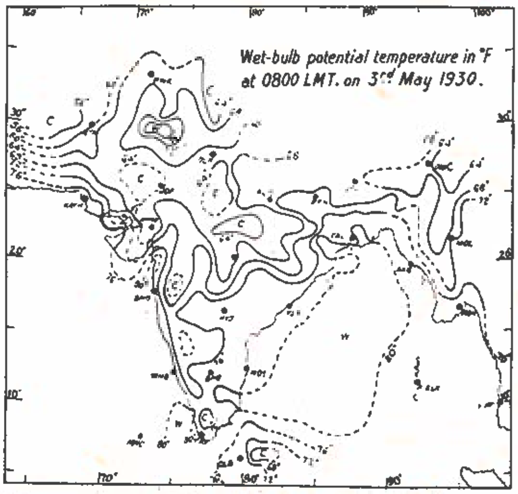
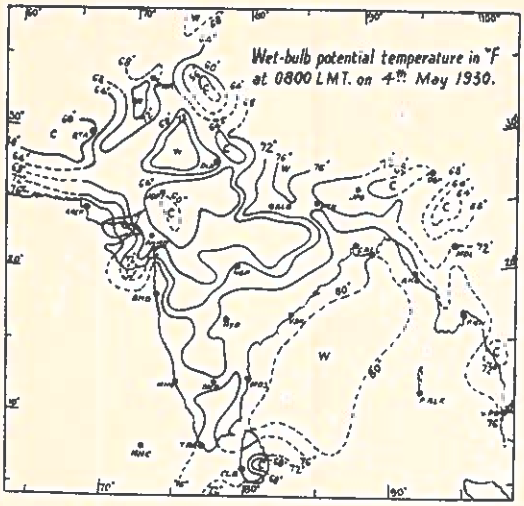


Fig. 17.





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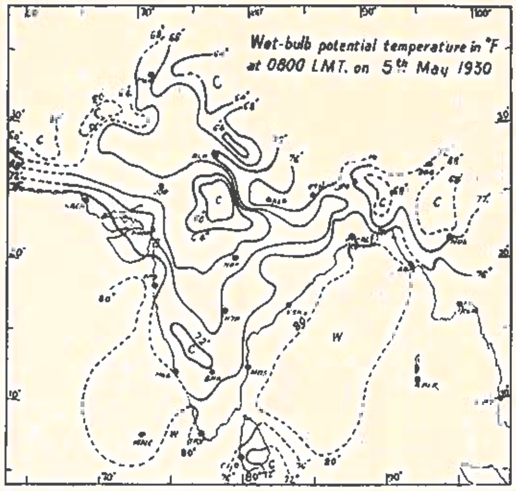


Fig. 19.

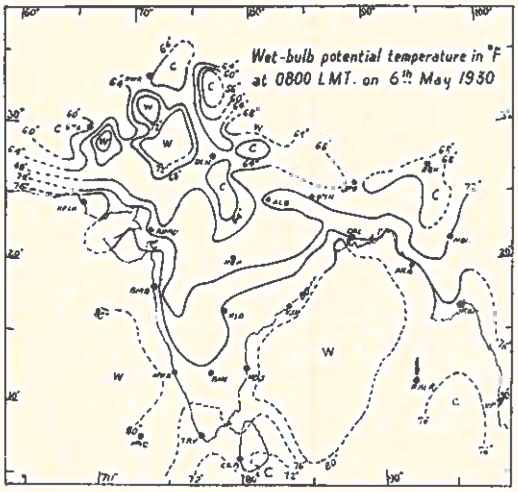


Fig. 20.

Fig. 21.

