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Diurnal variation of Upper Air Temperatures over India

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ABSTRACT. A statistical study of the diurnal variation of upper air temperatures over India is made utilising radiosonde data of four stations for four standard hours of the day and covering four representative months. A marked difference in the pattern of diurnal variation is found between a continental station like New Delhi and the three coastal stations—Bombay, Calcutta and Madras. Significant diurnal variations are found over New Delhi only upto 1 to 3 km depending on the season, the mean daily range being about 1 to 2° C in most cases. On the other hand, diurnal variations at the coastal stations extend higher upto 4-6 km, the amplitudes being of the same order. Apparent diurnal variations found at still higher levels are probably due to inadequacy of radiation corrections. Nocturnal cooling of the atmosphere between 600 and 400-mb levels is found to be in the range of 0·1 to 0·15° per hour.

1. Introduction

Experimental determinations of the diurnal variation of upper air temperatures provide valuable information on (1) the magnitude of the heating of the free atmosphere by direct absorption of solar radiation during the day, (2) the magnitude of the radiative cooling of the atmosphere during the night and (3) the height upto which the surface diurnal temperature wave is propagated upwards due to eddy conduction and turbulence. The determination is a somewhat difficult problem. Firstly, the magnitude of the true diurnal heating or cooling between about 3 km and the tropopause is small and sometimes the radiosonde instruments have probable errors of the same order. Secondly, the problem of applying radiation corrections to upper air temperatures observed with radiosonde instruments under varying conditions of the atmosphere, is a very difficult one. The general practice is to determine corrections by simulated laboratory experiments with certain assumed standard conditions and to apply them to the actual flight data. The only variable factor made use of in the actual application of radiation correction is the solar elevation angle. This assumption is not always justified because the magnitude of correction would also depend on varying factors, *e.g.*, cloud cover, the swinging of the instrument, etc.

Studies on diurnal variation of upper air temperatures have been made mainly by two methods. In the first method, special radiosonde observations are taken at short intervals of time, say 2 or 3 hours for a limited number of days and the data analysed. In the second method, a statistical analysis of routine radiosonde data pertaining to different synoptic hours covering both day and night is made and appropriate conclusions drawn. Among the first category may be mentioned the work of Riehl (1947) who investigated the diurnal variation of upper air temperatures over the Caribbean Sea. By analysing special radiosonde ascents taken at three-hourly intervals taking into account approximate corrections for solar radiation effects (these corrections were later found to be underestimated) he found diurnal temperature ranges of about 1 to 2°C upto 6 km and 2 to 3°C aloft upto 16 km. The maximum rise in the temperature was found to occur with the rise of solar elevation angle and the maximum fall with the decrease of solar elevation. Riehl found two distinct effects, *viz.*, (1) an effect due to turbulent exchange of heat with the ground which was confined to a layer of about 1·5 km and (2) an effect due to the direct absorption of solar energy by the atmosphere during the day and radiation during the night. The latter effect was seen to extend throughout the troposphere. It appears from the evidence gathered in subsequent years that the radiation corrections applied by Riehl were underestimated and hence the real magnitude of the warming during day was over estimated. Following the second method, Kay (1951) analysed upper air temperature data of five stations in U. K. covering four synoptic hours and extending over a period of two years. He found large apparent temperature rise of the order of 0·4°C/hour during the day for levels between 150 and 80 mb from sunrise to noon and a fall of similar order from noon to sunset. From various physical considerations, however, he concluded that a large part of the apparent diurnal rise of temperature could be due to direct absorption of solar radiation by the thermometer element. Later, Scrase (1954) who determined the radiation errors of the British radiosonde concluded that these errors could account for the whole of the observed differences between day and night observations upto 15 km. He also estimated the diurnal range at 20 km to be 1·5°C. Jordan (1960) has drawn attention to the importance of radiation correction and demonstrated that the larger values of diurnal variation of temperature at 200-mb level over the tropical Pacific Ocean observed in 1951, *viz*., 0.9 to 1·9°C when compared to those in 1956, *viz*., 0·0 to 0.8°C could be accounted for by applying proper radiation corrections to the instruments used in the two series. It is of interest to note that the mean diurnal range of temperature found at 200-mb level over the tropical Pacific was less than 0·7°C for all the twelve months of the year. Diurnal variation of temperatures in the lower stratosphere has been discussed by Chiu (1959) who estimated the diurnal variation at 200-mb level to be as low as 0·15 to 0·2°C over the United States. Teweles and Finger (1960) after a thorough study of daytime and night-time radiosonde data of the United States of America have come to the very important conclusion that the true diurnal temperature change in the free atmosphere is very small. They have even recommended 'that every country adopt temperature corrections which at least upto the 25-mb surface reduce the average temperature between day and night soundings to less than 1°C and to less than 2°C at the 10 mb surface".

