AFCRL-67-0115
APRIL 1967
AIR FORCE SURVEYS IN GEOPHYSICS, NO. 190

AD 654267

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

Mesoscale Structure of the Atmosphere in Regions of Clear-Air Turbulence Volume I

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OFFICE OF AEROSPACE RESEARCH
United States Air Force

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METEOROLOGY LABORATORY PROJECT 8628

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Abstract

The mesoscale structure of the atmosphere in regions of Clear-Air Turbulence (CAT) is investigated by means of aircraft observations of wind, temperature, and ozone obtained in the upper troposphere and in the lower stratosphere. Analysis from five CAT missions are shown, including vertical cross sections normal to flow patterns and also detailed vertical "soundings" of wind, temperature, and the Richardson number. A verification is obtained at intervals of 1000 ft between the occurrence of CAT and a Richardson criterion of 0.5. Over 70 percent of the 149 CAT cases are correctly specified by the criterion.

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Mesoscale Structure of the Atmosphere in Regions of Clear-Air Turbulence

Volume I

1. INTRODUCTION

Clear-Air Turbulence (CAT) is defined in this report as turbulence above 20,000 ft or so, and not associated with convective clouds. Thus, bumpiness in cirrus clouds would be identified as CAT. Our concern is with the scale of turbulence which can be felt as bumpiness by an aircraft. These turbulent eddies have dimensions of the order of 80 to 800 ft, hence, they are microscale structures. On the other hand, dimensions of turbulent regions are, on the average, 3000 ft thick and 50 miles on the horizontal. In view of the above facts, many investigators, including Reiter (1963), Endlich (1964), and Clodman et al. (1960), believe that CAT has its origin in the mesostructure of the atmosphere. Since that scale of strucutre cannot be adequately described by the standard radiosonde network, a program was initiated in the Meteorology Laboratory to obtain the required data by an instrumented U-2 aircraft. A number of CAT missions were flown, and in this volume detailed analyses are presented from five missions made in March and April 1965. The purpose of this report is to document and describe the mesoscale structures in areas of turbulence, as derived from a high resolution measuring system.

Volume I contains the analyzed results of the U-2 CAT program for the 1964-1965 winter and spring season. The U-2 was again used to collect data during the

(Received for publication 23 February 1967)

1965-1966 winter season, and these results will be presented in Volume II of this report, scheduled to be published by the end of 1967.

2. DATA AND METHOD OF ANALYSIS

The data used in the mesoscale analyses consist of high resolution measurements of wind, temperature, ozone, and turbulence obtained by a U-2 with a specially designed instrument measuring and recording system. This aircraft was used for research purposes by the Meteorology Laboratory of the Air Force Cambridge Research Laboratories. The instrument package has been described by Kahle (1963), whose group at the University of Dayton have been intimately involved with the data recording system and with data processing. It will be sufficient here simply to indicate that position and wind data are obtained from a Doppler radar set and gyro compass. Temperatures are measured by a Rosemount probe with open-wire, platinum-sensing elements. Time constant of the Rosemount probe is 0.3 sec. Ozone is detected by a dry chemical device, a modification of the Regener ozonesonde, and its cycling time is about 15 sec. Turbulence is measured by a low-range accelerometer mounted near the center of gravity of the airplane and oriented so that it is sensitive to vertical accelerations only. The accelerometer is used to separate the CAT into three broad classes of intensity. For purposes of this study, the following criteria for intensity of CAT were established: very light .01 to .05 g; light .06 to .10 g; moderate and severe > .10 g. These classes were determined on the basis of the pilot's remarks and by a comparison with reports of turbulence by commercial aircraft.

In general, the flight plans followed by the U-2 consisted of saw-tooth patterns, approximately normal to the wind direction. In all cases, the missions were made in a region of the jet-stream core, although the probing regions were selected on the basis of forecasts and the latest information (from FAA controllers) regarding locations of CAT. Data from the ascent-descent portions of a flight were used as vertical soundings to obtain vertical variations of parameters which could be related to the CAT problem. Wind and temperature data from these "soundings" were abstracted for five-sec intervals and smoothed by applying a five-point running mean to the wind speed and direction and a three-point running mean to the temperature. Ozone observations were made at 15- to 20-sec intervals and were not smoothed. Spacially, a 5-point mean, or 25-second mean, represents on the average 3 miles in the horizontal and about 750 ft in the vertical.

In addition to the mesoscale analyses, we have included constant pressure charts, maximum wind analyses, and RAOB cross sections in order to permit the reader to view the larger scale framework for each situation. The missions were generally about midway between the standard RAOB times, and this should be borne in mind when attempting to relate the aircraft observations to the RAOB data. Analyses for only one RAOB time are shown for those cases where it was felt that these would adequately describe the larger scale framework at the time of mission.

For the purpose of studying the effectiveness of criteria for specifying CAT or no CAT, we have included as CAT those layers of "very light" CAT which were atleast 1000-ft thick or any "very light" which was contiguous in the vertical to more intense turbulence. The remainder of the very light CAT was classified with the "no turbulence." These categories were used to verify the value of a Richardson criterion of 0.5 as a discriminator. The Richardson number, Ri, is defined as:

$$Ri = \frac{\frac{g}{\theta}\frac{\delta\theta}{\delta Z}}{\left(\frac{\delta U}{\delta Z}\right)^2}$$

where

g is acceleration due to gravity

$\frac{\delta\theta}{\delta Z}$ is lapse rate of potential temperature

$\frac{\delta U}{\delta Z}$ is the vector vertical wind shear

ΔZ was taken over 1000 ft

The verification was made at intervals of 1000 ft.

3. CAT MISSIONS

3.1 Mission ML-81 - Across a Slightly Anticyclonically-Curved Northwest Jet

3.1.1 MISSION DESCRIPTION

Mission ML-81 probed the area from Bedford, Massachusetts (BED) to Gordonville, Virginia (GVE) 8 April 1965, 17 to 20 GMT. Five probes were made on the southbound leg and three on the return flight. The probes were made mostly between 30,000 to 50,000 ft or 120 to 300 mb. Figure 1 shows for both legs, the flight plans, encountered turbulence, tropopauses, and pseudo-tropopauses. It is evident from Figure 1 that spacial and temporal continuity is excellent. The main temporal change is a general increase in height of the tropopauses and the associated CAT areas.

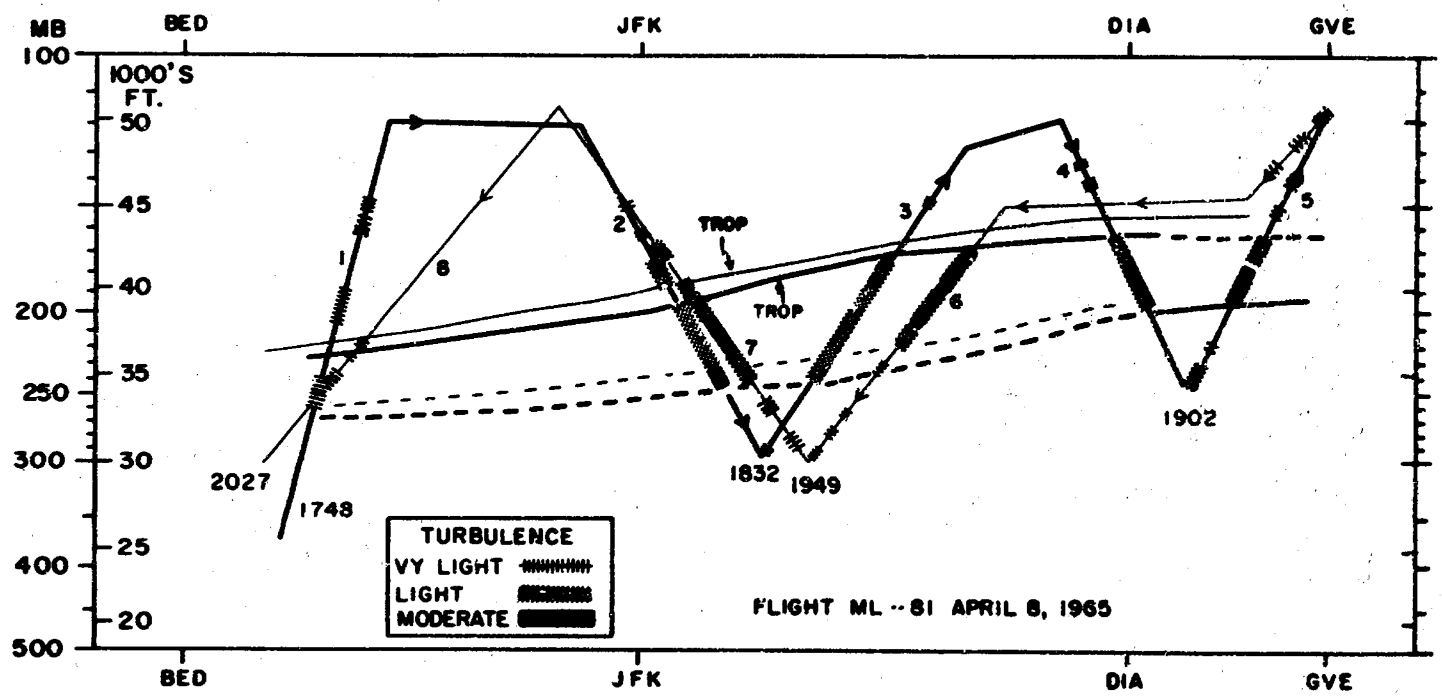

Figure 1. Southbound and Northbound Flight Tracks, Encountered CAT, Tropopauses, and Pseudo-tropopauses. Heavier lines refer to southbound track. Each ascent and descent identified by number, and time (GMT) is shown at few points

3.1.2 SYNOPTIC SITUATION

The 250-mb map for 09/00Z and the maximum wind charts for 08/12Z and 09/00Z are shown in Figures 2, 3, and 4 respectively. The mission track was on the cyclonic side of the jet and extended into the jet core; also, the track crossed slightly in advance of a weak upper-level ridge. During the 12-hour period covered by the maps, the ridge weakened considerably as it moved eastward. Weakening of the ridge was accompanied by a southward displacement of the jet and a decrease in maximum

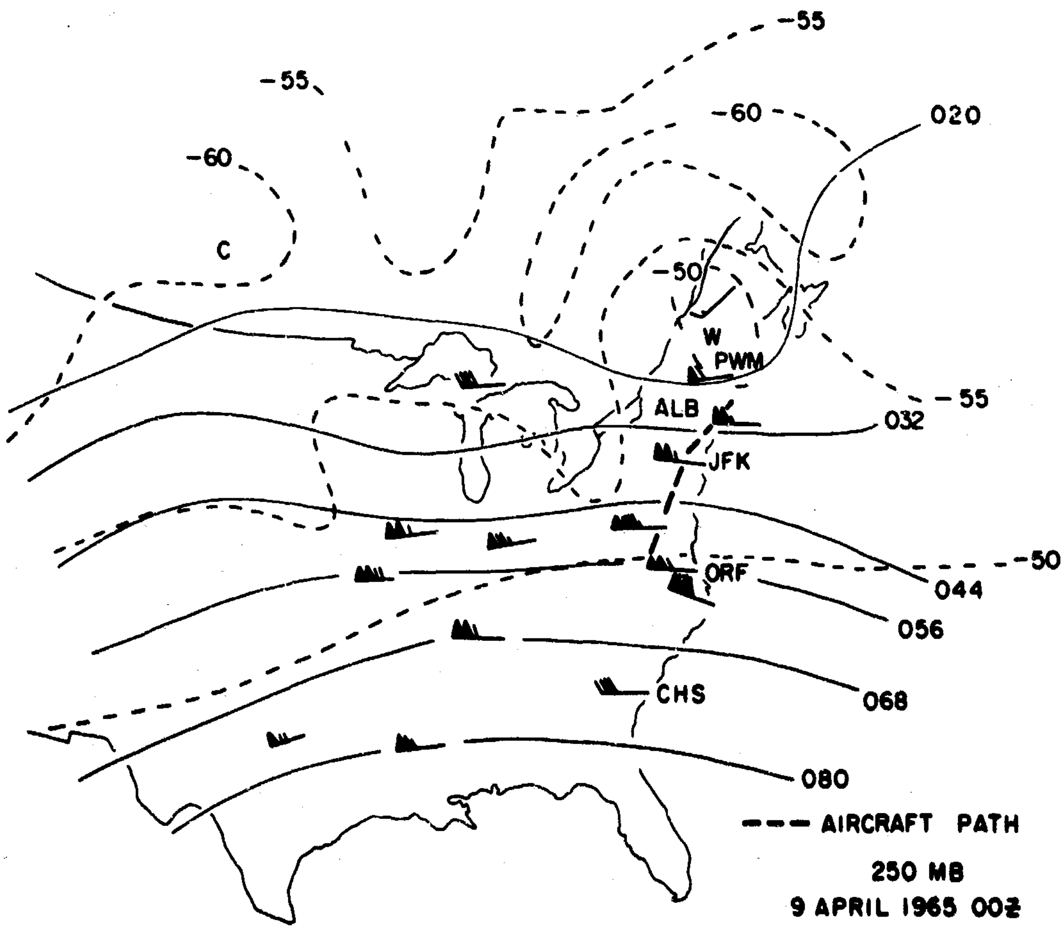

Figure 2. 250-MB Map, 9 April 1965, 00Z

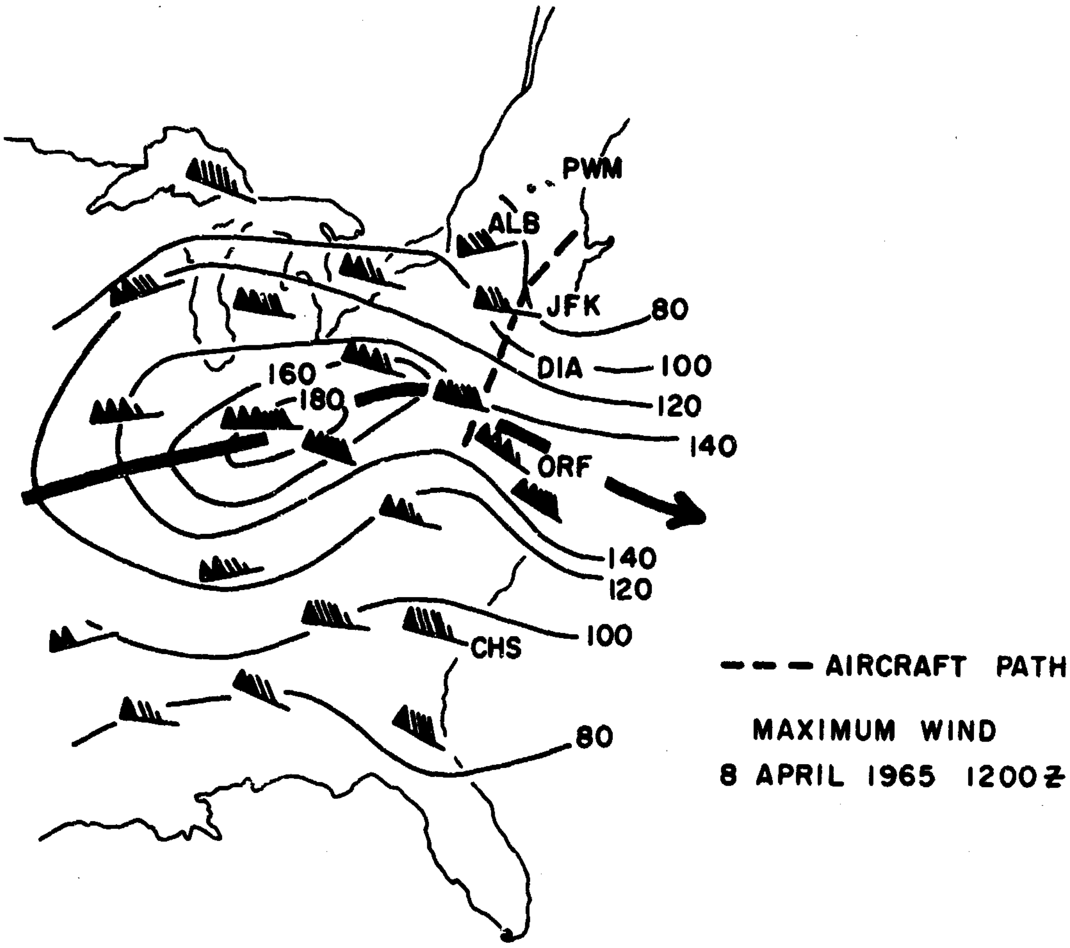

Figure 3. Maximum Wind, 8 April 1965, 12Z (Isotachs in knots)

wind speed from 180 knots to 140 knots. A cross section of the radiosonde data for 09/00Z is shown in Figure 5. The core speed is near 130 knots and located near 190-mb height. The level of maximum wind slopes downward to the north. The polar jet shown at the far left was not within the region of extensive probing. A feature to notice in Figure 5 is the double tropopause structure between stations JFK and DIA. Note that the lower tropopause is just above the level of maximum wind. These features will be more sharply defined in the mesoscale analyses.

