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The diurnal variation of upper winds over the Indian Sub-continent

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ABSTRACT. The diurnal variation of upper winds over the Indian sub-continent has been examined with reference to the normals of upper winds from pilot balloon ascents taken near about 0200, 0700 and 1500 IST upto 6 km. This has been accounted for as mainly due to differential heating or cooling of the various parts of the country associated with the vertical movement of air due to convection and an expression has been derived connecting diurnal variation with the differential heating and vertical movement. Differential heating of land and sea areas are found to affect winds upto 3 km in general and upto 6 km in April, the effect in the lower levels being more prominent in the west coast than in the east coast. Some notable instances of the diurnal variation which have an effect on the climatology of the various regions are also considered.

1. Introduction

Diurnal variation of upper winds play an important role in the tropics. For temperate latitudes it is generally assumed that little diurnal variation exists above the geostrophic wind level and that variation in lower levels are due to exchange of momentum from the geostrophic level to the surface. Farquharson (1939) first pointed out the existence of diurnal variation even in geostrophic levels over Tropical Africa as due to the difference in heating of the air layers in different regions. His conclusion was based on data from only one station and he did not examine the winds at higher levels in detail. It is also well known that considerable variation exists over India. In the climatic charts (1943) published by the India Meteorological Department winds are given separately for morning and afternoon only for 0·5 and 1·0 km and diurnal variation at higher levels has not been considered. A study of the broad features of the diurnal variation of winds in the free air at and above 1 km over India and neighbourhood has been made in the present paper. Normals of upper winds worked out by the India Meteorological Department from pilot balloon ascents for the three observational hours, *viz.*, 0000-0230, 0600-0900 and 1400-1600 IST were utilised and the study restricted to four representative months, *viz.*, January, April, July and October. The most important diurnal variation in the coastal stations, *viz.*, the phenomenon of land and sea breezes is intended to be discussed in a separate paper.

The diurnal variations were examined with charts in which vector differences in resultant winds between morning and afternoon (M-A), afternoon and night (A-N) and night and morning (N-M) were plotted. These diurnal differences in velocities (which for convenience may be called as diurnal vector) can give an idea of the nature of diurnal change if the winds at various stations are already known.

Such charts were constructed for the four months under consideration for 1, 2, 3, 4, 6 and 9 km with normals of all the stations which had at least 30 observations for each observational hour. The 9-km level was the highest for which charts could be prepared since regular ascents were made twice upto that level until recently. The charts for A-N and N-M could be prepared only upto 3 km since night observations are not generally available above 3 km. Charts for July were not prepared above 3 km because of few observations at the majority of the stations. Of the charts prepared, the 9 km ones were not of any use because of the absence of data for many stations and numerous inconsistencies. A select few of the charts are reproduced in Figs. 1 to 20 (pp. 215-219).

2. Testing the significance of the Diurnal Vectors

This was done by *t-test* (Fisher 1950) taking the mean diurnal vector differences for each month for all the years for which data were available and considering only the components along the direction of the average of the monthly means. Such tests were done for 4 stations, *viz.*, New Delhi, Jodhpur, Calcutta and Trichinopoly and for the maximum heights examined in the paper, *i.e.*, 6 km for January, April and October and 3 km for July. The results showed that the diurnal vectors were significant. An example is given below—

Diurnal Vectors—Morning to Afternoon
Station—New Delhi   Month—January
Height—6 km   Number of years (n)=11

Resultant diurnal vector averaged from the monthly means for each year } =Magnitude 4·1, Direction 330°

s^2=Variance of the components along the resultant direction } =31·9

t—(Resultant $\div\sqrt{s^2/n}$)=2·4

For $n-1=10$ probability of t exceeding 2·4 is $<5\%$

3. Theoretical considerations

Diurnal changes in the lower levels are generally accepted to be a result of diffusion due to turbulence brought about by the vertical shear in winds, and the vertical exchange of momentum or vorticity decreases the winds in the higher levels in the afternoon. But even a casual look at the charts will reveal that the prevailing westerlies of North India during January, April and October get accelerated in the afternoon which is just contrary to the generally accepted theory and hence it appears necessary to look into other factors for an explanation of the diurnal change.

If $\partial/\partial t$ represents the diurnal change at a station during a period, *i.e.*, M-A, A-N or N-M, differentiating the usual equation of motion in the cartesian co-ordinates and representing this differentiation (diurnal change) by dots over the symbols, wherever convenient they become

$$\frac{\partial}{\partial t}\left(\frac{du}{dt}\right)-l\dot{v}=-\frac{\partial}{\partial t}\left(\frac{1}{\rho}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial t}\left(K\frac{\partial^2 u}{\partial z^2}\right) \quad \ldots(1)$$

$$\frac{\partial}{\partial t}\left(\frac{dv}{dt}\right)+l\dot{u}=-\frac{\partial}{\partial t}\left(\frac{1}{\rho}\frac{\partial p}{\partial y}\right)+\frac{\partial}{\partial t}\left(K\frac{\partial^2 v}{\partial z^2}\right) \quad \ldots(2)$$

where the symbols have the usual meanings.

If diurnal variations are assumed to be brought about only by diffusion

$$\frac{\partial}{\partial t}\left(\frac{1}{\rho}\frac{\partial p}{\partial x}\right)=\frac{\partial}{\partial t}\left(\frac{1}{\rho}\frac{\partial p}{\partial y}\right)=0$$

and neglecting $\frac{\partial}{\partial t}\left(\frac{du}{dt}\right)$ etc ; equations (1) and (2) become after expansion

$$-l\dot{v}=K\frac{\partial}{\partial t}\left(\frac{\partial^2 u}{\partial z^2}\right)+\dot{K}\left(\frac{\partial^2 u}{\partial z^2}\right) \quad \ldots(3)$$

$$l\dot{u}=K\frac{\partial}{\partial t}\left(\frac{\partial^2 v}{\partial z^2}\right)+\dot{K}\left(\frac{\partial^2 v}{\partial z^2}\right) \quad \ldots(4)$$

All the terms except K and $\dot{K}$ in (3) and (4) are known and the solutions for K and $\dot{K}$ can be obtained. These were calculated for about 10 stations for the four months under consideration. As a rule K and $\dot{K}$ were found to be negative wherever there was an increase in the winds and were positive wherever there was a decrease in the afternoon winds. The order of magnitude in the latter case was 10^5 when there were small diurnal variations and 10^6 when there were large variations. A negative value for K is absurd which only suggests that the other factors are also to be considered in addition to diffusion. It is also, therefore, reasonable to assume that not all the retardation in winds noted in some regions are brought about by diffusion.

