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Observations of Turbulence over Minicoy with the F-type Radiosonde

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ABSTRACT. The paper discusses the F-type radiosonde ascents at Minicoy during the period May 1963 to April 1964. It is observed that the rate of rotation of the fan remains unchanged upto about 150 mb and that it decreases above. The rotation is related to the rate of ascent of the balloon and its decrease beyond 150 mb shown to be the same or decreases due to leakage of hydrogen through balloon fabric. The regions of turbulence in the upper tropopause and stratosphere are studied from the rate of rotation of the fan. From January to March, turbulence occurs in the tropopause and stratosphere causing often the balloon to burst. This observation confirms the inferences drawn from the blur at the end of the traces in the Dines' meteorograph ascents. The vertical component of gusts is estimated to be between 10-20 kmph. The thickness of the region of turbulence is found to be about 4 km and the region of turbulence during the monsoon months is in the upper troposphere below the tropopause.

1. Introduction

The detailed study of the rate of rotation of the fan in the F-type radiosonde of the India Meteorological Department has shown that in addition to being a switching mechanism, the rotation of the fan gives some details which other types of radiosondes using cup anemometer or wind mill type of motors to telemeter the meteorological data, do not do (Venkiteshwaran *et al.* 1948). For example, it is possible with the F-type radiosonde to distinguish between the descent of balloon due to accumulation of snow or due to strong downward vertical currents (Suryanarayana and Kachare 1951, Venkiteshwaran and Tilakan 1952). The cup anemometer type or wind mill type of motors rotate about an horizontal axis and are independent of the direction in which the wind blows. But, the paper fan in the Indian instrument differs in its construction design and it rotates about a vertical axis. It also rotates only when the relative motion of the air is greater and is from a higher to a lower level. Its rate of rotation varies with this downward component of the motion of air.

The rate of rotation of a cup anemometer increases with the wind. But the forces controlling such anemometers are too complex for analysis, and accurate measures of performance can be obtained only by exposing the instrument in a wind tunnel in an air stream of controlled variability (Fergusson 1934). However, instruments with low moments of inertia are more sensitive to the wind. Therefore the fan in the F-type radiosonde has its unique features both due to its ability to function only in a downward relative wind and due to its low moments of inertia. In view of the above, the fan responds quickly to even short period fluctuations in the vertical components of the wind as met with in turbulence, which are not reflected in the rate of ascent of the balloon. This feature has been utilised to locate regions of turbulence in the upper air (Venkiteshwaran and Jayarajan 1952). In addition, it has also been possible to estimate the value of the vertical components of the gusts from F-type radiosonde records (Venkiteshwaran 1966).

In this paper, the F-type radiosonde data of Minicoy have been examined for the year 1963-64 which relates to the period of International Indian Ocean Expedition. Since it is a small island off the west coast of India, the ascents will give the features of the monsoon un-affected by orography. An examination of the levels and intensity of turbulence over Minicoy as indicated by the variations in the rate of rotation of the fan, extending even into the stratosphere, has been made in this paper. For this purpose 41 ascents which entered the stratosphere during a period of 12 months have been selected. The monthly distribution of flights is given in Table 1.

2. Variation of rate of rotation of the fan with height and its relation to the rate of ascent

If the rate of ascent of the balloon is constant, the rate of rotation of the fan should decrease with

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TABLE 1

	1964				1963								Total
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
No. of ascents	4	4	4	4	3	2	5	4	3	2	2	4	41

TABLE 2

	Variation $(\rho_0/\rho)^{1/6}$ with height (km)										
	0	2	4	6	8	10	12	14	16	18	20
						POONA					
May-Jun	1	1·02	1·05	1·09	1·13	1·17	1·22	1·28	1·33	1·42	1·52
Dec-Jan	1	1·02	1·05	1·09	1·14	1·18	1·23	1·28	1·35	1·43	1·53
						AGRA					
May-Jun	1	1·03	1·06	1·10	1·14	1·18	1·23	1·28	1·34	1·42	1·52
Dec-Jan	1	1·03	1·07	1·11	1·15	1·19	1·25	1·32	1·38	1·46	—
					Temperate Latitudes (Middleton 1943)						
Year	1	1·04	1·08	1·11	1·15	1·19	—	—	—	—	—

TABLE 3

0-5 km (kmph)	5-10 km (kmph)	10-15 km (kmph)	Above 15 km (kmph)	Average rate of ascents per whole flight (kmph)	Av. of max. height reached (km)
		Minicoy (F-type, 41 ascents)			
21·0	23·1	22·9	21·9	22·0	22
		Lucknow (C-type, 47 ascents, Oct-Nov 1966)			
23·7	25·2	28·3	26·7	26·3	19·5

TABLE 4

	0-5 km (kmph)	5-10 km (kmph)	10-15 km (kmph)	Above 15 km (kmph)	Mean max. height reached (km)
Jan-Feb 1964	22·5	24·5	26·0	22·0	21·5
Jul-Aug 1963	20·5	23·0	23·0	20·0	21·0

TABLE 5

Date	0-5 km (kmph)	5-10 km (kmph)	10-15 km (kmph)	Above 15 km (kmph)	Maximum height reached (km)
16 Feb 64	25	27	31	27	22
21 Feb 64	21	23	27	21	20

height due to the decrease in the density of the air. However, the rate of ascent of a balloon increases with height unless there is loss of hydrogen through the rubber tissue of the balloon.