3.1.3 MESOSCALE STRUCTURES

The mesoscale structure of wind speed, wind direction, potential temperature, and ozone, as determined from the data on the southbound leg, are shown in

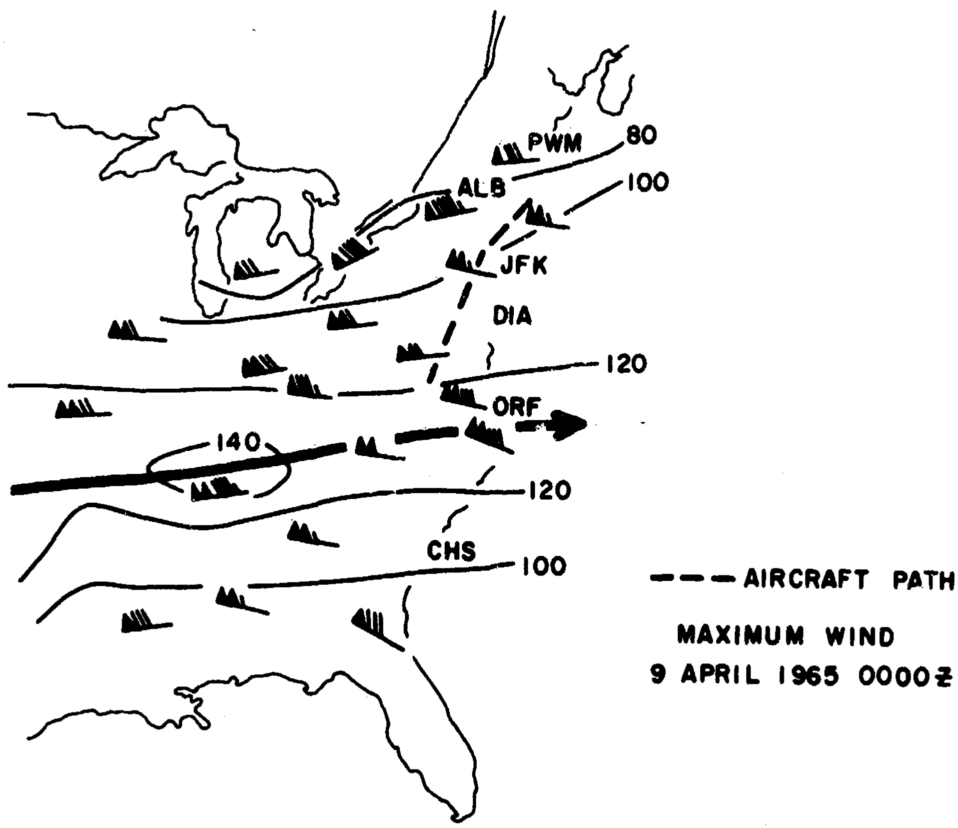

Figure 4. Maximum Wind, 9 April 1965, 00Z (Isotachs in knots)

Figures 6, 7, 8, and 9 respectively. Comparable cross sections for the northbound track are shown in Figures 10, 11, 12, and 13. In all, eight probes were made, and profiles of wind speed, wind direction, temperature, and Richardson number for each probe are shown in Figures 14 through 21. Probe numbers correspond with those in Figure 1. Spatial continuity of the measured parameters attests to the reliability of the data. In addition a comparison between the analyses from the southbound and northbound legs shows little change with time over the 2- to 3-hour period except for a systematic increase in height of about 1000 ft.

The most impressive feature found in this mission is the broad area of CAT (lateral extent at least 250 miles) sandwiched between the tropopause and a pseudo-tropopause. The significance of this feature will be pursued later. Layers of moderate CAT are shown within the extent of the core; however, the deepest layers are toward the cyclonic side. In probes numbers 2 and 7, layers of CAT were found above the tropopause. It is interesting to see that the stratospheric CAT layer in probe number 2 is one of relatively low stability. The turbulent area at the base of

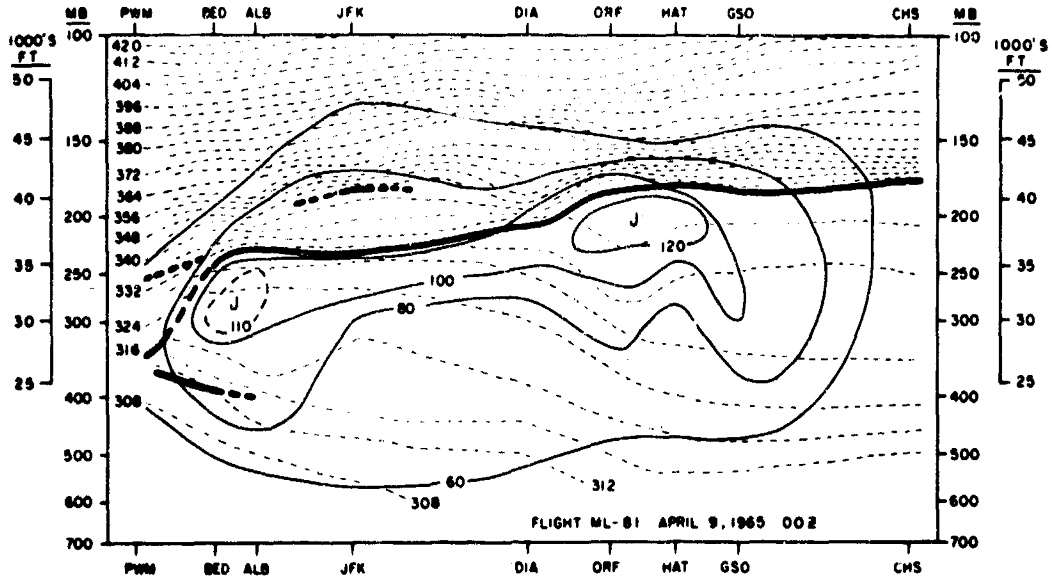

Figure 5. Vertical Cross Section From Portland (PWM) to Charleston (CHS). Thin solid lines are wind speed (knots), and thin dashed lines are potential temperature (°K). Heavy solid lines represent tropopause, heavy dashed lines represent pseudo-tropopause or base of stable region

of probe number 5 is associated with thick cirrus clouds. The layers of very light CAT were very shallow except for the ones in probe number 1.

We now return to a discussion of features in the region between the tropopauses. From the profiles shown in Figures 14 through 21, it is clear that the CAT area is based within a lower stable layer, extends through a layer of low stability, and is capped on top by the tropopause. The base of the lower stable layer coincides closely with the level of maximum wind speed. Above the level of maximum wind, the wind speed shear is large across the stable layer and less in the less stable layer. The wind direction also changes across the stable layer, resulting in a maximum northerly wind component in the middle of the CAT areas. The thermal fields shown in Figures 8 and 12 are interesting in that the horizontal temperature gradient is reversed between the stable layer and less stable region above. Since we are in a region where the wind is decreasing with height, it is clear that the thermal wind relationship is not being realised in the less stable zone. Of course, the deviation of the vertical shear from the thermal wind relationship may be equally as large in the stable zone. Our data was not entirely suitable for obtaining quantitative evaluations of the thermal wind relationship. We should also point out that a reversed horizontal temperature gradient, that is, where the thermal wind vector is opposed to the vertical wind shear vector, can be found even from the analysis of conventional data. This is shown in Figure 5 above the 200-mb level to the north of Station DIA.

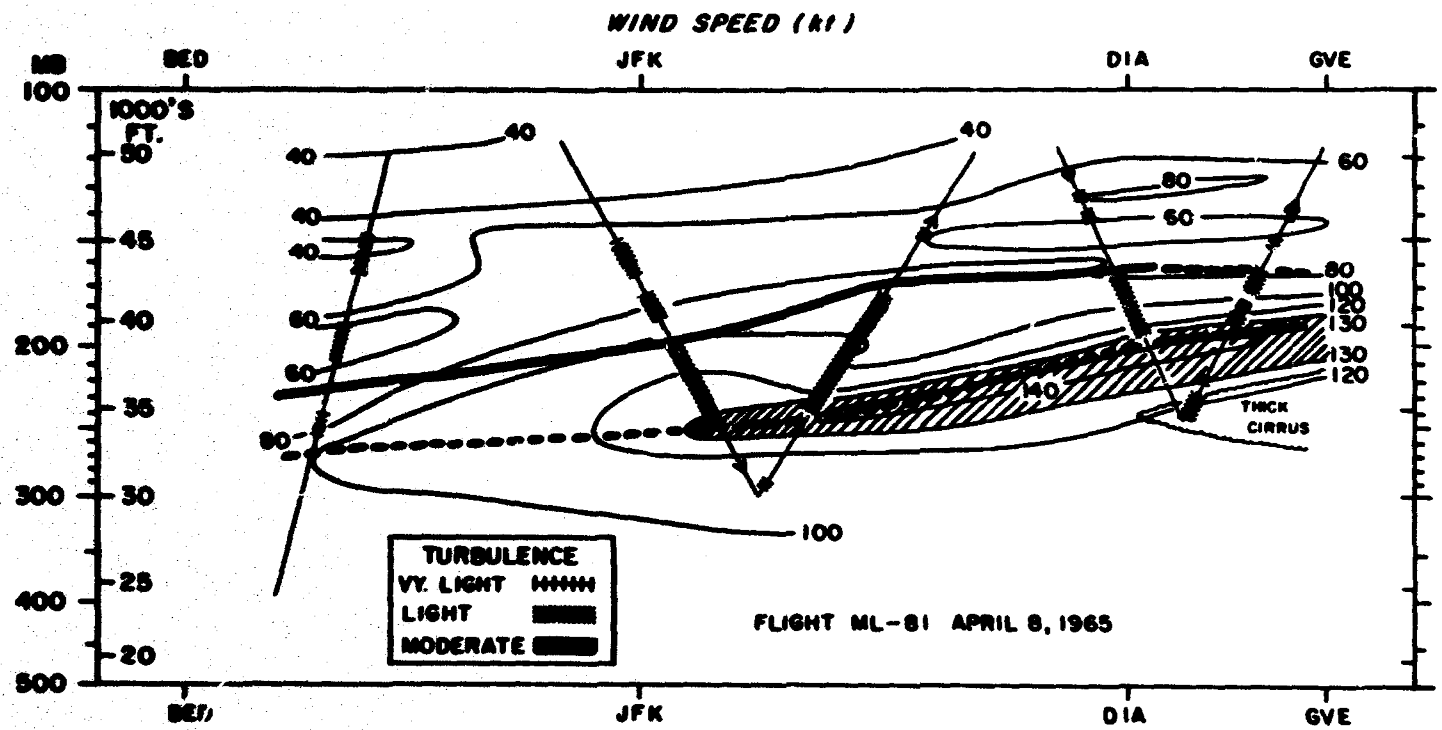

Figure 6. Cross Section of Wind Speed. Heavy lines represent tropopause and pseudo-tropopause

