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On the changes in the Thermal Structure of the Atmosphere over Agra associated with the passage of a Western Disturbance in winter

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1. *Introduction.*

DURING the months November to May, Northern India is visited by a series of depressions which enter the Indian region via Iraq, Afghanistan and Baluchistan and pursue an easterly course across the country. It has been recognised that these depressions—known as *western disturbances*—are analogous to the extra-tropical depressions of the middle latitudes. The typical cloud and weather sequence associated with the latter are also characteristic of western disturbances, although their vertical structure is far more complicated than that of the idealised extra-tropical cyclone model. Detailed synoptic studies of western disturbances have been made by Mal and Desai,[2] and a general account of the weather phenomena associated with them has been given by Malurkar.[3] The object of the present note is to draw attention to some remarkable changes in the thermal structure of the atmosphere over Agra revealed by the results of sounding balloon ascents over that station in the first week of January 1938 in association with the passage of a western disturbance.

2. *Weather situation.*

On the morning of 28-12-1937 a western disturbance, approaching Northwest India was causing cloudy skies over Baluchistan, the Northwest Frontier Province, Punjab, Kashmir and the West United Provinces. During the next 24 hours there was rapid deterioration of weather along the Mekran-Sind Coast. The skies over Karachi which were practically clear till the evening of the 28th, were overcast with nimbostratus on the morning of the next day, and 3/4 inch of rain had already fallen over the station during the night.* The upper winds which were westerly at all levels on the previous day had become easterly in the lower levels, and the synoptic chart of the 29th morning showed that a shallow depression had formed over the Mekran Coast.

The depression moved eastwards causing widespread rain in Sind and Baluchistan, Karachi having recorded 2" and Ormara 3" of rain during the 24 hours ending at 08 hrs. of 30-12-1937. The upper wind charts of the 30th morning showed that in association with the eastward movement of the disturbance, a vigorous inflow of equatorial maritime air had set in from lower latitudes towards the Punjab and the east U. P.

The morning observation of 31-12-1937 showed that the area of largest negative pressure departures had moved from over Sind to East Rajputana and the West Central India ; at the same time, the barometer registered the largest pressure falls of about 8·5 millibars since the previous morning at stations over the extreme north of the country. Widespread thunderstorms and showers had occurred to the north and northwest of a line running roughly from Bombay to Bahraich, while a solid current of maritime air from the Arabian sea and the Bay of Bengal was feeding into the Punjab and Kashmir across the Peninsula.

During the next 24 hrs. the disturbance followed a north-northeasterly course and by the morning of 1-1-1938 the area of maximum negative pressure departures lay over the extreme north of the country more or less coincident with the region over which the largest fall of pressure had been registered since 08 hrs. of the previous day. Widespread and locally heavy thunder-rain had fallen over the area extending from West U. P. to Kashmir, and the southerly feed from the Bay of Bengal and the Arabian Sea into the low pressure area over the Punjab and Kashmir was being sustained.

By the morning of 2-1-1938, the western disturbance was passing away eastwards

* January 6—7, 1945, provides a similar instance of sudden deterioration of weather over Karachi.

across the Western Himalayas. The upper winds in the *lower levels* over East Punjab and West U. P. which were southerly on the previous morning, were now blowing from a north to north-westerly direction, and temperatures were markedly below normal over most of Northwest India. However, *above 3 kms.*, the available pibal observations and directions of cloud movements showed that air from lower latitudes was still being drawn up towards North India.

During the next 24 hours there was a general fall of pressure over the country with a concentrated fall over North-West India. The upper winds between 2 and 6 kms. over the Indian area on the morning of 3-1-1938 constituted a large anti-cyclonic circulation with central region over the Bay of Bengal so that tropical air was being drawn up anti-cyclonically across the Peninsula towards North India. This circulation persisted for the next 24 hours although comparison of the winds and cloud movements at 6 kms. on the 2nd, 3rd, and 4th showed that the normal westerly circulation of the temperate latitudes was gradually tending to re-establish itself over North India.