Studies in India have been made by Pant (1960) by comparing the 00 and 12 GMT synoptic radiosonde data for the period 1957-1959 with the 03 and 15 GMT data of a different period, *viz*., 1955-1956. He found large diurnal variations of 1·5 to 4·5°C at 300-mb level. As the author has himself pointed out in this paper, the comparison is open to the objection that the period covered by the observations is not the same. The year to year variations in the mean temperature of the atmosphere have not been taken into consideration and consequently the results may be in some error. Recently Dhar and Mitra (1962) have analysed radiosonde data obtained at four different hours at New Delhi for a limited period of four days. They have come to the conclusion that the diurnal variation extends to even 12 km, where the magnitude of range is 8 to 10°C. Such high values have not been reported elsewhere. The authors have further reached the rather surprising conclusion that at high levels the temperatures are distinctly lower during day than during the night. It appears probable that these anomalous results might have been due to (1) the extremely few cases studied, (2) errors in the instruments and (3) synoptic changes not related to diurnal effects. (During the period covered by the observations the tropopause breakline was close to New Delhi.)

As the magnitude of the diurnal effect is small, there is a limit to the reliability with which its measurement can be made and this limit is set by the overall accuracy of the instrument. A statistical analysis making use of a fairly homogeneous set of observations may alone reveal real diurnal effects. The present study has been undertaken with this aspect in view.

2. Data utilised

In India, synoptic aerological observations are recorded as a routine for two hours during the day, *viz.*, 00 and 12 GMT. For a study of the diurnal variation of upper air temperatures, two extra radiosonde ascents per day were specially arranged at the four stations, New Delhi (28° 35′ N, 77° 12′ E), Calcutta (22° 39′ N, 88° 22′ E), Bombay (19° 04′ N, 72° 06′ E) and Madras (13° 00′ N, 80° 11′ E) for four representative months of the year. These special observations at 06 and 18 GMT together with the two routine synoptic observations provided a series of four observations per day separated by 6-hourly intervals. Such data were made available for July and October in 1960 and January and April in 1961. The radiosonde instruments used at New Delhi, Calcutta and Bombay were the India Meteorological Department Chronometric type and those at Madras the Fan type. Radiation corrections appropriate to the solar angle at the hour of observation were incorporated for the 00, 06 and 12 GMT observations for levels 400 mb and higher. All numerical computations were checked and a few doubtful values which could be attributed to instrumental defects were rejected. Tabulation of temperatures were made for 900, 850, 800, 700, 600, 500, 400, 300, 250, 200, 150 and 100-mb levels. Monthly means and standard deviations were worked out in all cases wherein at least fifteen individual observations were available for a particular level. As the data for 150 and 100-mb levels were not quite reliable and as the number of observations were small, they have been left out of consideration in this paper.

Generally, over 90 per cent of the ascents reached the 400-mb level, 80 to 90 per cent reached the 300 mb level and 55—70 per cent reached the 200-mb level. Table 1 gives the mean number of ascents (taking all the four ascents per day into consideration) that reached 850, 400, 300 and 200-mb levels at the four stations in the four months. In the same table, the standard deviations of temperatures at the different levels have also been given. These have been given in the form of ranges, taking into account actual standard deviations for the four different hours.