If it is assumed that diurnal changes are due to the change in the other elements in equations (1) and (2), *i.e.*, pressure and density changes, the equations can be written as

$$\frac{\partial}{\partial t}\left(\frac{du}{dt}\right)-l\dot{v}=-\frac{\partial}{\partial t}\left(\frac{1}{\rho}\frac{\partial p}{\partial x}\right) \quad \ldots(5)$$

$$\frac{\partial}{\partial t}\left(\frac{dv}{dt}\right)+l\dot{u}=-\frac{\partial}{\partial t}\left(\frac{1}{\rho}\frac{\partial p}{\partial y}\right) \quad \ldots(6)$$

The right hand side of (5) on substitution from the relation $p=\rho RT$ can be written as

$$-R\frac{\partial}{\partial t}\left(\frac{\partial \dot{T}}{\partial x}\right)-R\left[\dot{T}\frac{\partial \log \rho}{\partial x}+T\frac{\partial}{\partial t}\left(\frac{\partial \log \rho}{\partial x}\right)\right]$$

Since the rate of variation of density along any direction as well as the product of temperature change and density variation can be neglected in comparison with $l\dot{v}$ —(even taking account of extreme cases inland, it was found that the terms do not exceed 10% of $l\dot{v}$)—the right hand side of (5) reduces to

$$-R\frac{\partial}{\partial t}\left(\frac{\partial T}{\partial x}\right)=-R\frac{\partial \dot{T}}{\partial x} \quad \ldots \quad \ldots \quad (7)$$

Similarly the right hand side of (6) reduces to

$$-R\frac{\partial \dot{T}}{\partial y} \quad \ldots \quad \ldots \quad (8)$$

Equations (5) and (6), on substitution of the right hand sides by expressions (7) and (8) become almost similar to the gradient wind equation and can, therefore, be written as

$$l\dot{V}+\frac{\dot{V}^2}{r}=R\frac{\partial \dot{T}}{\partial n} \quad \ldots \quad \ldots \quad (9)$$

where $\dot{V}$ is the diurnal vector, r the radius of curvature of the isopleths of $\dot{T}$ and n the distance between unit isopleths of $\dot{T}$. $\dot{V}^2/r$ is generally negligible since $\dot{V}$ the diurnal vector change is of the order of 1 to 3 mps during the intervals of time considered. (Even at a latitude of 10°, for a radius of curvature of 500 km and diurnal vector 1 mps $\partial\dot{T}/\partial n$ was found to change only by 6%). Hence the equation for diurnal change reduces to

$$l\dot{V}=R\frac{\partial \dot{T}}{\partial n} \quad \ldots \quad \ldots (10)$$

i.e., the diurnal vector is proportional to the gradient of differential heating along a direction perpendicular to the vector. If $\dot{T}$ is positive or when there is diurnal heating the diurnal vectors have the region of lower heating to the left and when there is diurnal cooling, the region of greater cooling will be to the left of the vector.

Before proceeding to assess the relative importance of diurnal heating and diffusion on the diurnal variation of winds, it is necessary to know from other evidences whether there is really a noticeable diurnal variation in the upper air temperatures.

Diurnal variation of upper air temperatures— Upper air temperature observations are generally taken only once a day over all the radiosonde stations in India. Only Calcutta and New Delhi had both morning and evening ascents for some months for a few years. Table 1 gives the mean temperatures at Calcutta and New Delhi upto 500 mb (6 km).

At Calcutta the evening (2030 IST—after sunset) temperatures are higher than the morning temperatures during the years 1950 and 1951. This increase is significant if it is remembered that the morning data are apt to show a higher value because of the effect of solar radiation on the radiosonde instruments. For the same reason the decrease in the evening temperatures of 1949 is open to doubt since the morning observations might have registered a higher value due to radiative heating of the instruments.

At New Delhi only the values for 1952 show an increase in the evening temperature. It is important to remember that the morning ascents in this year were taken at 0530 IST, *i.e.*, before sunrise, while the morning ascents during 1950 and 1951 were taken at 0730 IST, *i.e.*, after sunrise. Hence the morning temperatures given for 1952 can be taken to be reliable while those for 1950 and 1951 might be open to doubt.

Thus the observations at both the stations indicate that there is diurnal heating during the day even upto 500 mb (6 km). The magnitude of diurnal heating based on the means of only those years which show higher evening temperatures is given in Table 2. These means cannot, however, be taken to be representative until they are

TABLE 1

Upper Air Temperatures (°A) at Calcutta and New Delhi

Year	Month	Morning			Evening (2030 IST)		
		850 mb (1·5 km)	700 mb (3 km)	500 mb (6 km)	850 mb (1·5 km)	700 mb (3 km)	500 mb (6 km)
		Calcutta					
1949	April	294·9	283·9	264·2	293·4	280·1	260·2
	May	295·0	284·9	269·5	295·5	284·5	267·7
1950	April	295·5	280·6	263·4	297·3	282·1	263·9
	May	295·4	283·5	264·3	296·9	284·5	265·5
1951	April	292·8	277·8	260·1	295·6	280·3	262·0
	May	295·6	281·7	263·9	297·2	283·6	266·0
		New Delhi					
1950	May	300·5	285·2	262·6	301·4	284·1	263·3
1951	May	298·7	284·7	264·2	299·6	283·8	262·5
1952	April	297·1	281·2	259·0	297·9	281·7	260·5
	May	299·7	284·1	262·4	302·1	284·9	261·3

TABLE 2

Diurnal heating from morning to afternoon over Calcutta and New Delhi

	850 mb (1·5 km)	700 mb (3 km)	500 mb (6 km)
Calcutta	1·9° C	1·7° C	1·5° C
New Delhi	1·6° C	0·7° C	0·2° C

based on more observations. However it can be qualitatively said that there is more diurnal heating at Calcutta than at New Delhi which is in conformity with the derived values from the diurnal vectors.

Diurnal variation due to turbulence—The value of the co-efficient of diffusion is subject to considerable local and time variations and at best only its order of magnitude is of significance. In Brunt's *Physical and Dynamical Meteorology* the order of magnitude is given from 10^3 to 10^5. As only the means are considered in this paper, an assumption of a mean value of K for the whole of India seems plausible. It has been found that the diurnal vector is approximately proportional to the gradient of differential heating (p. 207). Hence the determination of K from large vectors is impossible since the gradient of heating will also be involved. But if places and levels where the diurnal vectors are small are chosen, the error due to $\partial \dot{T}/\partial n$ will be negligible and the order of magnitude of K or $\dot{K}$ can be found. Values of K were obtained from such levels at representative places and they were found to be of the order of 10^5 at 1 to 2 km to 2×10^5 above 3 km. The order of $\dot{K}$ was of 5×10^4 to 10^5. These values are in agreement with the generally accepted values.