By the afternoon of 6-1-1938, the westerly circulation had been established at and above 3 kms. north of latitude 15°N, and this feature persisted for the next few days.

3. Upper air soundings over Agra.

During the period covered by the weather situation described above, successful sounding balloon meteorograph ascents were made from the Upper Air Observatory, Agra on the 2nd, 3rd, 5th, 6th, 7th, 8th and 11th January, 1938. All the ascents were made near about 1800 hours I.S.T., and in all cases they reached a height of 17 gkms, or more. Fig. 1 shows the height—temperature curves of these ascents. For the sake of comparison, the curve for 2-1-1938 has been superposed on the ascent curves for the succeeding days. Figs. 2(a) to (f) show the tephigrams of the ascents in question; the tephigram for 2-1-1938 has been superposed on the tephigrams for the remaining days to bring out prominently the progressive changes in the thermal structure of the atmosphere over Agra.

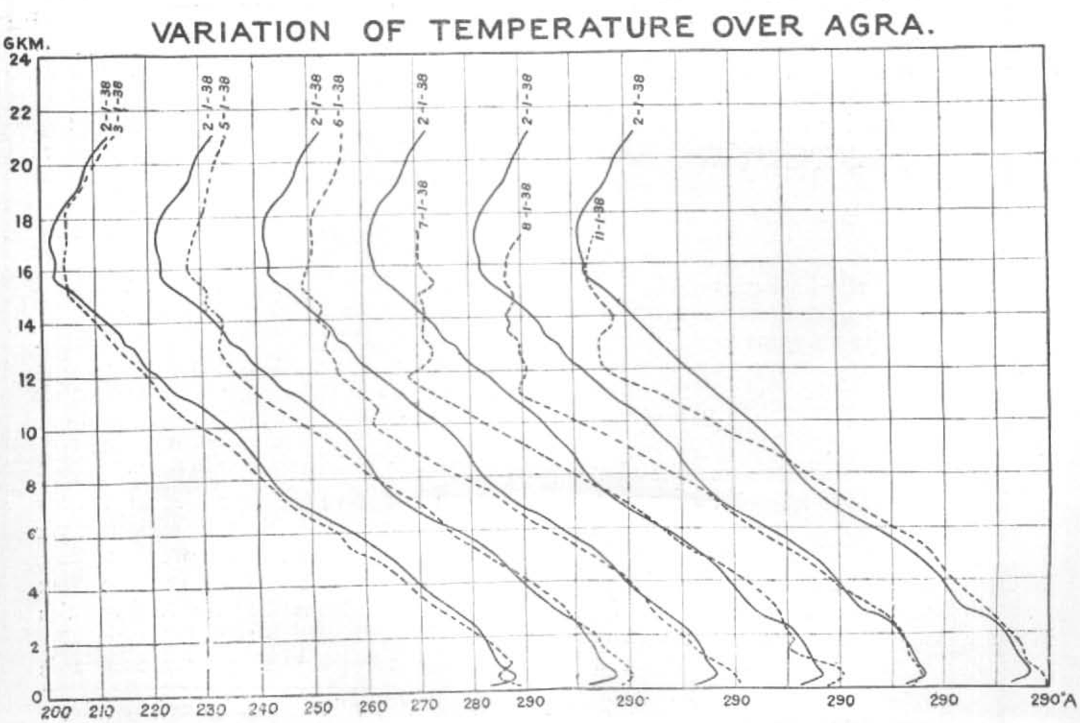

FIG. 1.

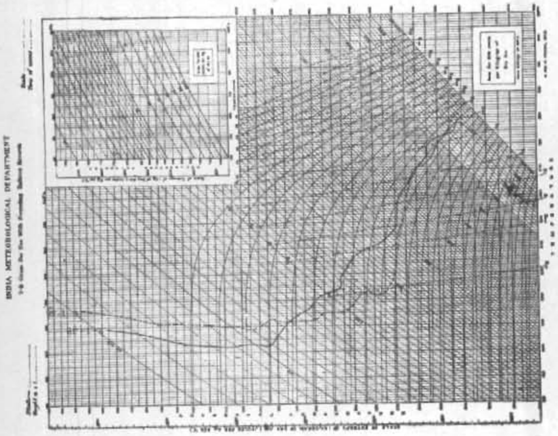

FIG. 2(c).