3. Statistical treatment of the observed data

The change in the mean temperature $\triangle T$ for each level from one observation to the next, *viz.*, 00 to 06, 06 to 12, 12 to 18 and 18 to 00 were tabulated. These may be designated as $T_{06}—T_{00}$, $T_{12}—T_{06}$, $T_{18}—T_{12}$, and $T_{00}—T_{18}$. In addition to these, the differences $T_{12}—T_{00}$ and $T_{06}—T_{18}$ were also tabulated to obtain the 12-hourly changes in the mean temperatures. The values in respect of the four stations are contained in Table 2. In the interpretation of the results a statistical method was adopted to determine whether a particular value, say $\overline{T_{06}}—\overline{T_{00}}$ is significant or not. This was necessary in view of the possibility that the diurnal variation of temperature might at some level become comparable with the random errors of observation. Let $\overline{T}_{00}$ and $\overline{T}_{06}$ be the mean temperatures at any level for a station based on N_{00} and N_{06} number of observations respectively and σ_{00} and σ_{06} be the respective standard variations of the two series. As we are concerned with determining the significance of a difference $\overline{T}_{06}—\overline{T}_{00}$ the standard error of this difference has to be evaluated. This parameter σ_d is given by the relation

$$\sigma_d = \sqrt{\frac{(N_{06} - 1)\,\sigma^2_{06} + (N_{00} - 1)\,\sigma^2_{00}}{N_{06} + N_{00} - 2}}$$

The Students' t - test of significance was applied in respect of the two series of temperatures one pertaining to 06 GMT and the other to 00 GMT. In accordance with the standard practice, $\overline{T_{06}}—\overline{T_{00}}$ was taken as significant only when t given by the relation—

$$t = \frac{\overline{T_{06}}—\overline{T_{00}}}{\sigma_d \sqrt{\dfrac{N_{00} + N_{06}}{N_{00}\,N_{06}}}}$$

exceeded the limiting value corresponding to 5% significance limit as read from Fisher's Tables. Similarly all other pairs of mean

TABLE 1

Number of radiosonde ascents (mean of four synoptic hours) that reached different levels as well as the standard deviations of the observed temperatures (given in brackets)

	850 mb	400 mb	300 mb	200 mb
		NEW DELHI		
JAN	31 (2·9—3·6)	31 (2·3—3·4)	29 (3·6—4·1)	25 (3·8—4·8)
APR	30 (3·1—3·3)	30 (2·5—3·1)	29 (2·9—4·4)	26 (3·9—5·6)
JUL	31 (2·4—2·6)	30 (1·5—2·2)	27 (2·0—2·3)	24 (2·0—3·0)
OCT	30 (2·3—3·1)	30 (3·7—4·2)	29 (3·8—4·7)	26 (3·3—4·3)
		CALCUTTA		
JAN	25 (1·8—2·7)	23 (2·7—3·7)	19 (3·1—4·6)	17 (2·3—4·3)
APR	30 (2·9—3·3)	29 (3·4—4·1)	25 (3·5—5·1)	21 (3·2—4·5)
JUL	31 (1·5—2·1)	29 (1·9—2·4)	23 (2·1—2·9)	17 (2·6—3·9)
OCT	30 (2·1—2·6)	29 (2·0—3·1)	25 (2·8—3·4)	21 (3·0—3·4)
		BOMBAY		
JAN	30 (2·3—3·1)	29 (2·7—3·1)	29 (2·9—3·5)	23 (2·1—3·7)
APR	30 (1·8—2·5)	30 (2·1—2·7)	27 (2·6—3·2)	23 (2·5—3·8)
JUL	31 (1·4—1·7)	29 (2·1—2·3)	20 (2·1—2·8)	15 (2·8—3·4)
OCT	31 (1·6—2·5)	31 (2·2—2·8)	28 (2·0—3·4)	23 (2·1—4·1)
		MADRAS		
JAN	31 (1·8—2·5)	30 (2·4—3·0)	29 (2·5—3·1)	23 (2·6—3·5)
APR	29 (2·3—2·5)	28 (2·1—2·5)	27 (2·3—3·9)	21 (2·8—4·1)
JUL	31 (1·6—2·2)	28 (2·6—3·5)	26 (2·6—4·1)	19 (3·8—5·4)
OCT	30 (1·9—2·0)	30 (2·1—2·7)	26 (2·8—4·3)	19 (3·5—5·4)