A pilot balloon ascending freely attains a vertical speed v, when the air resistance D has become equal to the free lift L. D is a function of v, ρ (density of the air) and the horizontal cross-section area of the balloon, A. From wind tunnel experiments on spheres, it may be observed that—

$$D = b_1 \rho v^2 A \; (= L = \text{Constant})$$

where b_1 is approximately constant.

It follows, therefore, that—

$$\left(\frac{v}{v_o} \right)^2 = \frac{\rho_o A_o}{\rho A}$$

where v_o, ρ_o and A_o refer to conditions near ground. If V is the volume of the balloon,

$$\frac{A_o}{A} = \left(\frac{V_o}{V} \right)^{\frac{2}{3}} = \left(\frac{\rho_o}{\rho} \right)^{-\frac{2}{3}}$$

Hence, $$\frac{v}{v_o} = \left(\frac{\rho_o}{\rho} \right)^{\frac{1}{6}}$$

It is seen that the rate of ascent of a pilot balloon is not constant, but varies with the air density and therefore with height. The variation $(\rho_o/\rho)^{\frac{1}{6}}$ with height for Poona and Agra for the summer (May–June) and winter (December–January) months and the annual data for middle latitudes (Middleton 1943) are given in Table 2.

Thus the rate of ascent in the stratosphere at the 20-km level is nearly 50 per cent more than that at the ground.

The mean rate of ascent of the radiosonde balloon at Minicoy was found from the time taken by the balloon to reach heights of 5, 10, 15 and above 15 km upto the maximum height reached. Such data were also computed for the radiosonde ascents at Lucknow for these ranges, where the C-type (Chronometric type) of instrument is in use. The comparative figures can be seen at Table 3.

It is observed from the above that on the average, the rate of ascent is higher in the regions above 5 km and it tends to decrease only above 15 km. We may assume from Table 3 that in the case of Minicoy, the rate of ascent gradually increases upto about 10 km, above which it remains steady upto about 15 km, and it tends to decrease aloft. It, therefore, shows that the leakage of hydrogen by diffusion is comparatively small upto about 10 km above which it is larger as a result of which the rate of ascent remains steady and even decreases.

3. Variation of the rate of rotation of the fan with height at Minicoy

An examination of the radiosonde ascent at Minicoy brings out some interesting facts.

The mean length of paper tape in inches per one complete Olland cycle, for the months January to March, June to August and for the whole year are given in Fig. 1. Since the tape moves with the uniform speed, the length of tape per cycle is a measure of the rate of rotation of the fan; a longer length indicates slower rotation while a shorter length reflects a faster rotation. It is seen from Fig. 1 that the rate of rotation of the fan remains almost constant upto about 300 mb (9·5 km) for January to March, while it is so only upto about 400 mb (7·5 km) during the monsoon months June to August. In general, the rate of rotation is slightly less during the monsoon than during January to March. Apparently moisture deposits on the balloon fabric and makes the balloon heavier causing a reduction in the rate of ascent. As a consequence, the decrease in the rate of rotation begins at a lower level by approximately 2 km than in the dry and clear months January to March. The rate of decrease at the higher levels, above say 300 mb, is greater during the monsoon months. The mean observed rate of ascent of the balloon computed from the time taken to reach 5, 10, 15 km and at maximum height above 15 km, for the 6 flights in January–February 1964 and some flights in July–August 1963 are given in Table 4.

Fig. 2 shows the variation of the rate of rotation with height at Minicoy on 16 and 21 February 1964. The rate of rotation remains unchanged even upto about 100 mb, above which it entered the tropopause and decreased rapidly. The mean rates of ascents in layers 0-5, 5-10, 10-15 km and above 15 km are shown in Table 5.

Thus, without going into details about the occurrence of regions of turbulence as indicated by the rapid fluctuations in the rate of rotation, it appears that the constant rate of rotation is maintained by the increasing rate of ascent of the balloon. The decrease in the rate of rotation, when observed in the higher layer, is due to the rate of ascent in these regions having ceased to increase with height. It is either constant or is decreasing due to the diffusion or leakage of gas through the balloon fabric which becomes very thin at these heights.