Corresponding to this order of magnitude of K and $\dot{K}$, the probable resulting diurnal vectors were calculated for a number of stations to find out how they compare with the actual diurnal vectors. Because of the large vertical shear at the 1-km level for January, April and October and 2 km for July (lowest level considered in this paper) the calculated diurnal vectors were of considerable magnitude. At 1 km above these levels the calculated values were hardly 10 per cent of the actual vectors and at higher levels they were negligible. The calculated and actual diurnal vectors at 1 km for January, April and October and at 2 km for July are given in Table 3.

TABLE 3

Actual and calculated Diurnal Vectors

		January (1 km)			April (1 km)			July (2 km)			October (1 km)			Months with actual D.V.'s agreeing with calculated ones for multiples of K and $\dot{K}$
		1	2	3	1	2	3	1	2	3	1	2	3	
Ahmedabad	D	15	150	300	295	225	180	55	340	10	75	360	220	July
	$\dot{V}$	1·5	0·9	0·4	0·5	0·3	3·1	1·3	1·3	1·1	0·3	0·1	0·4	
Allahabad	D	145	120	295	120	155	290	350	105	180	245	265	275	October
	$\dot{V}$	0·5	0·6	0·5	0·5	0·4	1·6	1·7	0·2	0·8	0·4	0·2	0·7	
Asansol	D	90	195	315	160	160	80	270	285	150	210	160	170	
	$\dot{V}$	0·3	0·9	0·2	1·0	0·2	1·6	0·3	0·2	2·7	0·4	0·2	0·9	
Cooch Bihar	D	205	245	240	205	205	260	195	245	200	195	160	250	July
	$\dot{V}$	0·7	0·3	2·0	0·8	0·7	3·5	2·1	0·1	2·0	0·5	0·2	2·3	
Gwalior	D	85	165	260	65	135	245	225	10	210	335	205	350	
	$\dot{V}$	0·8	0·7	0·9	0·7	0·1	1·7	0·2	0·8	1·0	0·4	0·3	0·9	
Hyderabad	D	70	190	340	205	245	60	250	360	170	15	200	300	
	$\dot{V}$	5·9	0·4	2·7	4·5	0·5	3·4	1·0	0·2	1·7	2·4	0·4	1·4	
Jagdalpur	D	350	235	260	235	320	45	—	—	—	305	75	320	
	$\dot{V}$	1·9	0·2	1·5	3·9	0·8	3·4				0·8	0·6	0·8	
Jodhpur	D	165	175	270	185	180	190	325	5	270	130	90	30	
	$\dot{V}$	0·9	0·2	0·8	0·5	0·3	1·0	3·1	0·6	1·5	0·7	0·1	0·8	
Nagpur	D	95	45	315	320	330	175	190	160	235	200	180	305	July
	$\dot{V}$	2·9	0·5	2·4	1·9	0·9	0·6	5·1	0·5	0·3	0·2	0·2	1·2	
New Delhi	D	315	90	140	230	240	155	329	270	255	115	205	140	October
	$\dot{V}$	0·1	0·1	0·6	0·7	0·6	0·4	0·9	0·1	1·3	0·4	0·2	0·4	
Poona	D	335	175	270	325	70	195	150	5	160	5	225	280	July
	$\dot{V}$	2·0	0·7	2·6	2·0	0·4	2·8	1·2	1·5	0·5	1·9	0·2	2·7	
Raipur	D	90	200	305	325	15	30	15	15	105	135	185	305	April
	$\dot{V}$	0·7	1·0	2·0	0·8	0·9	0·3	1·6	1·7	0·6	0·3	0·7	0·6	
Tezpur	D	185	145	240	175	165	270	45	45	215	205	180	240	
	$\dot{V}$	0·7	0·3	1·1	1·5	0·2	2·7	0·1	0·1	1·4	0·5	0·3	1·6	
Trichy	D	25	95	260	120	325	75	205	300	260	25	110	100	October
	$\dot{V}$	3·3	1·0	1·4	1·4	0·6	2·3	3·4	0·7	1·8	1·0	0·3	1·2	

(Col 1 gives diurnal vectors calculated for $K=10^5$ and $\dot{K}=0$

Col 2 gives diurnal vectors calculated for $K=\dot{K}=10^5$

Col 3 gives actual diurnal vectors)

D—Direction of vector in degrees from North

$\dot{V}$—Magnitude in mps

The differences between values in columns 1 and 2 of the table give vectors for $K=0$ and $\dot{K}=10^5$. Values with different multiple of K (from 5×10^4 to 5×10^5) and $\dot{K}$ (10^4 to 10^5) were tried to find whether they fitted with the actual diurnal vectors. Months in which such approximate fits could be obtained are given in the last column and it may be seen that they are very few.

If the calculated vectors are subtracted from the actual vectors in Table 3 the resulting vectors will give an idea of the gradient of heating alone. As the actual and calculated vectors are to some extent opposing for many of the stations, the subtracted diurnal vectors are greater in magnitude than the actual diurnal vectors. It was found that some of these subtracted diurnal vectors were fitting better in the charts (2 km for July and 1 km for the other three months) than the actual values and no substantial alteration in the isopleths of differential heating was necessary on account of this change. The error in using the actual values for drawing the isopleths, resulted more often in an underestimate for the gradient of heating.

Thus of the two factors which are responsible for producing diurnal variation, the effect of turbulent diffusion seems to be almost unimportant in the upper levels and the only other alternative is in the differential heating of the air. Hence isopleths of differential heating or cooling could be drawn on the vector diagrams on the basis of equation (10) to get an idea of regions of heating and cooling.

The following method was adopted for drawing the isopleths. Table 4 which gives distances in terms of degrees of latitude for 0·1° C variation producing a vector change of 1 mps was prepared, for different latitudes in India.

A convenient corner in the map was chosen and a line was drawn parallel to the run of the diurnal vectors. To draw a next isopleth at 0·1°C interval, points were fixed at distances from the initial line according to the magnitudes of the diurnal vectors in between, using the above table. A smooth line was

TABLE 4

Gradient of heating to produce a diurnal vector of 1 mps

Latitude °N	Distances in degrees of latitude between isopleths of 0·1°C variation
30	3.8
25	4.2
20	5.6
15	7.1
10	10·0

drawn through these points making sure while drawing that the line is as far as possible parallel to the diurnal vectors. Similarly other isopleths were drawn. Lines near about the least heated or cooled areas were marked as h or c and the other isopleths were marked as $h+0\cdot1$, $h+0\cdot2$......, $c-0\cdot1$, $c-0\cdot2$ etc. h was put in all the charts from M-A as there is generally heating from M-A. c was put in all the charts from A-N and N-M since the night observations were taken very late in the nights and hence cooling could be assumed.

