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Vertical gust velocities and variations in normal *g* associated with clear air turbulence and turbulence in cumulus clouds as studied from 'ESE data'

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ABSTRACT . 'Exercise Storm Exchange' (ESE) is a name given to the Project in which an RAF Canberra aircraft PR 7/9 was lent to India for undertaking atmospheric studies. The aircraft was flown in India during June to September 1972 from Bangalore, Pune, Calcutta and Agra, to study the synoptic and meso-scale systems in the summer monsoon circulation over India.

This paper deals with the analysis of the data on variations in normal gravity (g) and vertical gusts (Vg) encountered by the aircraft in two different conditions—(1) in clear air while it was flying at different levels in the upper troposphere between Bangalore and Trivandrum in July 1972 and (2) while it was flying through growing cumulus clouds in the vicinity of Bangalore on 20 September 1972. Using the data extracted at 0·1 second intervals, the vertical gust velocity and the variations in normal gravity were evaluated and this data has been analysed. The analysis showed only light or moderate turbulence in the fast easterly field between 20000 and 50000 ft over Peninsular India. Moderate to severe turbulent conditions were encountered while probing the cumulus clouds. The maximum gust velocity in the former case was 17·5 ft per sec and in the later case 32·5 ft per sec.

1. Introduction

1.1. During the last two decades studies on atmospheric turbulence in clear air and in clouds have been made using instrumented aircraft in many countries (*e.g.*, Fankhauser and Lee 1967, Burnham and Lee 1969, Lee 1971, Carlson and Sheets 1971). Such studies were made for the first time in India in the summer of 1972 when the Royal Aeronautical Establishment, Farnborough, U. K. loaned a Canberra aircraft PR 7/9 equipped with scientific instruments to India to undertake studies on atmospheric conditions. Details of the scientific equipment and the different atmospheric studies conducted by utilising this aircraft have been described elsewhere (National Aeronautical Laboratory 1973, Bhaskara Rao *et al.* 1974).

1.2. Rough air conditions are encountered by the aircraft both in clear air and in cumulus clouds. In clear air the turbulence is generally associated with strong vertical wind shear. During the summer monsoon months, strong easterly winds prevailed over the Peninsular India in the upper troposphere, overlying the westerly flow in the lower troposphere. The easterlies strengthened with height and reached maximum around 16 km a.s.l. where an easterly jet stream usually exists at this level with its mean position near about 12°N over Peninsular India. Strong vertical wind shears can be expected above and below the level of maximum wind. The aircraft was flown between Bangalore and Trivandrum at different levels to study the nature of turbulence associated with this fast easterly flow.

1.3. The aircraft was not intended to fly in severe convective clouds. However, it could penetrate safely in cumulus clouds of moderate vertical extent. So on 20 September 1972 the aircraft was flown through the growing cumulus clouds at different levels to obtain turbulence data. The data pertaining to the above two cases have been processed to obtain the vertical gust velocities and the variations in g. The results are presented in this paper.

2. Data

2.1. The parameters that need be digitised from the continuously recording autographic charts for obtaining vertical gust velocity are the angle of incidence (a), the pitch angle (θ), the normal gravity (g), indicated air speed (Vi), pressure altitude (H), and indicated outside temperature (T_0).

2.2. As temperature record was available only on the slow recorder which has one second time marks the digitisation of the parameters Vi, T_0 and H were made only at one second intervals.

