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Observations of Turbulence at Delhi during the winter months November 1966 to February 1967 with the F-type Radiosondes

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ABSTRACT. Study of turbulence at Delhi during the winter months when the westerly jets prevail was made by special F-type radiosonde ascents from November 1966 to February 1967 and in April 1967. The vertical components of gusts and their thicknesses were determined by measuring the rate of rotation of the fan from the length of complete Olland cycles which consists of 1000 impulses. Since the duration of the gust may not last as much as a full cycle, lengths of tapes for 100 impulses and 500 impulses were measured. It was then found that the duration of the gusts is only of the order of 200–300 impulses. The vertical components of the gusts were therefore larger and thicknesses smaller when the length of 100 impulses were used. One of the interesting features at Delhi was the presence of turbulence in thin layers of air (about 1500 m thick), in which the lapse rate was different from those in the layers above and below. These regions were above the jet stream and were between 150 and 100-mb levels.

1. Introduction

It is observed that the turbulent regions over Minicoy (Venkiteshwaran *et al.* 1968) during the months January–April are in the tropopause and the stratosphere. But during the monsoon months turbulence is observed below the tropopause and is associated with the easterly jets. All these show that turbulence is a standing feature of the air currents in the higher atmosphere with characteristic seasonal variations.

When these special features were observed over Minicoy in the tropical region, it was felt to study the conditions prevailing in the westerly jet stream over the northern parts of India during the winter. Special flights were therefore arranged once a week at New Delhi during the winter months November 1966 to February 1967 and April 1967. A few flights after sunset were also made in April 1967. The special features observed from these flights are discussed in the following paragraphs.

2. Variation of the rate of rotation of the fan with height

If hydrogen does not leak or diffuse through the balloon fabric, the rate of ascent of the balloon increases with height as shown in Table 1.

This is based on the variation of density with height over Poona but can be used without appreciable change over the whole of India.

Venkiteshwaran and Huddar (1966) have shown earlier that the variation of the rate of rotation of the fan (number of impulses per second) for different air speeds towards the fan along the axis of rotation is as given in Table 2.

It may be mentioned that the size and shape of the paper fan and the gearing have remained unchanged in the instrument. Therefore the rates of rotation of the fan are comparable at all times, and they are influenced only by the relative motion of the air past the fan.

From the variation of the rate of ascent with height (Table 1) and the relation between the airspeed along the axis of rotation of the fan and its rate of rotation (Table 2) it is possible to estimate the rate of rotation at any height. Thus with a balloon whose constant rate of ascent is 20 kmph, the rate of rotation at a height of 12 km provided there had been no leakage of gas will be $20\times1\cdot23=24\cdot6$ kmph, and the rate of rotation of the fan at this height will be $23\cdot5$ impulses per second.

If on the other hand, the rate of ascent of the balloon was constant at 20 kmph due to slight leakage/diffusion of gas, this rate of ascent at 12 km will be equivalent to $20/1\cdot23=16$ kmph near the ground; this corresponds to a rate of rotation of 19 imp/sec (Table 2). The rate of rotation of

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TABLE 1

Height (km)	Rate of ascent
0	1
2	1·02
4	1·05
6	1·09
8	1·14
10	1·18
12	1·23
14	1·28
16	1·35
18	1·43
20	1·53

TABLE 2

Air speed (kmph)	Number of impulses per second
30	33
24	27
18	22
12	13

TABLE 3

No. of impulses per second at different heights for a constant rate of ascent of 20 kmph

Height (km)	No. of impulses per second
0	23·5
4	22·5
8	21·0
12	19·0
16	17·0

TABLE 4

Height (km)	No. of impulses per second computed	No. of impulses per second observed (Poona)
0	22	22
8	18	18
12	17	15
16	14·5	9

the fan at different heights, for a uniform rate of ascent of 20 kmph, calculated as above, is given in Table 3.

Similarly, the computed values of the rate of rotation of the fan for a uniform rate of ascent of 18 kmph, and those actually observed for the soundings at Poona are given in Table 4.