What we get from these isopleths is an idea of diurnal heating or cooling at a place A as compared to that at a place B. The actual magnitudes of the changes of h or c are not known for want of observations. Some idea of the order of magnitude can be got from Table 2 though these values are for a different diurnal period.

The following limitations under which equation (10) was derived were to be kept in view while drawing the isopleths.

(1) Geostrophic balance was assumed and the usual restrictions in its application continue to hold good. The effect of cyclostrophic component was, however, shown to be negligible.

(2) Variation in density was neglected which is not strictly true in coastal areas, where abrupt changes at least in the lower levels are to be expected. Hence the isopleths could not be continued across the coast line.

(3) Though the diurnal vectors at 2 km for July and 1 km for other months are not strictly proportional to gradient

of differential heating because of the effect of diffusion the isopleths were still drawn on these charts since the picture was not found to be substantially different from the one based on subtracted vectors (page 210). The errors if any could only be in an underestimation of the gradient of heating.

4. Main features of Diurnal variation charts—Inland area

January—The diurnal vectors from M-A over the Indo-Gangetic plain have W components at all levels showing (1) increase in the afternoon winds and (2) increased diurnal heating from North to South. At 2 and 3 km the vectors are cyclonic over the Deccan diminishing the winds of the anticyclonic 'high' over the region (Fig. 2). It will be interesting to note that this is due to less heating over the Deccan than over the surrounding areas at these levels. At higher levels the anticyclone shifts southwards and correspondingly, the opposing vectors also shift southwards. This can be seen in the 6 km chart (Fig. 3) though this is not so well brought out as in the lower levels. During A-N, the middle parts of India between 20 and 25° N are least cooled at 1 and 2 km giving rise to the continuance of westerly vectors to the north. The same area gets more cooled during N-M.

April—The main feature is the position of maximum heating during M-A over Bengal and Chota Nagpur area, retarding the wind circulation to the south and accelerating winds to the north (Fig. 7). At and above 3 km this is changed to one of heating increasing from N or NW of India to S or SE, the gradient being shallow over the anticyclonic 'high' over the Deccan (Figs. 8 and 9). A noteworthy feature is the location of the maximum heating at 6 km confined to the land portion of the peninsula thereby showing less heating over the sea areas even at 6 km.

July—Since the geostrophic winds are not attained at 1 km in this month in many parts of this country the isopleths of differential heating were not drawn for this level. During M-A the northeast India is the most heated region at 2 and 3 km with lessening of winds in the afternoon, while in many other parts winds increase in speed (Figs. 13 and 14). The peninsula gets cooler than the rest of India during A-N. The westerly diurnal vectors in Bengal—Chota Nagpur area continue revealing less cooling and a further decrease in wind speed.

October—From 1 to 6 km the major portion of India is having westerly diurnal vectors increasing wind speeds over North India and decreasing the easterly wind speeds in the peninsula (Figs. 17 and 18). The peninsula gets most heated. The gradient of heating is shallow over the centre of the anticyclonic 'high'.

5. Discussion of the diurnal variation of winds in different months

Upper levels (above 3 km)—Excepting July for which reliable data are not available the general picture is one of greater heating from North to South. This should be expected since the sun's mean declinations for these months are less than the latitudes of any place in India. The prevailing westerlies in North India are hence accelerated in the afternoons. In the peninsula, however, where there are the warm anticyclones, the same gradient of diurnal heating is not maintained and this region is either less heated than the surrounding areas or the gradient of heating is very shallow as shown by the dilation of the isopleths. This is also to be expected since the warm anticyclone is likely to inhibit to some extent the convective transport of heat from the surface levels. That there is heating in upper levels by convective transport of heat is also evident by the location of the maximum heated area over the land regions alone of the peninsula at 6 km in April.

Lower levels (1 to 3 km)—In the lower levels the warm anticyclones, situated over the Deccan in January, April and October, continue to be less heated than the surrounding area or the north south gradient is shallow over the region. But there are some marked variations distinct from those of the upper levels. At 1 and 2 km in April the region of maximum heating is over Bengal-Chota Nagpur (22°N) area inspite of the sun's declination being only 8°N. It is well known that this is a region of much thunderstorm activity. In July when the sun's declination is about 17° N the region of maximum heating coincides with the region of much rain and thunderstorms at about 23° N and the gradients of heating are from W to E instead of N to S. Hence the location of maximum diurnal heating does not seem to depend on the sun's declination and other causes have to be looked into for this peculiar variation.

Neglecting the acceleration term in equations (5) and (6) and neglecting variations of density* with time the equation can be written as

$$\frac{1}{\rho}\frac{\partial \dot{p}}{\partial n} = l\dot{V} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (11)$$

which has been also proved approximately $= R\partial\dot{T}/\partial n$ ......(eqn 10). n is same in both the equations since the same vectors are considered (It may be of interest to note that the ratio of $\dot{p}$ to $\dot{T}$ is near about 2 to 3 in the lower levels).

Differentiating the Bjerknes' tendency equation at any level z

$$\frac{\partial p}{\partial t} = \dot{p} = \int_z^{\infty} \nabla_H \cdot (\rho V)\, dz + g\rho w \ldots .(12)$$

—where w is the vertical displacement during ∂t and other symbols have the usual meaning —along the direction of the radius of curvature in (11), and omitting variation in density along the horizontal,

$$\frac{1}{\rho}\frac{\partial \dot{p}}{\partial n} = \frac{g}{\rho}\frac{\partial}{\partial n}\int_z^{\infty} \nabla_H.(\rho V)\, dz + g\frac{\partial w}{\partial n} \ldots .(13)$$

From equations (11) and (13)

$$R\frac{\partial \dot{T}}{\partial n} = \frac{g}{\rho}\frac{\partial}{\partial n}\int_z^{\infty} \nabla_H.(\rho V)\, dz + g\frac{\partial w}{\partial n}$$

Of the two factors in the tendency equation, temperature variation in the vertical can be brought about only by the energy due to vertical movement of the air (Holmboe, Forsythe and Gustin 1945) when it is not completely compensated by divergence. Hence

$$R\ \partial\dot{T}/\partial n = g\ \partial w'/\partial n$$

where w' represents extra vertical movement after compensation for divergence in equation (13), *i.e.*, horizontal variation in diurnal heating is proportional to variation in the extra vertical movement after compensation for divergence. This equation does not take into account the actual heating of the air directly due to radiation and to that extent it is faulty.