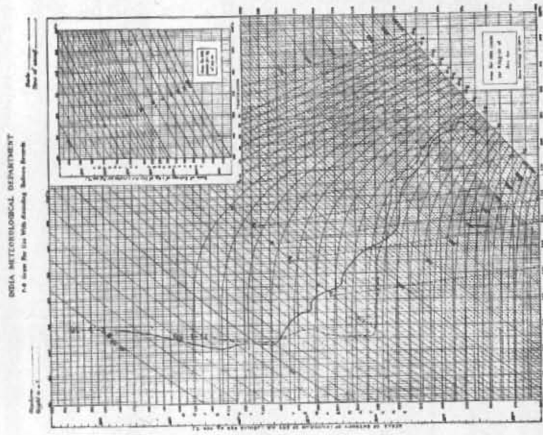

FIG. 2(f).

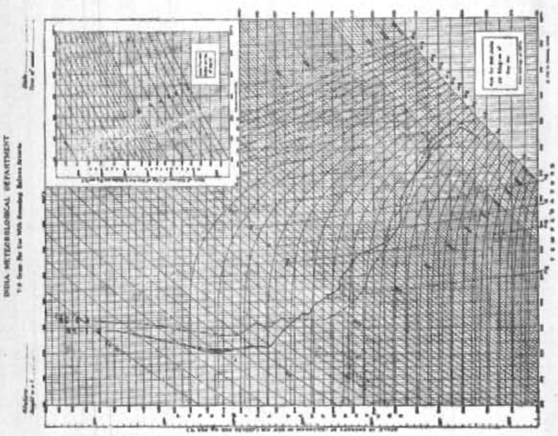

FIG. 2(b).

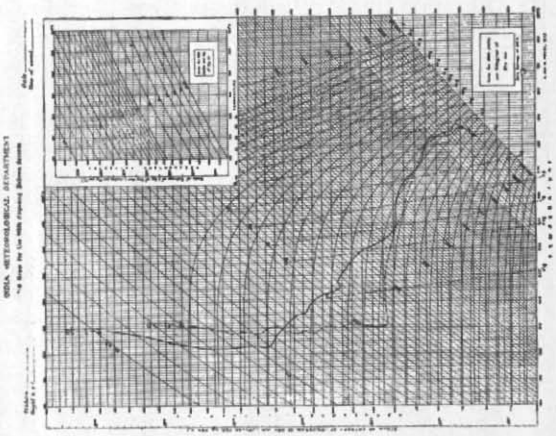

FIG. 2(e).

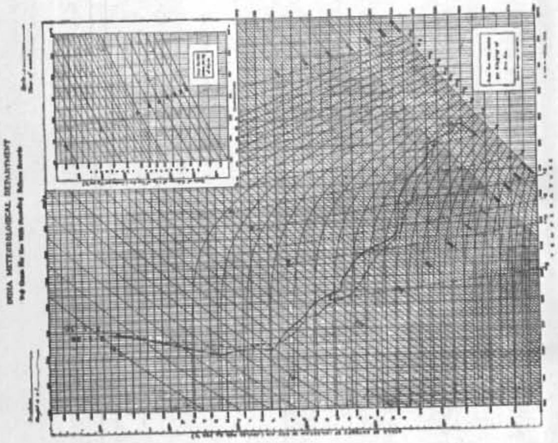

FIG. 2(a).

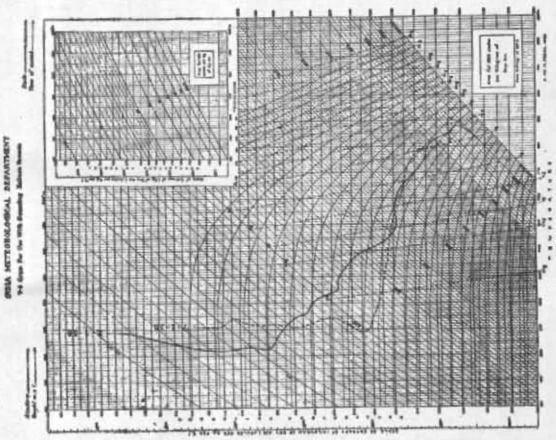

FIG. 2(d).