TABLE 2

PPP	$T_{06}-T_{00}$	$T_{12}-T_{06}$	$T_{18}-T_{12}$	$T_{00}-T_{18}$	$T_{12}-T_{00}$	$T_{06}-T_{18}$	$T_{06}-T_{00}$	$T_{12}-T_{06}$	$T_{18}-T_{12}$	$T_{00}-T_{18}$	$T_{12}-T_{00}$	$T_{06}-T_{18}$
						NEW DELHI						
	January						April					
900	+0·7	+0·3	—0·2	—0·8	+1·0	—0·1	+0·6	+2·1*	—1·3	—1·4*	+2·7*	+0·8
850	+0·6	—0·2	—0·3	—0·1	+0·4	+0·5	+0·5	+1·0	—0·7	—0·8	+1·5	—0·3
800	+0·7	+0·1	—0·2	—0·6	+0·8	+0·1	+0·3	+0·7	—0·6	—0·4	+1·0	—0·1
700	+0·7	—0·3	0·0	—0·4	+0·4	+0·3	+0·9	—0·6	—0·2	—0·1	+0·3	+0·8
600	0·0	+0·6	+0·3	—0·9	+0·6	—0·9	+0·6	—0·1	—0·3	—0·2	+0·5	+0·4
500	+0·7	+0·5	—0·2	—1·0	+1·2	—0·3	+0·8	+0·2	—1·3	+0·3	+1·0	+1·1
400	+0·7	+0·2	—0·3	—0·6	+0·9	+0·1	—0·1	+0·6	—0·6	+0·1	+0·5	0·0
300	+0·9	—0·5	—0·8	+0·4	+0·4	+1·3	—0·6	+1·0	—1·2	+0·8	+0·4	+0·2
200	+1·2	—1·5	0·0	+0·3	—0·3	+1·5	—1·2	+1·3	—2·1	+2·0	+0·1	+0·8
	July						October					
900	+0·7	+2·3*	—1·5*	—1·5*	+3·0*	—0·8	+0·6	+1·1	—0·5	—1·2	+1·7*	—0·6
850	0·0	+2·0*	—1·0	—1·0	+2·0*	—1·0	+0·8	+0·6	—0·4	—1·0	+1·4*	—0·2
800	+0·2	+0·9	—0·8	—0·3	+1·1*	—0·1	+0·9	+0·5	—0·4	—1·0	+1·4*	—0·1
700	+0·2	+0·5	—0·7	0·0	+0·7	+0·2	+1·1	+0·5	—0·6	—1·0	+1·6*	+0·1
600	+0·5	+0·3	—0·5	—0·3	+0·8	+0·2	+1·8	—0·1	—0·4	—1·3	+1·7	+0·5
500	+0·9	+0·4	—0·7	—0·6	+1·3*	+0·3	+0·6	+0·9	—0·8	—0·7	+1·5	—0·1
400	+0·7	+0·3	—0·5	—0·5	+1·0	+0·2	+1·2	+0·4	—0·5	—1·1	+1·6	+0·1
300	—0·5	+0·9	—0·3	—0·1	+0·4	—0·6	+0·2	+1·2	—0·1	—1·3	+1·4	—1·1
200	—0·4	+0·2	—0·8	+1·0	—0·2	+0·6	0·0	+0·8	—0·2	—0·6	+0·8	—0·6
						CALCUTTA						
	January						April					
900	+2·5*	+0·2	—2·3*	—0·4	+2·7*	+2·1*	+1·5	+2·0*	—1·8*	—1·7*	+3·5*	—0·2
850	+2·1*	+0·2	—1·6*	—0·7	+2·3*	+1·4*	+1·0	+1·6*	—0·8	—1·8*	+2·6*	—0·8
800	+1·7*	—0·6	—1·4*	+0·3	+1·1	+2·0*	+0·9	+1·3	—0·3	—1·9*	+2·2*	—1·0
700	+2·0*	—0·3	—1·3*	+0·2	+1·7*	+2·2*	+0·7	+0·9	0·0	—1·6*	+1·6*	—0·9
600	+1·9*	+0·1	—1·2	—0·8	+2·0*	+1·1	+0·2	+1·7	—0·6	—1·3	+1·9*	—1·1
500	+2·2*	—0·4	—1·3	—0·5	+1·8*	+1·7*	0·0	+1·1	—0·2	—0·9	+1·1	—0·9
400	+2·6*	—1·5	—1·0	—0·1	+1·1	+2·5*	—0·4	+1·5	+0·6	—1·7	+1·1	—2·1
300	+1·3	—0·2	—0·8	—0·3	+1·1	+1·0	+0·3	+1·0	+0·5	—1·8	+1·3	—1·5
200	+3·1*	—1·7	+0·2	—1·6	+1·4	+1·5	0·0	+1·1	+0·6	—1·7	+1·1	—1·7

