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L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

Meteorological Conditions Associated With CAT Observations in Project HAVEN HOP

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PETER A. GIORGIO

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AIR FORCE SYSTEMS COMMAND
United States Air Force

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Meteorological Conditions Associated with CAT Observations in Project HAVEN HOP

1. INTRODUCTION

Clear air turbulence (CAT) is generally defined as turbulence occurring several kilometers above the ground in a clear atmosphere and implies that the turbulence is strong enough to have a noticeable effect on an aircraft's motion. CAT is potentially dangerous to aircraft operations because it is usually encountered without any warning. Consequently, unexpected encounters with the more intense type of CAT can result in injuries to air crews and interfere with operations.

Since mesoscale meteorological data particularly applicable to CAT are so sparse, the Meteorology Laboratory designed a mesoscale network of rawinsonde stations in the Virginia-Maryland-Delaware area for the specific purpose of acquiring data to support a program with the ultimate purpose of improving CAT forecasting. Observational systems included five mobile rawinsonde stations provided by Air Weather Service, existing NOAA stations at Wallops Island and Dulles Airport, Virginia, Pittsburgh, Pa., Huntington, W. Va., and Greensboro and Hatteras, N.C., and the Army facility at Aberdeen, Md. In addition RB-57 aircraft (both C and F models) operated at selected altitudes to sense and record the turbulence encountered and to provide background navigational and meteorological data. At the same time the NASA high power radar at Wallops Island was used to detect

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turbulence in the immediate area of Wallops Island. Some of the radar aspects are described by Boucher and Glover (1971).

2. MECHANISM FOR FORMATION OF CAT

Theoretical considerations and experimental observations strongly suggest that CAT is largely a manifestation of Kelvin-Helmholtz (K-H) instability. K-H waves are shearing-gravity waves produced in statically stable layers of the atmosphere, and there is evidence that these waves act as a mechanism for the transfer of kinetic energy from the mean flow into turbulent eddies. Convincing evidence of these waves comes from visual observations of cloud billows by Ludlam (1967) and from high-power radar observations of the clear atmosphere by many groups, for example, Hicks and Angell (1968).

The onset of instability is determined by the Richardson number,

$$Ri = \frac{g}{\theta}\frac{\partial\theta}{\partial Z} \Big/ \left|\frac{\partial \mathbb{V}}{\partial Z}\right|^2 \qquad (1)$$

where Z is height, $\mathbb{V}$ the vector wind, θ the potential temperature, g gravity. Ri is the ratio of the buoyancy forces to the shearing stresses. Theoretical studies (see Miles, 1961) generally indicate that a critical Richardson number (Ri_c) of 0.25 is required for the onset of turbulence. The observed Richardson number in a given situation will depend to a large extent upon the accuracy and resolution of the basic observations. With more precise instrumentation a Ri_c near 0.25 has been observed in the free atmosphere by Browning (1971) and by Delay and Dutton (1971). The important point from an operational view is not the precise value of Ri but rather the determination of the factors which produce low Ri and can cause the breakdown of the shearing-gravity waves. An explanation for the breakdown has been offered by Scorer (1969). In Scorer's theory the wind shear in an upstream layer can increase as the layer undergoes vertical displacement by a gravity wave. He gives the following relationship for the shear increase.

$$\delta\left(\left|\frac{\partial \mathbb{V}}{\partial Z}\right|\right) = g\beta \times \frac{\delta Z}{V_o} \qquad (2)$$

where $\beta = \frac{1}{\theta}\frac{\partial\theta}{\partial Z}$, δZ is the amplitude of a standing lee wave, and V_o is the wind speed at the level from which the stable layer was displaced. By substituting the above expression for the shear increase, a new or minimum Richardson number evolves, namely

$$Ri_{min} = \frac{g\beta}{\left[\left|\frac{(\delta W)}{\delta Z_o}\right| + \frac{g}{V_o}\beta\,\delta Z\right]^2} . \quad (3)$$

As Scorer points out, this result offers an explanation of why so much CAT has been observed in stable layers. A verification of the above equation for the free atmosphere is a difficult matter; however, some success has been reported by Clark (1969) using HICAT aircraft data obtained in lee wave cases in the western United States. According to the above theory, the probability of finding CAT, where lee waves are present, is increased in those regions where both the initial shear and stability are large.

The observations discussed in this paper were obtained downwind of topographic ridges 1000-2000 ft in elevation, where lee waves would be likely to develop. Because of basic difficulties with GMD-1 rawinsonde equipment, we obtained very little information on the vertical wind structure at altitudes of interest. Due to the wind limitations, our analyses are restricted principally to considerations of the mesoscale structure of the stability in situations favoring the presence of lee waves.

During our analyses of the data, we found that CAT appeared to be associated with regions of the jet stream flow in the following manner. All of our CAT incidences were located either on the cyclonic (low pressure) side or the anti-cyclonic (high pressure) side of the wind maximum. No CAT was found in the jet core. In several cases observations were carried on as the wind maximum shifted position, i.e., to the left or right with respect to the sampling area, and no CAT incidences were noted as the wind maximum passed over the area. A theoretical explanation for the above relationship is not apparent. In addition to the analyses of stability and jet stream characteristics, this paper presents the spatial and temporal variations in the turbulence over mapped sections of 100 miles long and several thousand feet thick.

3. FIELD PROGRAM

Figure 1 shows the location of the rawinsonde network and the track of the aircraft. The aircraft track was fixed between Westminster, Md. and Richmond, Va.—a distance of about 115 miles. There were eight stations in the mesoscale network, surrounded by four peripheral synoptic stations. In the mesoscale network, rawinsondes were taken at two-hour intervals during the operational phases, while at the peripheral stations releases were made at six-hour intervals. Turbulence observations were obtained from RB-57 aircraft operating along the

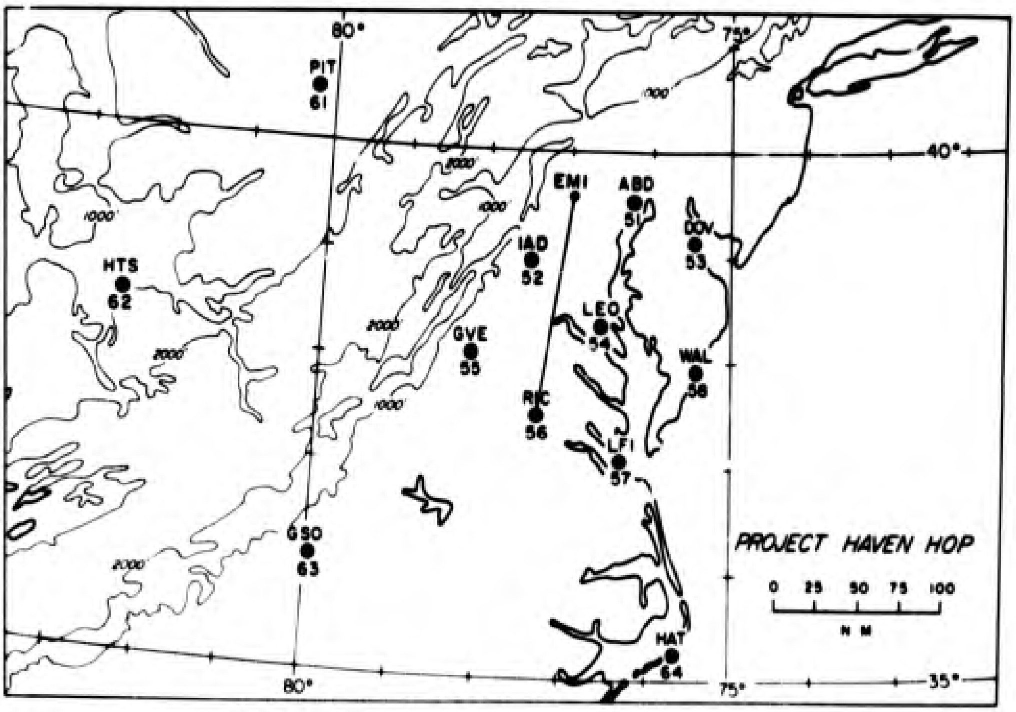

Figure 1. Mesoscale Network of Rawinsonde Stations and Peripheral NOAA Stations Showing Aircraft Track

north-south track shown in Figure 1. Uninstrumented RB-57C aircraft were used to map the turbulence in January with the observations being logged by the navigator. In February RB-57F aircraft were substituted, and these contained an oscillograph recording system. The aircraft measurements included Doppler winds, air temperatures, and vertical gust accelerations. The turbulence data to be discussed in this paper were obtained 50-75 miles downwind of topographic ridges 1000-2000 ft in elevation. It is obviously difficult to estimate the extent of the terrain influence. In any case, the terrain effect would not vary significantly in a given situation over a period of a few hours, and it is that order of temporal change in the turbulence patterns with which we will be concerned.