TABLE 1

Presures and Temperatures at Standard Gkm. Levels over Agra.

Height (gkm.)	2-1-38 (19h15m IST)		3-1-38 (16h34m IST)		5-1-38 (18h3m IST)		6-1-38 (17h40m IST)		7-1-38 (18h4m IST		8-1-38 (18h20m IST)		11-1-38 (17h50m IST)	
	P (mb)	T (°A)	P (mb)	T (A°)	P (mb)	T (°A)	P (mb)	T (°A)	P (mb)	T (°A)	P (mb)	T (°A)	P (mb)	T (°A)
22	...	...	...	...	...	...	37·5	216·0						
21	44	212·5	43·5	214·0	44·5	215·0	44	1·70						
20	52	09·0	51	10·5	52·5	13·0	51·5	16·5						
19	61·5	07·0	60·5	07·5	61·5	12 0	60·5	14·5						
18	73	03·0	71·5	04·5	72·5	11·0	71·5	11·0						
17	86·5	02·0	85	05·0	86	08·5	84·5	11·0	85	211·0	83	210·5	84	2₀4·5
16	103	03·0	101	04·5	102	07·5	99·5	10·0	100	11·5	98	07 5	100	03·5
15	123	07·0	119	05·5	120	11 5	118	10·0	118	11·5	117	08·5	11⁹	05·0
14	144	12·5	141	10·5	142	14·0	139	11·5	139	12·0	137	07 5	141	08·0
13	170	17·5	167	14·5	167	13·5	163	13 0	165	13·0	163	10 0	167	05·5
12	199	22·5	195	20·0	196	17·0	193	15·5	193	10·0	192	11 5	197	07·0
11	232	28·0	228	23·0	230	21·5	226	20·5	227	15·0	226	10·5	231	17·0
10	270	34·5	266	29·5	268	28·5	264	22·0	267	23·0	264	21·0	271	26·0
9	313	39·5	310	36·0	312	35·5	308	28·5	312	31·0	310	31·0	315	36·0
8	361	42·5	357	41·0	360	41·5	357	37·5	361	40·0	358	39·0	364	43·5
7	416	48·0	412	46·0	415	50 5	413	46·5	415	49·0	413	47 5	418	52·0
6	476	57·0	474	55·0	476	56·0	474	54·5	478	56·5	475	54·0	480	60·5
5	546	65·0	544	61·5	545	63 0	544	63 0	546	65·0	545	62·5	548	68·0
4	621	70·0	618	68·0	621	71·0	619	70·5	621	72·5	619	69·0	623	71 5
3	705	76·0	705	74·0	705	78·0	704	74·5	706	78·5	704	77·0	707	78·0
2·5	750	80·0	750	78·0	750	80·0	749	77·0	751	79·5	749	80·5	752	80·5
2 0	797	82·0	798	82·0	798	84 0	797	80·5	800	80·5	797	82·5	800	83·0
1·5	848	84·0	848	85·0	849	85·5	848	83·0	850	80·5	848	83·0	850	85·5
1·0	903	85·0	902	87·0	901	88·5	902	86·5	904	86·0	901	84·5	904	86·0
0·5	960	88·0	957	85·0	956	90·5	957	90·0	960	91·0	957	86·5	960	89·0
Surface (169m a. s. l.)	999	83·0	997	89·0	995	89·0	997	91·0	999	88·0	999	85·0	999	89·5

TABLE 2

Lapse Rates of Temperature over Agra (°C/gkm.)