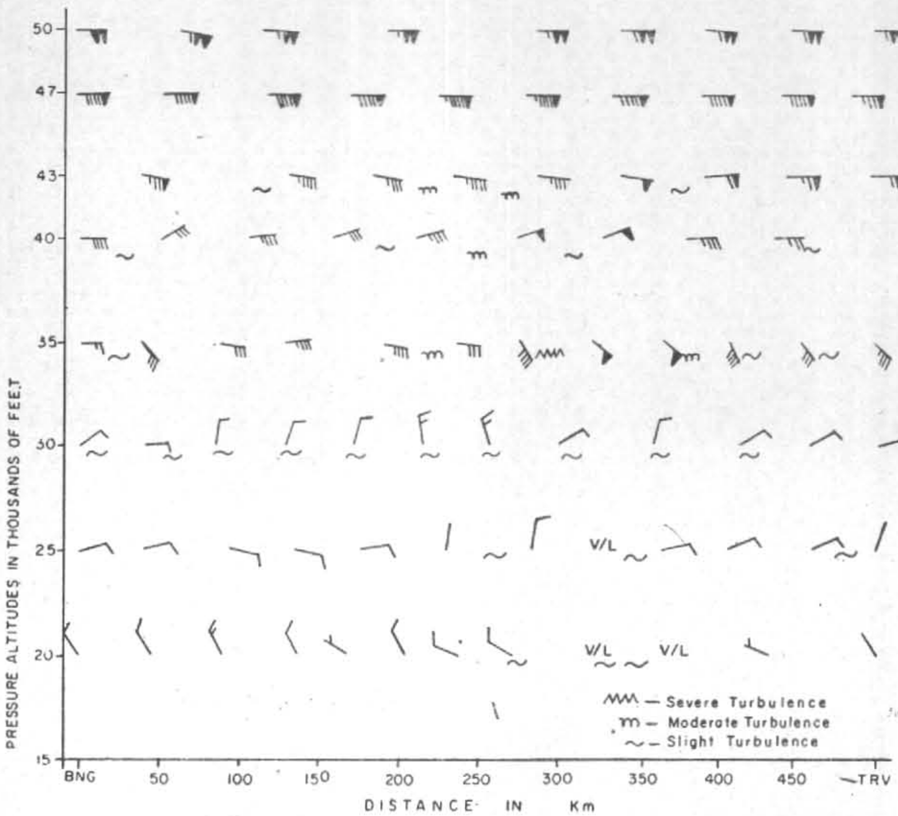

Fig. 1. Winds and turbulence of different levels obtained from Navigator's log

Digitisation of the rest of the parameters was done at 0·1 second intervals. The true air speed was calculated at one second intervals and utilised for calculating the vertical gust velocity.

2.3. The vertical gust velocity is worked out using the formula.

$$V_g = V_T\,(\alpha - \theta) + L_g + \int^t N_g\, dt$$

where V_T is the true air speed, α is the angle of incidence, (positive for nose up condition) θ is the pitch attitude (positive for nose up attitude), L is the distance between the centre of gravity of the aircraft and the incidence vane located on the nose pole of the aircraft, q is the pitch rate (positive in the positive direction of pitch attitude), N_g is the normal acceleration measured as difference from the value of one g and t is the time. Both the angle of incidence and pitch attitude are referred to aircraft axis (Exercise Storm Exchange Project Report, 1973).

3. Case I—Clear Air turbulence and upper torpospheric easterlies

3.1. On 25 July 1972, the aircraft flew between Bangalore and Trivandrum at flight levels 200, 250 300, 350, 400, 430 470 and 500 (approximately).

The aircraft was in clear air at all levels. Scattered cumulus clouds with small vertical extent were observed below the flight levels along the track. Large *Cb* build ups were noticed out at sea to the south and west of Trivandrum. Some large cumulus were also observed about 50-100 miles to the west of the track between 10° and 11°N.

The slow recorder was on continuously. The fast recorder was switched whenever rough air conditions were encountered. The purpose of this experiment was two fold. One is synoptic scale study of the structure of the easterly flow over Peninsular India in the upper half of the troposphere during the southwest monsoon period. This aspect has been studied and the results have been published (Bhaskara Rao *et al.* 1974).

3·2. The second purpose was to study the nature and amount of turbulence that may be expected in the fast easterly flow. Considerable vertical wind shears are often observed in synoptic data between 12 and 18 km asl associated with the easterly jet. The Canberra aircraft had a ceiling of about 55000 ft (16·8 km) but was flown up to flight level 500 only (50000 ft=15·2 km) due to some technical difficulties. Thus only the flow below the jet level could be explored.

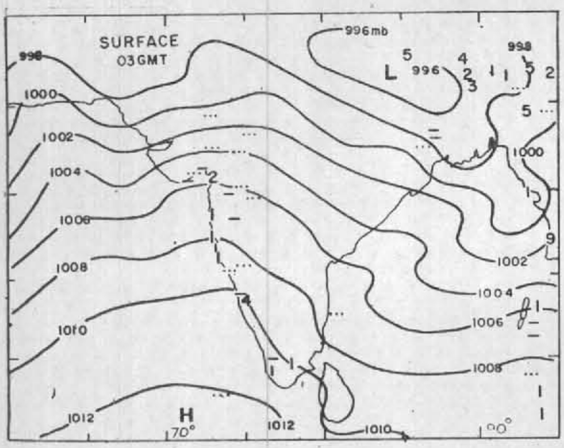

Fig. 2. Surface isobar & rainfall at 0300 GMT on 25 July 1972

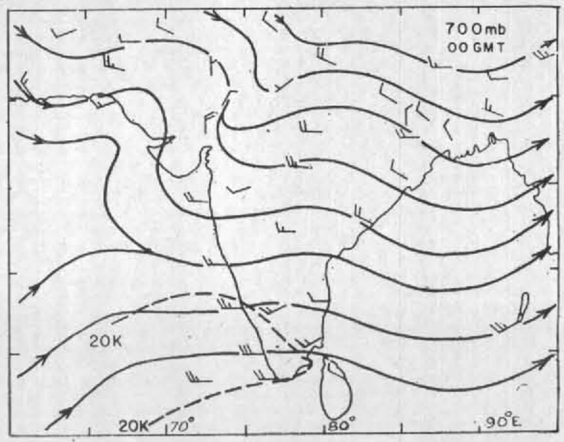

Fig. 3. Winds and Streamlines at 700 mb at 0000GMT on 25 July 1972.