The turbulence intensity was described by the navigators in accordance with "DOD Flight Information Publication, Weather and Notam Procedures" which establishes criteria for the intensity of turbulence in terms of aircraft reaction on a scale of seven categories from light to extreme. We did not encounter any CAT in the highest two categories. As mentioned above, the RB-57's were equipped to record the turbulence "g" values. The agreement between the "g" values and the navigator's descriptive observations was good. The grouping of the categories vs "g" values established for the turbulence observations is shown in Table 1.

Table 1

g values	category
.03 - .09	light
.10 - .19	light - moderate
.20 - .29	moderate
≥ .30	moderate to severe

For the purpose of this study, significant turbulence starts with moderate intensity, and one of our objectives is to determine whether meteorological mesostructure can be used to discriminate the "significant" type CAT from the "non-significant."

4. DATA TREATMENT

The GMD-1 rawinsonde data were extracted at 30-second intervals and smoothed by fitting a second order polynomial to these data. Smoothing intervals used were 7 and 15 data points for the thermodynamic and wind information, respectively. Derivatives of wind and thermodynamic data were computed using the differential form of the polynomials rather than using a finite difference method.

5. CAT CASES

Seven CAT cases are discussed in the sections to follow. In each case two or three probing missions were made for a total of 18 missions. In one case, composed of two missions, no significant CAT was found. We define significant CAT as those cases where the intensity was at least moderate, i.e., 0.20 g or greater, and the patch was at least five miles in length. The cases will be described in chronological order. Those meteorological features to be presented include the large jet flow on a standard upper level map near the level of interest, vertical profiles of wind shear and the buoyancy force. The buoyancy term is used more or less interchangeably to define stability. Where reliable wind data were not available in the probed layer, no shear information is shown. The vertical profiles are derived from the rawinsondes released from Dulles International Airport (IAD) or Gordonsville, Va. (GVE). Since the upper winds were mostly westerly, it is clear from Figure 1 that Dulles and Gordonsville are best located with respect to the aircraft track where the turbulence measurements were made. Because of the non-simultaneity between the CAT and meteorological observations, an allowance should be made for small variations between the two sets of data.

5.1 Case of 19-20 January

Figure 2 shows the 200 mb isotachs and height contours at 0000 GMT 20 January near the level of the strongest CAT. The probing area is on the left or cyclonic side of the jet. A vertical section from 7.2 - 12.5 km was probed three times, and the encountered CAT is shown in Figure 3. Only slight turbulence was found on the first probe, but moderate CAT was encountered on the second probe, some at 8.8 km and more in the 11.3 - 12.0 km layer. On the third probe the turbulence had diminished to light. Figure 4 shows the temperature and stability profiles for the Dulles sounding, 2330 GMT 19 January. The CAT intensity code is the same as in Figure 3. The moderate CAT observations coincide quite well with stability maxima. The lower stable layer represents the base of the tropopause. Without wind data, it is not possible to explain the change in CAT intensity during the three sampling periods.

5.2 Case of 21-22 January

Figure 5 shows the 300 mb flow at 0000 GMT 22 January. The probing area is on the cyclonic side of a cyclonically-curved jet. Three sets of probes were made, and the encountered CAT is shown in Figure 6. A patch of moderate CAT is shown near 10.7 km about 1900 GMT. The Dulles stability soundings for 1930 and 2130 GMT are shown in Figure 7. The soundings are quite similar. On the first sounding the stability maximum near 10 km is just below the moderate CAT. On the second sounding a stability peak again showed near 10 km; however, this time the turbulence was only light.

The moderate CAT in the first probe was associated with a nearby stable layer and was located on the cyclonic side of the jet. The stability features continued into the period of the second and third probes where only light CAT was found. One can speculate that vertical wind shears were not of sufficient magnitude during the last two sets of probes to maintain the CAT.

5.3 Case of 27 January

Figure 8 shows the 300 mb map at 0000 GMT 27 January. The probing area is located on the cyclonic side of a westerly jet. Three probing missions were made and the encountered CAT is seen in Figure 9. Moderate CAT was encountered on the first probe near 0200 GMT from 10 - 11.3 km. Figure 10 shows the Dulles soundings for 0230, 0430, and 0830, including the wind shears for the 0230 sounding. The CAT intensity is coded as in Figure 9. The shears are relatively small, about 0.8×10^{-2} sec^{-1} (5 kt per 1000 ft). Continuity in the stability profiles can readily be traced. The peak near 9.5 km seemed to diminish with time.

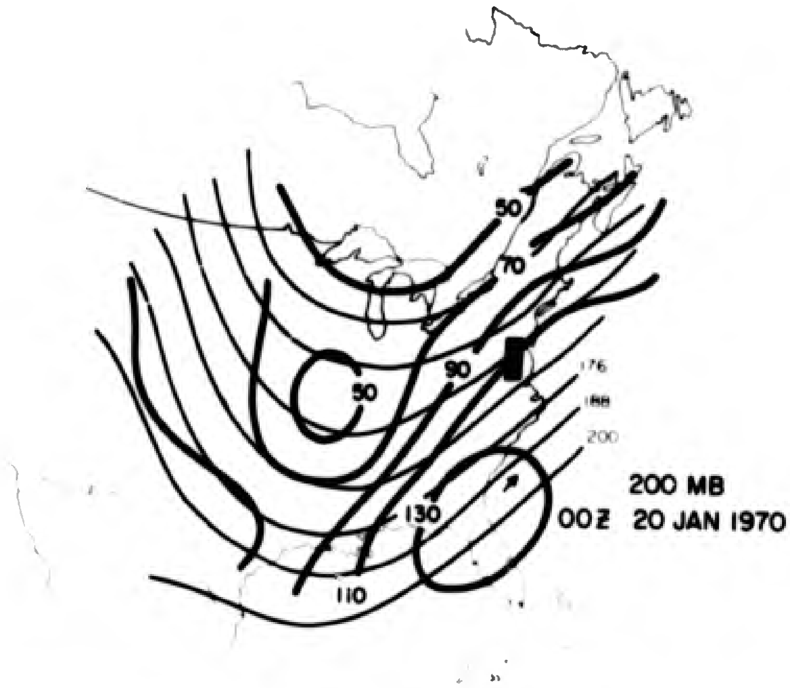

Figure 2. 200-MB MAP Showing Heavy Lines as Isotachs in Kts. Aircraft probing area is shown