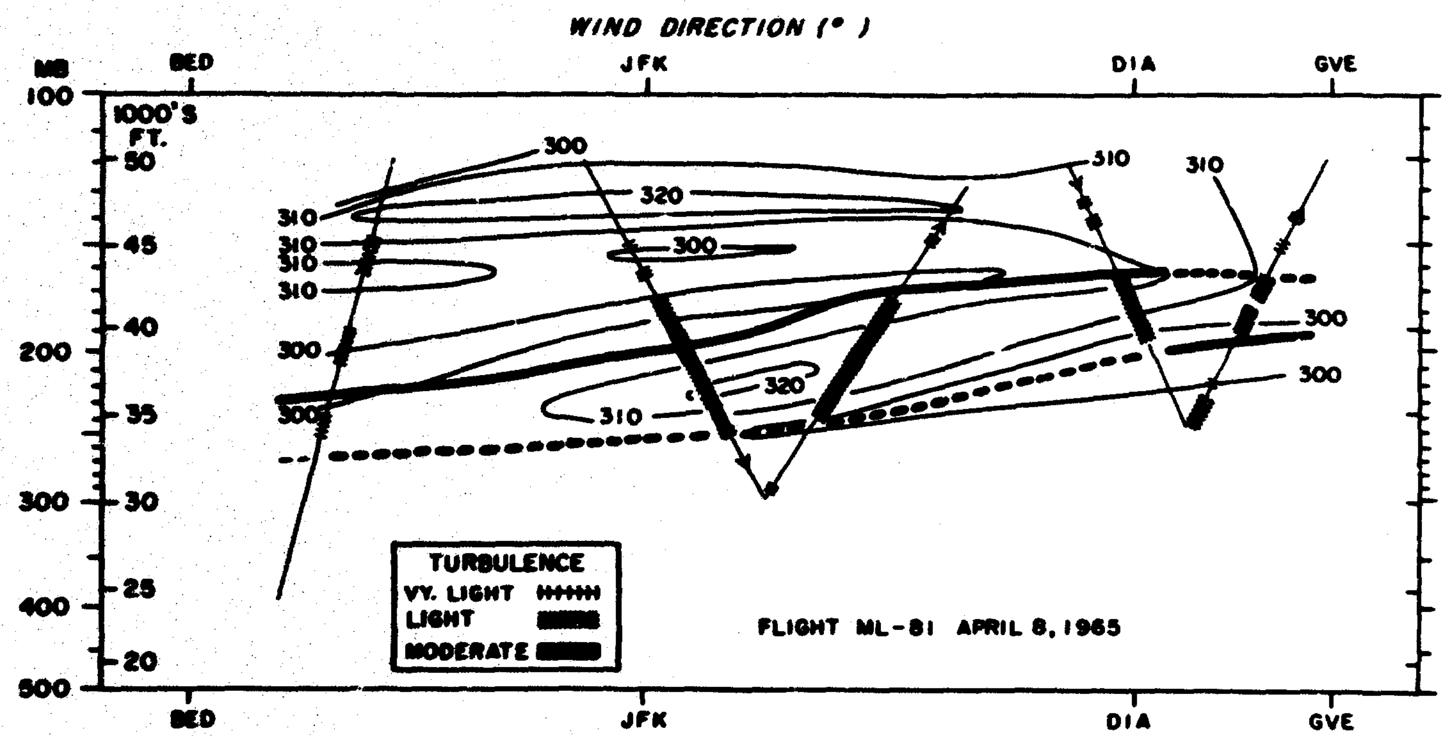

Figure 7. Cross Section of Wind Direction. Conventions same as in Figure 6

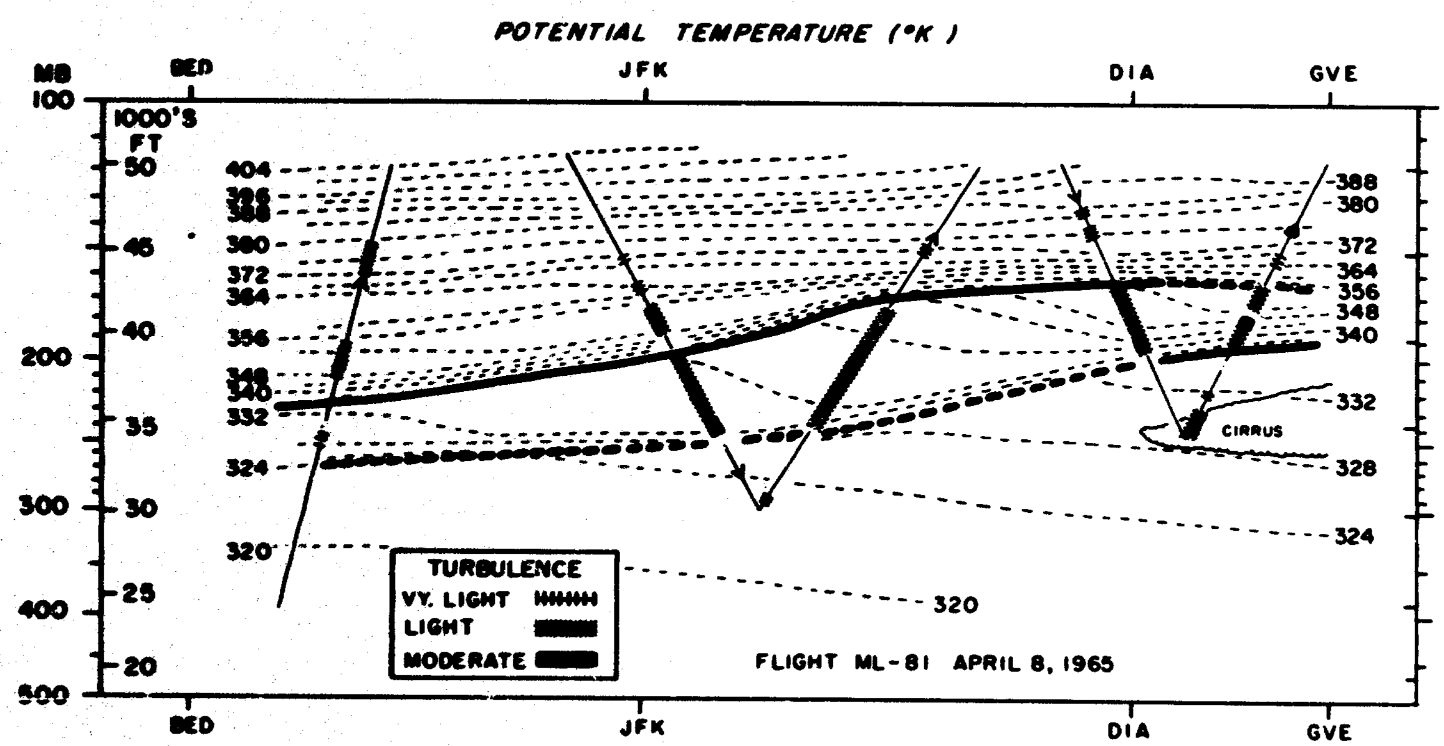

Figure 8. Cross Section of Potential Temperature. Conventions same as in Figure 6

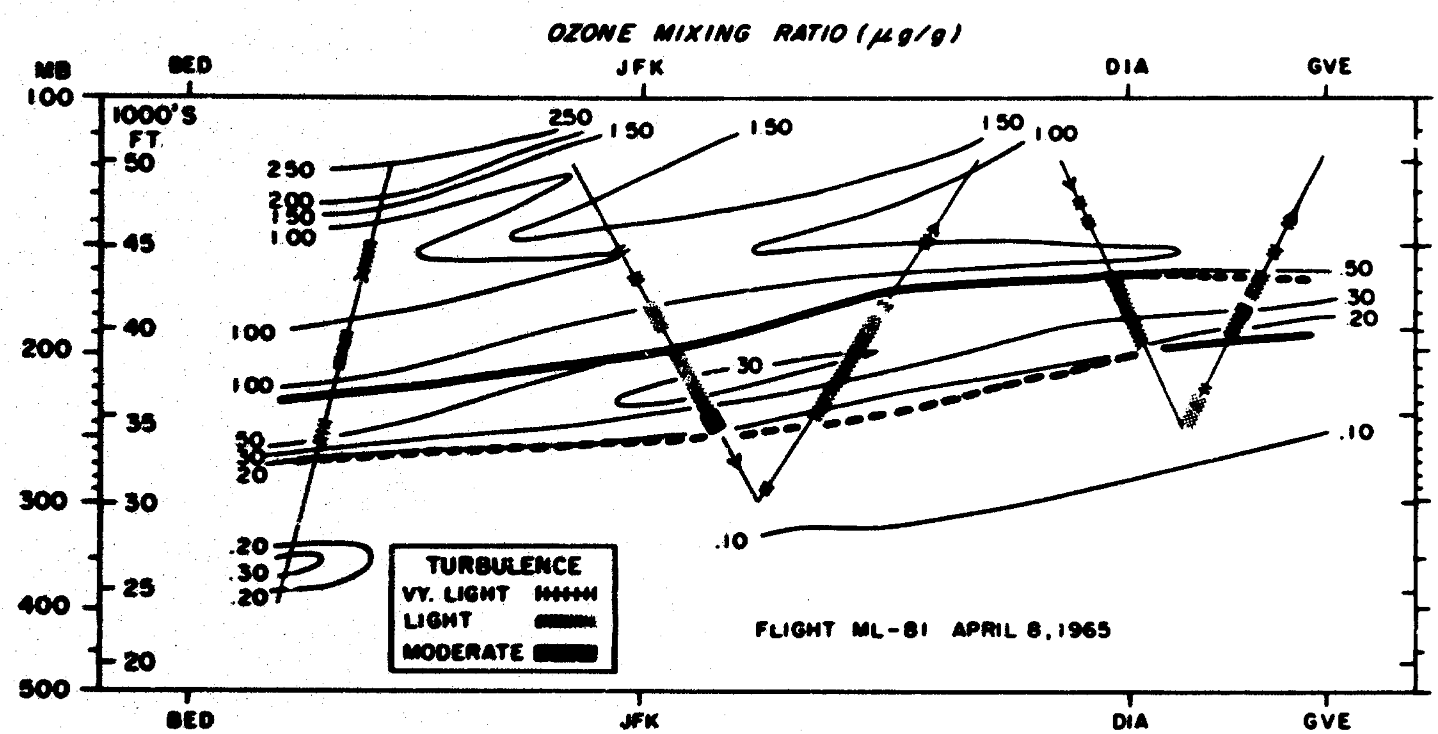

Figure 9. Cross Section of Ozone (μg/g). Conventions same as in Figure 6

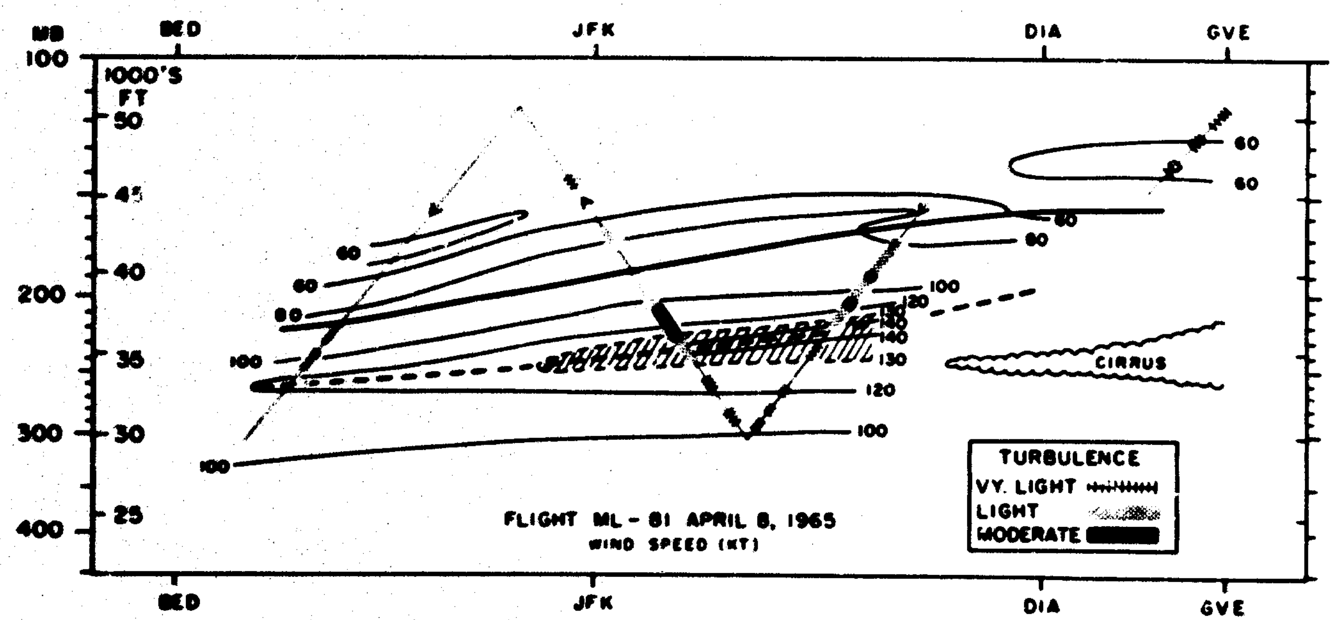

Figure 10. Cross Section of Wind Speed on Return Flight. Conventions same as in Figure 6

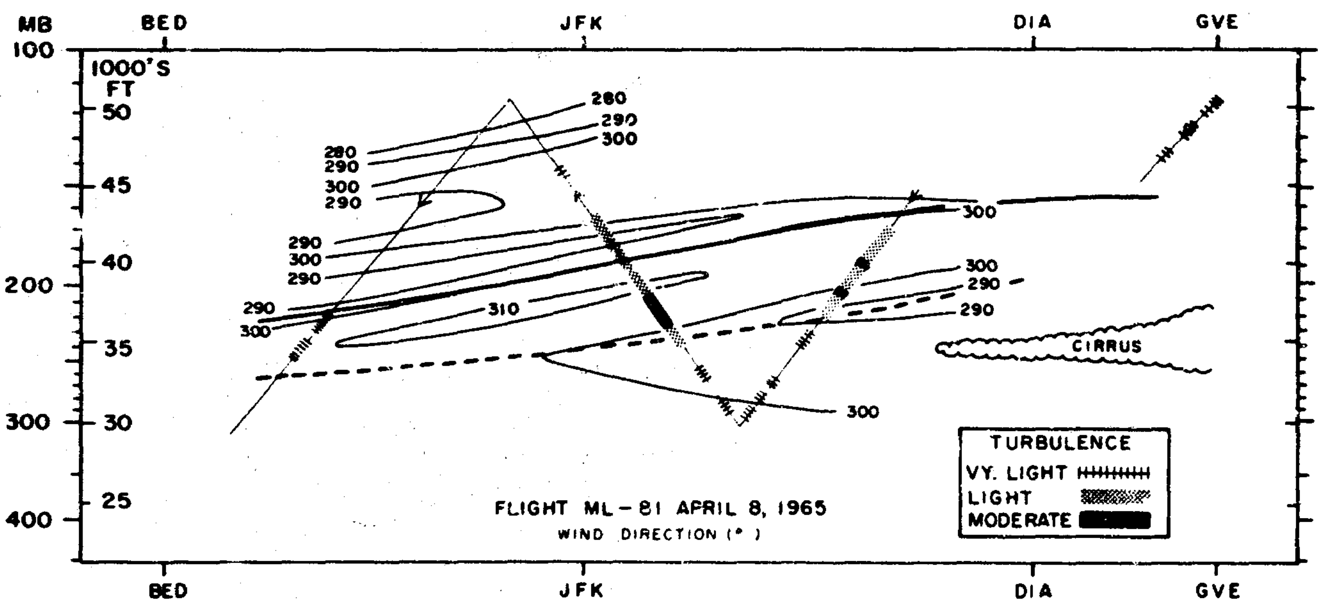

Figure 11. Cross Section of Wind Direction on Return Flight. Conventions same as on Figure 6