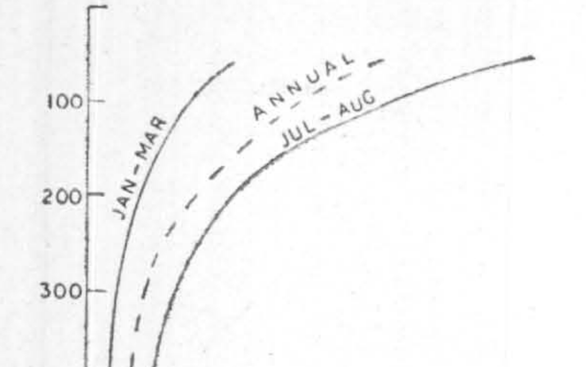

Fig. 1. Mean rate of rotation of the fan for Minicoy

4. Calculated rates of ascents of radiosonde balloons used in India (Type SR 875)

The empirical formula generally used to calculate the rate of ascent of a pilot balloon is —

$$v = b \ \frac{L^{\frac{1}{2}}}{(L+W)^{\frac{1}{3}}}$$

where the rate of ascent v is in m/min, the free lift L and the weight of the balloon W are in grams and b, the constant has the value 84. However, when larger balloons are used, the value of this constant is to be changed. For example, assuming the constant as 84, the rate of ascent of the balloon ($W = 900$ gm) used with the F-type radiosonde ($W_t = 2020$ gm), with a free lift of 1480 gm is 11·8 kmph. But the actual observed rate of ascent is 20 kmph. The constant b that has to be employed with the balloon to get the observed rate of ascent is equal to 149. In the case of balloon that is used at Lucknow with C-type instruments the constant b is 139.

5. Thickness of balloon fabric at bursting

The balloons at Minicoy reach generally 50 mb where the temperature is of the order of −75°C. Since the balloon weighing about 900 gm, is filled with hydrogen for a buoyancy of 4400 gm, the hydrogen required at N.T.P. is 3659 litres. The approximate diameter at 50-mb level is 4·68 m. Assuming a density of 0·935 gm/cm³ for rubber, the thickness of balloon at bursting is approximately 0·014 mm. Since in the above calculation the neck which is also included in the weight of balloon, does not function, the thickness of the balloon may be a little less than 0·014 mm. This is, however, higher than 0·01 mm estimated by Middleton (1943) which is probably based on the bursting diameter at ground level. If we take into consideration the effect of low temperature prevailing at 50-mb level on the balloon fabric, the bursting thickness of 0·014 mm is probably of the correct order.

6. Turbulence in the stratosphere, and in the upper tropopause from the rate of rotation of the fan

The flights of 8 and 9 January 1964 as well as on 21 February 1964 (Figs. 3 and 2b) are all associated with the increase in the rate of ascent of the balloon and it is seen that the rate of rotation of the fan has remained unchanged upto about 10 km, while above this level, it gradually decreases due to the rate of ascent not increasing further; but it will be observed that in the regions of the tropopause and above, there is large turbulence. On 8 January 1964, the turbulence at 18 km (75 mb) had caused the rate of rotation of the fan to reach approximately the value at 10 km. If we assume that the rate of ascent of the balloon continued to increase even above 10 km (26 kmph), as described in Section 2 above, it would have been about 33 kmph at 18 km; as a result, the rate of rotation of the fan could have been the same as at 10 km. But the actual average rate of ascent above 15 km was about 23·5 kmph. It may, therefore, be roughly estimated that on 8 January 1964 the vertical component of the gust in the stratosphere was about 10 kmph. Similar data for other days are given in Table 6.

The vertical components of the gusts, upward or downward, were also computed from the rate of rotation of the fan. Venkiteshwaran (1966) has shown from experiments in the wind tunnel, the variation of the rate of rotation of the fan for different wind speeds and also estimated the rate of rotation of the fan at different levels for