The vertical movement of the air depends upon two factors, *viz.*, the diurnal surface heating and the stability conditions of the upper air and if the charts are seen with these in view, the location of maximum heating (vertical rise) and cooling can be easily explained. The increase in diurnal heating from N to S will in general be due to greater surface heating of the south and instability compared to the north of India. During April unstable conditions exist over Bengal-Chota Nagpur area and thus large vertical

*This is approximately true for the following reasons—

$\frac{\partial}{\partial t}\left(\frac{1}{\rho}\frac{\partial p}{\partial x}\right) = \frac{1}{\rho}\frac{\partial \dot{p}}{\partial x} + R\,\frac{\partial p}{\partial x}\frac{\partial}{\partial t}\left(\frac{T}{p}\right)$. The second term on the right hand side becomes

$$R\frac{\partial p}{\partial x}\left(\frac{\dot{T}}{p} - T\,\frac{\dot{p}}{p^2}\right) = \frac{1}{\rho}\frac{\partial p}{\partial x}\left(\frac{\dot{T}}{T} - \frac{\dot{p}}{p}\right) = lv\left(\frac{\dot{T}}{T} - \frac{\dot{p}}{p}\right)$$

Hence $\frac{1}{\rho}\frac{\partial \dot{p}}{\partial x} = l\dot{v} + lv\left(\frac{\dot{p}}{p} - \frac{\dot{T}}{T}\right)$ and similarly $\frac{1}{\rho}\frac{\partial \dot{p}}{\partial y} = -l\dot{u} - lu\left(\frac{\dot{p}}{p} - \frac{\dot{T}}{T}\right)$

$$\therefore \frac{1}{\rho}\frac{\partial \dot{p}}{\partial n} = l\dot{V}\left[1 + \frac{V}{\dot{V}}\left(\frac{\dot{p}}{p} - \frac{\dot{T}}{T}\right)\right]$$

Maximum of $\dot{p}$ is of the order of 4 mb at surface to about 1 mb at 2 km and $\dot{T}$ of the order of 3—4°C at 1 km to 2° at higher levels. Maximum of $V/\dot{V}$ would be 7 and of $(\dot{T}/T - \dot{p}/p)$ would be ·01 and hence the product is negligible. Hence the approximation is justifiable.

displacements can be expected; similarly during July, over Bengal which is a region of convergence.

6. Main features of diurnal variation charts—coastal areas

It is well known that for all antitriptic winds like the land and sea breezes there are return currents above these layers. Such return currents are not often noticeable in India either because of the high extent of the land and sea breezes and the consequent effect of the geostrophic components on the winds, or because the distinct tendencies at such high levels merge with the winds at these levels. What cannot be seen as distinct return currents can be noticed as an opposing vector in the diurnal vector charts.

M-A. The diurnal vectors are westerly and are prominent at 1 km in the west coast during January, April and October. Above this level the vectors are easterly upto 3 km and they can be called return land diurnal vectors. At higher levels they merge with the general trend. In the east coast the return land diurnal vectors begin even at 1 km and at higher levels they merge with the general trend. In July the diurnal vector from the sea side are visible even at 2 km over both the coasts.

A-N. The diurnal vectors are from land regions only in the lower levels and the distinct return sea diurnal vectors have begun at 1 km over both the coasts. Excepting in April, the diurnal vectors in the coastal stations merge with the general trend even at 2 km. In July, however, the diurnal vectors from sea area continue even at 2 km in the east coast, while nothing is known in the west coast for want of observations. At Bhuj and northwards in the west coast, the monsoon is not so strong and hence land diurnal vectors are observable.

N-M. The land diurnal vectors get intensified during N-M. In January and October they are prevalent upto 1 km while in April they extend to 3 km in the west coast. Above these are the return sea diurnal vectors. In July the land diurnal vectors are observable even at 2 km in the east coast. Because of the weak monsoonic effect north of Saurashtra, the return sea diurnal vectors are seen at Bhuj.

7. Discussion of the diurnal variation in coastal area

One interesting fact which can be deduced from the above account is that the effect of differential heating of land and sea is more prominent in the west coast than in the east coast. This is probably due to the proximity of the western ghats to the coast by which temperature differences can be maintained upto high levels. The prominence in the diurnal vectors seem to occur according to the distance of the ghats from the coastal station. Thus Veraval near which there are no mountains has distinct land and sea diurnal vectors only in the lower levels above which the vectors are of the same type as in the adjacent land areas. Cochin and Nagercoil which are farther from the high ghats, also have distinct land and sea diurnal vectors only in the lower levels above which they merge with the general trend. Similar influences of the ghats in the east coast at Visakhapatnam and Gopalpur have also been noticed to some extent in the lower levels. These influences are not seen in the 1 km chart except for Gopalpur in October because of the high ghats being not very near the coast.

Another important feature is that the vertical extent of land and sea effects increase with the sun's declination. It is maximum in July especially in the east coast as seen from diurnal vector charts for 3 km. This means that there is greater heating over the land in spite of the month being cloudy and probably the lapse rates over this region which are greater than the saturated adiabats are favourable for vertical transport of air.

8. Diurnal variation and Climatology

An explanation for the location of maximum heated area in the lower levels over Bengal has already been given in Section 5. If the climatic charts are also seen along with the diurnal vector charts it will be apparent that instability phenomena, which occur more often due to surface heating, occur at not all the places of maximum heating, but at places wherever the diurnal vectors oppose the winds. This is easily explainable; for the 'highs' intensify when they get heated resulting in an increase in wind and divergence while the 'lows' diminish in intensity, resulting in convergence and decrease in winds.

Thus all the regions south of the maximum heated area over Bengal-Chota Nagpur in April, Bengal-Chota Nagpur area in July (Blanford 1886) and southern parts of the peninsula in October (Eliot 1898 and Venkiteshwaran 1933) get heat thunderstorms and rain towards afternoon. During July in many parts of the rest of India the winds increase producing more stability in the afternoons and it is well known that the monsoon is generally active in those regions during the nights and the mornings.

Regions in North Bengal and Assam also get thunderstorms in April but generally in the nights and mornings when winds have less speed. These thunderstorms are due to the katabatic flow of moist air from the Assam hills and are not due to heating (Ind. met. Dep. Tech. Note 1944). In fact there is a complete absence of thunderstorms during the afternoon when winds are strong. Similarly in October afternoon winds in Madras increase in the lower levels and it is known that rainfall occurs more in the nights and mornings (Krishnaswamy 1952) when wind speeds are less.

Thus the diurnal variation of upper winds is not an isolated phenomenon but closely connected with the general circulation of the atmosphere. It introduces the time factor in upper air climatology and the associated weather phenomena.