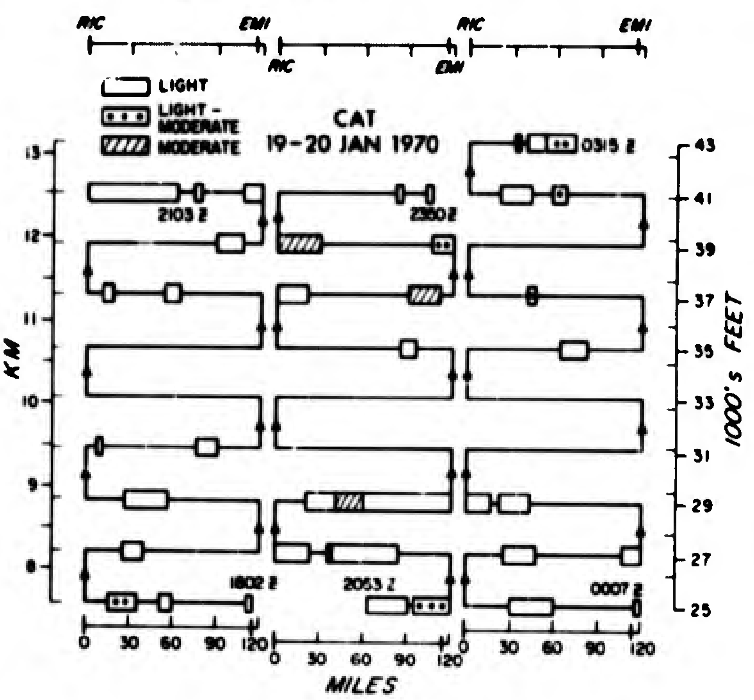

Figure 3. Turbulence Encountered by Probing Aircraft

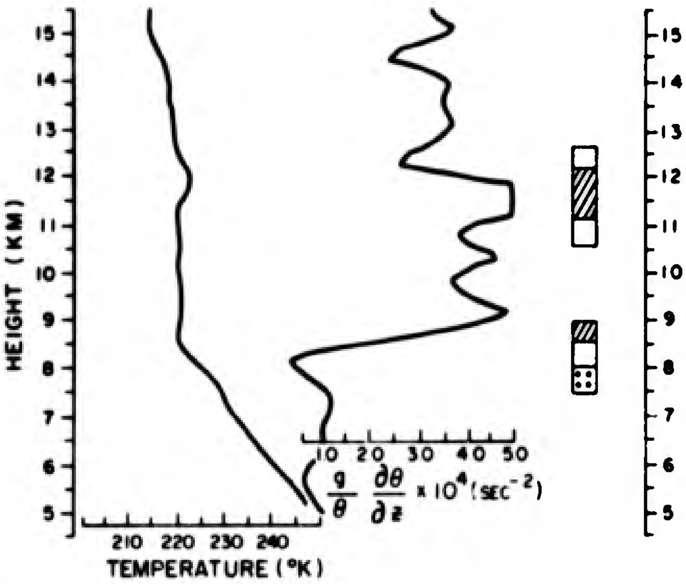

Figure 4. Temperature and Stability Profiles for Dulles, 2300 GMT 19 January. Indicated CAT taken from Figure 3