TABLE 2 (*contd*)

PPP	$T_{06}-T_{00}$	$T_{12}-T_{06}$	$T_{18}-T_{12}$	$T_{00}-T_{18}$	$T_{12}-T_{00}$	$T_{06}-T_{18}$	$T_{06}-T_{00}$	$T_{12}-T_{06}$	$T_{18}-T_{12}$	$T_{00}-T_{18}$	$T_{12}-T_{00}$	$T_{06}-T_{18}$
CALCUTTA (*contd*)												
	July						**October**					
900	+0·9*	+0·1	—0·6	—0·4	—1·0*	+0·5	—1·0*	+0·5	—1·6*	+0·1	+1·5*	+1·1*
850	+0·7	+0·1	—0·7	—0·1	+0·8*	+0·6	+1·4*	+0·1	—1·0	—0·5	+1·5*	+0·9
800	+0·8	—0·1	—0·7	0·0	—0·7*	+0·8	+1·3*	+0·2	—0·8	—0·7	—1·5*	+0·6
700	+0·9*	+0·1	—0·8	—0·2	—1·0*	+0·7	—1·8*	0·0	—0·5	—1·3*	—1·8*	+0·5
600	+0·9*	0·0	—0·9	0·0	+0·9*	+0·9*	—1·0	—0·1	—0·5	—0·4	—0·9	+0·6
500	+1·1*	—0·3	—0·9	—0·1	+0·8	+1·2*	+0·8	—0·2	—1·3	+0·7	+0·6	+1·5*
400	+1·4*	—1·6*	—0·2	+0·4	—0·2	+1·8*	+0·3	—0·3	—0·8	+0·8	0·0	+1·1
300	+1·4	—0·8	—0·1	—0·5	+0·6	+0·9	—0·6	—0·1	—0·2	+0·9	—0·7	+0·3
200	+0·8	—0·8	—1·0	+1·0	0·0	+1·8	+0·5	0·0	—1·6	+1·1	+0·5	+1·6
BOMBAY												
	January						**April**					
900	+1·6*	+0·5	—1·1	—1·0	+2·1*	+0·6	+1·2*	+2·0*	—0·5	—2·7*	+3·2*	—1·5*
850	+1·3*	+0·4	—0·5	—1·2	+1·7*	+0·1	+1·9*	+1·0	—0·4	—1·5*	+1·9*	—0·6
800	+2·1*	—0·6	—0·6	—0·9	+1·5*	+1·2*	+0·4	+1·0	—0·1	—1·3*	+1·4*	—0·9
700	+2·9*	—1·8*	—0·8	—0·3	+1·1*	+2·6*	+0·6	+0·9	—0·7	—0·8	+1·5*	—0·2
600	+2·2*	—1·2*	—1·3*	+0·3	+1·0*	+2·5*	+1·2	+0·9	—1·2*	—0·9	+2·1*	+0·3
500	+2·1*	—0·8	—1·1	—0·2	+1·3*	+1·9*	+1·8*	+0·6	—1·2*	—1·2*	+2·4*	+0·6
400	+2·4*	—0·6	—2·3*	+0·5	+1·8*	+2·9*	+1·4*	+0·9	—0·9	—1·4*	+2·3*	0·0
300	+2·3*	—1·1	—1·5	+0·3	+1·2	+2·6*	+1·8*	+0·3	—1·6	—0·5	+2·1*	+1·3
200	+2·9*	—0·3	—1·3	—1·3	+2·6*	+1·6*	+2·4*	+0·2	—2·5*	—0·1	+2·6*	+2·3*
	July						**October**					
900	+0·5	+0·3	—1·0*	+0·2	+0·8*	+0·7	+1·1*	+0·7	—1·2	—0·6	+1·8*	+0·5
850	+0·6	+0·2	—1·0*	+0·2	+0·8*	+0·8	+1·5*	0·0	—0·9	—0·6	+1·5*	+0·9
800	+0·7	+0·2	—0·8*	—0·1	+0·9*	+0·6	+1·6*	0·0	—0·9	—0·7	+1·6*	+0·9
700	+1·2*	—0·7	—0·9*	+0·4	+0·5	+1·6*	+1·6*	+0·7	—2·2*	—0·1	+2·3*	+1·5*
600	+1·4*	—0·4	—1·1*	—0·1	+1·0*	+1·5*	+2·0*	—1·0	—0·5	—0·5	+1·0*	+1·5*
500	+1·7*	—0·9	—1·2*	—0·4	+0·8*	+2·1*	+2·6*	—1·5*	—0·4	—0·7	+1·1*	+1·9*
400	+1·4*	+0·1	—2·1*	+0·6	+1·5*	+2·0*	+2·7*	—1·3*	—0·9	—0·5	+1·4*	+2·2*
300	+0·7	+0·8	—1·8*	+0·3	+1·5	+1·0	+1·8*	+0·2	—2·5*	+0·5	+2·0*	+2·3*
200	—	—	—	—	+2·0	—	+1·1	+0·7	—2·6*	+0·8	+1·8	+1·9