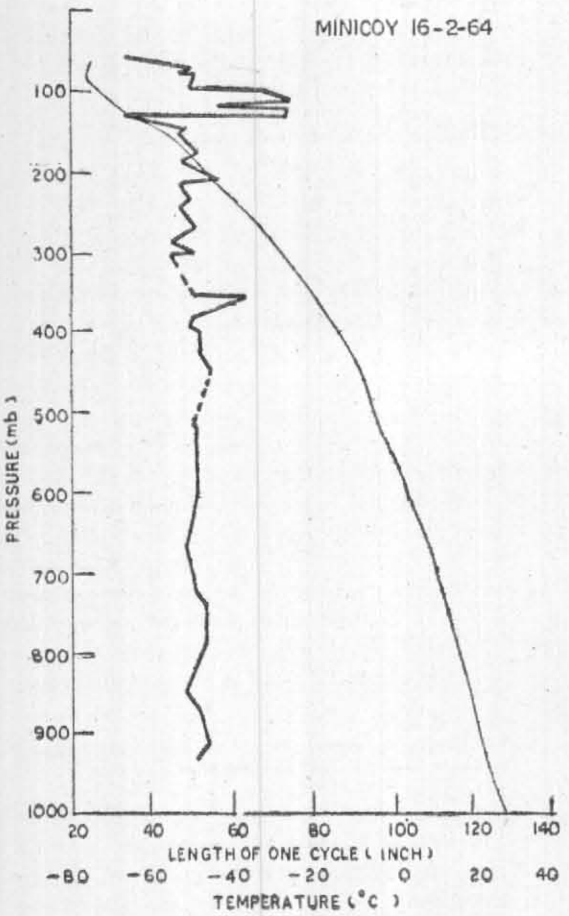

Fig. 2(a)

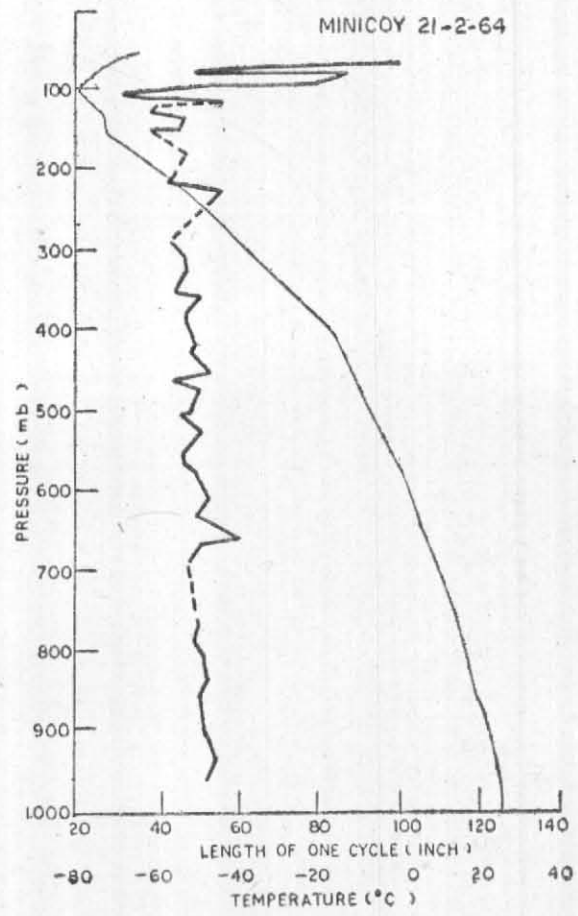

Fig. 2(b)

a uniform rate of ascent of 18 kmph. These values are given in Tables 7 and 8.

From these values and from the observations made in this paper that the rate of rotation remains unchanged at different heights due to the increased rate of ascent of the balloon, it has been possible to estimate the values of the gusts as shown in the examples. As the size and shape of the paper fan and the type of gearing have remained unchanged in the instrument, the rate 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.

Example 1 : The upward gust at 255 mb (11 km) on 8 January 1964 (Fig. 3a)—Let us take the case when the rate of rotation has suddenly decreased from 55″ of tape per cycle to 76″.

The rate of ascent of balloon on release is 22·5 kmph. Since the rate of rotation has remained unaltered, the rate of ascent at 11 km $(22{\cdot}5\times1{\cdot}2)$ is 27·0 kmph (*vide* Table 2).

The rate of rotation for 22·5 kmph near the ground (same as at 11 km when it is 27·0 kmph) is 26 imp./sec (Table 7).

The length of tape at peak of gust is 76″ and this is equivalent to $(26\times55)/76=18$ imp./sec at ground or 16·0 kmph (Table 7) which is equivalent to $16{\cdot}0\times1{\cdot}2=19{\cdot}2$ kmph at 11 km (Table 2). Therefore the value of the upward gust due to which the rate of rotation has decreased is 27-19 = 8 kmph. The air layer within which this has occurred is 25 mb at about 250-mb level. This is approximately 0·6 km.

It may, therefore, be inferred that the balloon experienced an upward gust of approximately 8 kmph in a layer of 0·6 km. Similarly, the downward gust experienced by the balloon in the subsequent gust was 15 kmph in a layer of 0·4 km.