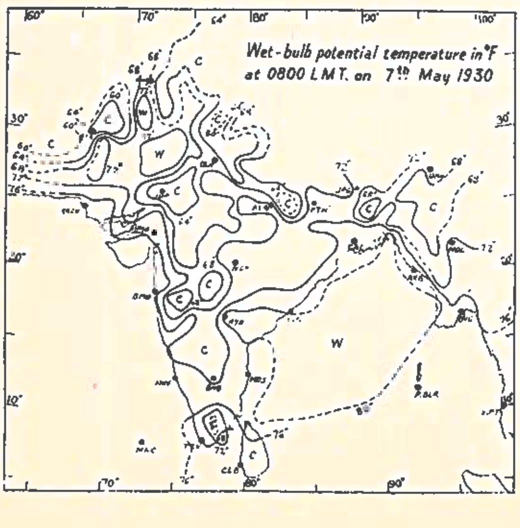
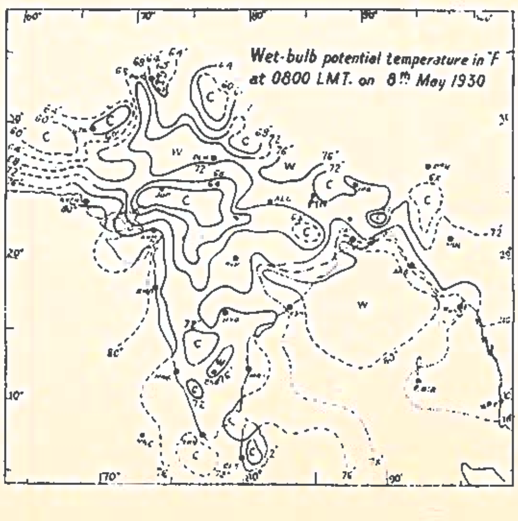
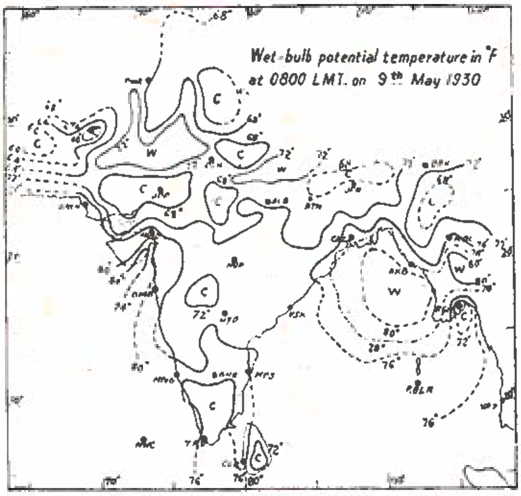


Fig. 22.





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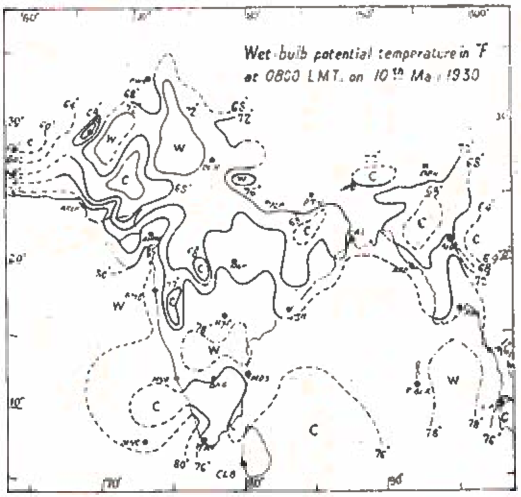

Fig. 24.

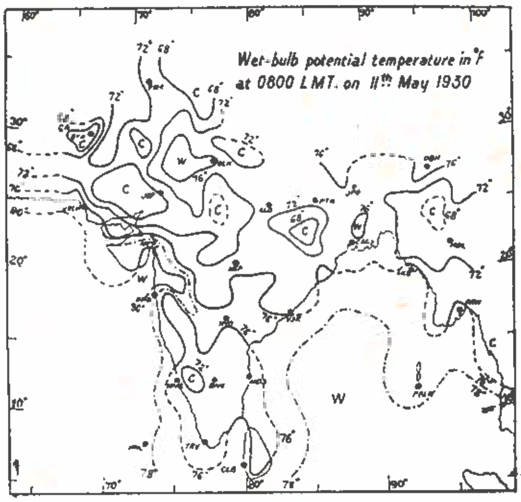

Fig. 25.

Fig. 26.

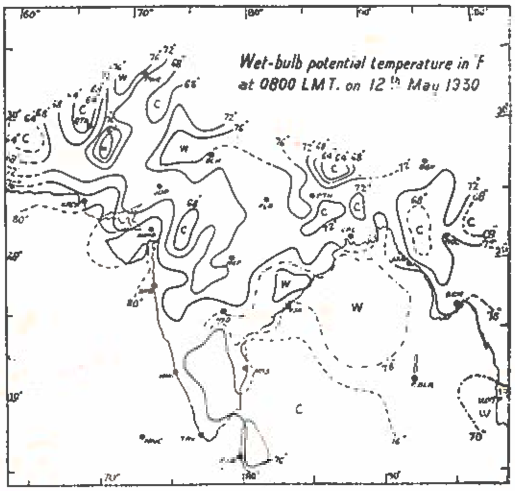

Fig. 27