While there is good agreement between the observed and computed values in Table 4 upto a height of about 12 km, the observed rate of rotation above this level is lower, which shows that presumably in these cases there is greater leakage of gas from the balloon, and the rate of ascent is less than 18 kmph.

3. Turbulence in the upper air over Delhi

From the variation of the rate of ascent with height for no leakage of gas (Table 1) and the rate of rotation of the fan at different air speeds (Table 2), it has been possible to estimate the upward or downward movement of air in a gust in a turbulent region. Fig. 1 shows the rate of rotation of the fan (length of tape in inches per Olland cycle), the temperatures and the wind speeds at different heights for an ascent over New Delhi on 13 January 1967 at 1100 IST.

The method of estimating the value of the upward gust from 490 mb and the downward gust from 255 mb for the above ascent are described below —

(*a*) *Example 1: Upward gust from 490 to 460 mb*

The rate of ascent of balloon at start

$= 18{\cdot}0$ kmph

$= 22$ imp/sec (Table 2)

$= 70''$ of tape

The rate of rotation at beginning of gust at about 490 mb (6 km), where the length of tape per cycle is $74'' = (22\times70)/74 = 21$ imp/sec.

From Table 2, 21 imp/sec near the ground corresponds to a relative wind of 17 kmph, and this rate of rotation at 6 km will correspond to a wind of $17\times1\cdot09 = 18\cdot5$ kmph (Table 1).

The rate of rotation at peak of gust, corresponding to 100″ of tape $= (22\times70)/100 = 15\cdot5$ imp/sec at 6 km. 15·5 imp/sec at ground corresponds to 13·5 kmph and this in turn corresponds to $13\cdot5 \times 1\cdot09 = 15\cdot5$ kmph at 6 km.

Therefore, the decrease in the rate of rotation was due to an upward gust of $(18\cdot5—15\cdot5) = 3\cdot0$ kmph.

The thickness of the levels between which this occurred was from 490 mb to 460 mb = 0·36 km.

(*b*) *Example 2 : Downward gust from 255 mb to 240 mb*

The rate of rotation of the fan at the start of the gust at 255 mb (10·5 km) $= (22\times70)/100$ imp/sec = 15·5 imp/sec (The start of the downward gust which increased the rate of rotation has been taken as the point in the mean curve).

15·5 imp/sec corresponds to a relative wind of 14 kmph near the ground or $14 \times 1\cdot18 = 16\cdot5$ kmph at 10·5 km.

Similarly, the relative wind at the peak of the gust when the length of the tape was 68″ per cycle $= 18\cdot5 \times 1\cdot18 = 22$ kmph. Therefore the velocity of the downward gust was $(22—16\cdot5) = 5\cdot5$ kmph over a thickness of 0·45 km above the 255-mb level.

Table 5 shows the upward or downward component of some significant gusts and the thickness of the atmosphere in which this was experienced. It is observed from the table that the vertical components of the gusts are about 2–3 kmph, occasionally reaching 5 kmph. The thickness of the region varies between 0·2 to 0·5 km. In this connection it may be stated that the computation of the vertical components of the gusts and the thickness, are based on the mean rotation of the fan per Olland cycle, since the unit of measurement is the length of paper tape for a complete cycle. Thus for a rate of rotation of the fan of 25 impulses per second, the unit of time is about 40 seconds, since a complete cycle consists of nearly 1000 impulses. But, if the downward vertical component of the gust had only a much smaller duration than 40 seconds its value computed from the length of tape for a complete cycle, will be less than the actual. Similarly, for an upward gust of small duration, the computed value will be higher than the actual.