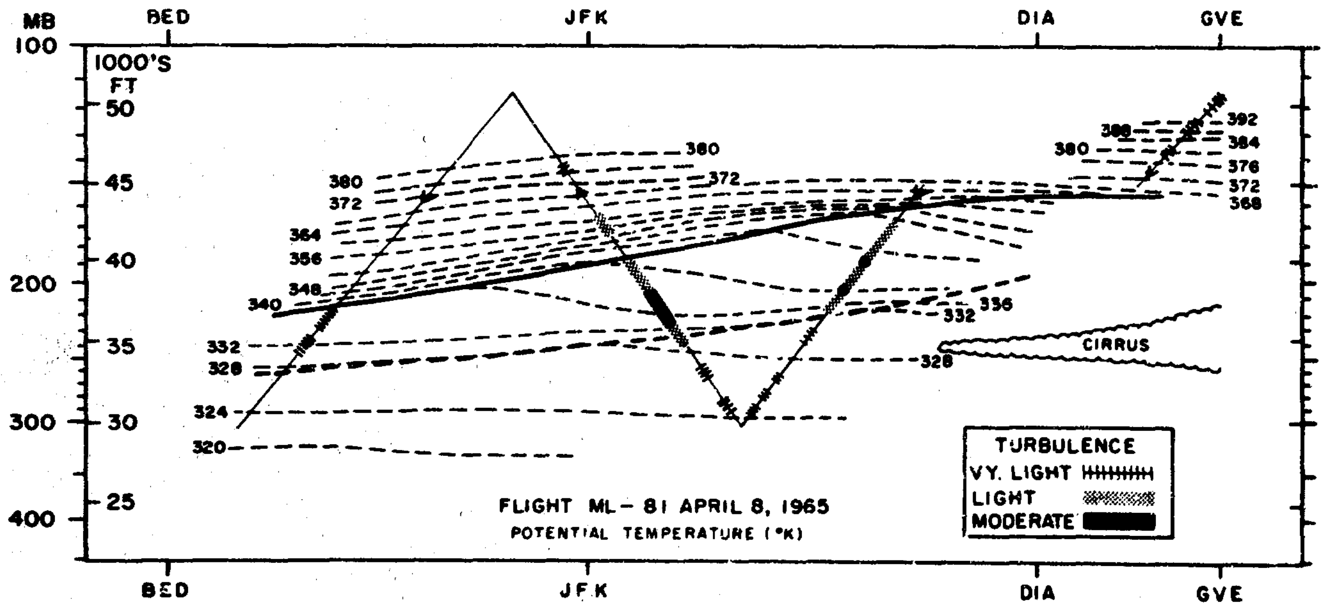

Figure 12. Cross Section of Potential Temperature on Return Flight. Conventions same as in Figure 6

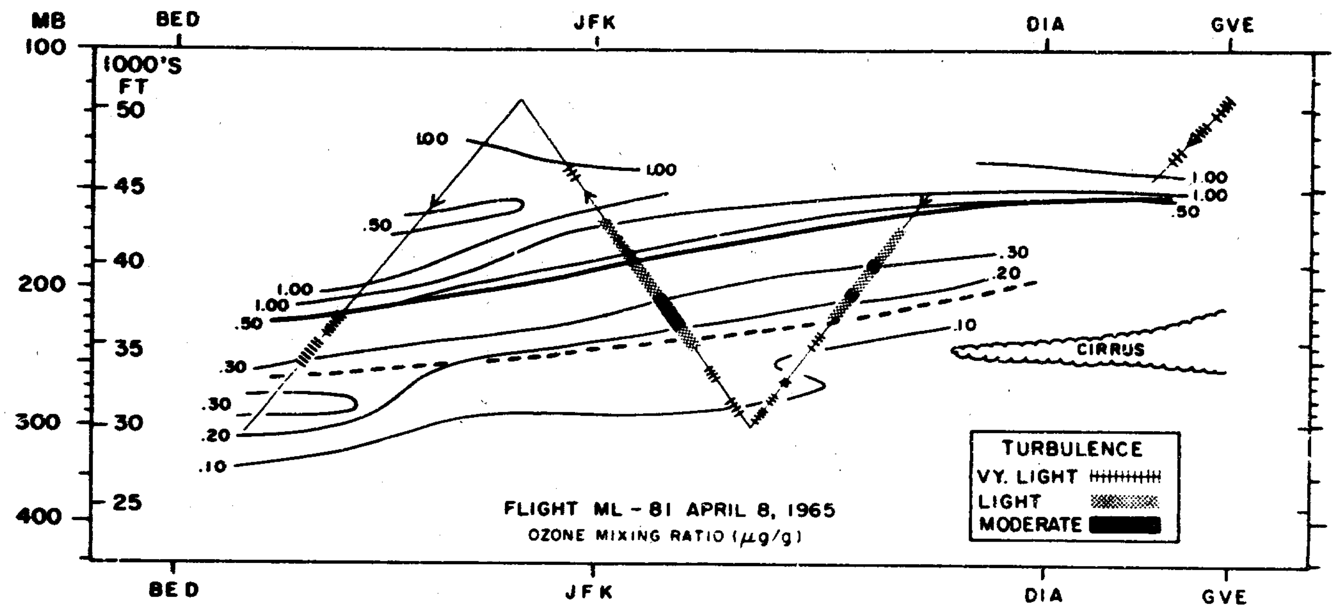

Figure 13. Cross Section of Ozone Mixing Ratio on Return Flight. Conventions same as in Figure 6

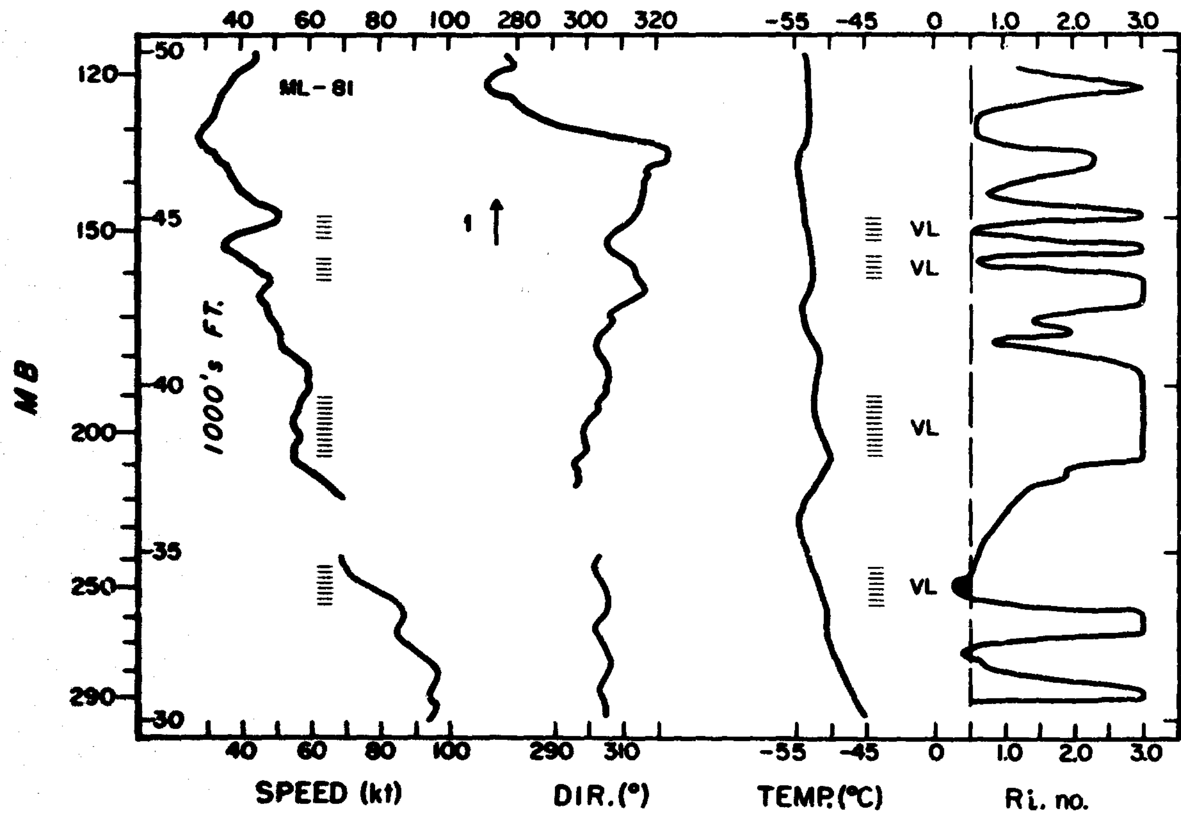

Figure 14. Vertical Profiles of Wind, Temperature, and the Richardson Number for Probe Number 1

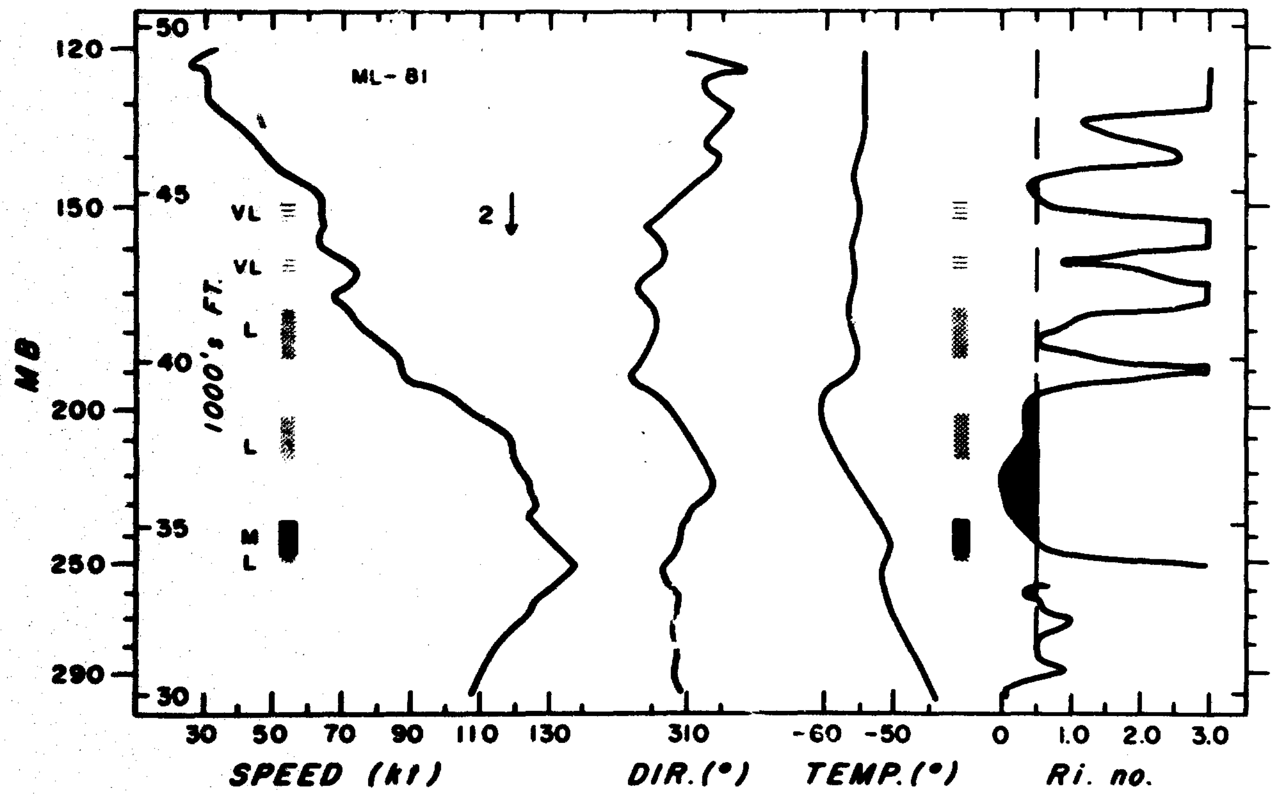

Figure 15. Vertical Profiles of Wind, Temperature, and the Richardson Number for Probe Number 2

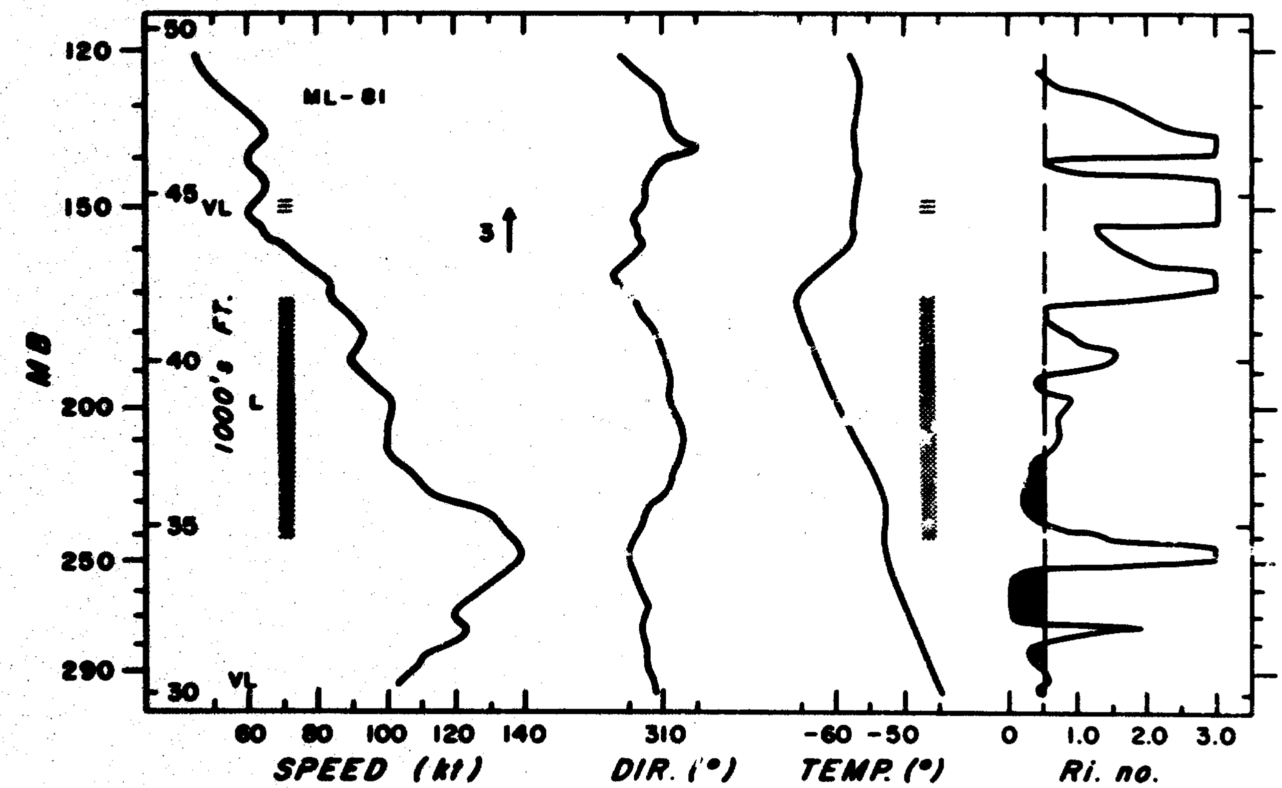

Figure 16. Vertical Profiles of Wind, Temperature, and the Richardson Number for Probe Number 3