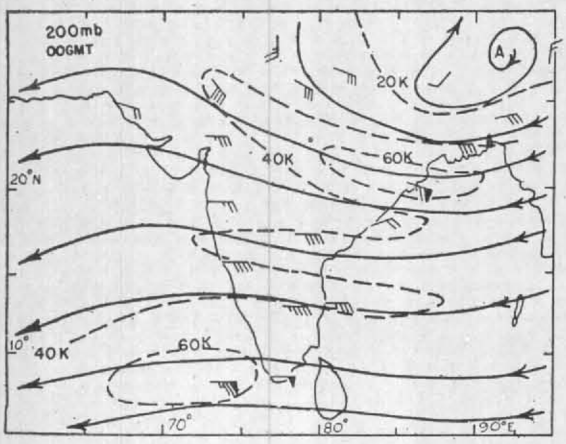

Fig. 4. Winds and Streamlines at 200 mb at 0000GMT on 25 July 1972

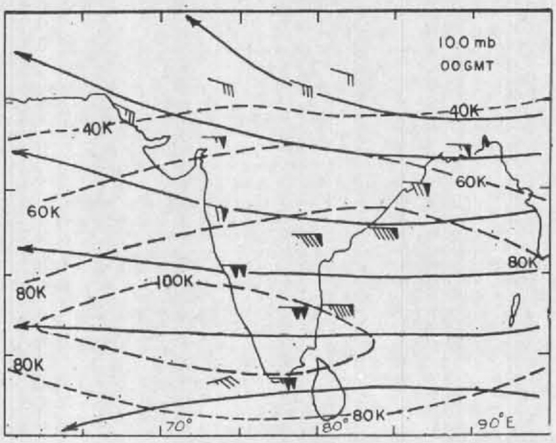

Fig. 5. Winds and stream lines at 100 mb at 0000GMT on 25 July 1972

3.3. According to pilot/navigator's log and debriefing reports light, moderate and severe turbulence in the clear air was encountered at various levels of flow. Fig. 1 shows the winds obtained from the navigator's logs at different heights between Bangalore and Trivandrum and the location of turbulence and their intensity, encountered during these flights.

3.4. *Synoptic situation*

Fig. 2 shows the surface isobars and the rainfall at 03 GMT of 25 July 1972. Figs. 3 to 5 show the upper air flow patterns at 700, 200 and 100 mb levels at 00 GMT of that day. Synoptic data indicated that the easterly jet was located near about latitude 13°N over the Peninsular India on this day. The southwest monsoon was generally weak over the country on this day. Incidentally 1972, was a *drought year* in India.

3.5. *Turbulence*

3.5.1. All told there were 31 patches of rough air conditions encountered during these flights (Fig. 1); out of which, the pilot/navigator has reported 25 cases as light, 5 as moderate and one as severe.

3.5.2. The total duration of all the rough air conditions encountered works out to be 13 min 35 sec out of total flight time of 5 hr 28 min giving a percentage of rough air condition to the total flight time as 4 per cent.

3.5.3. CAeM V 1971 has recommended that both the aeronautical and the research meteorologists be urged to adopt the following turbulence reporting criteria, in order to improve subjective description of moderate and severe turbulence :

TABLE 1

Maximum changes in normal gravity g encountered in the different patches of rough air on 25 July 1972

S. No	Time (IST)	Ht. (ft)	Position of the turbulent patch		Subjective description of turbulence as given in Pilot/Navigator's log	Max. g	Min. g	Maximum change g
			Lat. (°N)	Long. (°E)				
1	0919·8	20000	10° 27′	77° 25′	Slight	1·04	0·92	0·10
2	0924	20000	10° 03′	77° 22′	Do.	1·00	0·96	0·04
3	0926	20000	09° 36′	77° 18′	Do.	1·17	0·89	0·26
4	·0945	25000	08° 59′	76° 55′	Do.	1·00	0·96	0·04
5	0956·5	25000	09° 59′	77° 06′	Do.	1·00	0·96	0·04
6	1002·8	25000	10° 35′	77° 14′	Do.	1·00	0·96	0·04
7	1030·3	30000	12° 38′	77° 33′	Do.	1·04	0·92	0·12
8	1034	30000	12° 18′	77° 28′	Do.	1·07	0·96	0·08
9	1036	30000	11° 58′	77° 25′	Do.	1·07	0·92	0·08
10	1038	30000	11° 38′	77° 22′	Do.	1·00	0·85	0·11
11	1041·3	30000	11° 18′	77° 17′	Do.	1·15	0·91	0·19
12	1044	30000	10° 56′	77° 14′	Do.	1·07	0·92	0·12
13	1050	30000	10° 15′	77° 08′	Do.	1·04	0·96	0·08
14	1054·5	30000	09° 46′	77° 05′	Do.	1·11	0·85	0·17
15	1058	30000	09° 18′	76° 58′	Do.	1·00	0·94	0·08
16	1114·3	35000	09° 09′	76° 44′	Do.	0·98	0·87	0·07
17	1115	35000	09° 23′	76° 48′	Do.	1·02	0·94	0·06
18	1118	35000	09° 14′	76° 53′	Mod.	1·15	0·81	0·34
19	1123·5	35000	10° 31′	76° 59′	Severe	1·26	0·70	0·45
20	1127·5	35000	10° 52′	77° 01′	Mod.	1·30	0·78	0·41
21	1140	35000	11° 20′	77° 14′	Slight	1·15	0·81	0·19
22	1142	35000	12° 44′	77° 23′	Do.	1·15	0·85	0·30
23	1421·7	39700	12° 40′	77° 40′	Do.	1·29	0·51	0·44
24	1433·2	40000	11° 29′	77° 27′	Do.	0·92	0·62	0·23
25	1435	39990	10° 58′	77° 22′	Mod.	1·03	0·44	0·44
26	1440	40150	10° 24′	77° 17′	Slight	1·00	0·51	0·34
27	1452	40000	08° 55′	77° 02′	Do.	1·00	0·62	0·38
28	1515	42950	09° 26′	77° 04′	Do.	1·11	0·47	0·45
29	1525·4	52950	10° 27′	77° 14′	Mod.	0·92	0·51	0·33
30	1531·2	42200	11° 18′	77° 25′	Do.	1·00	0·51	0·33
31	1535·8	42800	11° 42′	77° 29′	Slight	1·03	0·47	0·33

Moderate turbulence—Changes in accelerometer reading between 0·5 and 1·0 g.