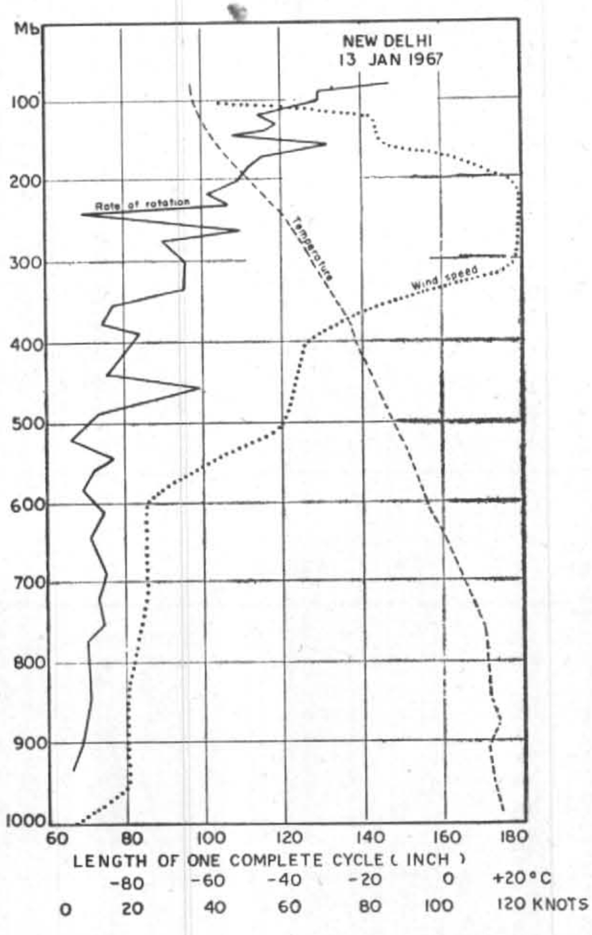


Fig. 1. Rate of rotation of the fan (length of tape in inches per Olland cycle), temperature and wind speeds at different heights for an ascent over New Delhi on 13 Jan 1967 at 1100 IST

4. Computation of vertical components of gusts for periods shorter than that for a full cycle

Since it was likely that the estimates of vertical components of gusts and the thicknesses of the air layers in which they occur may not be correct when the unit of measurement for the rate of rotation is based on the length of paper tape for a full cycle, the rate of rotation of the fan was computed for shorter periods, *viz.*, the length of paper tape for 100 impulses and for 500 impulses. A comparative study of the values so obtained was made for radiosonde ascent at New Delhi on 16 December 1966. Fig 2 shows the rate of rotation so obtained. However, for purposes of comparative study, the rate of rotation obtained as lengths for 100 and 500 impulses were converted to lengths of paper tape for 1000 impluses which corresponds to an Olland cycle. The lengths so obtained are given in Table 6.

TABLE 5

Vertical components of gusts and their thicknesses over Delhi

Date	Rate of ascent immediately on release (kmph)	Ht. of gusts km (mb)	Relative vertical component of gust: At start (kmph)	Relative vertical component of gust: At peak (kmph)	Vertical component of gust (kmph)	Approx. thickness (km)	Direction of gust
7 Nov '66	19·0	3 (700)	20·0	23·0	3·0	0·25	Downward
	19·0	4 (800)	20·0	24·0	4·0	0·4	Do.
25 Nov '66	19·0	7 (440)	17·0	20·0	3·0	0·2	Do.
	19·0	7 (390)	17·0	21·0	4·0	0·25	Do.
9 Dec '66	20·0	6 (535)	18·5	24·0	5·5	0·6	Do.
	20·0	8 (365)	17·0	15·0	2·0	0·6	Upward
	20·0	8 (350)	16·0	19·0	3·0	0·2	Downward
	20·0	9·5 (295)	16·0	22·0	6·0	0·3	Do.
16 Dec '66	18·0	5 (545)	16·0	19·0	3·0	0·45	Do.
	18·0	6 (485)	15·0	17·0	2·0	0·5	Do.
	18·0	10 (270)	15·0	18·0	3·0	0·4	Do.
	18·0	12 (190)	15·0	17·0	2·0	0·45	Do.
	18·0	15 (125)	14·0	17·0	3·0	0·4	Do.
23 Dec '66	20·0	4 (660)	19·0	17·0	2·0	0·45	Upward
	20·0	6 (495)	17·5	20·5	3·0	0·4	Downward
	20·0	10 (290)	17·0	19·5	2·5	0·5	Do.
6 Jan '67	20·0	11 (225)	21·5	25·0	3·5	0·5	Do.
	20·0	13 (185)	22·0	25·0	3·0	0·75	Do.
13 Jan '67	18·0	6 (490)	18·5	15·5	3·0	0·36	Upward
	18·0	11 (240)	16·5	22·0	5·5	0·45	Downward
	18·0	14 (155)	16·0	14·5	1·5	0·6	Upward
4 Apr '67	22·0	12 (205)	13·5	16·5	3·0	0·3	Downward
	22·0	13 (180)	13·75	16·25	2·5	0·2	Do.
	22·0	16 (100)	14·0	16·0	2·0	0·8	Do.
	22·0	18 (80)	14·0	16·0	2·0	0·2	Do.
5 Apr '67	22·0	10 (240)	21·0	17·5	3·5	0·2	Upward
	22·0	14 (150)	17·0	19·0	2·0	0·3	Downward
	22·0	16 (105)	16·5	19·5	3·0	0·2	Do.