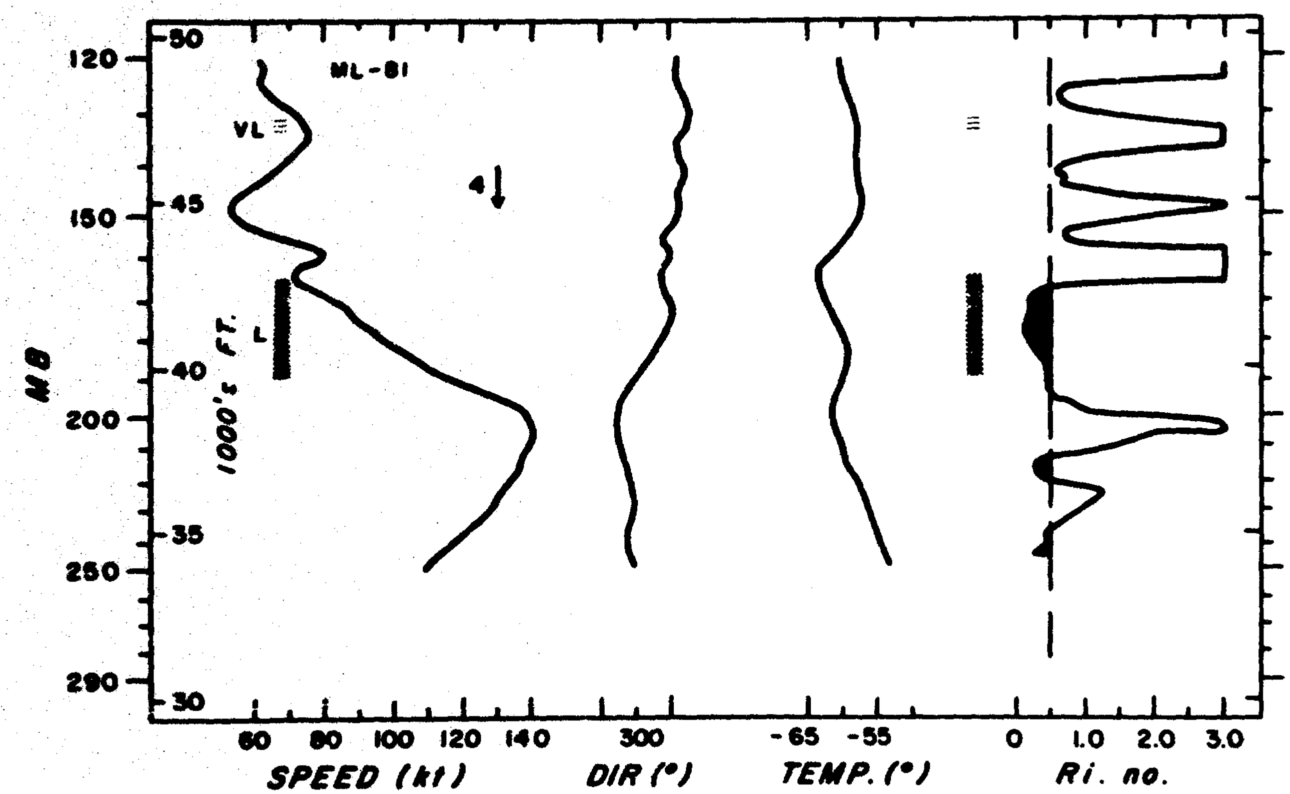

Figure 17. Vertical Profiles of Wind. Temperature, and the Richardson Number for Probe Number 4

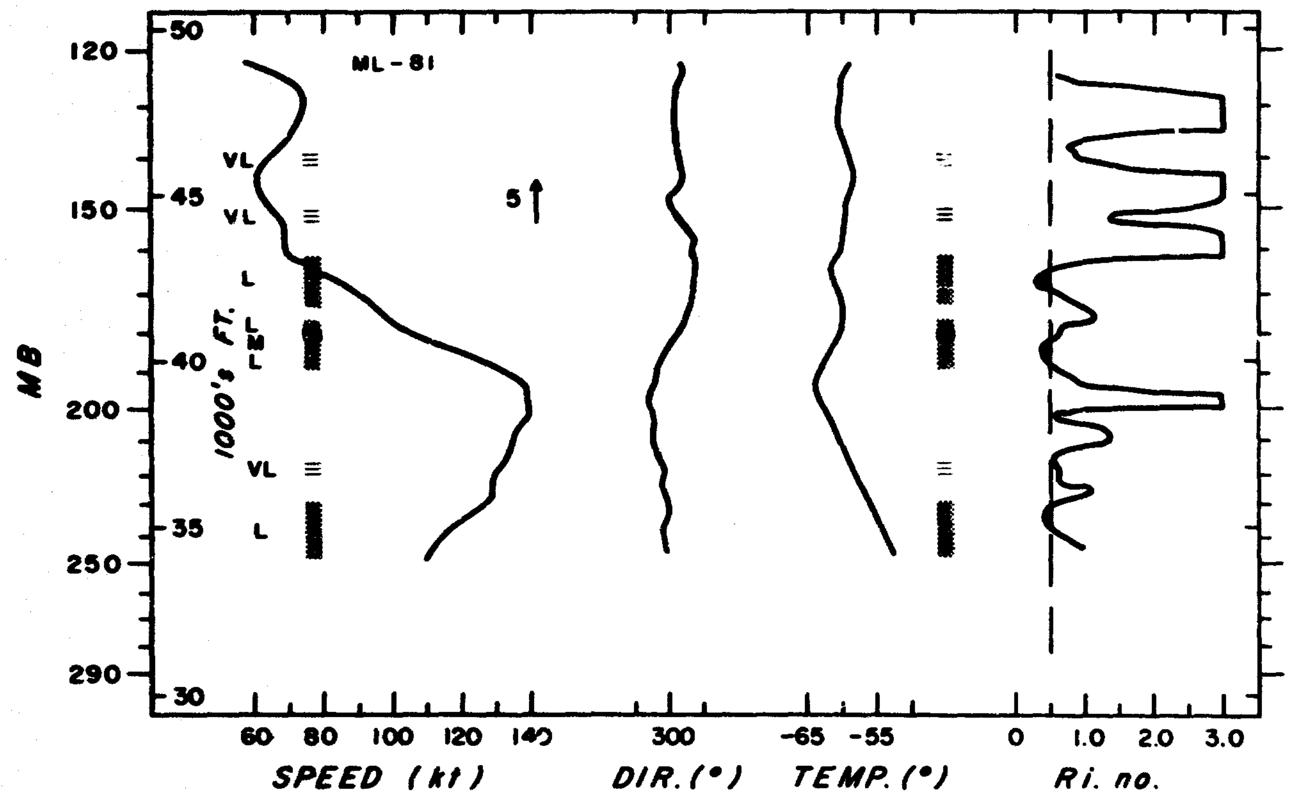

Figure 18. Vertical Profiles of Wind, Temperature, and the Richardson Number for Probe Number 5

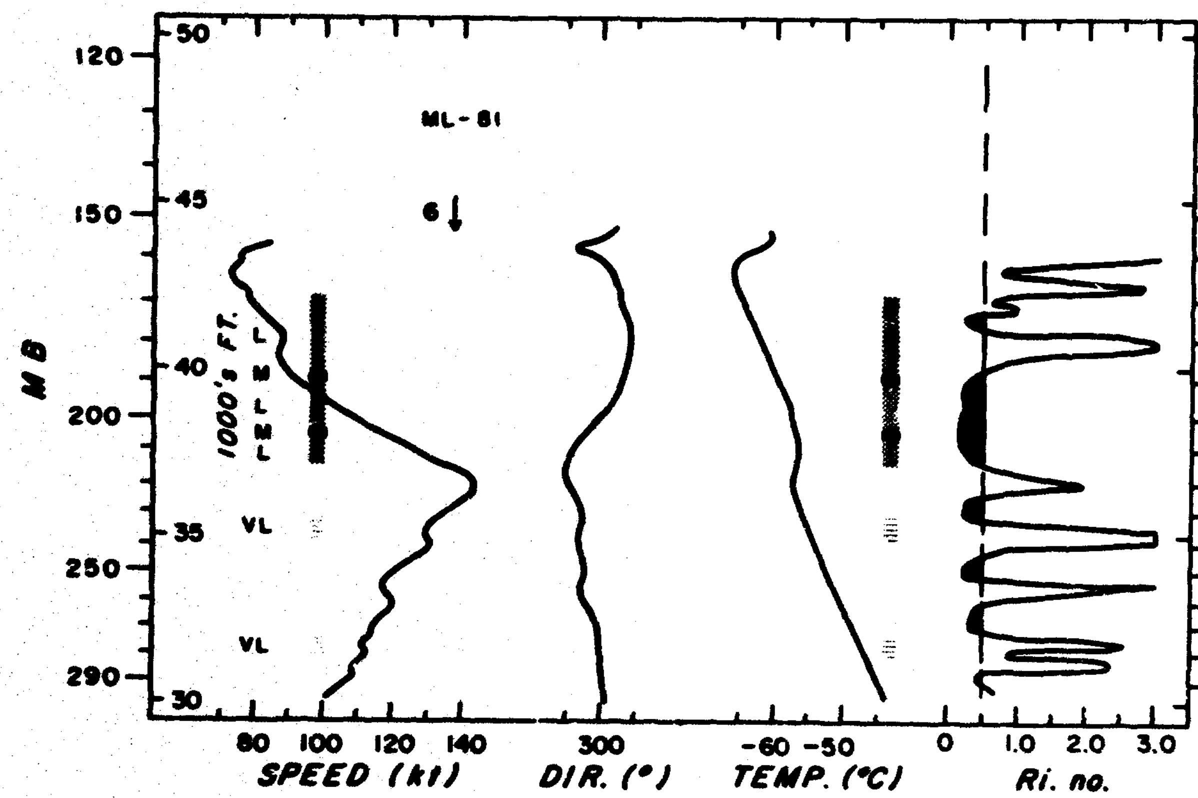

Figure 19. Vertical Profiles of Wind, Temperature, and the Richardson Number for Probe Number 6

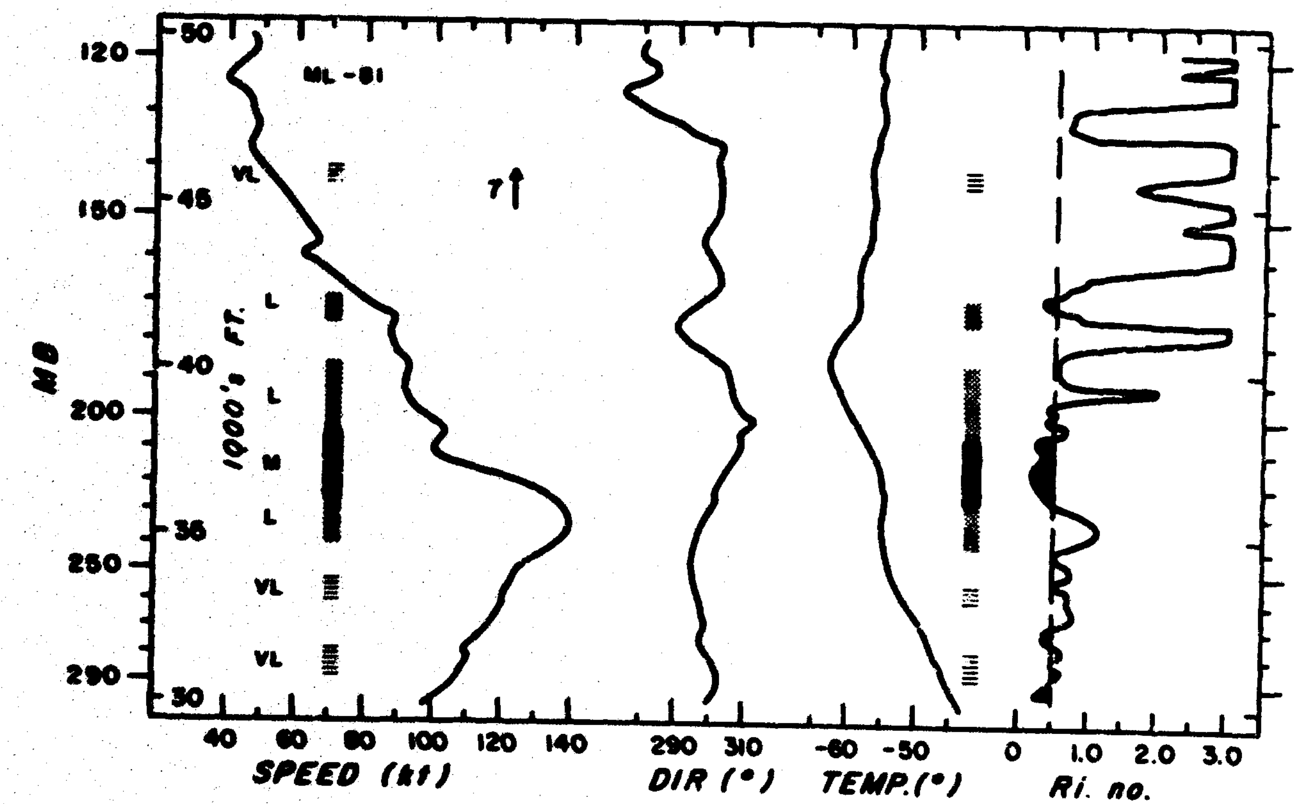

Figure 20. Vertical Profiles of Wind, Temperature, and the Richardson Number for Probe Number 7

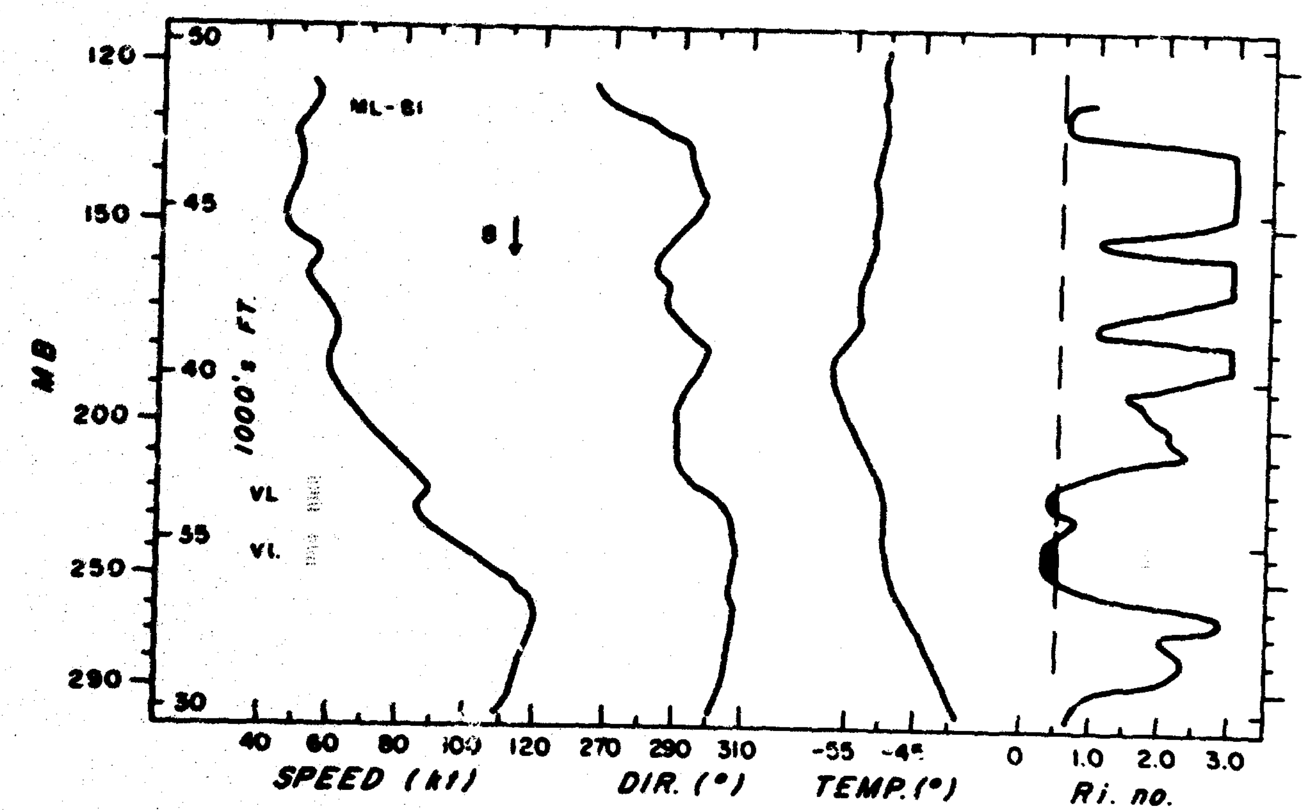

Figure 21. Vertical Profiles of Wind, Temperature, and the Richardson Number for Probe Number 8