TABLE 6

Date	Rate of ascent at start of flight (kmph)	Height of gust (km)	Observed rate of ascent in region of gust (kmph)	Computed rate of ascent for no change in rate of rotation (kmph)	Downward vertical component of gust (kmph)
8-1-64	22·5	20	23·5	34	10·5
9-1-64	23·5	20	21	36	15
21-2-64	21·5	18	21	31	10
4-7-63	21·0	14	17	27	10

TABLE 7

Speed of wind (kmph)	No. of impulses/sec
30	33
24	27
18	22
12	13

TABLE 8

Height (km)	No. of impulses/sec
Near ground	22
8	18
12	15
16	9

Example 2 : *Downward gust at 90 mb (17 km) on 8 January 1964* (Fig. 3a) — In the earlier example, the vertical component of the gust was calculated when the rate of ascent of the balloon increased uniformly, maintaining the rate of rotation unchanged, when there were no effects due to turbulence. But above 250 mb, the rate of ascent of the balloon was decreasing. The rate of rotation of the fan corresponding to no effects of turbulence, will be represented by the smooth curve above 250 mb passing through the centres of the regions of turbulence which cause the fan to go faster and slower alternately.

The rate of ascent of balloon at start of flight = 22·5 kmph = 26 imp./sec (tape length of 55″) (Table 7).

The rate of rotation at 90 mb (17 km), if no turbulence existed is given by a tape length of 83″ which is equivalent to (26×55)/83 = 17 imp./sec. 17 imp./sec represents a rate of ascent of balloon of 16 kmph near the ground (Table 7) and it is equivalent to 22·4 kmph at 17 km (Table 2).

At the highest value of the downward gust, the rate of rotation was equivalent to about 55″ of tape, *i.e.*, 22·5 kmph near the ground or 31 kmph at 17 km. Therefore, the downward gust = 31·0—22·4 = 8·6 kmph. This was affecting the balloon in a layer of about 0·4 km.

Similarly the vertical components and the thickness of the gusts were calculated for a number of cases from the radiosonde ascents for a few days and they are given in Table 9.

It is observed that the vertical components of the gusts in the tropopause/stratospheric regions are of the order of about 10 kmph. It may not be feasible to record higher values in these regions, because the balloon becomes very fragile. However, values of the order of 15 kmph and 19 kmph have been observed at 7 and 11 km respectively. It is, therefore, possible with this technique to estimate the values of vertical components of the gusts and their thicknesses at all levels in the atmosphere. While Table 9 gives the thicknesses of individual gusts the thickness of the turbulent region can be much greater.

7. Other evidences of turbulence in the stratosphere

The above observations are direct evidence for the existence of turbulence in the stratosphere; the approximate value of vertical components of the gust in these flights is about 10 kmph.

It will be noticed that the radiosonde record generally terminates abruptly under these turbulent conditions, where the balloon fabric is only about 0·014 mm thick.

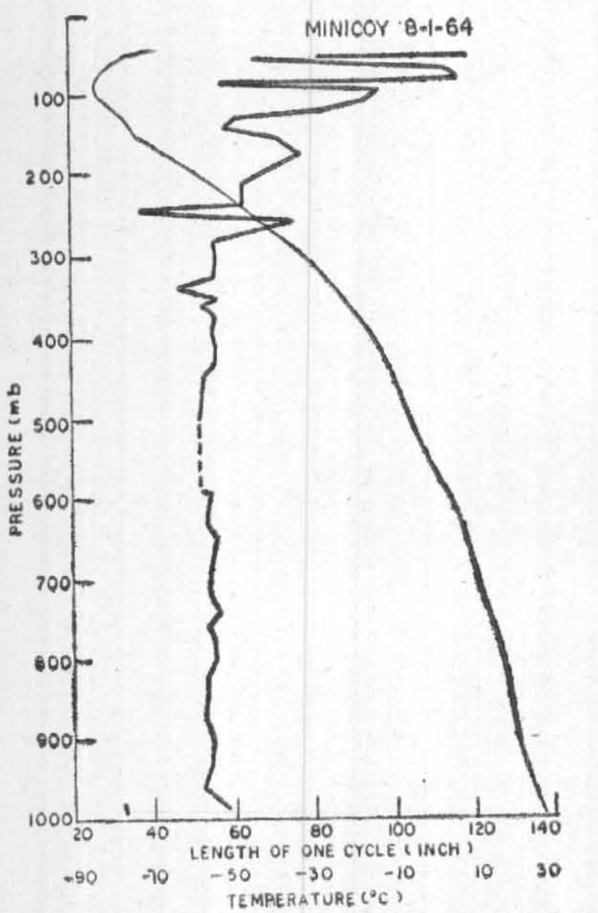

Fig. 3(a)