Severe turbulence — Changes in accelerometer reading greater than 1·0 g.

This was earlier recommended by Sixth Air Navigation Commission also in 1969.

3.5.4. Table 1 shows the maximum changes in normal gravity (g) encountered in the different patches of rough air during these flights. It can be seen from the table that in none of these cases the limits of moderate or severe turbulence suggested by the Air Navigation Committee have been encountered. In general the pilot's estimate are on the higher side than the objective classification as per the criteria given by the CAeM (1971).

A typical example of the variations in vertical 'gust' in a period of seven seconds is shown in Fig. 6.

3.5.5. The frequencies of vertical gust obtained by analysis of data of 3 patches of rough air conditions which have been described by the pilot as light, moderate, severe are shown in Fig. 7. With a view to examine whether there are preferential

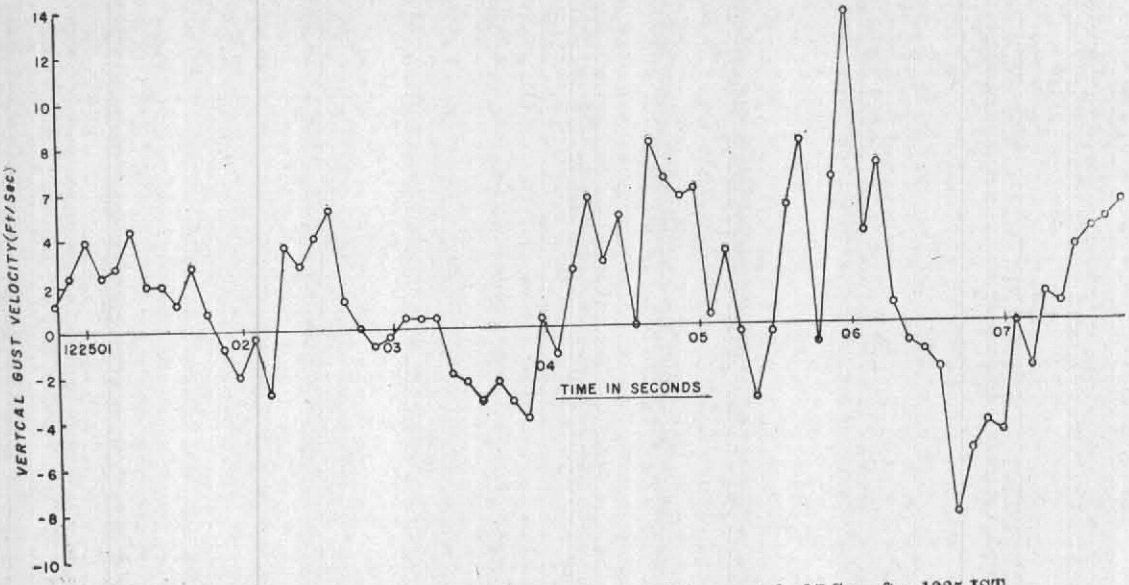

Fig. 6. Variation in vertical gust velocity which occured in a period of 7 Sec after 1225 IST