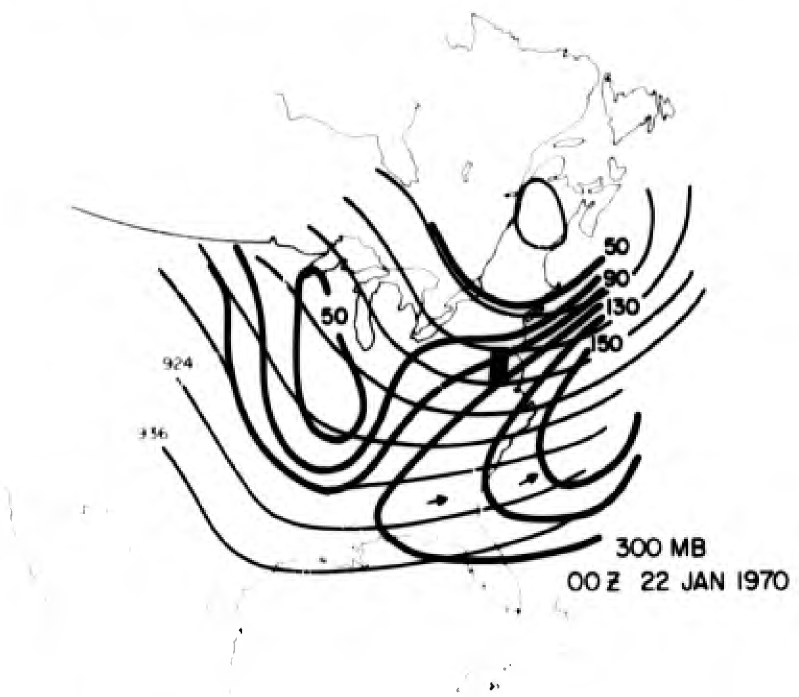

Figure 5. 300-MB MAP. Identifications as in Figure 2

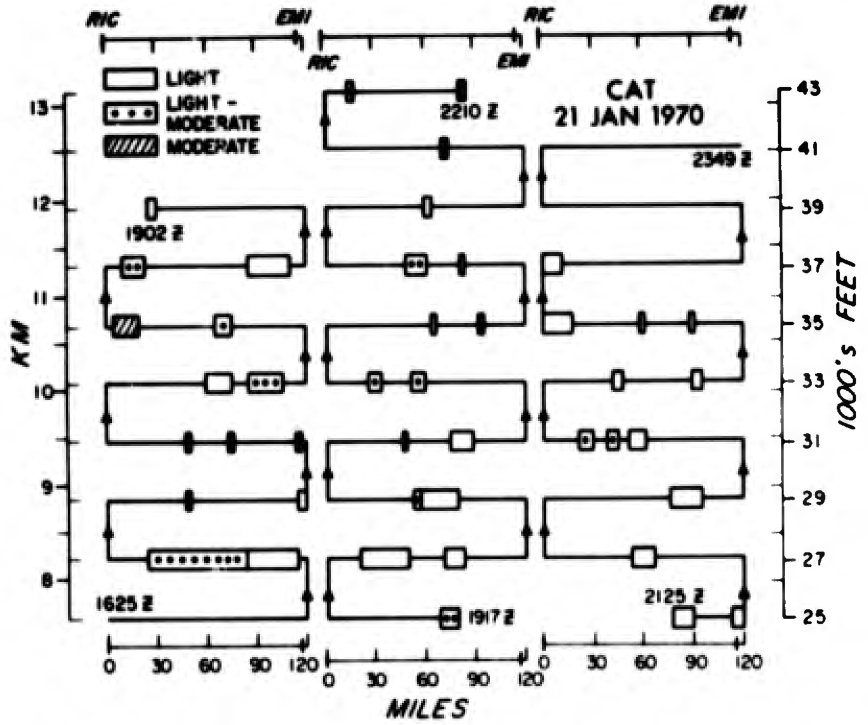

Figure 6. Turbulence Encountered by Probing Aircraft

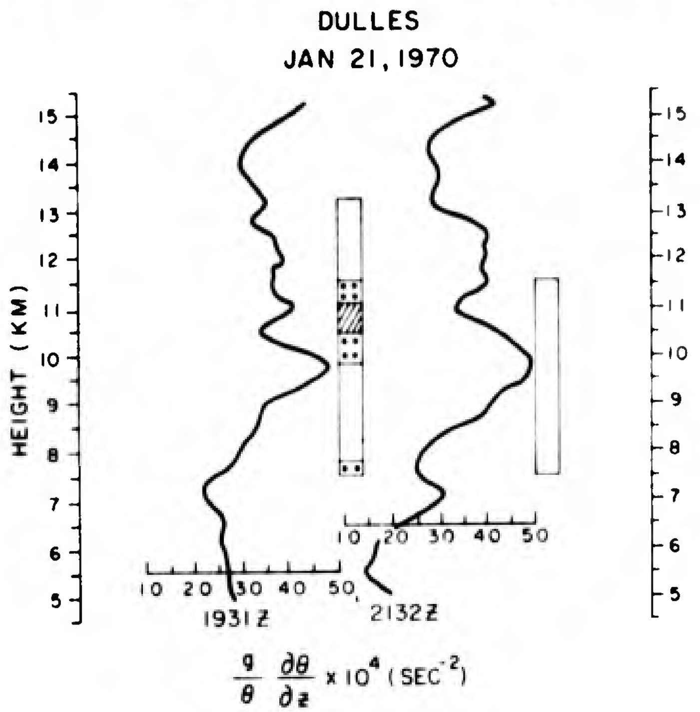

Figure 7. Stability Profiles for Dulles 1930 and 2130 GMT 21 January

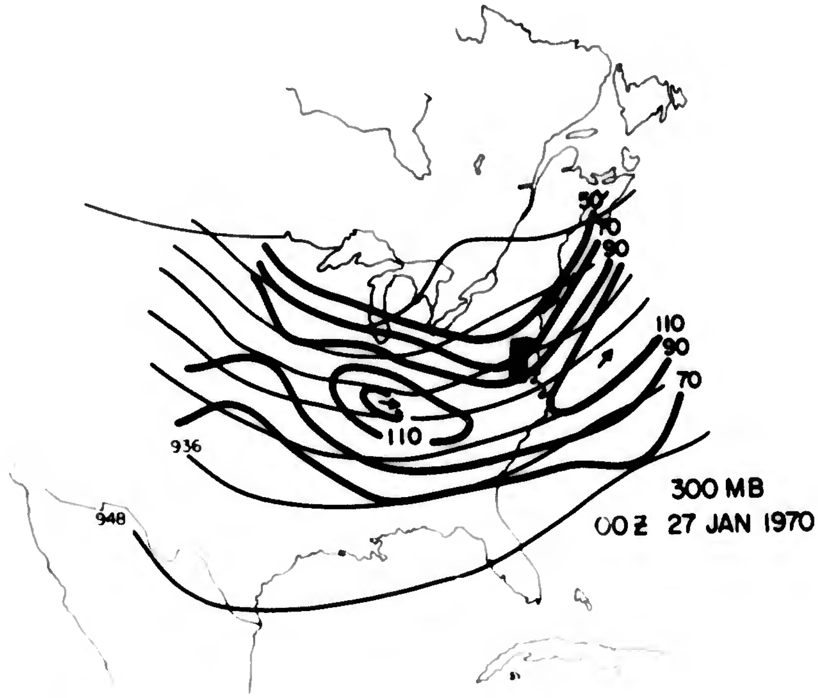

Figure 8. 300-MB MAP. Identifications as in Figure 2

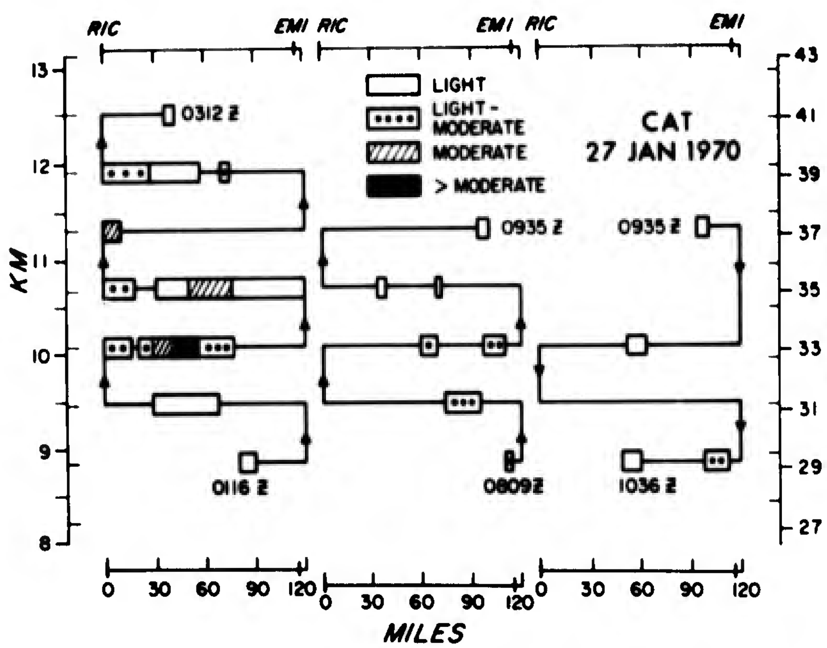

Figure 9. Turbulence Encountered by Probing Aircraft

We do not know whether or not this feature was related to the decreasing CAT intensity. It is more likely that the decrease in the turbulence was due to a decrease in the shear which had been small at the 0230 GMT.

5.4 Case of 30 January

Three probing missions were made, one near 12 - 1400 GMT and the other two from 18 - 2100 GMT. The 300 mb map for 1200 GMT, Figure 11, indicates a strong southwest jet maximum through the probing area. Figure 12 shows the situation 12 hours later at 0000 GMT 31 January. The jet is displaced to the southeast, and the probe area is clearly on the cyclonic side of the jet. From the observations obtained in the mesoscale network, it was evident that during the last two probes the probe area was located on the cyclonic side of the jet flow.

The encountered CAT is shown in Figure 13. No significant CAT was found during the first mission. Moderate-severe CAT was encountered during the second mission near 9 km, and during the third mission near 8.2 and 9.5 km. Figure 14 shows the Gordonsville soundings for 1230, 1730, and 1930 GMT. The association of the moderate and stronger CAT with the stability peaks is quite good. It is interesting to note the change at 9 km between the 1730 and 1930 observations. The stability peak and strong CAT shown at 1730 are replaced with low stability and weak turbulence. This case is a good example where an increase in CAT intensity is accompanied by a large increase in horizontal shear as the jet maximum was displaced out of the area.

5.5 Case of 16-17 February

Figures 15 and 16 show the 200 mb maps for 1200 GMT 16 February and 0000 GMT 17 February, respectively. It would appear that a jet maximum was located over the area during the 12-hour period between the maps. Aircraft probing was carried out in two periods; first, one from 1240 - 1840 GMT, 9 - 12.5 km, and second, one 2114 - 2241 GMT, 10.7 - 12 km. Only light CAT was encountered in both periods, with longer patches of light in the second period. The results from the second probe are shown in Figure 17. Only during the first period did the aircraft penetrate up into the stable strata. Figure 18 shows the 1330, 1730 and 2130 GMT Dulles soundings. The critical cut-off in the elevation angle in the 1330 sounding occurred at 11 km near the base of the probed layer. We have in this case taken the liberty of using wind data up to 12.5 km. The principal reason for relaxing this restriction was because the wind and shear profiles were relatively smooth to 14 km and showed considerable persistence through the next four two-hour soundings. As can be seen in Figure 18 the aircraft sampling during the first probe extended up into the base of the stratosphere where the atmosphere was very stable. Furthermore, it appears that in the 12 - 12.5 km layer the wind shears may have been fairly large, equivalent to 12 km per 1000 ft.