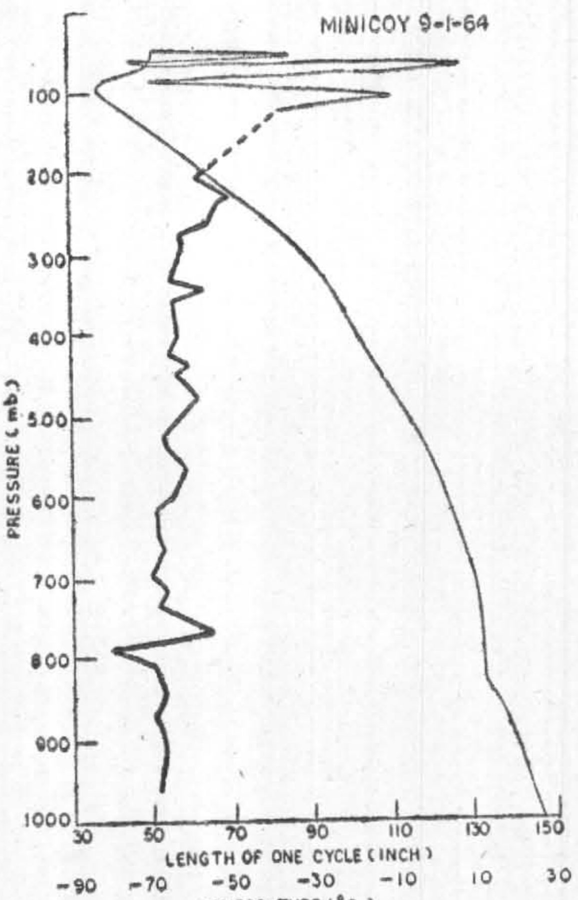

Fig. 3(b)

Prior to the introduction of radiosonde in India, Dines' meteorograph ascents were being made. These often showed a blur at the end of the trace in the stratosphere. This blur is noticed not only in the temperature trace but also on the humidity trace and the datum pen at corresponding position. Since all the pens are joined to a frame which shifts with pressure, it appears that the blurs are associated with the vibrations experienced by the aneroid. The only possible cause of such vibration appears to be the existence of turbulence in the stratosphere.

Sinha (1954) has examined the blur occurring in the records of Dines' meteorograph ascents at Agra, and he found that in 250 records examined, the blur occurred above 16 km on 66 occasions, and in 26, they were at about 26 km. Mani *et al.* (1959) studied the Dines' meteorograph ascents in the region of Poona-Hyderabad and Madras-Bangalore. In the Poona-Hyderabad region, the number of flights studied was 126, and of these, 22 had blurs above 100 mb (16 km). In the case of Madras-Bangalore, the corresponding figures were 180 and 79. It was observed that the mean level of turbulent region was about 23 km.

Arnold (1954) observed considerable turbulence in the stratosphere on 4 different occasions at Balmar, New Jersey, while tracking balloons with a telescope and a radio-direction finder. The turbulence was so severe that the radiosonde separated from the balloon though it was suspended by a cord with a nominal breaking strength of about 70 lbs. During these observations in June 1960, the instrument separated from the balloon at heights ranging from 28 to 30 km, while in the observation in October, it separated at 24 km. He has estimated that an ascending current of about 10 m/sec could provide the necessary condition for a free fall of sonde of about 10 ft which could break the line.

As already stated in the previous para, all flights for Minicoy were made after sunset, and, therefore, the balloon fabric was not affected

TABLE 9

Date	Rate of ascent immediately on release of balloon (kmph)	Height of gust	Rate of ascent with no turbulence (computed) (kmph)	Rate of ascent at peak of gust (computed) (kmph)	Vertical component of gust (kmph)	Approximate thickness of gust (km)	Direction of gust
8-1-64	22·5	255 mb (11 km)	27·0	19·0	8·0	0·6	Upward
8-1-64	22·5	240 mb (11 km)	27·0	42·0	15·0	0·4	Downwad
8-1-64	22·5	90 mb (17 km)	22·4	31·0	8·6	0·4	Downward
8-1-64	22·5	75 mb (18 km)	22·4	16·0	6·4	0·4	Upward
9-1-64	23·5	90 mb (17 km)	22·0	32·5	10·5	0·8	Downward
9-1-64	23·5	65 mb (19 km)	22·0	13·0	9·0	1·2	Upward
9-1-64	23·5	57 mb (18·5 km)	21·0	28·0	7·0	0·6	Downward
21-2-64	21·5	85 mb (18 km)	31·0	20·0	11·0	1·2	Upward
16-6-63	21·0	200 mb (12 km)	25·0	14·5	10·5	0·5	Upward
13-7-63	19·0	425 mb (7 km)	19·0	38·0	19·0	0·3	Downward
21-7-63	21·5	210 mb (12 km)	20·0	23·0	3·0	0·25	Downward
21-7-63	21·5	200 mb (12 km)	20·0	17·0	3·0	0·25	Upward
21-7-63	21·5	150 mb (14 km)	20·0	25·5	5·5	0·4	Downward
26-8-63	19·0	165 mb (13 km)	24·0	17·0	7·0	0·6	Upward

by solar radiation. Similarly, all the Dines' meteorographs were released only after the sunset. It has been observed that in the flights made during the day, the balloon fabric was warmed up by the solar radiation and, therefore, hydrogen diffused through the fabric rapidly, at higher levels, as a result of which the rate of ascent was affected. Turbulence was, therefore, not so frequently observed during these day flights.