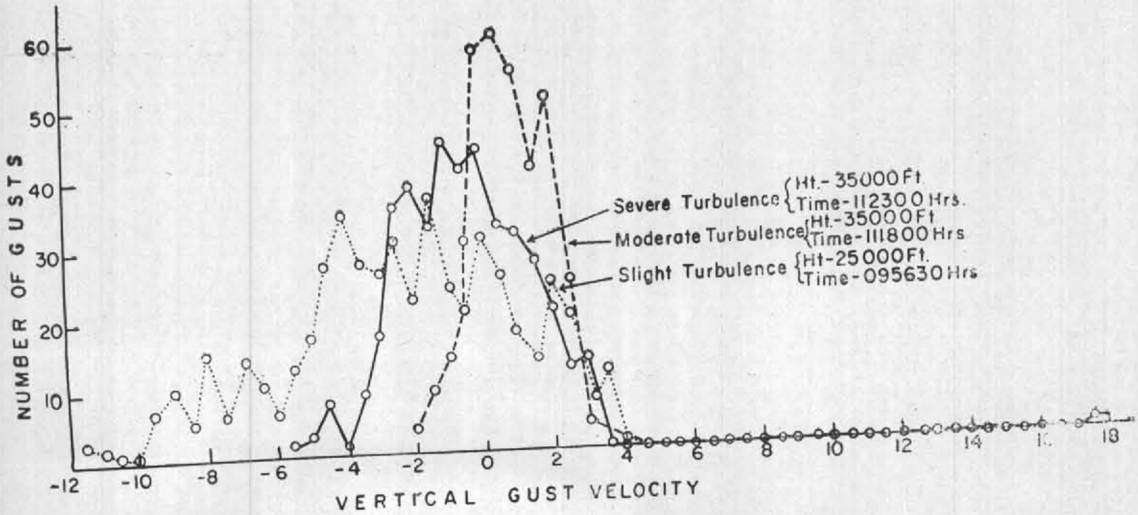

Fig. 7. Frequencies of vertical gust **for three types of turbulence**

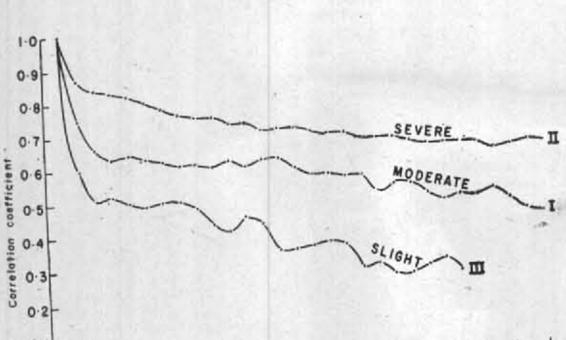

Fig. 8. Auto-correlation coefficient of gust velocity with different lags (0·1 sec interval)

periodicities in the eddies associated with different types of turbulence encountered, the data was analysed and the auto-correlation coefficient for different lags were done. Fig. 8 shows the auto-correlation coefficient for the three cases of turbulence. To eliminate the trends auto-correlation coefficient were also calculated for changes in the gust velocities (Fig. 9). These analyses did not show any preferential periodicity in the worked out data.

4. Case II—Turbulence in growing cumulus cloud

4.1. *Synoptic situation*

The surface isobars along with rainfall on 20 September 1972 (03 GMT) are shown in Fig. 10.

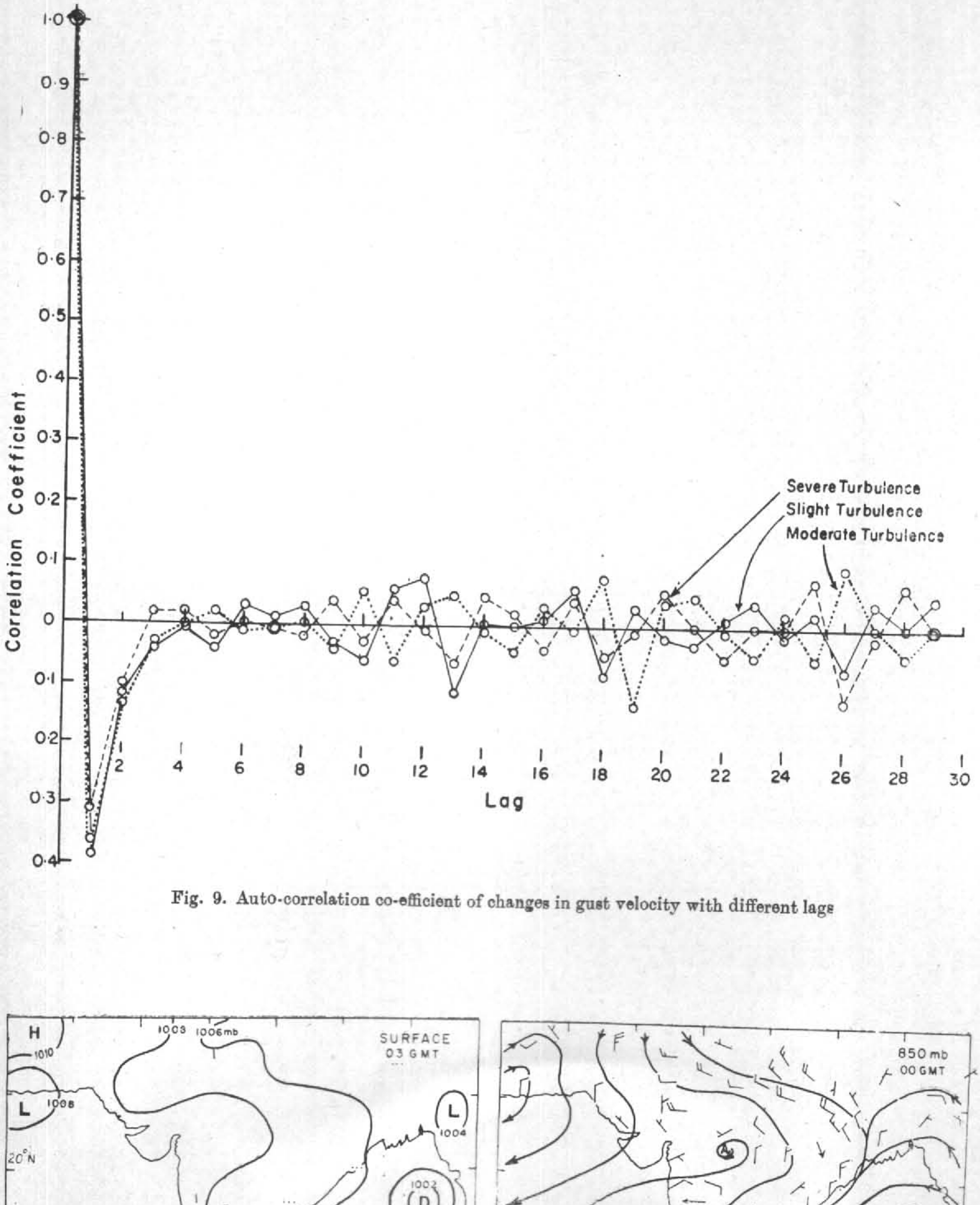

Fig. 9. Auto-correlation co-efficient of changes in gust velocity with different lags