The ozone cross sections shown in Figures 9 and 13 indicate air containing stratospheric concentrations of ozone extending down to the pseudo-tropopause. As noted earlier, stability is relatively low between the tropopause and the lower stable layer. One now is faced with the problem of how to reconcile low stability with "stratospheric" ozone because its solution may be related to the generation of turbulence. In this report we want simply to suggest some possible processes to account for association of reduced stability with high ozone. First, we could view the indicated vertical structures of temperature and ozone as one resulting from the vertical stretching of a stratospheric layer. This could be either the upward movement of air from the midlatitude air mass or the subsidence of a subtropical stratospheric layer. While vertical stretching reduces the static stability, it also acts to diminish the vertical wind shear. The net result would be to increase the Richardson number (indicative of less favorable conditions for CAT) as can be seen from the expression below. The symbols are defined in a previous section.

$$Ri = \frac{\frac{g}{\theta}\frac{\delta\theta}{\delta Z}}{\left(\frac{\delta U}{\delta Z}\right)^2}$$

Differential advection is another possible process to consider. In the region of the tropopause "break," two air masses are flowing side by side. Here, by differential advection, incursions could readily take place. Since there is a significant horizontal temperature gradient in the "break" region, the incursions could readily alter the static stability. An evaluation of the above-mentioned processes as well as others is a subject for further study.

3.1.4 RICHARDSON NUMBER CRITERION

Figures 8 through 17 show the relationship between the Richardson number and turbulence. A critical value of 0.5 was applied to the observations at height intervals of 1000 ft. A verification is shown in the contingency table which follows. The overall correct score was 79 percent, and 5[illegible] percent of CAT cases were correctly specified.

3.2 Mission ML-70 - Across an Anticyclonically Curved Northeast Jet

3.2.1 MISSION DESCRIPTION

Mission ML-70 probed the area from the coast of Maine to Syracuse, New York, on 7 April 1965, 17 to 19 GMT. The altitude range covered was mostly 30,000 to 40,000 ft or 200 to 300 mb. Figure 22 shows the aircraft track, the encountered

Table 1. Frequency of Turbulence vs Richardson Criterion of 0.5. Marginal figures in percent

	CAT	No CAT	
Ri ≤ 0.5	23	12	66%
Ri > 0.5	16	85	84%
	59%	88%	

NOTE: All Cases Percent Correct = 79

turbulence, the tropopause, and the pseudo-tropopause. The flight track was rather complex but consisted essentially of a descent and ascent near the coast of Maine, a fairly long level stretch near 175 mb, a descent east of Albany, and an ascent west of Albany. On the return flight a descent-ascent was made between Albany, New York and Portland, Maine. A single set of cross sections were constructed from the data. Most of the turbulence was found in the tropopause, and there was a layer of turbulent air between the tropopause and the pseudo-tropopause in the Maine-New Hampshire area.

3.2.2 SYNOPTIC SITUATION

The 200-mb maps for 06/12Z and 07/00Z and cross sections of the radiosonde data for the same periods are shown in Figures 23, 24, 25 and 26 respectively. The upstream ridge weakened while moving eastward. The aircraft track, which appears to be near the inflection part of the northwest flow at 06/12Z, is actually positioned close to the upper level ridge by 07/00Z. The eastward displacement of the upper level wave pattern was accompanied by similar movement of the tropopause "break" region, as can be seen from Figures 25 and 26. In response to these displacements, the tropopause at Portland, Maine (PWM) rose from 352 mb (27,000 ft) to 202 mb (39,000 ft).

3.2.3 MESOSCALE STRUCTURE

The mesoscale structures of the wind speed and wind direction, and of potential temperature and ozone are shown in Figures 27 and 28, respectively. Eight probes were made, and these are shown in detail in Figures 29 through 34. Probe numbers correspond to the numbers in Figure 22, except probe number 1, which was made near Bedford, Massachusetts. The jet core is near 250-mb level and has a velocity of NW 107 knots. There is a widespread incidence of turbulence in the troposphere. An area of particular interest is along the eastern end of the cross sections where a volume of CAT was sandwiched between the tropopause and pseudo-tropopause, and

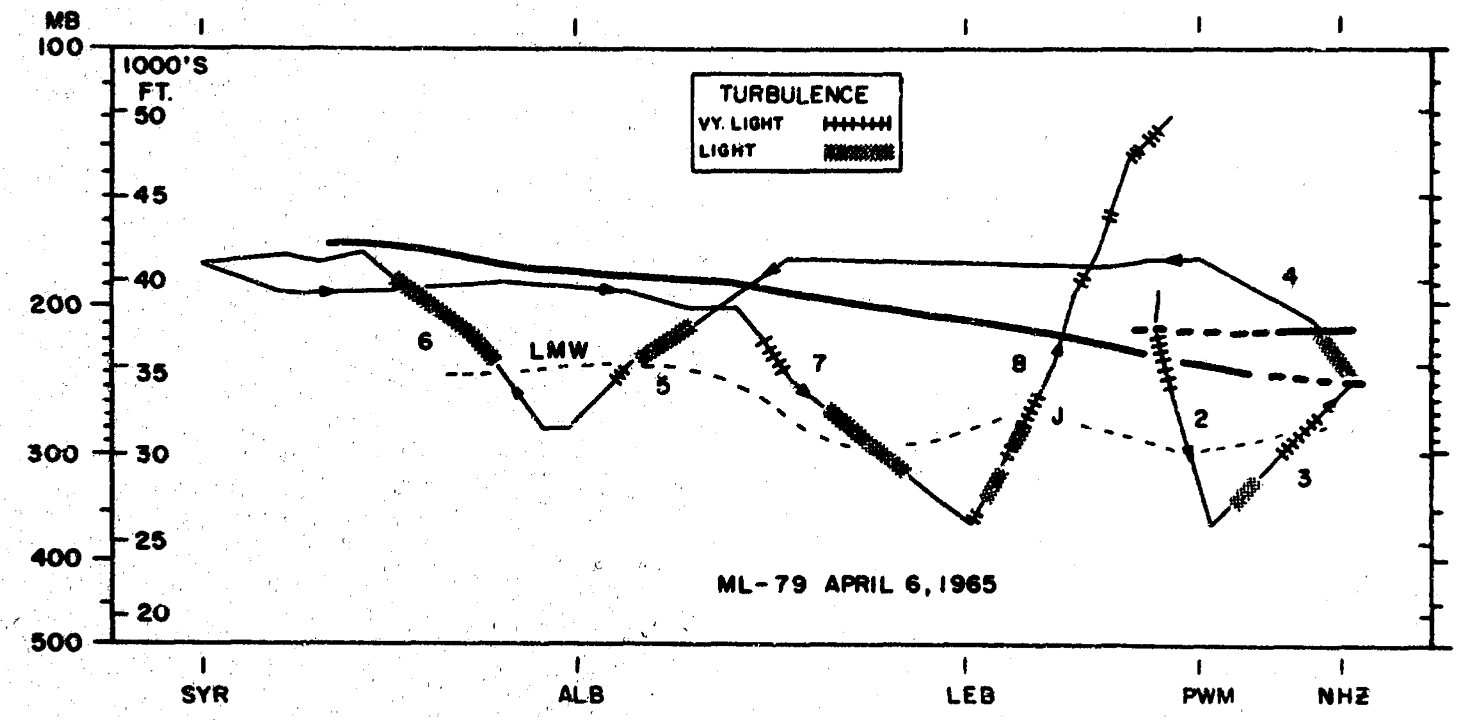

Figure 22. Flight for ML-79 From Brunswick (NHZ) Maine to Syracuse (SYR) New York. Encountered CAT shown. Heavier lines refer to tropopause and pseudo-tropopause, and numbers identify the ascents and descents. LMW is level of maximum wind

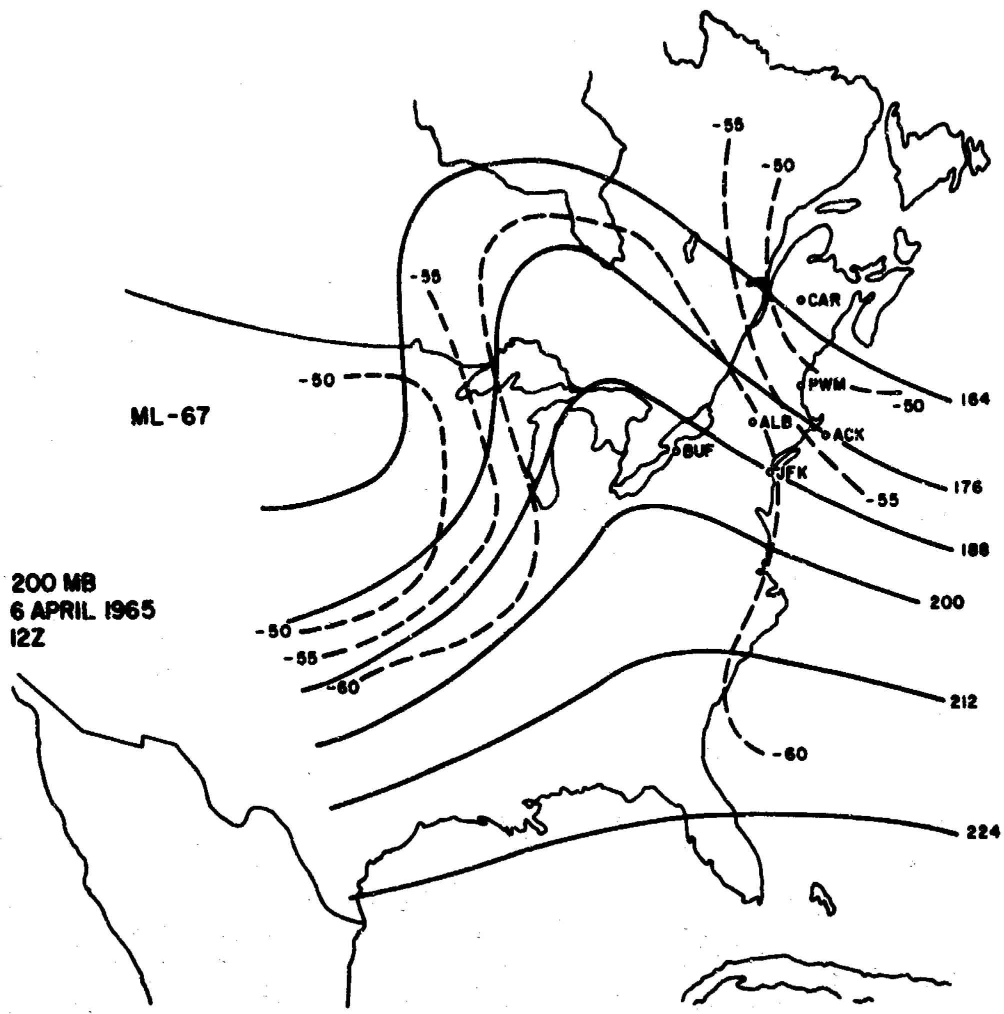

Figure 23. 200-MB Map, 6 April 1965, 12Z

the entire structure is above the level of maximum wind. The ozone analysis shown in Figure 28 indicates that air containing stratospheric amounts of ozone extends downward to the lower stable layer, from New Brunswick (NHZ) to Portland (PWM). This structure appears to be similar in a reduced sense to the situation in mission ML-81 where the turbulent zone between stable layers is much broader and intense. The question of reconciling high ozone and low stability in the turbulent zone is touched upon in the discussion of ML-81.

3.2.4 RICHARDSON NUMBER CRITERION

Figures 29 through 34 show the relationship of the Richardson number to turbulence. A statistical verification of 0.5 as a critical number relation to CAT or no CAT is presented in the contingency table which follows. We see that the criterion

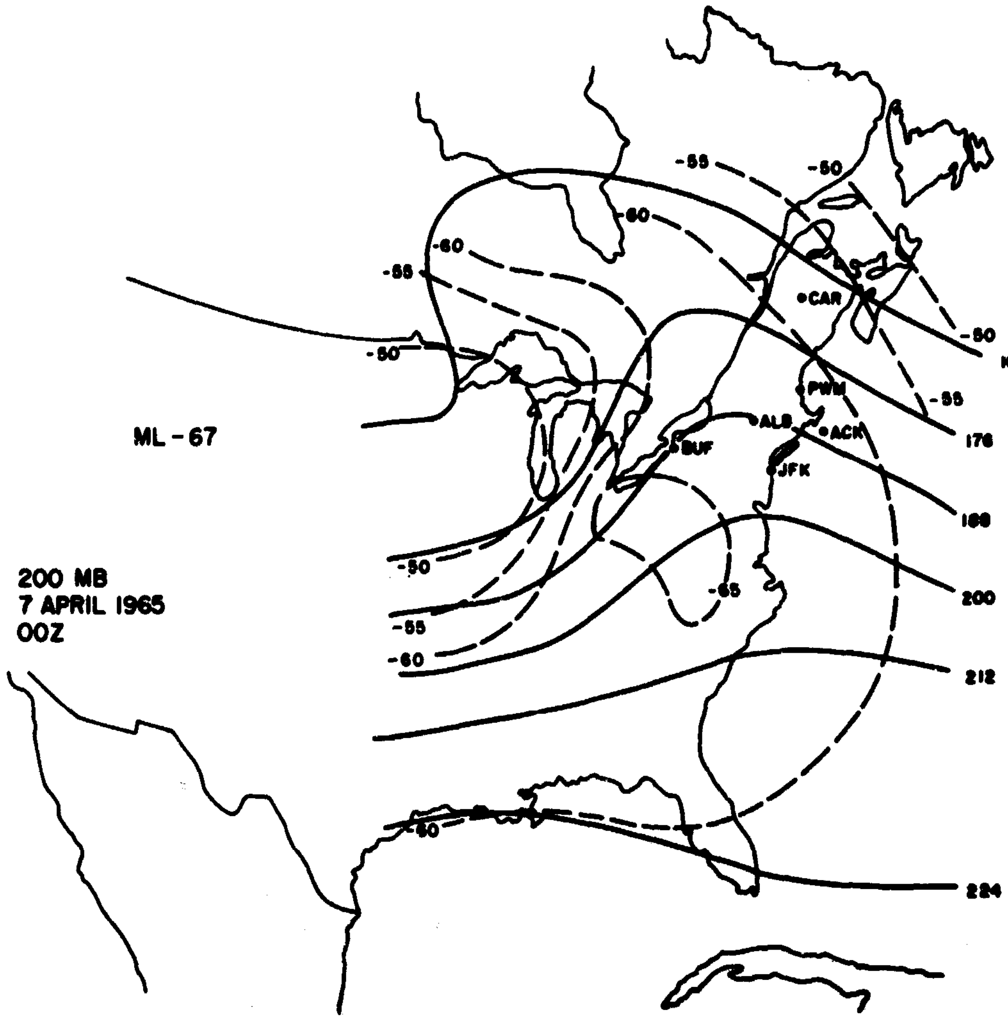

Figure 24. 200-MB Map, 7 April 1965, 00Z

Table 2. Frequency of Turbulence vs Richardson Criterion of 0.5. Marginal figures in percent

	CAT	No CAT	
Ri ≤ 0.5	22	7	76%
Ri > 0.5	9	52	85%
	71%	88%	

NOTE: All Cases Percent Correct = 82

correctly specified CAT 76 percent of the time, and 71 percent of the CAT cases were correctly identified. Overall score of hits was 82 percent.