TABLE 6

Rate of rotation of fan with 100,500 and 1000 impulses at significant levels of turbulence over Delhi on 16 Dec 1966

Level km	Level (mb)	Impulses (inches): 100	500	1000
5	(545)	65	72	75
6	(485)	68	76	82
10	(270)	68	90	93
12	(190)	74	100	109
15	(125)	96	106	113

TABLE 7

Vertical components of gusts and thicknesses of regions of turbulence with different scales

Level km	Level (mb)	100 impulses V.C. (kmph)	100 impulses T (km)	500 impulses V.C. (kmph)	500 impulses T (km)	1000 impulses V.C. (kmph)	1000 impulses T (km)
5	(545)	6·0	0·075	4·0	0·4	3·0	0·45
6	(485)	5·5	0·08	3·0	0·4	2·0	0·5
10	(270)	7·5	0·15	3·5	0·3	3·0	0·4
12	(190)	7·5	0·1	3·0	0·4	2·0	0·45
15	(125)	4·0	0·15	3·0	0·2	3·0	0·4

V.C. = Vertical component of gust T = Thickness

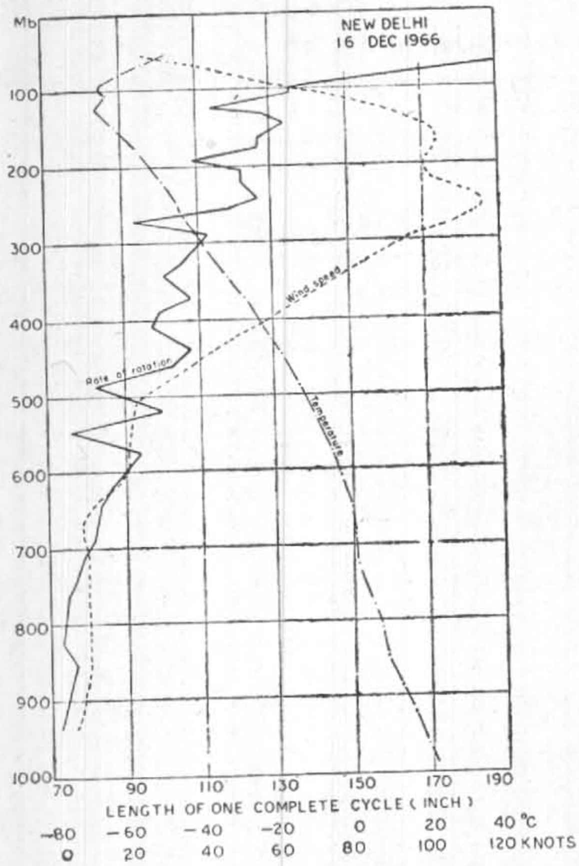
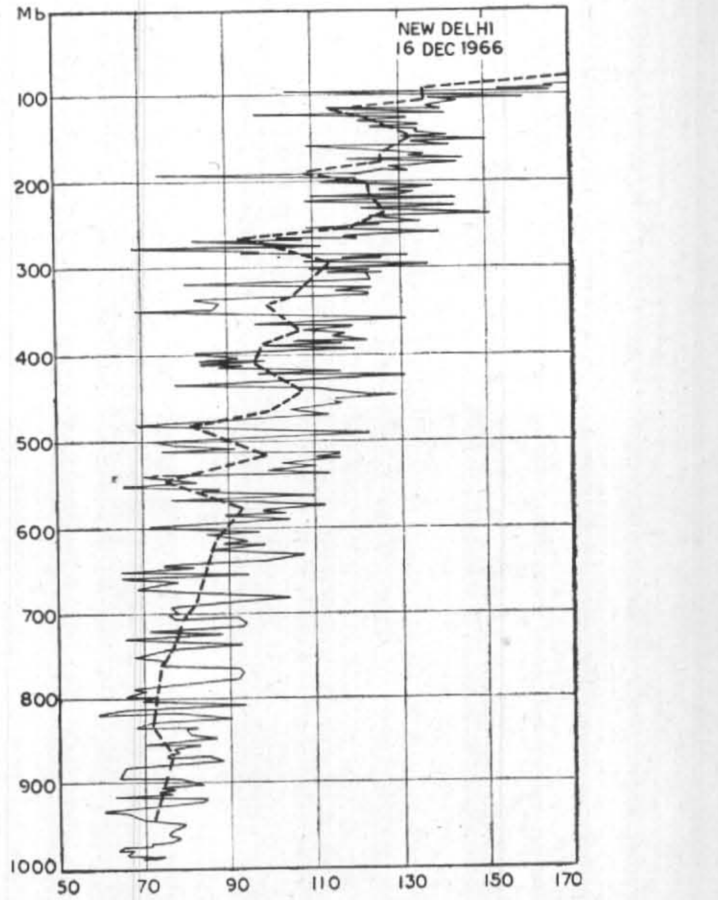