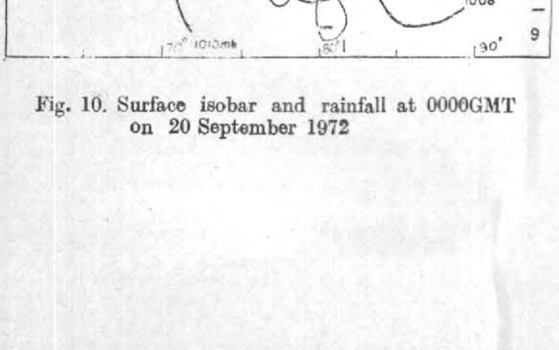

Fig. 10. Surface isobar and rainfall at 0000GMT on 20 September 1972

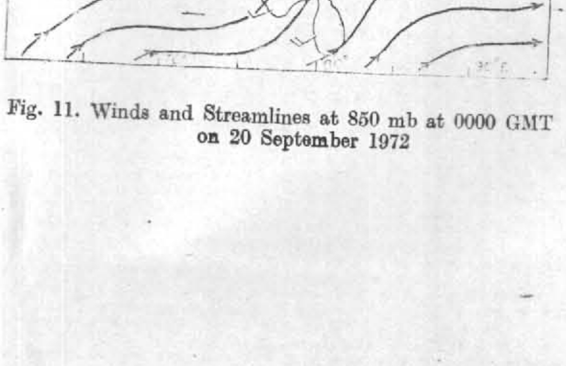

Fig. 11. Winds and Streamlines at 850 mb at 0000 GMT on 20 September 1972

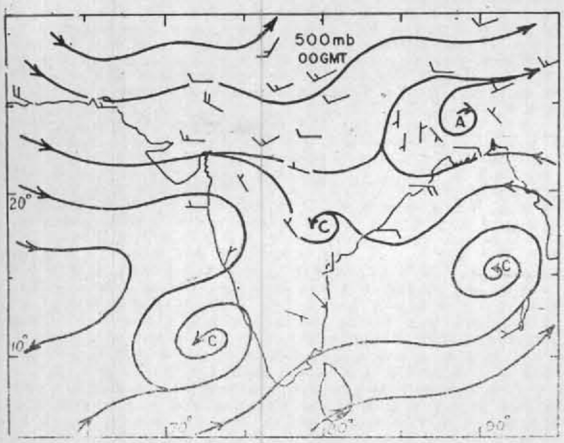

Fig. 12. Winds and Streamlines at 500 mb at 0000 GMT on 20 September 1972

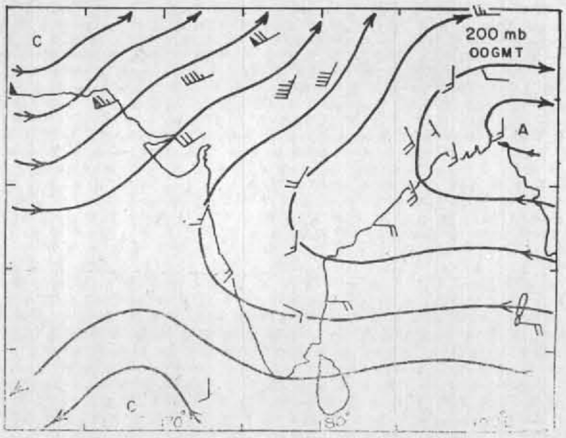

Fig. 13. Winds and Streamlines at 200 mb at 0000 GMT on 20 September 1972

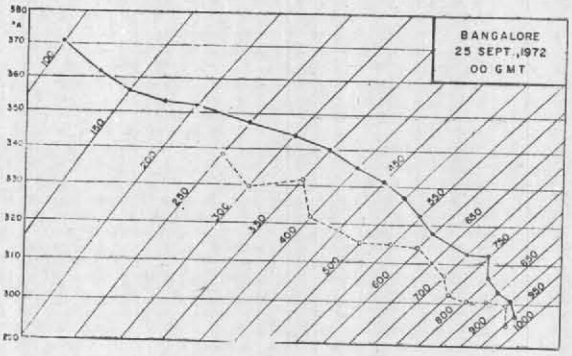

Fig. 14

The flow patterns at 850, 500, 200 mb are shown in Figs. 11, 12 and 13. Monsoon was weak on this day also, but a good amount of convective activity was taking place in the interior parts of the Peninsular India. There were plenty of large and small cumulus clouds scattered around Bangalore on this day. The tephigram of Bangalore is shown in Fig. 14.

4.2. The flights were arranged so that the aircraft can probe into growing cumulus clouds of vertical extent of about 10000 ft at different levels. The first probe was made at 5000 ft (at about 1220 IST) when the cloud was having the base at 3000 ft and top around 10000 ft. Further probes were made at 6000, 7000, 8000, 9000 ft and by that time the cloud has grown considerably and further penetrations were abondoned. Another nearby small cumulus of moderate extent was chosen for penetration. Probes were made at 5600, 8000, 10000 and 12500 ft. As even this cloud was growing rapidly and severe turbulence was being encountered, further probes were abondoned.