Height gkm.	2-1-38	3-1-38	5-1-38	6-1-38	7-1-38	8-1-38	11-1-38
21—22	...	...	...	1·0			
20—21	—3·5	—35	—2·0	—0·5			
19—20	—2·0	—3·0	—1·0	—2·0			
18—19	—4·0	—3 0	—1·0	—3·5			
17—18	—1·0	0·5	—2·5	0·0			
16—17	1·0	—0·5	—1·0	—1·0	0·5	—3 0	- 1·0
15—16	4·0	1·0	4·0	0·0	0·0	1·0	1·5
14—15	5·5	5·0	2·5	1·5	0·5	- 1·0	3·0
13—14	5·0	4·0	- 0·5	1·5	1 0	2·5	—2·5
12—13	5·0	5·5	3·5	2·5	—3·0	1·5	1·5̄
11—12	5·5	3·0	4·5	5·0	5·0	—1·0	10·0
10—11	6·5	5·5	7·0	1·5	8·0	10·5	9·0
9—10	5·0	6·5	7·0	6 5	8·0	10·0	10·0
8—9	3·0	5·0	6·0	9·0	9·0	8·0	7·5
7—8	5·5	5·0	9·0	9 0	9·0	8·5	8 5
6—7	9·0	9·0	5·5	8·0	7·5	6·5	8·5
5—6	8·0	6·5	7·0	8·5	8·5	8·5	7·5
4—5	5·0	6·5	8·0	7·5	7·5	6·5	3·5
3—4	6·0	6 0	7·0	4·0	[6·0	8 0	6·5
2·5—3 0	8·0	8·0	4·0	5·0	2·0	7·0	5·0
2·0—2·5	4·0	8·0	8·0	7·0	2·0	4·0	5·0
1·5—2 0	4·0	6·0	3·0	5·0	0·0	1·0	5·0
1·0—1 5	2·0	4·0	6·0	7·0	11·0	3·0	1·0
0 5—1·0	6·0	—4·0	4·0	7·0	10·0	4·0	6·0

Table 1 gives the values of pressure and temperature at standard geodynamic levels for all the seven ascents. These are taken from the published values. Table 2 gives the lapse-rates between standard geodynamic levels for the different ascents. Table 3 gives the values of the potential temperature θ at standard geodynamic levels. Figure 3 gives the corresponding isopleth diagram.