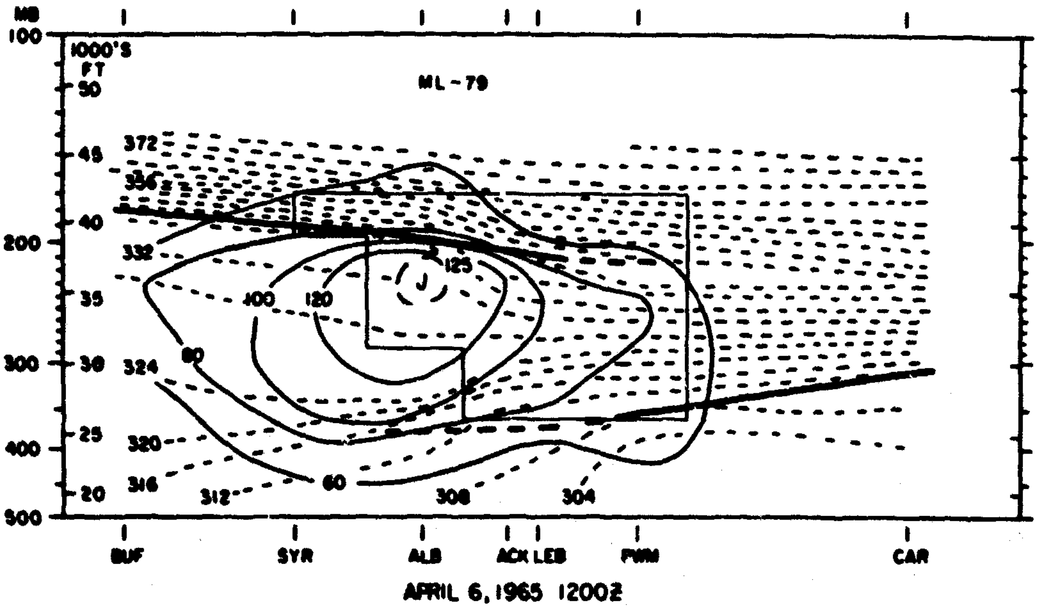

Figure 25. Vertical Cross Section From Buffalo (BUF) New York to Caribou (CAR) Maine, 6 April, 12Z. Thin solid lines are wind speed (knots) and thin dashed are potential temperature (°K). Heavy lines refer to tropopause and pseudo-tropopause

3.3 Mission ML-78 - Across Straight Northwest Jet

3.3.1 MISSION DESCRIPTION

Mission ML-78 probed the region between Bedford, Massachusetts (BED) and Raleigh-Durham, North Carolina (RDU) 5 April 1965, 16 to 22 GMT. Eight probes were made on the southward leg and six on the return flight. The probes were made mostly between 30,000 to 40,000 ft or 190 to 300 mb, except higher at the extremities of the mission. Figure 35 shows the aircraft's tracks, the encountered turbulence, tropopauses, and pseudo-tropopauses. South of the jet core the tropopauses apparently rose a few hundred feet over the two-hour period. From the core northward, the tropopause lowered as much as 400 ft. The mission was characterized by widespread very light turbulence, some of patches of light, and a layer moderate CAT in probe number 4. Rather thick cirrus clouds were encountered in probes 8, 9, and 12.

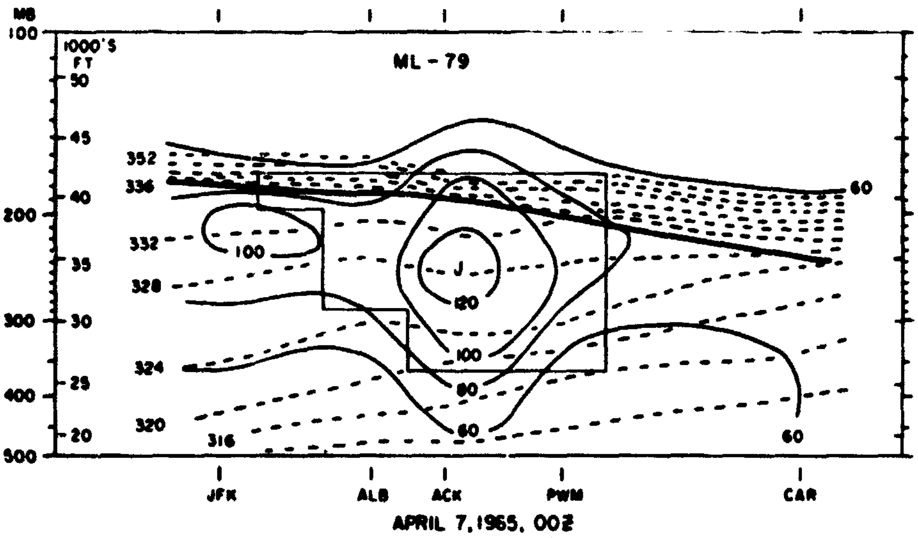

Figure 26. Vertical Cross Section From Buffalo (BUF) New York to Caribou (CAR) Maine, 7 April, 12Z. Thin solid lines are wind speed (knots) and thin dashed are potential temperature (°K). Heavy lines refer to tropopause and pseudo-tropopause

3.3.2 SYNOPTIC SITUATION

The 250-mb maps for 5/12Z and 6/00Z and the maximum wind charts for the same periods are shown in Figures 36, 37, 38, and 39 respectively. The upper level ridge in the western Great-Lakes region was essentially stationary and expanding to the north. This ridging was accompanied by a noticeable northward displacement of the jet stream. The exit region of the jet intersects the northern section of the aircraft path, while a weak subtropical jet is located west of the southern portion of the track. Cross sections derived from the radiosonde data for 5/12Z and 6/00Z are shown in Figures 40 and 41 respectively. The jet is shown to be displaced northward about 250 miles in the 12-hour period. The tropopause "break" shown on the 05/12Z cross section is difficult to portray 12 hours later because our cross section does not extend far enough to the north. The northward displacement of the jet was accompanied by rising tropopauses and decreasing stability between 250 to 200 mb from Virginia to New York City. We see later that here is where the main layer of CAT was found.

3.3.3 MESOSCALE STRUCTURE

The mesoscale structures of wind speed and wind direction, and of potential temperature, and ozone are shown in Figures 42 and 43 respectively for the southbound portion of the mission. Comparable analyses are shown for the return flight in Figures 44 and 45. Profiles of wind, temperature, and Richardson number

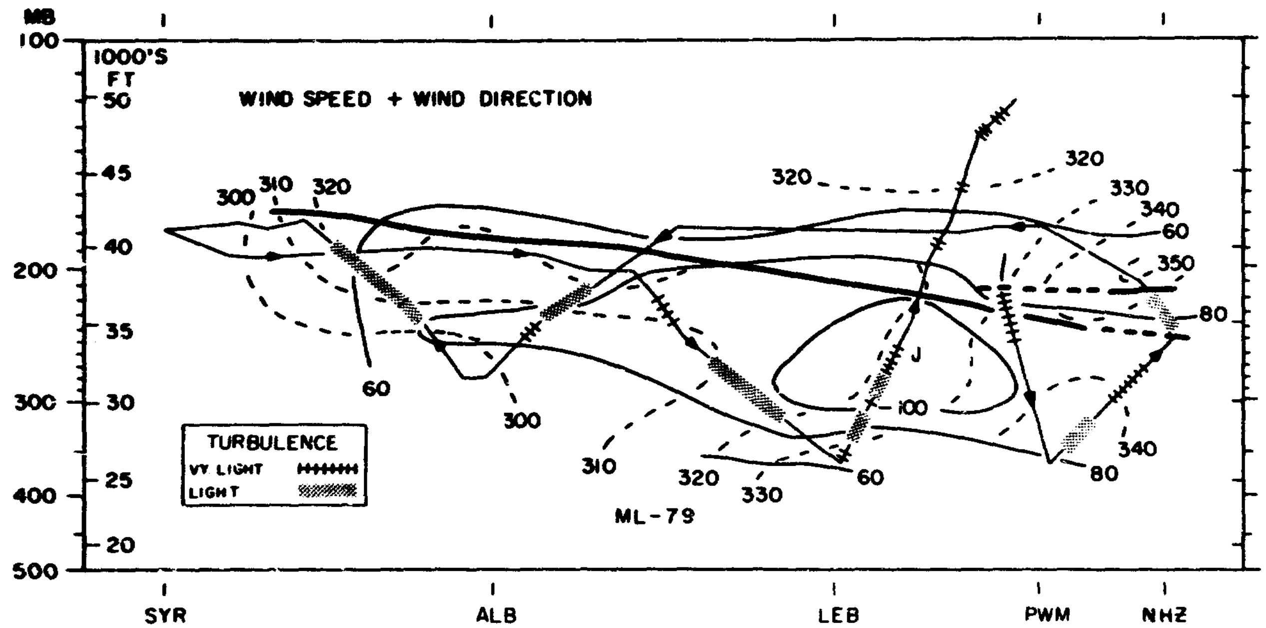

Figure 27. Cross Section of Wind Speed (Solid Lines and in Knots) and of Wind Direction (Dashed Lines and in Degrees). Heavier lines identify tropopause and pseudo-tropopause

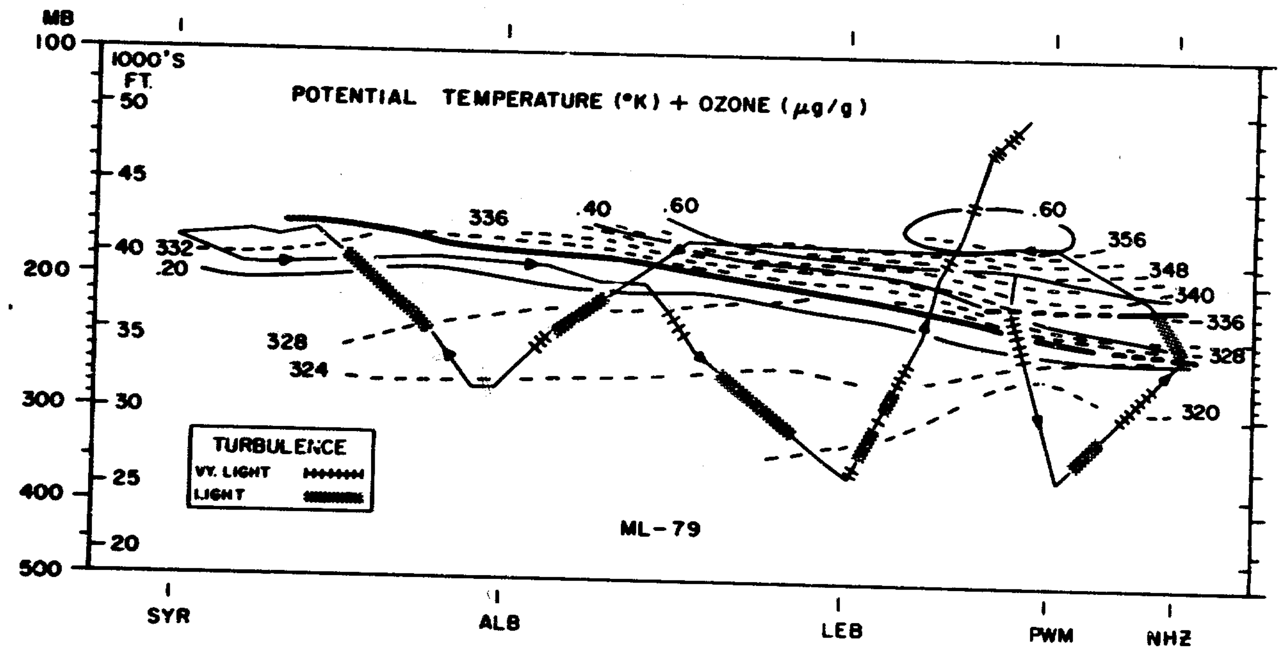

Figure 28. Cross Section of Potential Temperature (Dashed Lines) and of Ozone Mixing Ratio (Solid Lines). Conventions same as in Figure 27

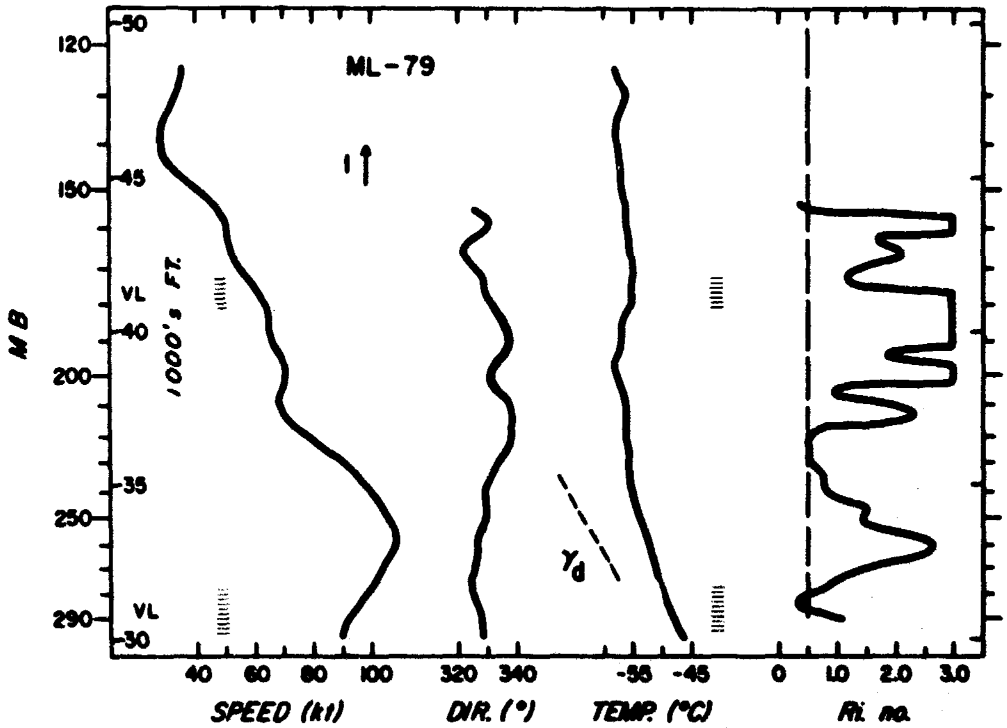

Figure 29. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Number 1

are presented for the eight probes in Figures 46 through 53. The location of the jet core and the double tropopause structure to the right of the jet resemble similar features, as shown in the 06/00Z cross section in Figure 43. The southbound and northbound cross sections, two to four hours apart in time, are in good general agreement. Differences between the two sets of analyses are consistent with 12-hour changes in the RAOB analyses. Over the two- to four-hour period, we find that the jet core is displaced slightly to the north, and the tropopause and pseudo-tropopause south of the jet are a few hundred feet higher in elevation. North of jet, the tropopause has dropped in height.