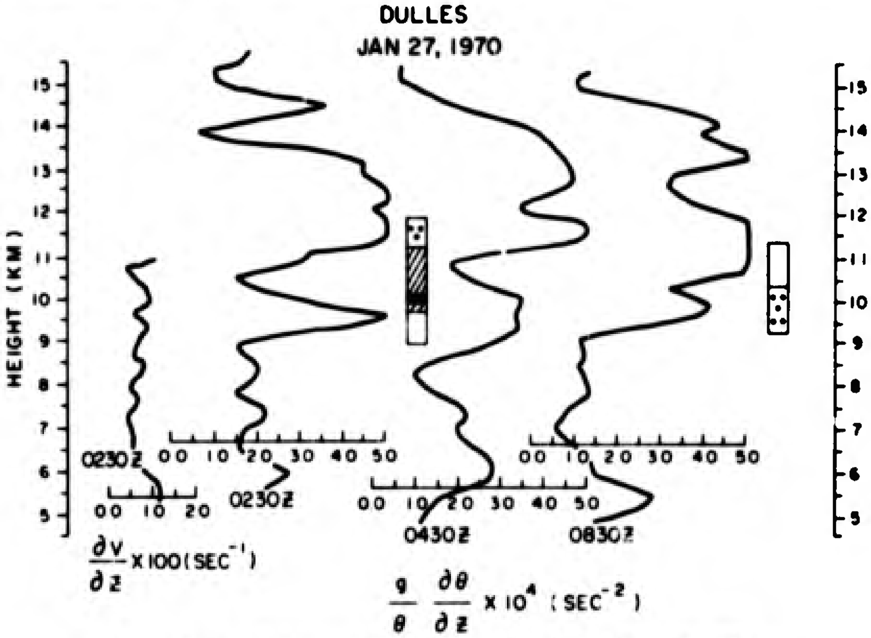

Figure 10. Stability and Shear Profiles for Dulles

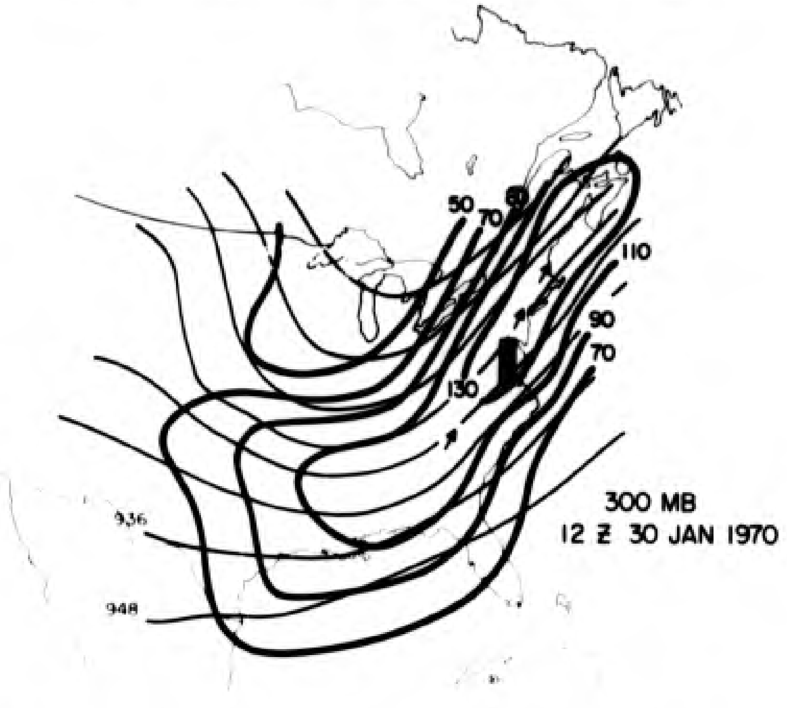

Figure 11. 300-MB MAP. Identifications as in Figure 2

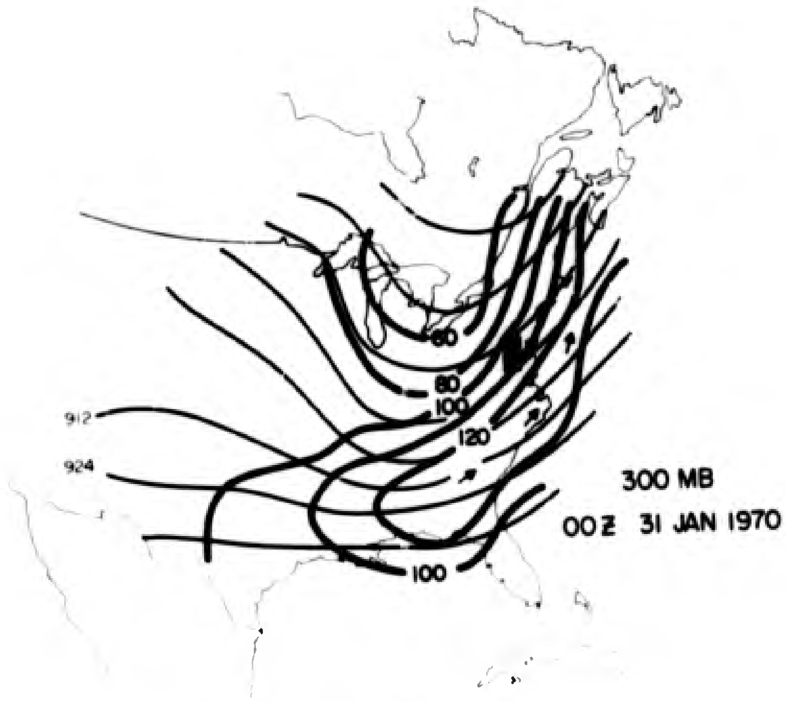

Figure 12. 300-MB MAP. Identifications as in Figure 2

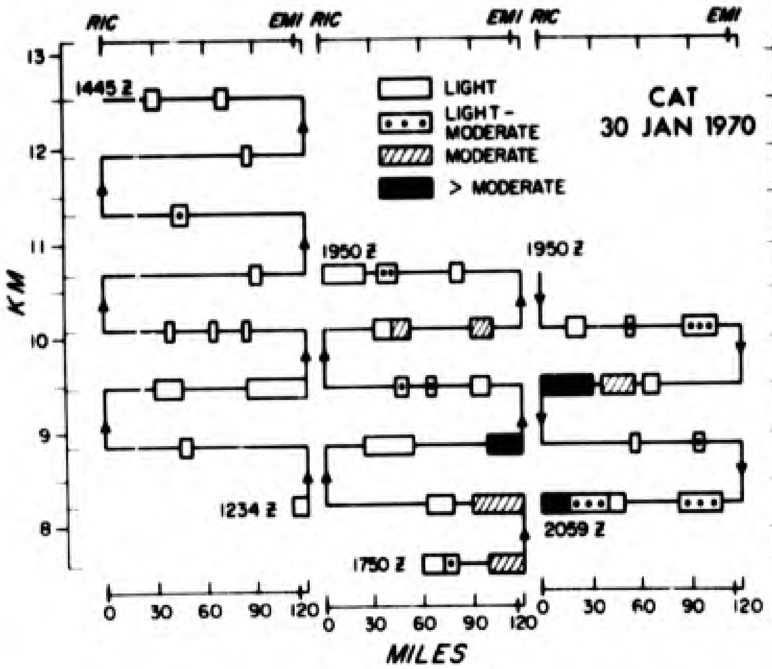

Figure 13. Turbulence Encountered by Probing Aircraft

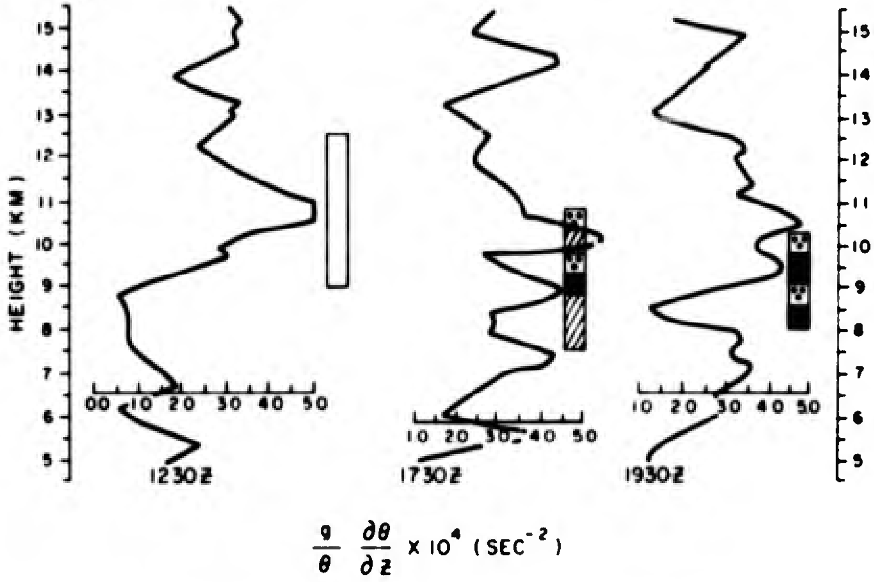

Figure 14. Stability Profiles for Gordonsville

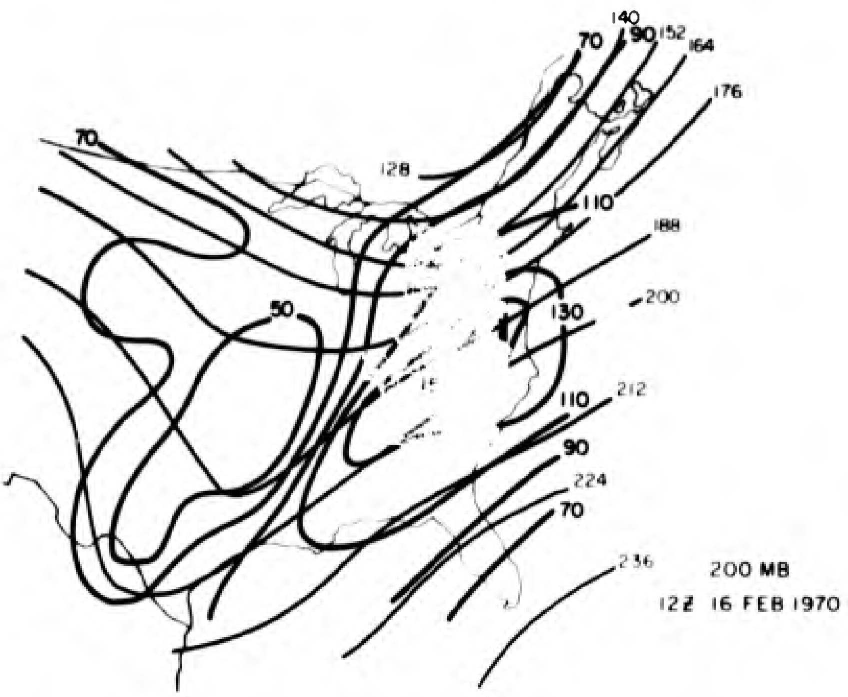

Figure 15. 200-MB MAP. Identifications as in Figure 2

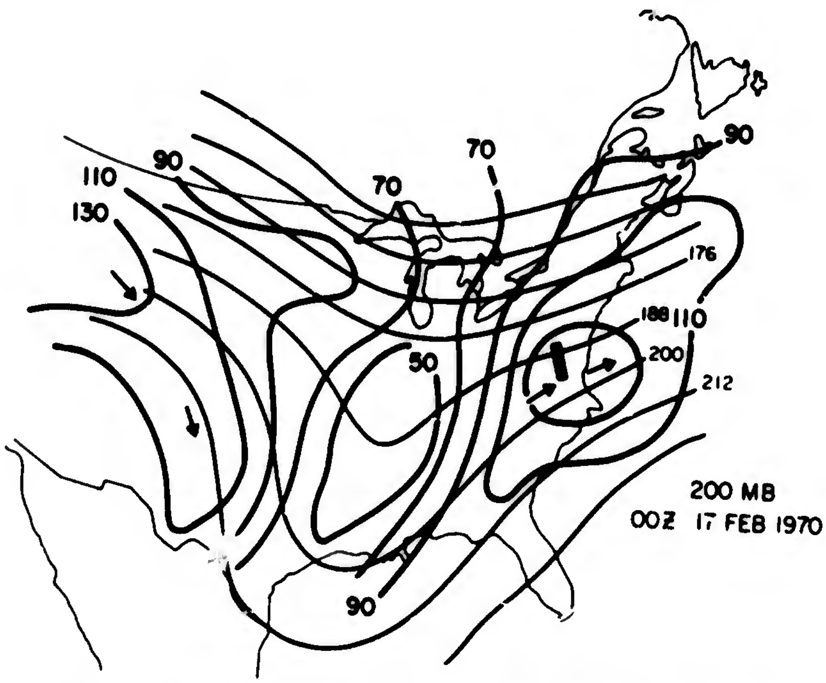

Figure 16. 200-MB MAP. Identifications as in Figure 2

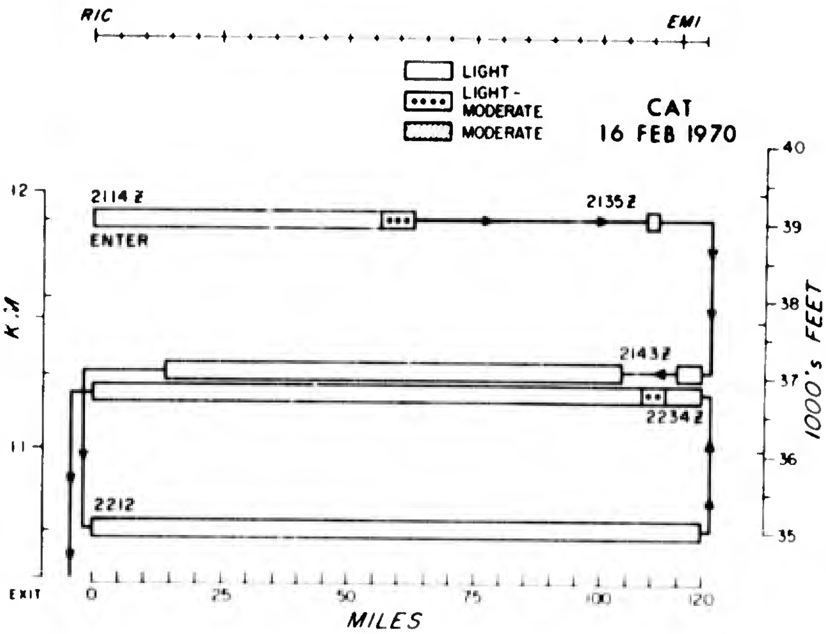

Figure 17. Turbulence Encountered by Probing Aircraft

In this case extensive probing was carried out in the jet core, and no significant CAT was encountered. The sampling early in the period included a layer from 12 - 12.5 km where apparently both stability and shear were marked. We cannot readily explain why CAT was not found. It can only be pointed out that all the sampling was carried out in the jet maximum.

5.6 Case of 18-19 February

This was a case of tropospheric turbulence with moderate CAT occurring above 14 km. Figure 19 shows the 0000 GMT 19 February 200 mb map close in time to the encounter with the strongest CAT. The probing area is shown to be on the anticyclonic side of the jet. The results of the aircraft probing are shown in Figure 20. From 2000 - 2300 GMT widespread light - moderate CAT, with moderate CAT occurring near 14.3 km about 2300 