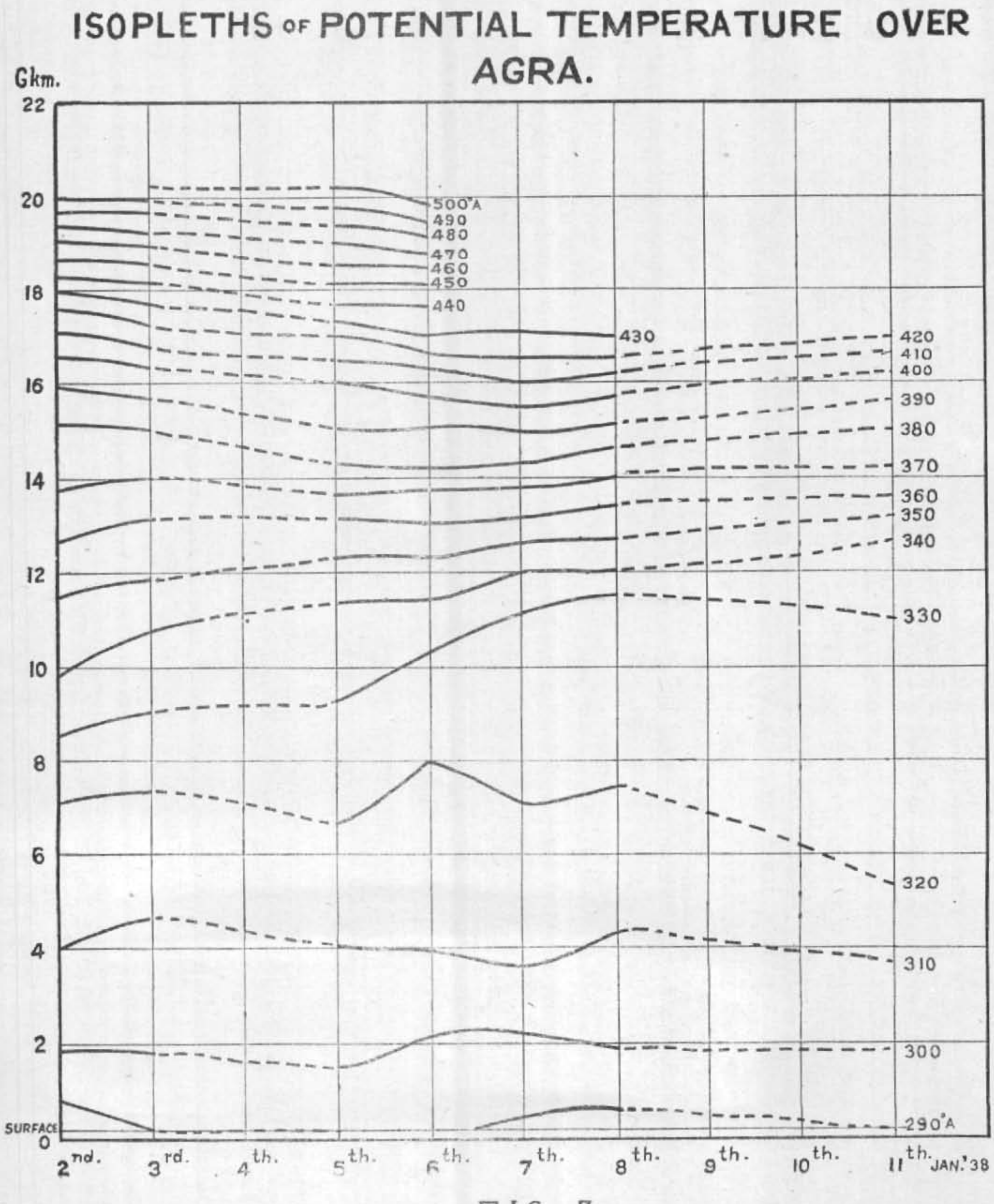

FIG. 3.

TABLE 3

Potential Temperatures (°A) at Standard Gkm. Levels over Agra.

Height (gkm).	θ_2	θ_3	θ_5	θ_6	θ_7	θ_8	θ_{11}	$\theta_3-\theta_2$	$\theta_5-\theta_2$	$\theta_6-\theta_2$	$\theta_7-\theta_2$	$\theta_8-\theta_2$	$\theta_{11}-\theta_2$
22													
21													
20	487	492	495	505				+5	+8	+18			
19	459	462	470	476				+3	+11	+17			
18	430	435	447	447				+5	+17	+17			
17	407	415	420	428	428	430	419	+8	+13	+21	+21	+23	+12
16	390	394	400	407	410	405	394	+4	+10	+17	+20	+15	+4
15	378	380	389	388	390	386	379	+2	+11	+10	+12	+8	+1
14	372	369	376	373	374	368	365	−3	+4	+1	+2	−4	−7
13	363	359	357	359	357	353	344	−4	−6	−4	−6	−10	−19
12	354	352	346	345	337	340	330	−2	−8	−9	−17	−14	−24
11	346	341	337	337	328	322	330	−5	−9	−9	−18	−24	−16
10	341	335	333	325	325	324	329	−6	−8	−16	−16	−17	−12
9	334	330	329	320	323	323	329	−4	−5	−14	−11	−11	−5
8	325	324	324	320	322	321	326	−1	−1	−5	−3	−4	+1
7	319	317	322	317	320	319	324	−2	+3	−2	+1	0	+5
6	318	316	317	315	317	315	322	−2	−1	−3	−1	−3	+4
5	315	311	313	313	315	312	319	−4	−2	−2	0	−3	+4
4	310	308	310	310	312	309	311	−2	0	0	+2	−1	+1
3	305	302	307	303	307	306	307	−3	+2	−2	+2	+1	+2
2	301	301	303	299	298	301	301	0	+2	−2	−3	0	0
1	293	295	297	295	294	293	294	+2	+4	+2	+1	0	+1
Surface	283	290	290	292	288	285	290	+7	+7	+9	+5	+2	+7

TABLE 4.