TABLE 2 (*contd*)

MADRAS

PPP	T_{06}—T_{00}	T_{12}—T_{06}	T_{18}—T_{12}	T_{00}—T_{18}	T_{12}—T_{00}	T_{06}—T_{18}	T_{06}—T_{00}	T_{12}—T_{06}	T_{18}—T_{12}	T_{00}—T_{18}	T_{12}—T_{00}	T_{06}—T_{18}
	January						**April**					
900	+2·1*	—1·4*	—0·2	—0·5	+0·7	+1·6*	+0·7	+1·7*	+0·1	—2·5*	+2·4*	—1·8*
850	+1·3*	—0·5	—0·2	—0·6	+0·8	+0·7	+0·1	+1·1	+0·1	—1·3*	+1·2*	—1·2*
800	+1·4*	—1·0	—0·2	—0·2	+0·4	+1·2*	+0·4	+0·5	—0·5	—0·4	+0·9	0·0
700	+1·7*	—1·0	—0·6	—0·1	+0·7	+1·6*	+1·5*	—0·9	—1·3*	+0·7	+0·6	+2·2*
600	+1·7*	—1·5*	0·0	—0·2	+0·2	+1·5*	+1·3*	—1·1	—1·0	+0·8	+0·2	+2·1*
500	+2·2*	—2·0*	0·0	—0·2	+0·2	+2·0*	+1·6*	—0·7	—1·6*	+0·7	+0·9	+2·3*
400	+1·8*	—1·4*	—0·5	+0·1	+0·4	+1·9*	+0·1	+0·5	—1·4*	+0·8	+0·6	+0·9
300	+0·9	—0·9	—0·1	+0·1	0·0	+1·0	—0·8	+1·5	—1·0	+0·3	+0·7	—0·5
200	—0·7	+1·2	—0·7	+0·2	+0·5	—0·5	—0·9	—3·4*	—3·8	+1·3	+2·5	+0·4
	July						**October**					
900	+1·3*	+1·1*	—2·0*	—0·4	+2·4*	+0·9	+1·0*	+0·3	—0·9*	—0·4	+1·3*	+0·6
850	+1·0*	+0·1	—1·3*	+0·2	+1·1*	+1·2*	+0·8	—0·4	—0·1	—0·3	+0·4	+0·5
800	+1·2*	—0·6	—0·6	0·0	+0·6	+1·2*	+1·6*	—0·6	—0·6	—0·4	+1·0*	+1·2*
700	+1·3*	—0·6	—0·5	—0·2	+0·7	+1·1	+2·6*	—0·8*	—0·4	—1·4*	+1·8*	+1·2*
600	+1·4*	—0·5	—1·1	+0·2	+0·9*	+1·6*	+1·8*	—1·4*	—0·1	—0·3	+0·4	+1·5*
500	+2·2*	—0·5	—1·9*	+0·2	+1·7*	+2·4*	+2·3*	—1·5*	—0·4	—0·4	+0·8	+1·9*
400	+0·5	+0·4	—2·4*	+1·5	+0·9	+2·0	+0·9	—0·7	+0·2	—0·4	+0·2	+0·5
300	+2·2	—1·2	—1·0	0·0	+1·0	+2·2*	+2·7*	—1·9	—0·4	—0·4	+0·8	+2·3*
200	+2·7	—0·4	—2·2	—0·1	+2·3	+2·6	+2·6	—1,8	—0·4	—0·4	+0·8	+2·2