Fig. 2(a). Rate of rotation of fan, temperature and wind speed at different heights for an ascent over New Delhi on 16 December 1966



Length per 1000 impulses (in inches) when unit of measurement is 100 impulses

Fig. 2(b)

(Length of full Olland cycle of 1000 impulses is indicated by the dashed line)

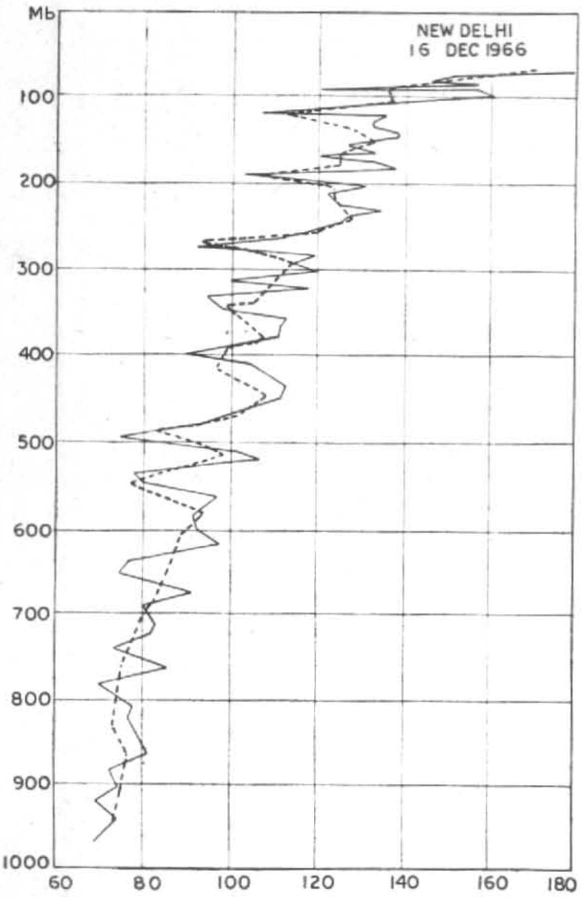
The vertical components and thicknesses of the regions of significant gusts, by adopting the different scales are given in Table 7.

It is seen from Figs. 2(a) and 2(b) that the fluctuations in the vertical components of the wind are more frequent and larger when the length of 100 impulses is used as the unit for measuring the rate of rotation (Fig. 2b), instead of a complete cycle of 1000 impulses (Fig. 2a).