Thus the F-type radiosonde balloons show clearly the occurrence of turbulence in the tropopause and lower stratosphere over Minicoy. It also gives an estimate of the vertical components of the gusts associated with the turbulence. It has, however, to be noted that the balloon is very fragile, and particularly so at the higher level, and as such turbulence exceeding a certain degree cannot be recorded since the balloon will not be able to withstand the same.

8. Turbulence in the strong easterlies over Minicoy during the monsoon

It has already been shown that the horizontal wind does not affect the rate of rotation of the fan (Venkiteshwaran and Jayarajan 1952). This feature has been observed with the Minicoy flights also. But during the monsoon the observed sharp changes in the rate of rotation of fan at Minicoy, in the regions of strong winds is due to turbulence only.

The winds increase in speed with height above the 400-mb level at Minicoy and reach the maximum of about 60-80 kt between 100-150 mb above which they rapidly decrease to values between 20-40 kt and increase again at higher levels. The region of minimum wind here generally corresponds with the level of tropopause with minimum temperature. The region of turbulence is generally in the regions of strongest winds below the tropopause. It occurs sometimes also

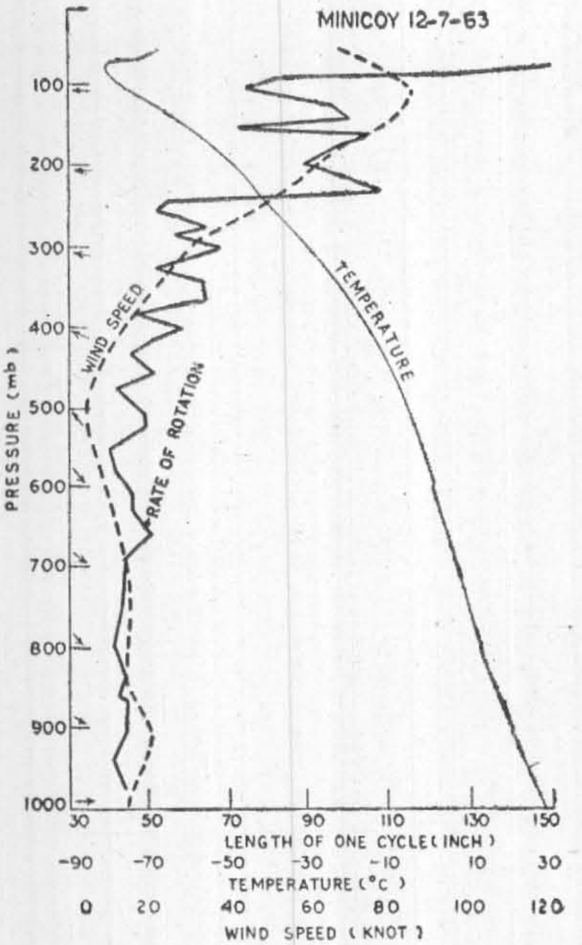

Fig. 4(a)

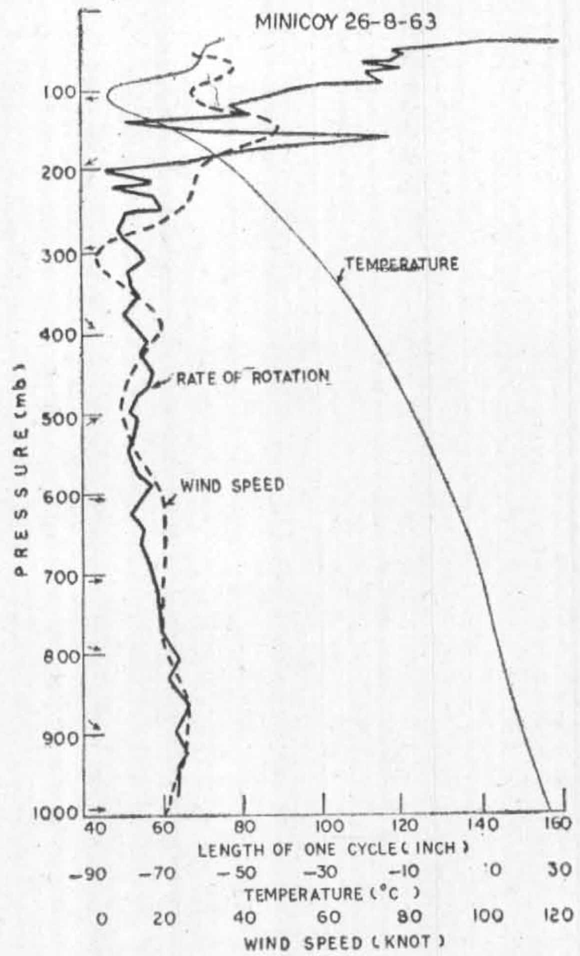

Fig. 4(b)

in the levels below the region of these strongest winds. However from the available data, turbulent regions have not been observed above the 100-mb level as in winter. It appears from these observations that the tropopause is the lower boundary of turbulence in the winter. The upper limit is not known from the available data. On the other hand during the monsoon, the tropopause is the upper layer of turbulent region. These are very significant features of the turbulent regions in the upper tropopause and lower stratosphere.