GMT. Figure 21 presents the Dulles sounding at 2130, 2330 and 0130. The major features between 10 - 15 km appear in the first two profiles. Moderate CAT is located at a well-marked stability peak near 14.5 km. A second probing mission from 0000 - 0350 GMT 19 February (not shown) did not encounter any significant CAT.

5.7 Case of 20 February

This is another case of tropospheric CAT above 14 km. The 200 mb maps for 12 GMT 20 February and 0000 GMT 21 February are shown in Figures 22 and 23, respectively. The probing area was located initially on the anticyclonic side of the jet, and in jet maximum by 0000 GMT. The mapped turbulence for the first mission is shown in Figure 24, with the strongest CAT occurring between 14 to 15 km near 1750 GMT. The Dulles soundings for 1730 and 1930 GMT are shown in Figure 25. There is a strong stability peak at 14 - 14.5 km or at the base of the moderate CAT. A second probing mission from 2200 - 2330 GMT was carried out in 11.6 - 15.0 km layer, and only light CAT was encountered.

6. SUMMARY

Analyses of data for several cases showed the stronger CAT to be associated with strong static stability. This is in agreement with theoretical considerations in which K-H instability may develop in stable layers associated with strong vertical wind shear. The analyses also suggested an association between CAT and the horizontal shear regions of the jet core. An explanation for this relationship is not offered and the nature of the wind data at the altitudes of our interest was not suitable for any further investigation of this possibility.