4.3. *Turbulence data*

4.3.1. Table 2 shows the maximum change in g encountered during the different probes with the two cumulus clouds. The data in this table are on similar lines to those shown in Table 1. It can be seen by comparison of the two tables that the turbulence encountered in these cases were of much greater severity than that encountered in the previous case.

4.3.2. The frequency distribution of vertical gusts of different velocities obtained from the data for all the probes are shown in Fig. 15. These figures also indicate that turbulence even in a cumulus cloud of moderate extent is far greater than that encountered in the clear air of the earlier case.

4.3.3. As in the case of the clear air turbulence auto-correlation coefficients were made for these data also. The data did not indicate any preferential periodicity in the vertical velocity data.

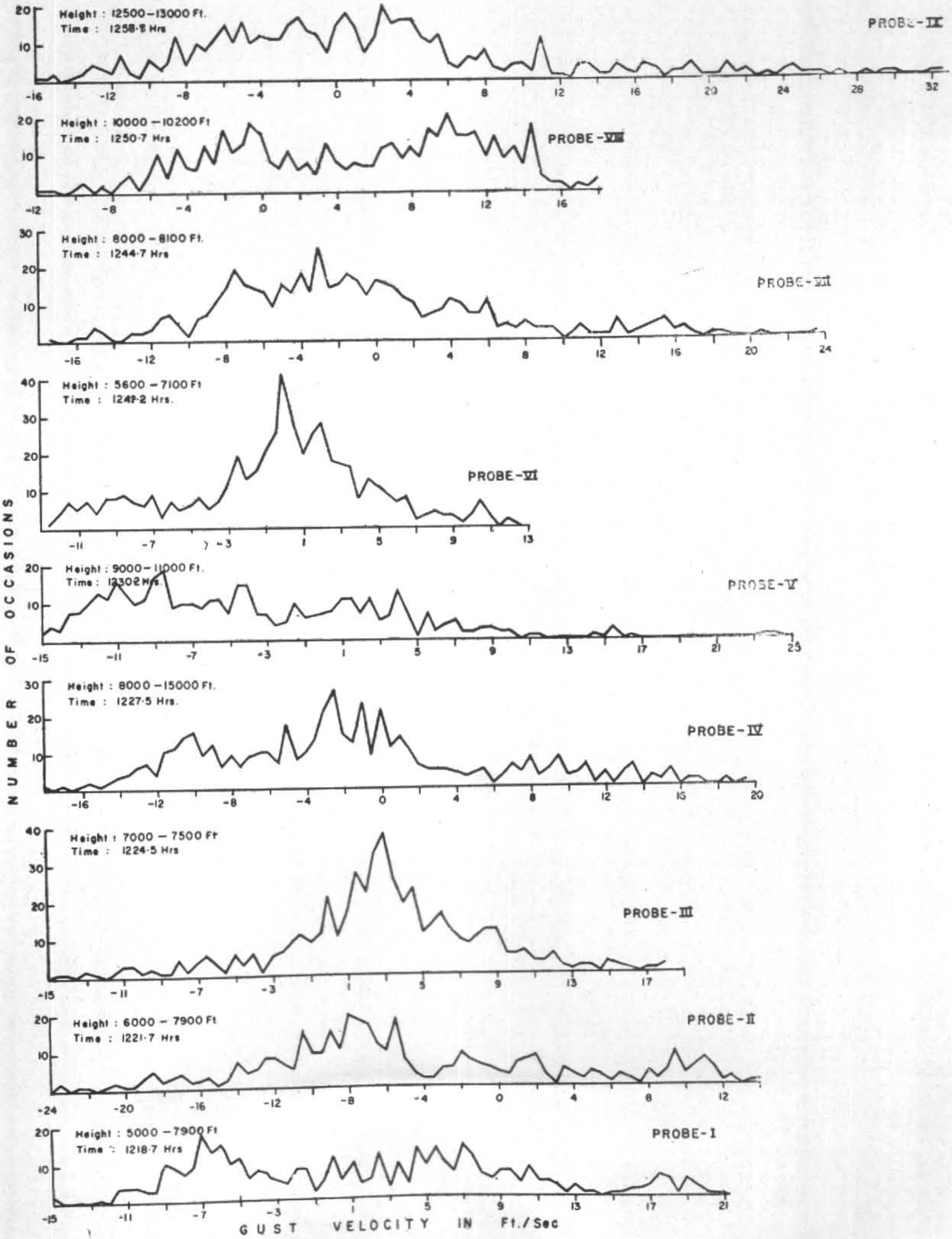

Fig. 15. Frequency of vertical gust velocity obtained from the data of the probes made in *Cu* clouds plotted at 0·5 ft/sec range, e.g., 5·1-5·5 ft/sec plotted at 5·5.0 corresponds to —0·5 to 0·0