values were subjected to this significance test. Those differences which were found significant have been marked by an asterisk in the tables.

4. Discussion of the results

The salient features of the results in respect of the four stations are given below stationwise.

New Delhi—In January, it is of interest to find that significant diurnal variation does not extend even upto the 900-mb level (1 km). Probably the stable air characteristic of winter season prevents the upward propagation of the surface temperature wave. In April, the 900-mb level temperature has a fluctuation of 2—3°C during the course of the day, the maximum temperature probably occurring near about 12 GMT or local evening. In July and October the effect of the diurnal variation extends higher upto 800—700 mb levels (2 to 3 km) probably due to the greater instability of the air and the consequent vertical mixing. The amplitude of the variation is about 1 to 1·5°C only. No significant variation is observed at levels above 700 mb in any of the four months.

Calcutta—In marked contrast with New Delhi, the diurnal variation in January is seen to extend as high as the 400-mb level. It is not known what part of the observed significant variation is ascribable to uncertainties in the radiation correction. The amplitude of the variation is seen to be about 2·0° to 2·5° C and part of this is probably real. Calcutta, located on the coast is subject to the diurnal effects of land and sea breezes. The local solenoidal fields generated by horizontal temperature gradients near the coast are apparently effective in causing a more vigorous diurnal mixing of air than at New Delhi. In April, the variation of 2 to 3°C is observed at 850-mb level, 1·5 to 2·0°C aloft upto 600-mb level and no variation aloft. The reason for the diurnal variation extending to a higher altitude in January, than in April is not clear. In July significant variation is seen to extend upto 400-mb level though the amplitude is only about 1·0 to 1·5° C. Convective activity during the monsoon season is probably also effective in maintaining a diurnal variation upto this height. In October, variations of the order of 1·5 to 2·0° C extend upto the 700-mb level only.

Bombay—As at Calcutta, significant diurnal variations are observed in January at Bombay upto even greater heights, *viz.*, the 200-mb level. Here again some doubt is cast on the genuineness of the variations. The constant value of about 2·0 to 2·5°C observed at all levels from 700 mb to 200 mb is probably indicative of the inadequacy of the radiation corrections that have been applied. This situation is similar to that observed by Riehl (1947) over the tropical Caribbean Sea. Such variations are seen in all the four months at Bombay, the observed amplitude being smaller in April and July. In the absence of any reliable correction for radiation error, it may be assumed that a part of the observed diurnal variation is real.

Madras—Significant diurnal variations are observed at Madras during all the four months upto about 500-mb level. The observed amplitude of diurnal variation generally increases from about 1·5°C at 700-mb level to about 2·0 to 2·5°C at 500-mb level. If the vertical propagation of the surface temperature oscillation by eddy diffusion and convection were the primary cause for the occurrence of diurnal variation of temperature in the middle troposphere (as it appears to be the case from various sources of evidence),-one would expect the amplitude to diminish with height. In view of the observed increase of amplitude with height it would appear probable that the radiation corrections applied to the observations might be an underestimate. These facts emphasise the need for obtaining more reliable radiation corrections.