9. Conclusion

(1) Diurnal variations of winds are known to occur upto 6 km over India

(2) Though these variations are partly due to diffusion at the lower levels the main cause is the differential heating of the air layers

(3) The diurnal heating is caused by the differential vertical ascent of the air column whose intensity will depend on the surface heating of the air and instability conditions of the atmosphere. The measure of this differential heating is proportional to the extra energy due to vertical ascents after compensation for divergence

(4) Diurnal heating increases from north to south in the upper levels during all the months

(5) Local conditions, such as instability, control diurnal variation in the lower levels

(6) Diurnal variation controls the general climatology of the regions and introduces the time element in producing weather

(7) The effect of differential heating of land and sea is seen upto as high altitudes as 6 km in April and 3 km in other months. The distinct effects of land and sea heating are more over the west coast than over the east coast.

10. Acknowledgements

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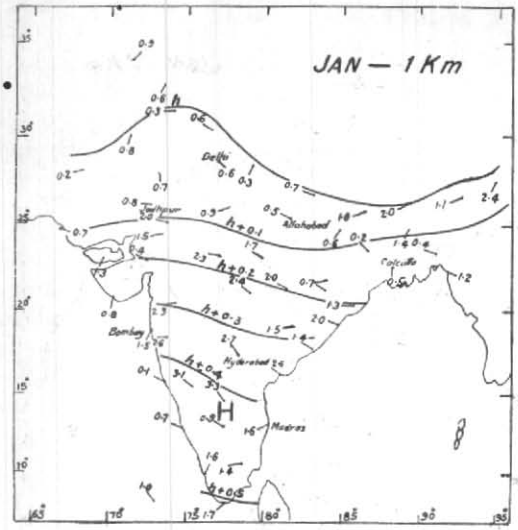

Fig. 1. Diurnal vectors and heating from M—A

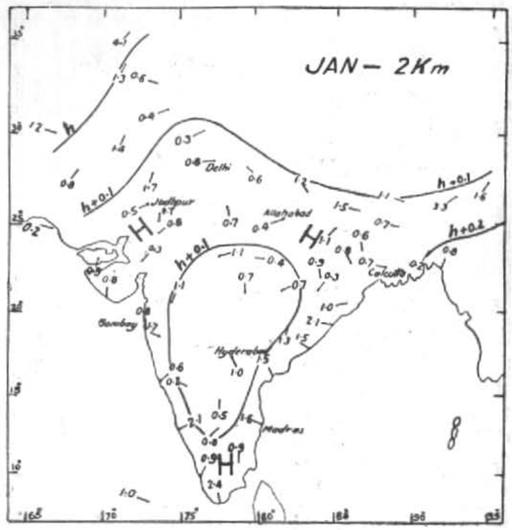

Fig. 2. Diurnal vectors and heating from M—A

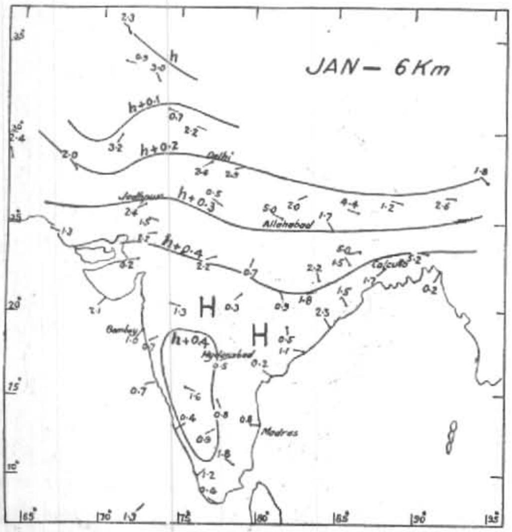

Fig. 3. Diurnal vectors and heating from M—A

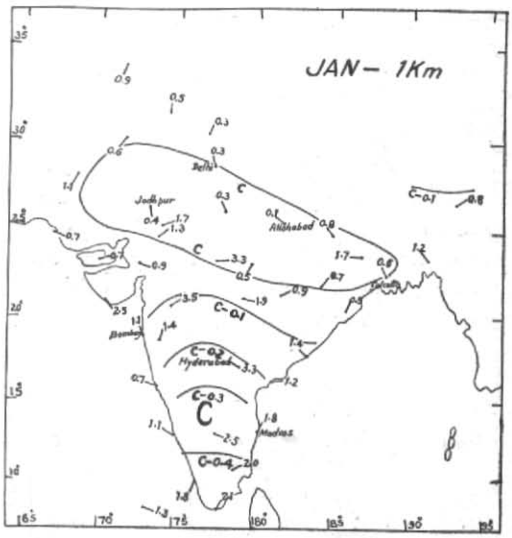

Fig. 4. Diurnal vectors and cooling from A—N

NOTE : The arrows indicate the direction of the diurnal vectors or resultant winds and the figures at the end of the arrows indicate the magnitude of the vectors in mps. H indicates the area of maximum heating and C of maximum cooling