TABLE 2

Maximum change in g encountered while flying through Cu clouds on 20 Sep 1972

Time (IST)	Ht (ft)	Subjective description of turbulences as given in Pilot/ Navigator's log.	Max. g	Min. g	Maximum change g
1218·7	5000	Slight	1·30	0·68	0·44
1221·7	6000	Do.	1·31	0·53	0·32
1224·5	7000	Do.	1·33	0·55	0·64
1227·5	8000	Mod.	1·41	0·82	0·36
1230·2	9000	Severe	2·04	0·25	1·16
1239·8	5600	Mod.	1·37	0·62	0·45
1244·7	8000	Do.	1·86	0·25	0·97
1250·7	10000	Severe	1·89	0·21	0·97
1257·5	12500	Do.	1·89	0·23	1·60

Note: Position of the turbulent patch ÷ near about Bangalore

4.3.4. The variations in the height of the aircraft as it penetrated the cloud are shown in Fig. 16. It can be seen from the figure that in almost all cases the aircraft gained height during its flight through the clouds which is well in keeping with the fact that the cloud chosen was a growing convective cloud. The two exceptions were probes VI & VIII, probe VI was made at 5600 ft near about the base of the cloud and probe VIII at 10000 ft where severe turbulence encountered seemed to have determined the height of the aircraft. It may be mentioned that during these probes the aircraft was flown as a "free body", *i.e.*, the pilot did not take any corrective actions using the controls.

5. General conclusions

5.1. The general object of the ESE project was to explore the possibilities of using scientifically instrumented aircraft for different types of atmospheric studies during the summer monsoon period, Accordingly, the aircraft was flown on varied types of sample studies both for synoptic and meso-scale phenomenon. Necessarily they were not intended to make an exhaustive study of any one single aspect of the atmospheric condition. Thus the results obtained above can be considered as the results of exploratory studies on the subject. The tentative conclusions that are arrived at are as follows :

(1) Only light turbulence (as per the definition given by CAeM and adopted by Sixth Air

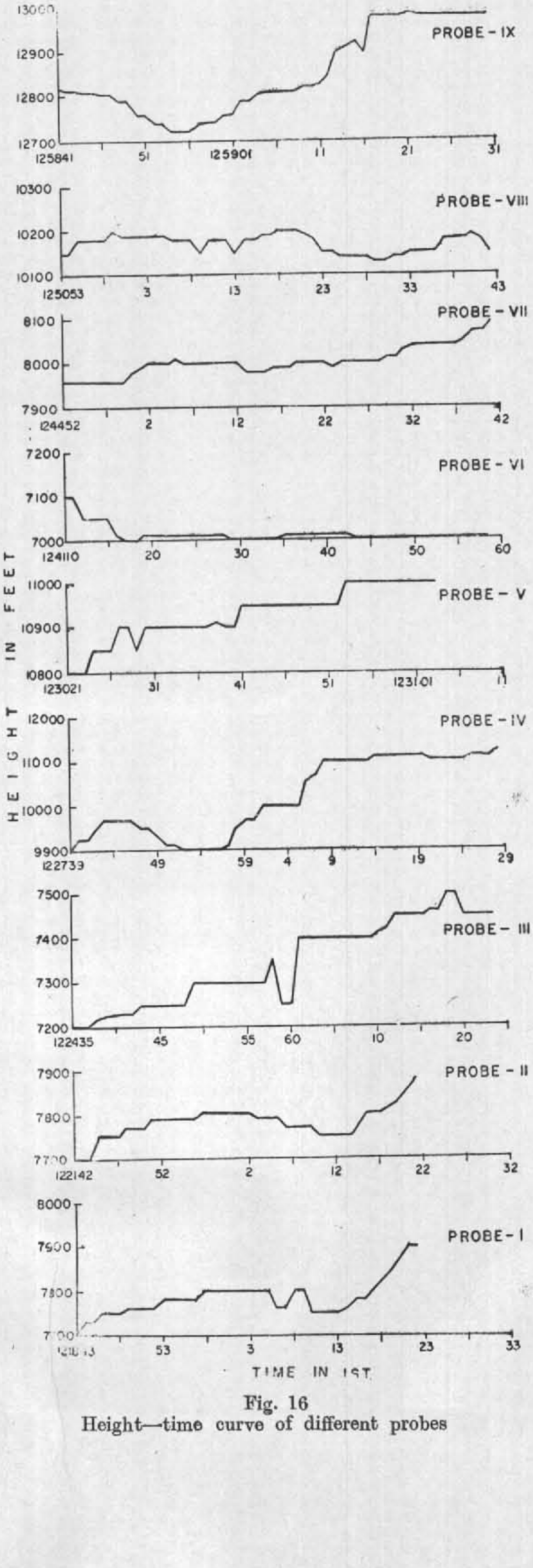

Fig. 16
Height—time curve of different probes

Navigation Commission) was encountered in the upper tropospheric easterly flow over Peninsular India during the summer monsoon period (below the jet core level). It must be mentioned in this connection, however, that this need not necessarily mean that severe turbulence need not be expected in the upper tropospheric levels especially very near the core of the jet or just above it where vertical wind shear can be greater. Also on this particular day the vertical wind shears were below the normal values given by Mokashi (1971) about 4 kt per 1000 ft in the area concerned even though the winds were of the order of 100 kt at 100 mb level.

(2) The turbulence experienced in a growing cumulus cloud of moderate extent was moderate to severe.

(3) Even though the tephigram of Bangalore on that day showed that instability was not very great, the stability of the atmosphere was near about neutral (for moist air) on that day.

Acknowledgements

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