General conclusions—A few other salient points that can be deduced from the observations are—

(1) The observed amplitude of the diurnal variation of temperature (the determination is only approximate in so far as only four observations per day were available for study) as deduced from the maximum value of $\triangle T$ occurring in the tables is about 2·5 to 3·5°C at 900-mb level decreasing to 1·0 to 1·5°C at 700-mb level. The amplitude is larger in April and October than in January. In July, the diurnal variations extend upto 500 mb but the amplitude is smaller.

(2) The rise of temperature during the day takes place at Bombay, Calcutta and Madras between 00 and 06 GMT, *i.e.*, the first half of the day. But in the case of New Delhi, the main rise is delayed and takes place generally during the latter part of the day. This difference is probably related to the location of the first three stations over coasts and the last station in inland.

5. Direct heating of air during day; nocturnal cooling

The above diurnal variation may be pictured as the vertical propagation of the surface temperature wave. The amplitude of this decreases as we go upwards until the true effects become mixed up with the

TABLE 3

Mean cooling of the layer 600-400 mb (°C/hr)

	January	April	July	October
New Delhi	0·13	Indeterminable	0·1	0·16
Bombay	Indeterminable	0·2	Indeterminable	0·1

'background noise' in the data resulting from instrumental errors. At higher levels, diurnal variation of temperature could occur as a result of direct absorption of solar radiation by the atmospheric constituents especially water vapour. The magnitude of this effect is small being of the order of 0·05 to 0·1°C per hour as estimated from the previous works of Jordan (1960) and Kay (1951). With the accuracies attainable by the radiosondes now in use in India and with the possible uncertainties in the radiation corrections, it may not be possible to determine the magnitude accurately.

The observations made at 18 and 00 GMT fell wholly during the dark hours at Bombay and New Delhi. As the disturbing effects of direct solar radiation are not present in respect of the data of these two stations, it was decided to compute the nocturnal cooling of the free atmosphere although the random errors of the radiosonde still constituted a vitiating factor. Table 3 gives the nocturnal cooling in °C per hour as deduced from the Bombay and New Delhi temperatures at 18 and 00 GMT.

The most probable value of nocturnal cooling is in the range 0·1 to 0·15°C per hour. This value is in qualitative agreement with those determined elsewhere and with the values predicted by theory.

6. Summary

Summarising, the broad features that are brought out by the study are—

(1) For a continental location like New Delhi the observed diurnal effects extend to a much smaller height (700 mb) than those at the coastal stations, Bombay, Calcutta and Madras (500 to 400 mb).

(2) Under stable atmospheric conditions in winter the diurnal variation at New Delhi hardly extends even to 1 km above ground. In July and October, variations of 1·0 to 1·5°C extend up to 700 mb only.

(3) For the coastal stations, variations of the order 1·5 to 2·5°C are observed up to 500—200 mb. A part of the observed range at heights above 500 mb appears to be caused by inadequacy of radiation corrections applied to the radiosonde instruments.

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REFERENCES

Chiu, Wan-Cheng 1959 *J. Met.*, **16**, p. 354.

Dhar, N. C. and Mitra, H. 1962 *Meteorology in relation to high level aviation over India and surrounding areas*, p. 93, India met. Dep., New Delhi.

Jordan 1960 *J. Met.*, **17**, p. 569.

Kay, R. H. 1951 *Quart. J. R. met. Soc.*, **77**, p. 427.

Pant, P. S. 1960 *Indian J. Met. Geophys.*, **11**, p. 371.

Riehl, H. 1947 *Bull. Amer. met. Soc.*, **28**, p. 311.

Scrase, F. J. 1954 *Quart. J. R. met. Soc.*, **80**, p. 565.

Teweles, S. and Finger, F. G. 1960 *J. Met.*, **17**, p. 177.