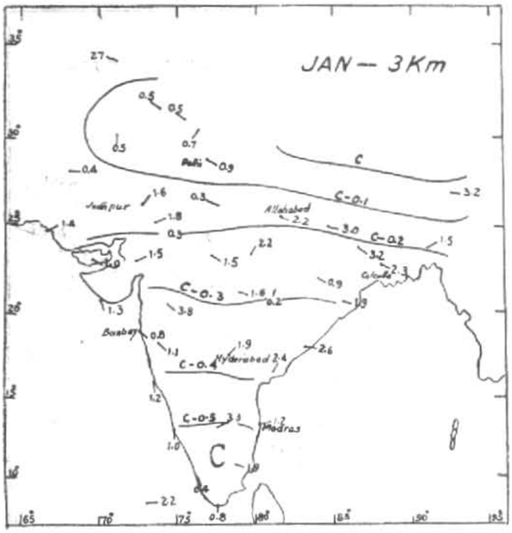

Fig. 5. Diurnal vectors and cooling from A—N

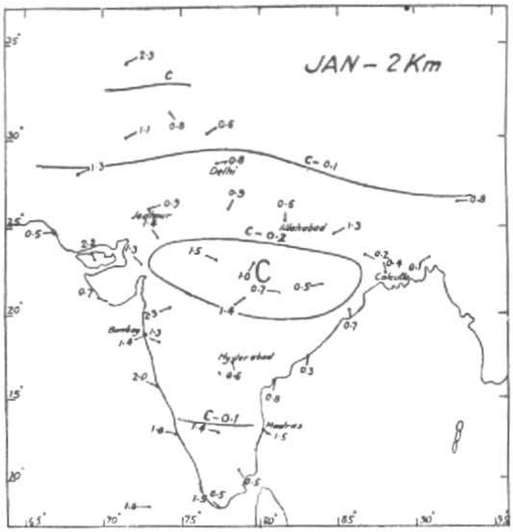

Fig. 6. Diurnal vectors and cooling from N—M

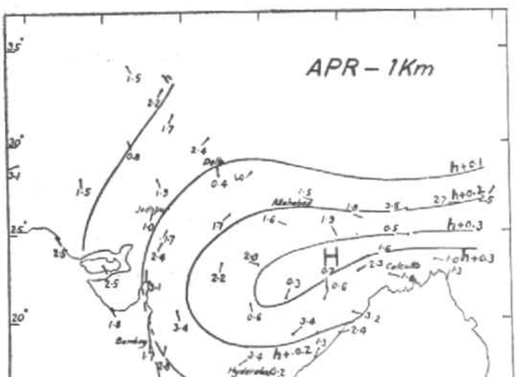

Fig. 7. Diurnal vectors and heating from M—A

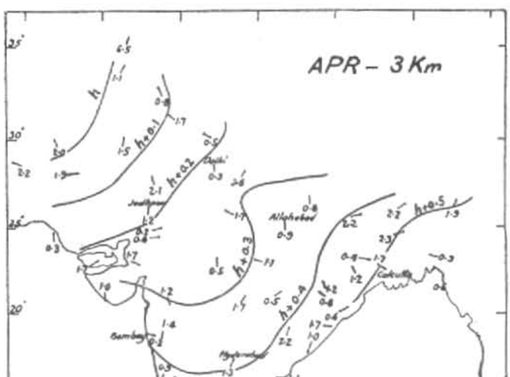

Fig. 8. Diurnal vectors and heating from M—A

NOTE: The arrows indicate the direction of the diurnal vectors or resultant winds and the figures at the end of the arrows indicate the magnitude of the vectors in mps. H indicates the area of maximum heating and C of maximum cooling

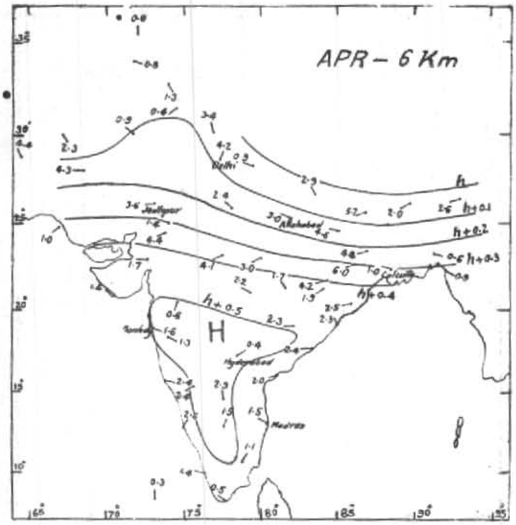

Fig. 9. Diurnal vectors and heating from M—A

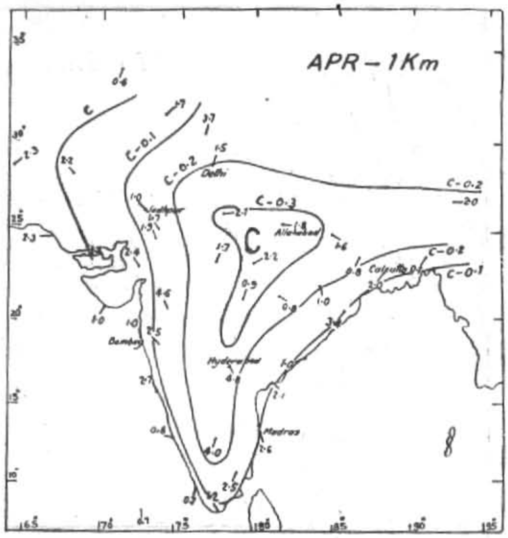

Fig. 10. Diurnal vectors and cooling from A—N

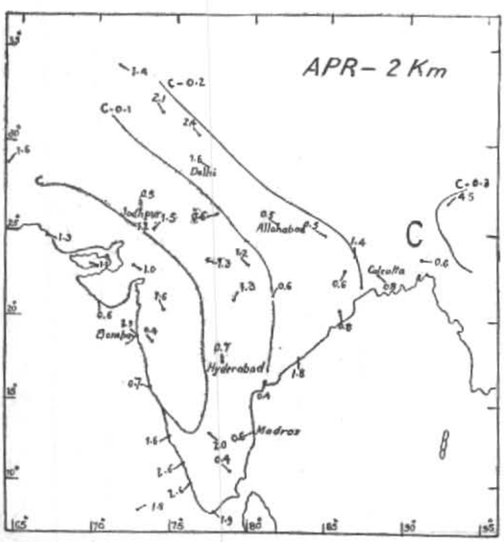

Fig. 11. Diurnal vectors and cooling from A—N

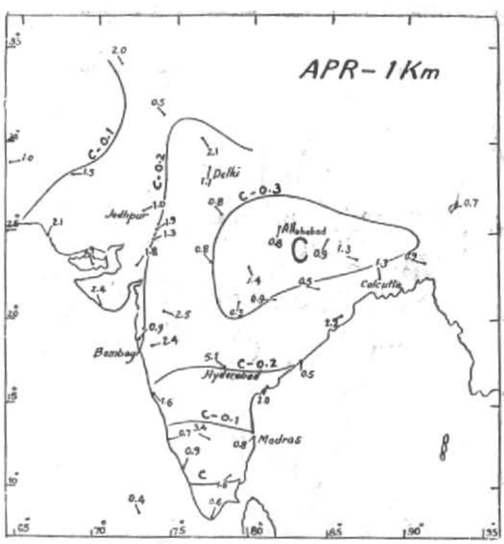

Fig. 12. Diurnal vectors and cooling from N—M

NOTE : The arrows indicate the direction of the diurnal vectors or resultant winds and the figures at the end of the arrows indicate the magnitude of the vectors in mps. H indicates the area of maximum heating and C of maximum cooling