When the length of the tape for a complete cycle is used to measure turbulence, the short period fluctuations are smoothed out and the significantly large ones due to the turbulence in the air are brought out. The full Olland cycle as the unit, therefore, helps to locate regions of large turbulence. Since the approximate period for a complete Olland cycle of 1000 impulses is of the order of about 45 sec at 10-km level and since the period for 100 cycles is much smaller and is of the order of only about 4–5 sec, the absolute values of the vertical component get reduced when the Olland cycle is used as the scale. Thus for estimating the value of the vertical component, length of 100 impulses appears to be a better scale.

Fig. 2(c) shows the distribution of turbulence when the length of 500 impulses is used as the scale for the rate of rotation. It is observed that in this case a few extra regions of turbulence are observed which are not indicated with 1000 impulses. With 500 impulses, the vertical component of the turbulence is slightly larger than with 1000 impulses, but the thicknesses of these regions appear to be similar. These are brought out in Table 7 also.

Thus from the above, it appears that it may be more representative if length of 500 impulses is adopted to locate regions of turbulence while the length of 100 impulses will be useful to estimate values of the vertical components and the thicknesses of the gusts. It is observed that



Length per 1000 impulses (in inches) when unit of measurements is 500 impulses

Fig. 2(c)

(Length of full Olland cycle of 1000 impulses is indicated by the dashed line)

roughly the maximum value of the gust is reached in about 300 impulses. Since the rate of ascent of the balloon is 18 kmph, which corresponds to about 22 impulses per second, the maximum value of the gust is attained in such cases in about 15 seconds, which corresponds to approximately about 75 m; therefore the total thickness of the region in which the vertical component increases from the mean to the maximum and decreases back to the mean is of the order of 150 m.

5. Turbulence and its relation to the jet stream

Table 8 gives the levels at which turbulence was significant as observed from the rate of rotation of the fan in the radiosonde ascents at New Delhi during the months November 1966 to February 1967. The length of tape for one complete cycle has been used to measure the rate of rotation. It is observed from Table 8 that from December to January the levels at which turbulence occurs seem to be higher; this is followed by a decrease from January to February. In December, the region of turbulence lies between 6·5 and 8 km. In January, it is mostly at about 11 and 15 km. With the weakening of the winter in February, the region lowers to about 8 km again.

Regions of the atmosphere with sharp changes in the temperature lapse rates are sometimes associated with turbulence. Fig. 3(a) shows for Delhi on 20 January 1967, the turbulence observed between 150 mb and 100-mb levels using the length of tape for 100 impulses. The turbulence observed when the length of a complete Olland cycle (1000 impulses) is used, is shown by the dashed line. The variation of temperature with pressure is also shown. Fig. 3(b) shows the turbulence over this region on 10 February 1967. It is interesting to observe in these figures, the significant regions where appreciably greater turbulence occurs, and to compare the turbulent regions using the length of the Olland cycle and only that of 100 impulses. The occurrence of turbulence associated with region of inversion has already been observed by Jayarajan (1953) and by Anderson (1957). The instances at Delhi described above, in which turbulence in such detail is observed in small thicknesses of the atmosphere even in the regions of 14–16 km bring out the effectiveness of the fan in locating such regions.

It is not quite evident from the few flights made at Delhi as to the circumstances under which turbulence occurs in association with the westerly winter jet streams. From Figs. 1 and 2 it appears that it occurs in layers of no change in speed between layers of rapid change of speed with height. However, there are also instances in which it occurs in regions where there is change of speed with height. This requires further examination.

6. Turbulence in the Stratosphere

In the ascents made at Delhi during the winter months November–February, only a few have crossed the tropopause, and even in all these instances, there has been a rapid fall in the rate of rotation of the fan due to the leakage of gas from the balloon at the high levels. However, in the case of Minicoy, there were a number of