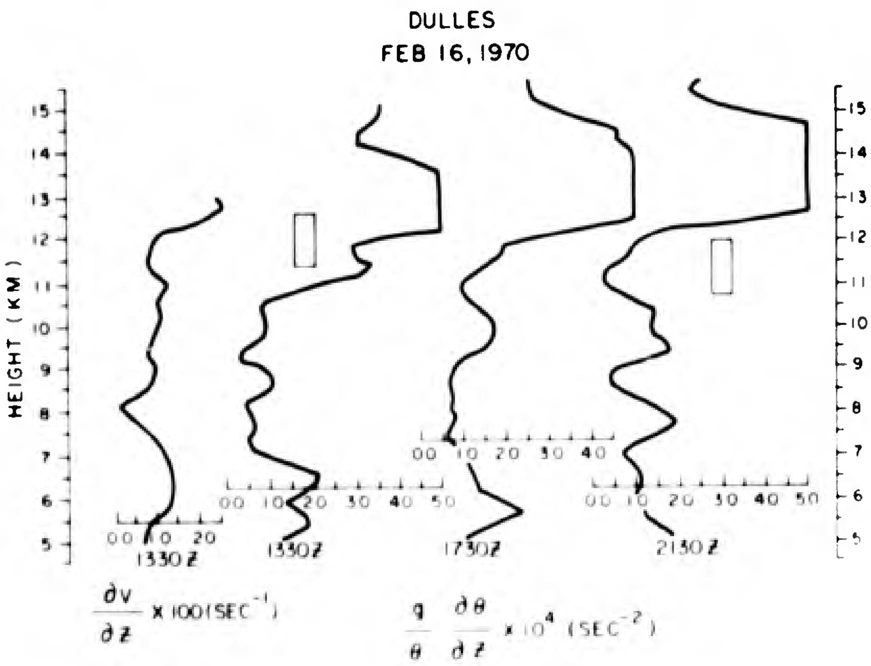

Figure 18. Stability and Shear Profiles for Dulles

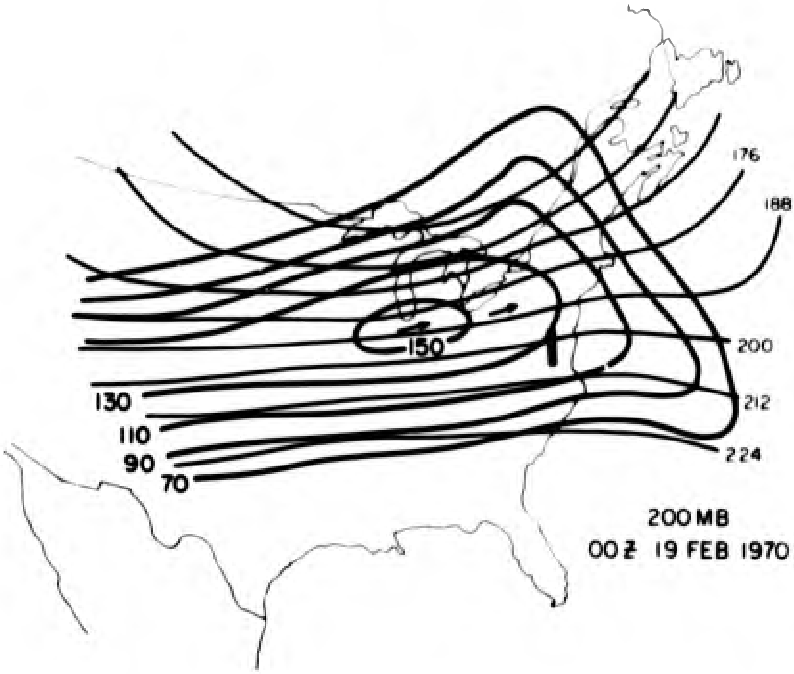

Figure 19. 200-MB MAP. Identifications as in Figure 2

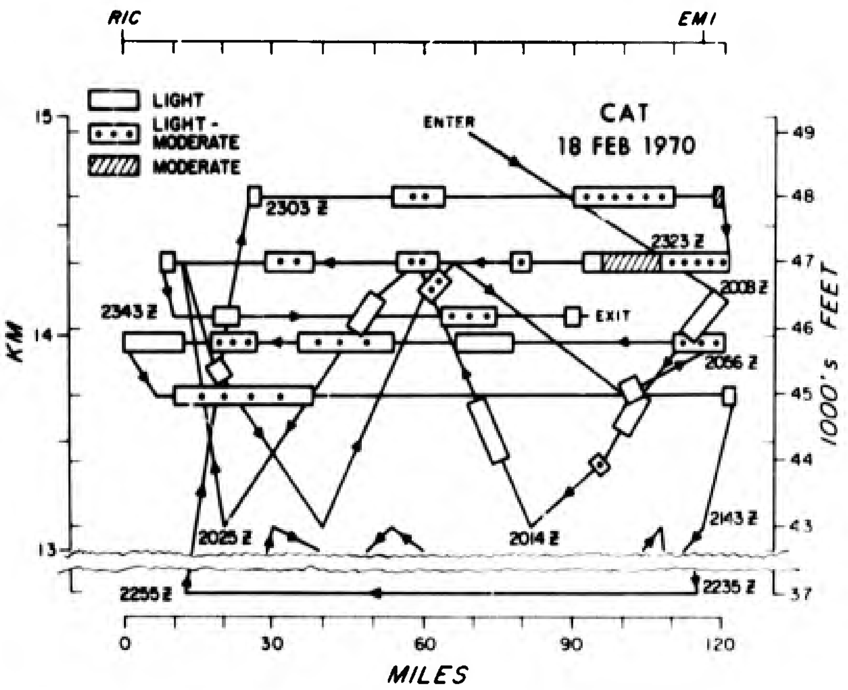

Figure 20. Turbulence Encountered by Probing Aircraft

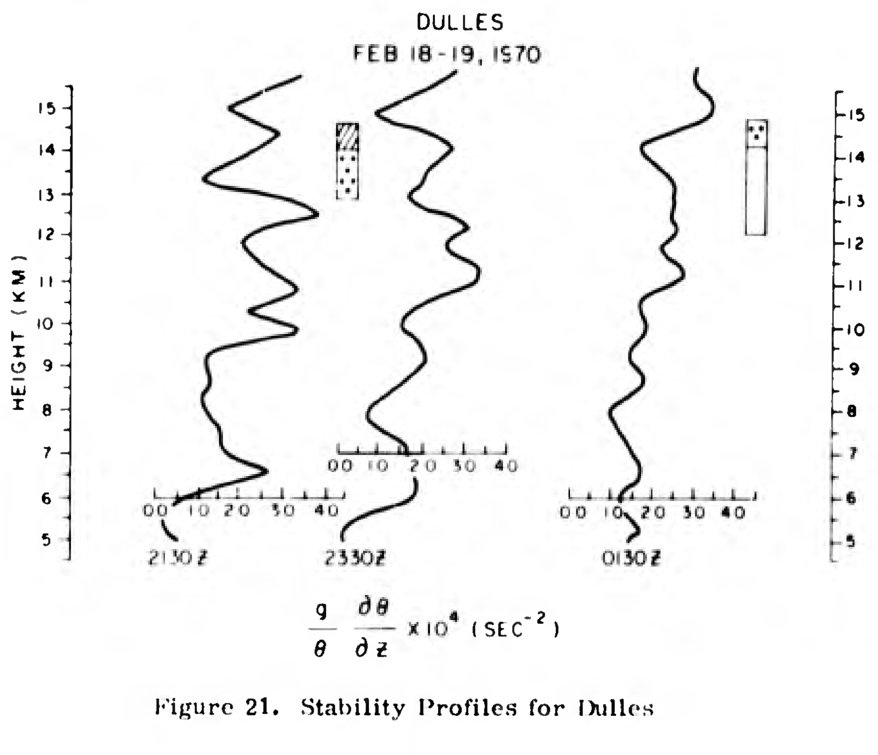

Figure 21. Stability Profiles for Dulles

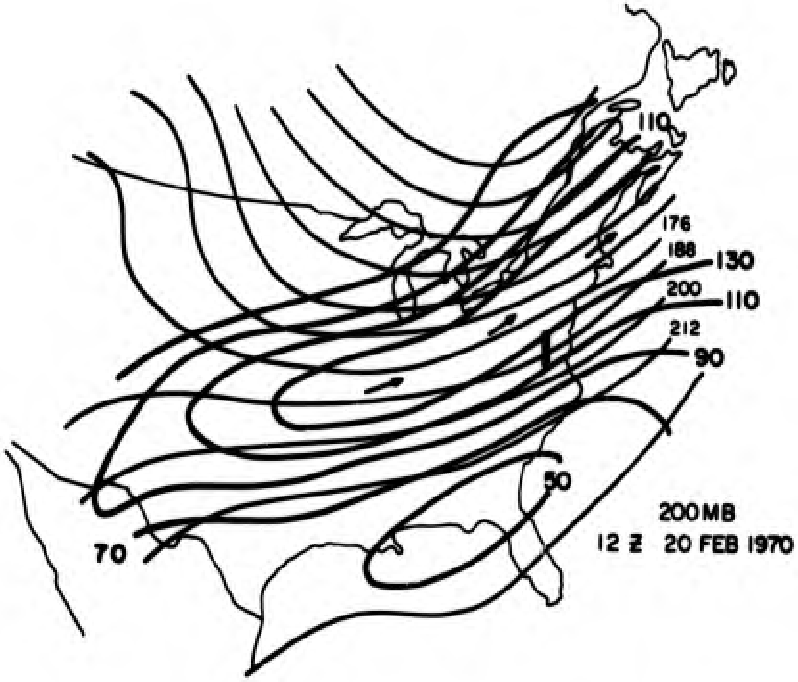

Figure 22. 200-MB MAP. Identifications as in Figure 2

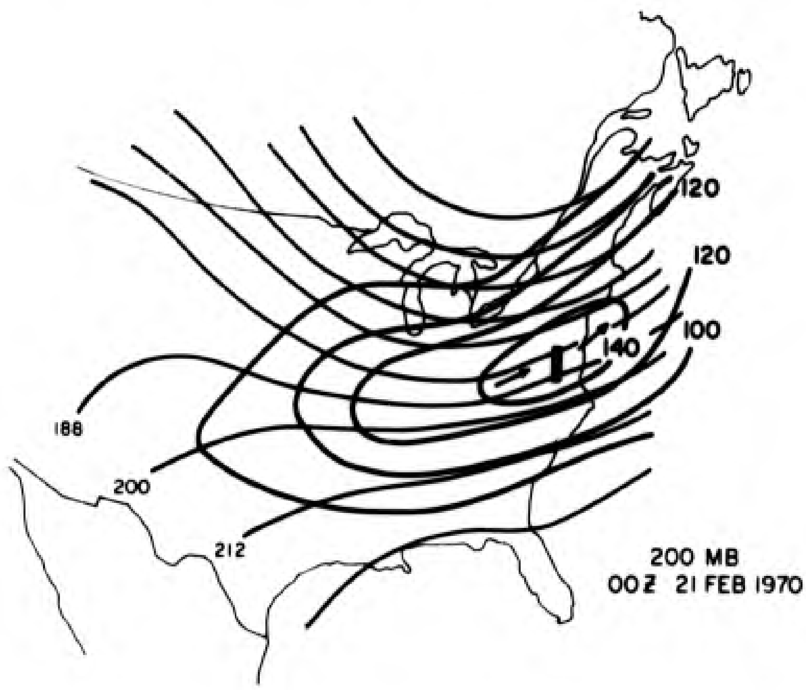

Figure 23. 200-MB MAP. Identifications as in Figure 2

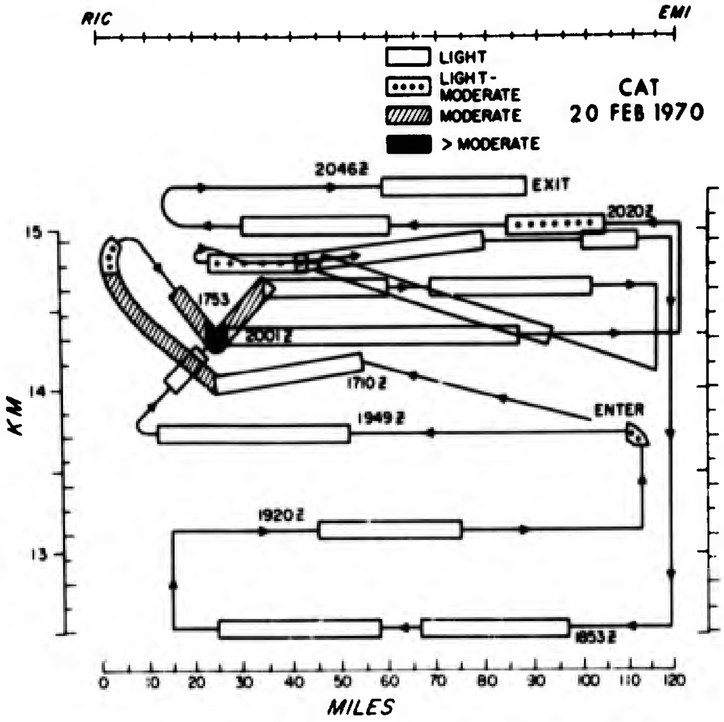

Figure 24. Turbulence Encountered by Probing Aircraft

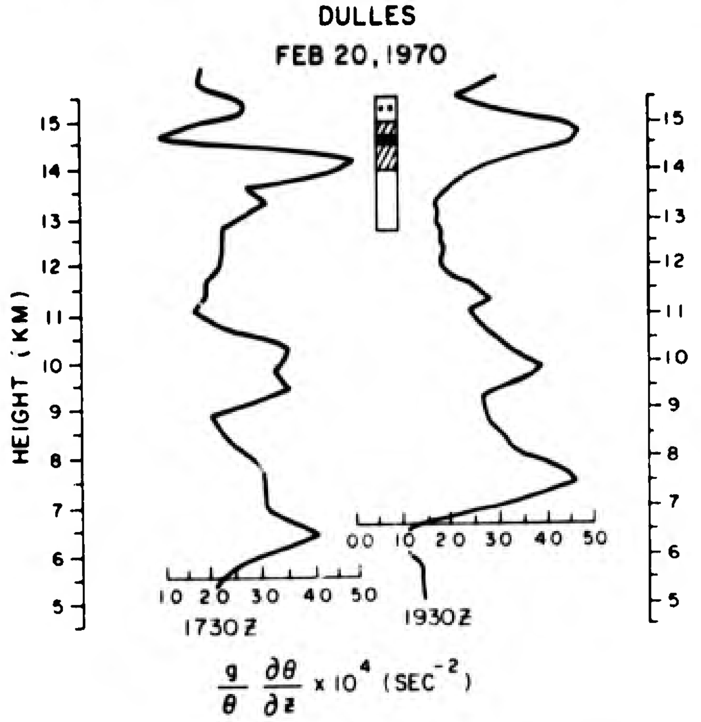

Figure 25. Stability Profiles for Dulles

Winds at our levels of interest were obtained in only two instances; however, even those data were on the border of acceptability with respect to their elevation angles. Because of this wind limitation, no significant analysis was made of such parameters as shear and Ri. Table 2 below summarizes the relationship principally of stability and regions of the jet maximum with the CAT incidences. Jet regions in Table 2 are described by "Low" for low pressure side, "High" for high pressure side, and "Core" for jet maximum. Included in the table is one case of no CAT.

Table 2

Case	Mission	CAT Alt (Km)	Stability Peak Alt (Km)	Jet Region	Alt (Km)	Shear Intensity (Kt/1000 Ft)
Jan 19-20	2	8.8	9.1	Low	--	--
		11.5	11.5	Low	--	--
Jan 21	1	10.6	9.8	Low	--	--
Jan 27	1	10.1	9.8	Low	10	5
Jan 30		9.0	9.0	Low	--	--
	3	8.2	8.0	Low	--	--
	3	9.5	9.5	Low	--	--
Feb 16	1	No CAT	12.5	Core	12.5	12
Feb 18	1	14.5	14.0	High	--	--
Feb 20	1	14.3	14.0	High	--	--

The mapped turbulence showed that regions containing patches of operationally significant CAT at times extended as much as 100 miles in the cross-wind direction; however, individual patches generally were less than 35 miles long. In the vertical direction, the CAT was mostly less than 1 km in depth. The general turbulent character of a probed region appeared to last for two to four hours; however, individual patches probably persisted for only minutes.

In a follow-up field program a special technique will be used with the rawinsonde observations to overcome the low elevation angle difficulty. The data from that program should enable us to extend the findings derived in this report.

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