Local changes of Pressure and Temperature over Agra.

Gkm.	(3) — (2)		(5) — (2)		(6) — (2)		(7) — (2)		(8) — (2)		(11) — (2)	
	$\delta_1 p$ (mb)	$\delta_1 T$ (°C)	$\delta_1 p$ (mb)	$\delta_1 T$ (°C)	$\delta_1 p$ (mb)	$\delta_1 T$ (°C)	$\delta_1 p$ (mb)	$\delta_1 T$ (°C)	$\delta_1 p$ (mb)	$\delta_1 T$ (°C)	$\delta_1 p$ (mb)	$\delta_1 T$ (°C)
22												
21	−0·7	+1·5	+0·5	+2·5	0	+4·5						
20	−0·8	+1·5	+0·5	+4·0	−0·2	+7·5						
19	−1·0	+0·5	+0·3	+5·0	−0·6	+7·5						
18	−1·3	+1·5	0	+8·0	−1·2	+8·0						
17	−1·7	+3·0	−0·5	+6·5	−2·0	+9·0	−1·4	+9·0	−3·2	+8·5	−2·4	+2·5
16	−2·2	+1·5	−1·1	+4·5	−3·1	+7·0	−2·5	+8·5	−4·4	+4·5	−3·0	+0·5
15	−2·6	−1·5	−1·7	+4·5	−4·2	+3·0	−3·6	+4·5	−5·6	+1·5	−3·5	−2·0
14	−2·9	−2·0	−2·3	+1·5	−5·0	−1·0	−4·5	−0·5	−6·3	−5·0	−3·7	−4·5
13	−3·1	−3·0	−2·6	−4·0	−5·6	−4·5	−5·0	−4·5	−6·7	−7·5	−3·4	−12·0
12	−3·2	−2·5	−2·3	−5·5	−5·7	−7·0	−4·6	−12·5	−6·5	−11·0	−2·0	−15·5
11	−3·1	−5·0	−1·8	−6·5	−5·5	−7·5	−3·4	−13·0	−5·3	−17·5	−0·3	−11·0
10	−2·8	−5·0	−1·0	−6·0	−4·7	−12·5	−1·8	−11·5	−3·5	−13·5	+1·3	−8·5
9	−2·4	−3·5	−0·3	−4·0	−3·2	−11·0	−0·2	−8·5	−2·1	−8·5	+2·7	−3·5
8	−2·3	−1·5	+0·2	−1·0	−2·0	−5·0	+0·9	−2·5	−1·3	−3·5	+3·4	+1·0
7	−2·2	−2·0	0	+2·5	−1·6	−1·5	+1·2	+1·0	−1·0	−0·5	+3·3	+4·0
6	−2·0	−2·0	−0·2	−1·0	−1·3	−2·5	+1·3	−0·5	−0·7	−3·0	+2·8	+3·5
5	−1·6	−3·5	+0·2	−2·0	−0·9	−2·0	+1·6	0	−0·1	−2·5	+2·3	+3·0
4	−0·9	−2·0	+0·5	+1·0	−1·7	+0·5	+1·4	+2·5	+0·4	−1·0	+2·0	+1·5
3	−0·5	−2·0	0	+2·0	−0·7	−1·5	+0·8	+2·5	+0·4	+1·0	+1·7	+2·0
2	−0·1	0	−0·7	+2·0	−0·3	−1·5	+0·8	−1·5	+0·2	+0·5	+1·4	+1·0
1	−0·6	+2·0	−2·1	+3·5	−0·3	+1·5	+1·0	+1·0	+0·3	−0·5	+1·2	+1·0
Surface	−2·0	+6·0	−4·0	+6·0	−2·0	+3·0	0	+5·0	0	+2·0	0	+6·5

The local changes of temperature at standard geodynamic levels ($\delta_t T$) have been obtained from the ascent data in Table 1, the changes for the respective dates being obtained by subtracting the temperature values from the corresponding values for 2nd January, 1938. To get the local changes of pressure ($\delta_t p$) accurately, the values have been worked out using the formula :

$$\delta_t p = \frac{p}{p_o} \cdot \delta p_o + p \cdot \frac{g}{R} \int_o^z \frac{\delta_t T}{T^2} \cdot dz$$

Where p_o is the surface pressure, and δp_o, the change in the surface pressure.