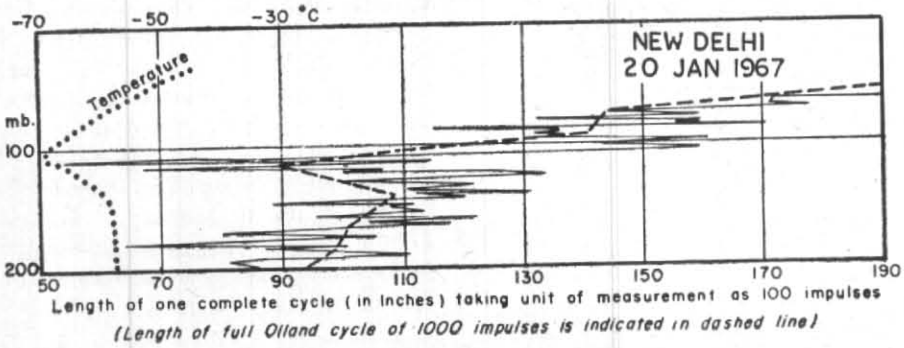


Fig. 3(a)

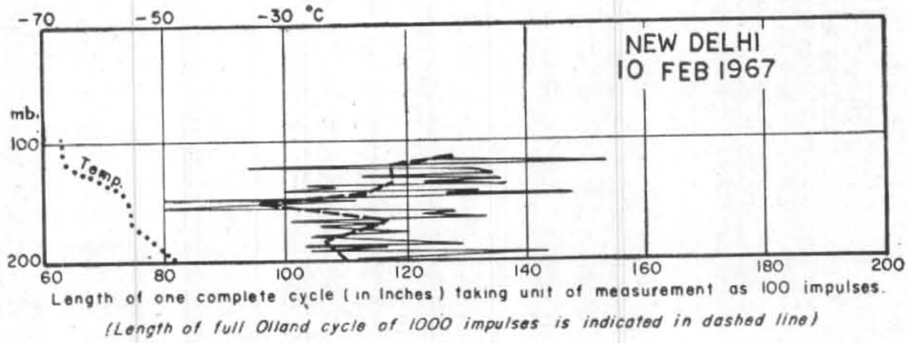


Fig. 3(b)

TABLE 8

Levels at which significant turbulence was observed

Date	Levels (mb)									
	700–600	600–500	500–400	400–300	300–250	250–200	200–150	150–100	100–50	Max. level reached in sounding
1966										
7 Nov	700	600	—	—	—	—	—	—	—	225
18 Nov	610	—	410	360	260	—	—	140	199	50
25 Nov	—	—	440	390	—	—	—	—	—	300
3 Dec	—	—	420	360	—	—	190	—	—	125
9 Dec	—	535	—	365, 250	295	—	—	—	—	125
16 Dec	—	545	485	—	270	—	190	125	—	50
23 Dec	660	—	495	—	290	—	—	—	100	75
30 Dec	—	—	—	—	—	—	170	—	—	150
1967										
6 Jan	—	—	—	—	—	225	185	—	—	50
13 Jan	—	—	490	—	—	240	—	105	—	75
20 Jan	—	—	—	—	—	230	—	120	—	50
27 Jan	—	—	—	—	—	230	—	—	—	75
4 Feb	—	—	—	330	300	—	—	—	—	200
10 Feb	—	600	540	320	—	—	—	150	—	100
17 Feb	—	—	—	325	—	—	—	—	—	325
25 Feb	—	600, 550	—	390	—	—	—	125	—	100

occasions when significant turbulence was observed above the 100-mb level. The flights at Minicoy were made in the evening and the balloons were not affected by solar radiation. However, since the ascents at Delhi were by day it is felt that the balloon fabric was affected by radiation, as a result of which, the hydrogen diffused out. A few ascents were arranged at Delhi after sunset also, in April, 1967; but of these only one crossed the tropopause; in this instance also, there was indication of the failure of the balloon fabric even while it was in the tropopause at about 75 mb.

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REFERENCES

Anderson, A. D.	1957	*J. Met.*, **14**, 6, pp. 477-494.
Jayarajan, A. P.	1953	*Indian J. Met. Geophys.*, **4**, 3, pp. 260-261
Venkiteshwaran, S. P. and Jayarajan, A. P.	1952	*Ibid.*, **3**, 3, pp. 40-48.
Venkiteshwaran, S. P. and Huddar, B. B.	1966	*Ibid.*, **17**, 4, pp. 563-566.
Venkiteshwaran, S. P., Sinha, Har Surendra Sahai, and Jayaraman, K.	1968	*Ibid.*, **19**, 2, pp. 193-202.