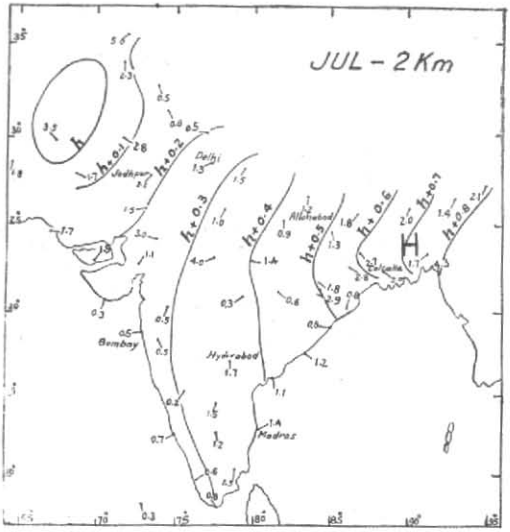

Fig. 13. Diurnal vectors and heating from M—A

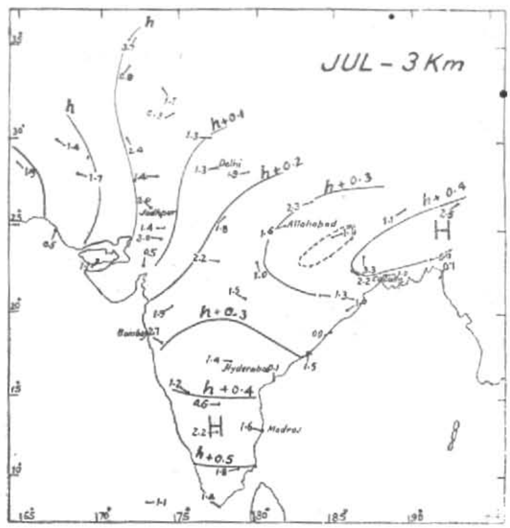

Fig. 14. Diurnal vectors and heating from M—A

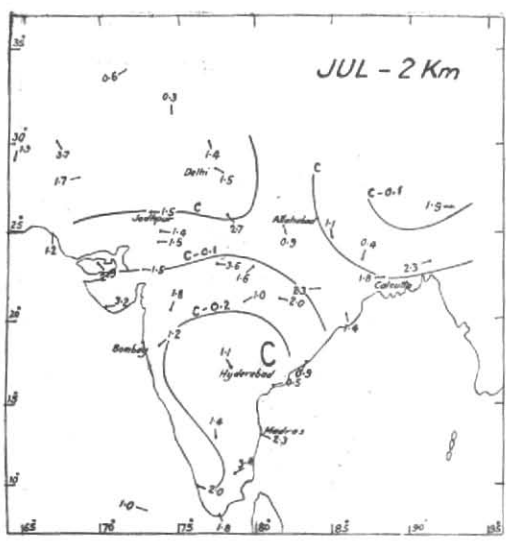

Fig. 15. Diurnal vectors and cooling from A—N

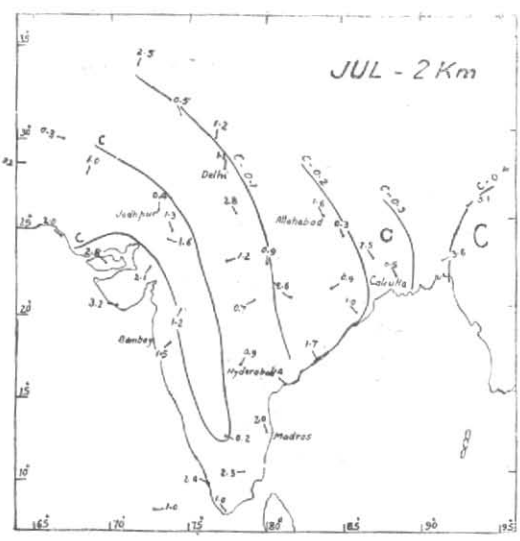

Fig. 16. Diurnal vectors and cooling from N—M

NOTE : The arrows indicate the direction of the diurnal vectors or resultant winds and the figures at the end of the arrows indicate the magnitude of the vectors in mps. H indicates the area of maximum heating and C of minimum cooling

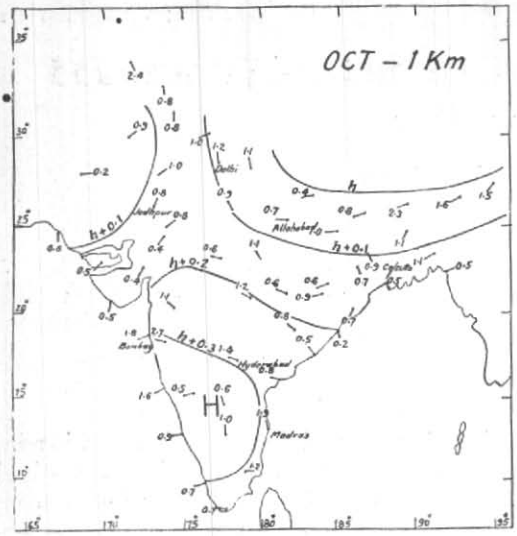

Fig. 17. Diurnal vectors and heating from M—A

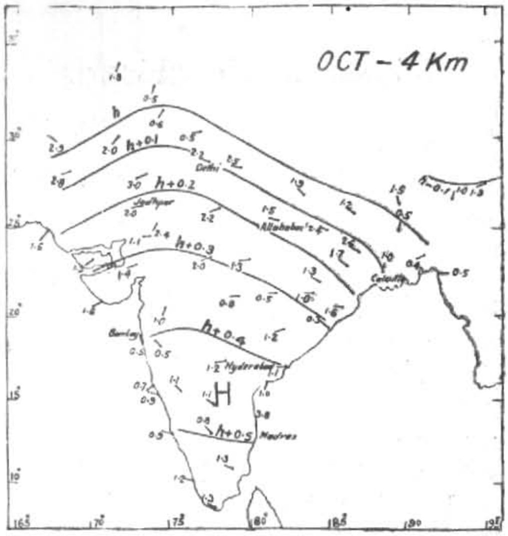

Fig. 18. Diurnal vectors and heating from M—A

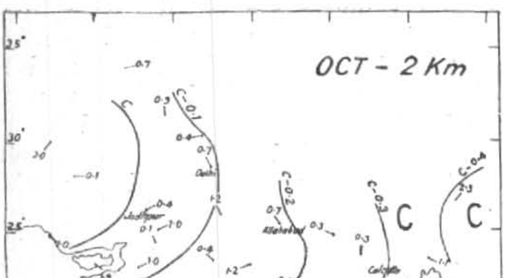

Fig. 19. Diurnal vectors and cooling from A—N

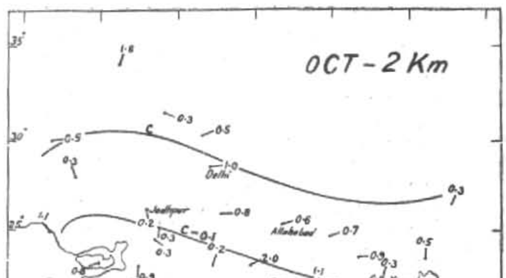

Fig. 20. Diurnal vectors and cooling from N—M

NOTE : The arrows indicate the direction of the diurnal vectors or resultant winds and the figures at the end of the arrows indicate the magnitude of the vectors in mps. H indicates the area of maximum heating and C of minimum cooling