The values of $\delta_t p$ and $\delta_t T$ are given in Table 4. It will be seen that the calculated values of $\delta_t p$ show more regular variation with height than those obtained by subtracting the pressure values in Table 1.

4. *Discussion of Results.*

One of the striking results brought out by the sounding balloon ascents over Agra during the period 2-1-1938 to 11-1-1938 is the large variations of temperature which occurred above a height of 8 gkms., with comparatively little variations below this level. On 2-1-1938, the thermal structure of the atmosphere over Agra is more or less of the tropical type with the tropopause at a height of nearly 16 gkm., and a fairly pronounced inversion above this level. Following this, we notice a progressive fall of temperature in the upper troposphere and rise of temperature in the lower stratosphere, in other words, a gradual changing over from tropical conditions to the conditions obtaining in temperate latitudes. On the 7th and 8th January, 1938, the fall of temperature stops abruptly at 12 gkms. and 11 gkms. respectively above which the atmosphere is more or less isothermal for the next few kilometers. The development of high lapse-rates practically approaching the dry-adiabatic lapse-rate in the upper troposphere, below the tropopause is also noteworthy. (*Vide* Table 2.)

All the features described above suggest that in association with passage of the western disturbance described in Section 2, there has been horizontal air movements extending to very great altitudes. In advance of the depression, tropical air has been drawn up to an elevation of at least 20 gkm. and after the passage of the disturbance this air has been displaced by air from the temperate latitudes. In the absence of high altitude upper winds it is not possible to adduce more definite evidence in support of this thesis, although the variation in the thermal structure shown in Figures 1 and 2 lend strong support to this view.

In this connection we might recall the theory of "*tropopause waves*" which has been dealt with at some length by Bjerknes and collaborators in "Physikalische Hydrodynamik". According to this theory, "waves" can be set up on the inclined surface of the tropopause over the temperate latitudes. These tropopause waves can be pictured as originating from *horizontal oscillations* of the atmosphere. The meridional component of these oscillations displaces the inclined surface of the tropopause alternately polewards and equatorwards. The wave crests correspond to regions where equatorial air has pushed polewards while the wave-troughs are regions of greatest penetration of polar air towards lower latitudes. A region coming under the influence of a wave crest will have a comparatively warm troposphere with high tropopause while the reverse conditions will obtain over a place under a wave-trough. Thus we may picture the short period changes in the thermal structure of the atmosphere over Agra described above as resulting from the passage of a tropopause wave over the station.

For want of sufficient upper air data it has not been possible to examine the thermal changes of the atmosphere associated with other western disturbances. In the case of such disturbances which produce horizontal oscillations of large amplitude at the tropopause levels, the thermal structure of the atmosphere over a station coming under the influence of the disturbance might be expected to undergo fluctuations affecting several kilometers of the upper troposphere and lower stratosphere. In such cases it should be possible to detect marked variations in the ozone content of the atmosphere, as the centre of gravity of atmospheric ozone is near about 25 gkms., and there is a latitudinal variation in the ozone content of the atmosphere. In this connection it is interesting to recall that from a personal conversation with Dewan Bahadur Dr. K.R. Ramanathan, the author came to understand that the systematic ozone measurements carried out by Mr. Karandikar at New Delhi show appreciable fluctuations of ozone content in association with certain western disturbances while showing little variations in other cases.

5. *Summary.*

The large fluctuations in the thermal structure of the upper troposphere and lower stratosphere over Agra in association with the passage of a western disturbance in January 1938 are described. It is suggested that these fluctuations can be explained as resulting from large-scale "horizontal oscillations" of the atmosphere of the type pictured by Bjerknes and collaborators in their theory of tropopause waves.

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