9. Thickness of regions of turbulence in the upper troposphere and in the lower stratosphere

During January–March, the turbulence generally starts at about 150–100 mb and is observed till 50-mb level where the balloon bursts. One may, therefore, infer that during these months the thickness of the turbulent region is at least 4 km above the 15-km level. The extent and intensity above 20-km level is not known, because of the balloons not reaching higher heights. However, in the months June–September, when the prevailing winds over Minicoy are due to southwest monsoon, the turbulent regions are below the tropopause and in the upper troposphere. They begin at about 250 mb and extend upto about 100 mb, *i.e.*, a thickness of approximately 5-6 km. This region corresponds generally to the level of the strong easterly current over Minicoy.

The existence of turbulence above the tropopause in the winter months and its shift to regions below the tropopause and in the upper troposphere in the other months is significant. It appears from these observations that turbulence is a characteristic feature of the circulation in the upper atmosphere.

Aviation is making rapid progress and supersonic transport is not far. The structure of the first prototype of the Concorde, on which Sud-Aviation of France and the British Aircraft Corporation of Great Britain are working on a 136 passengers, Mach 2·2 (1450) transport is likely to make its first flight soon. Similar

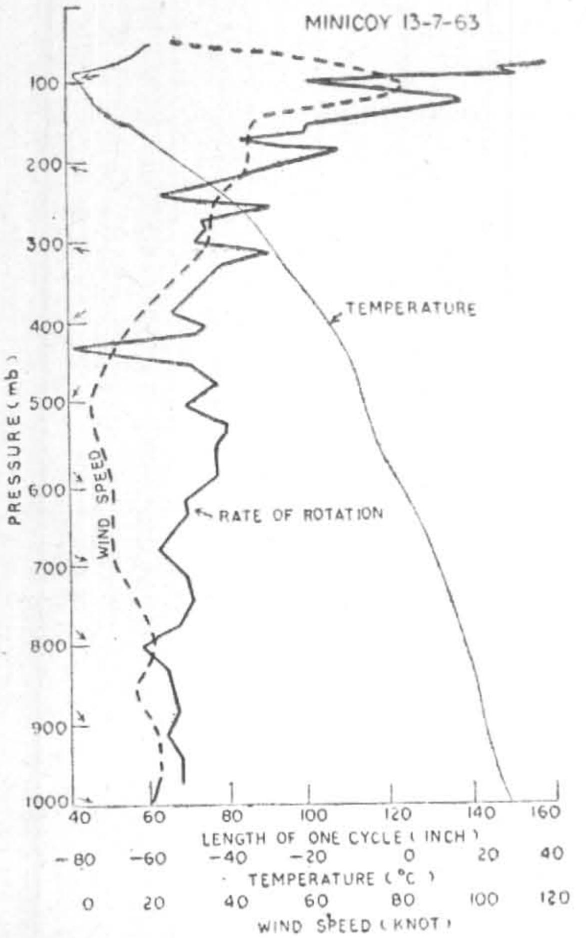

Fig. 5

supersonic transport are being planned in the U.S.A. and the Soviet Union. The speeds will be between 1400 to 1800 mph and the altitude of these planes will be between 60,000 to 70,000 ft. These transport planes will, therefore, be cruising in the stratosphere. These observations of turbulence described in the present paper may be of some value to this programme.

10. Turbulence in the lower troposphere

Turbulence, as indicated by significant changes in the rate of rotation of the fan, is not a frequent occurrence during January–April in the regions below the 400-mb level at Minicoy. It does occur occasionally in the regions of l rge changes in the lapse rate (F g. 3 b). Turbulence associ ted with inversions have been located by Jayarajan (1953) at other stations also from the rate of rotation of the fan. This feature has been noticed by Anderson (1957) with gust sondes, in the U.S.A., in connection with troposph ic inversions. He found that regions above and below inversions are associated with above normal turbulence. Sinha (1954) also observed that turbulence often occurs under extreme conditions of temperature, *e.g.*, high lapse rate or inversion.

It is noticed that the deep westerly monsoon current extending into even 8 km is not turbulent. However, a sharp region of turbulence is sometimes observed in the region where the westerlies change over to the easterlies (Fig. 5). However, this has been observed only in a few flights, and not in every one.

11. Acknowledgements

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