An area of CAT is shown just above the level of maximum wind in each of probes 3, 4, 5, 6, and 11. A logical assumption is that these observations represent a broad layer of turbulence where the CAT is of moderate intensity above the jet core and tapers off to very light intensity to the north and south. On the southbound flight the CAT areas appear to be trapped between the tropopause and a lower stable layer. However, on the return trip, the CAT area in probe number 11 is entirely within a stable layer. The same is true for the CAT area between 200 to 230 mb in probe number 13. Stratospheric layers of CAT over 2000 ft in depth are shown in probes 8 and 9. Asside from a few shallow stratospheric patches, the remaining

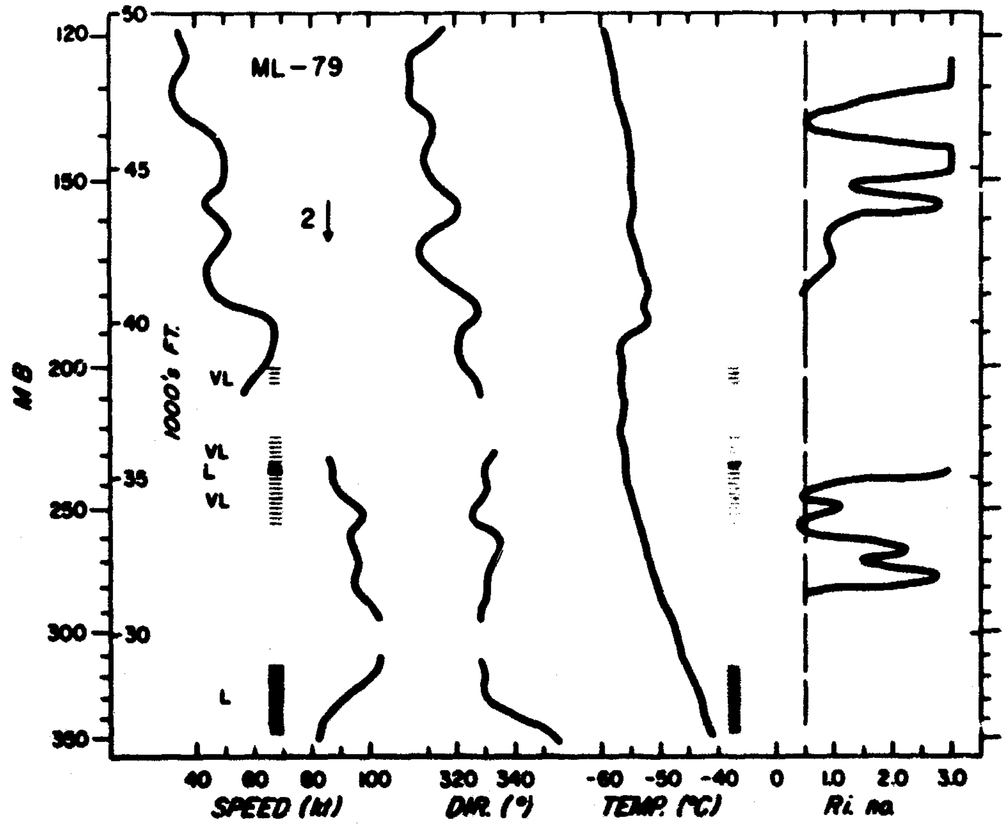

Figure 30. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Number 2

areas of CAT are found in regions of low stability and, at or below, the level of maximum wind. The three encounters through cirrus clouds in probes 8, 9, and 12 were in turbulent regimes.

The ozone analyses, see Figures 43 and 45, show tropospheric amounts extending above the indicated tropopause in the vicinity of station RDU. Meanwhile, both RAOB cross sections show that tropopause south of the jet is in the 170- to 180-mb height range, agreeing with the ozone indications. The conflicting tropopause heights are due to the fact that the temperature profile near tropopause level was "rounded," and in the aircraft data, the criterion for a tropopause was met near the bottom of the "rounded" curve. Note, however, that in the vicinity of jet that stratospheric ozone amounts extend below the tropopause.

Our main concern is with the region containing the broad layer of CAT. This layer is in the vicinity of the jet and above the level of maximum wind. Here we see features common to some of our other cases. The turbulence is above the level of maximum wind and is contained between the tropopause and a lower stable layer or pseudotropopause. The base of the lower stable layer appears to follow the

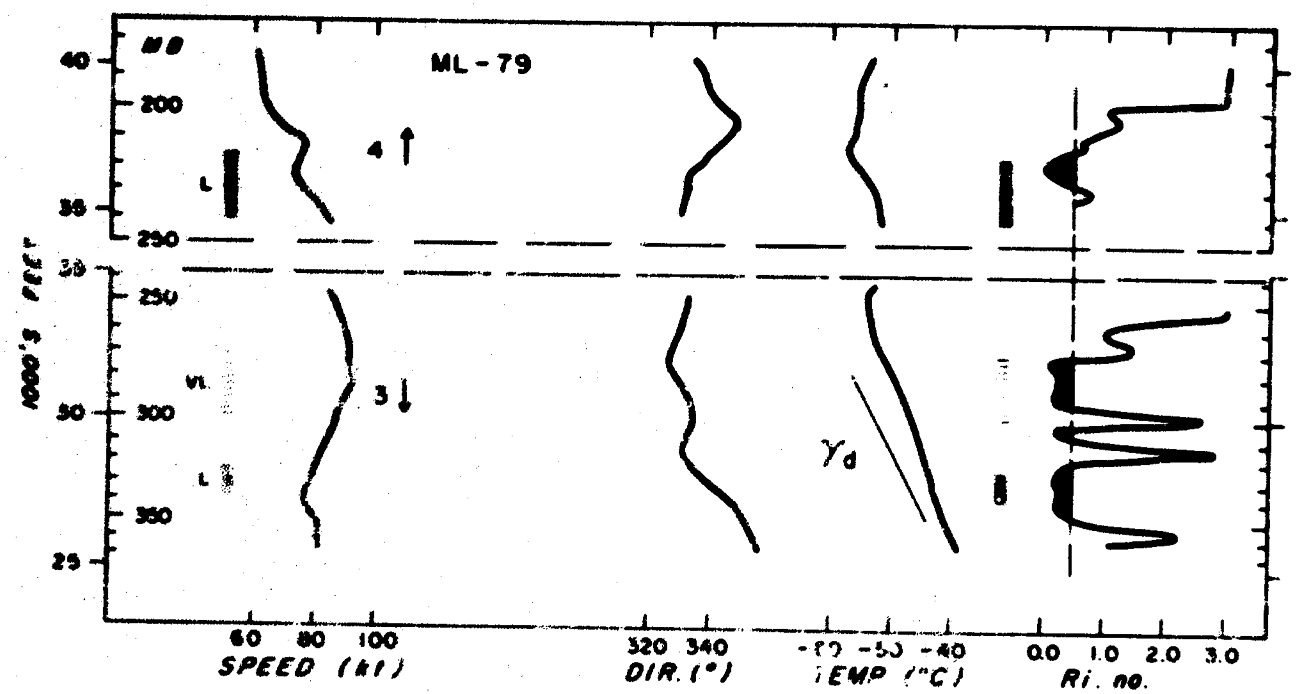

Figure 31. Vertical Profiles of Wind, Temperature, and Richardson Number for Probes Numbers 3 and 4

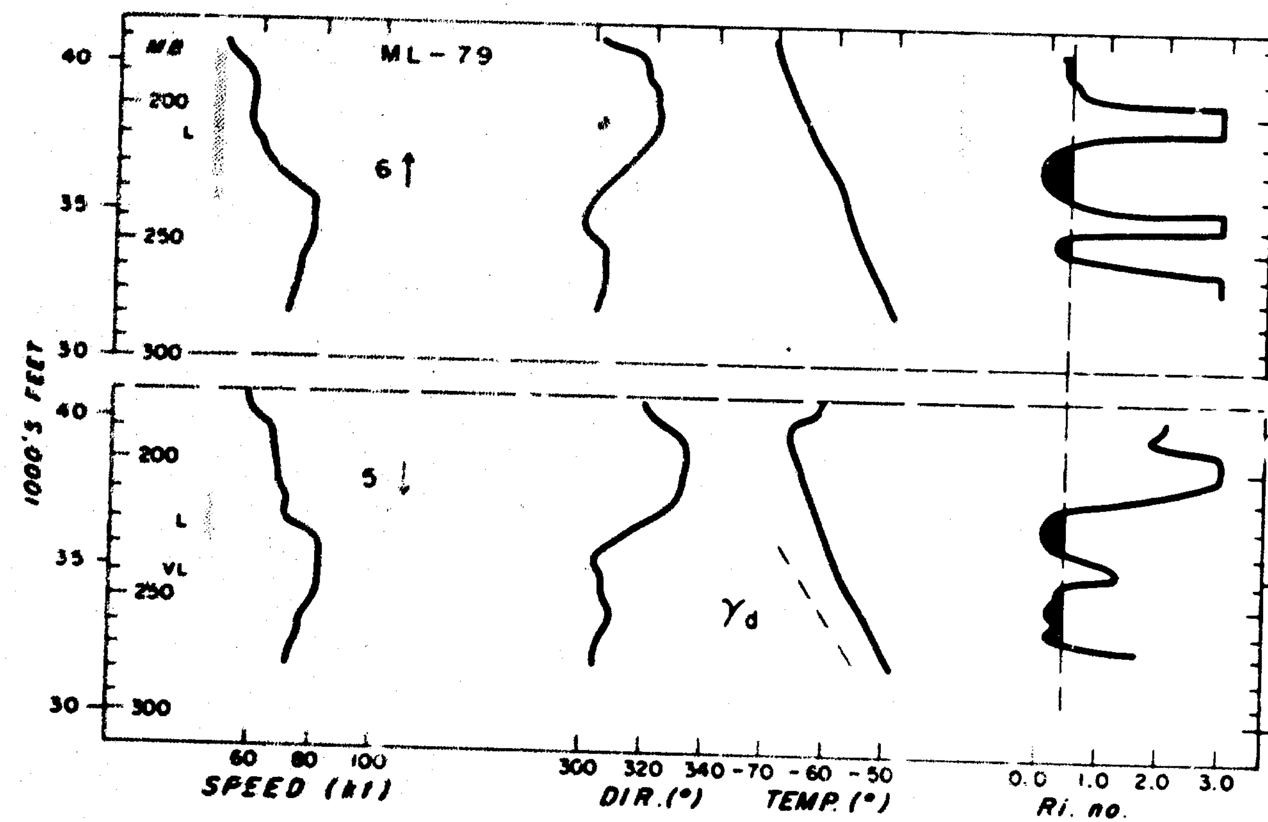

Figure 32. Vertical Profiles of Wind, Temperature, and Richardson Number for Probes Numbers 5 and 6

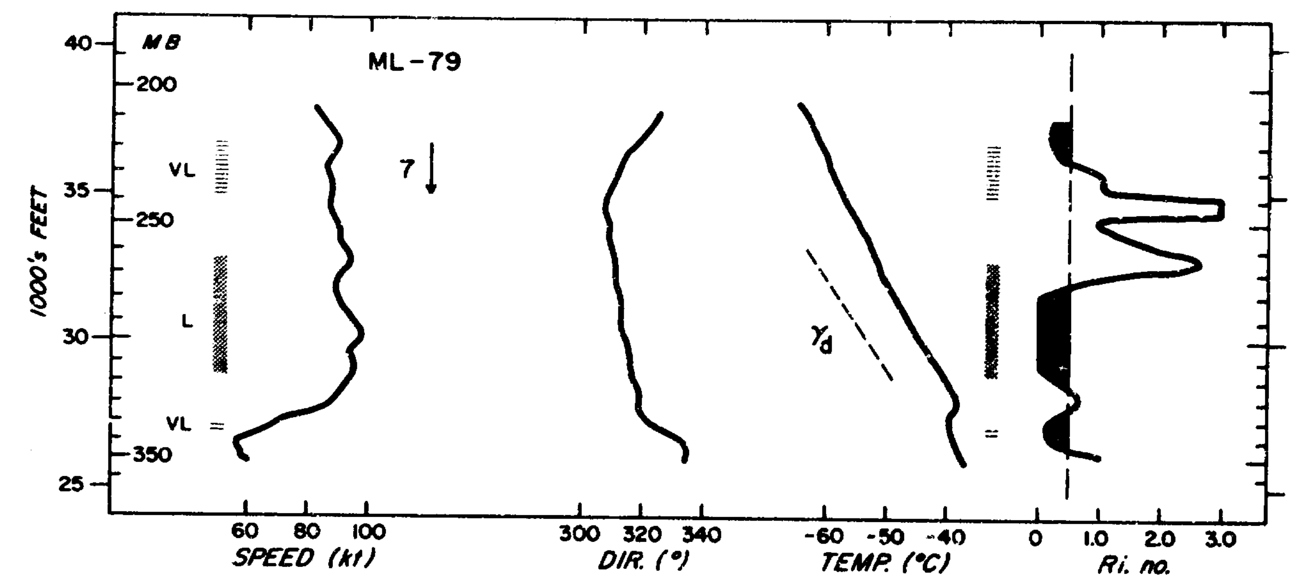

Figure 33. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Number 7

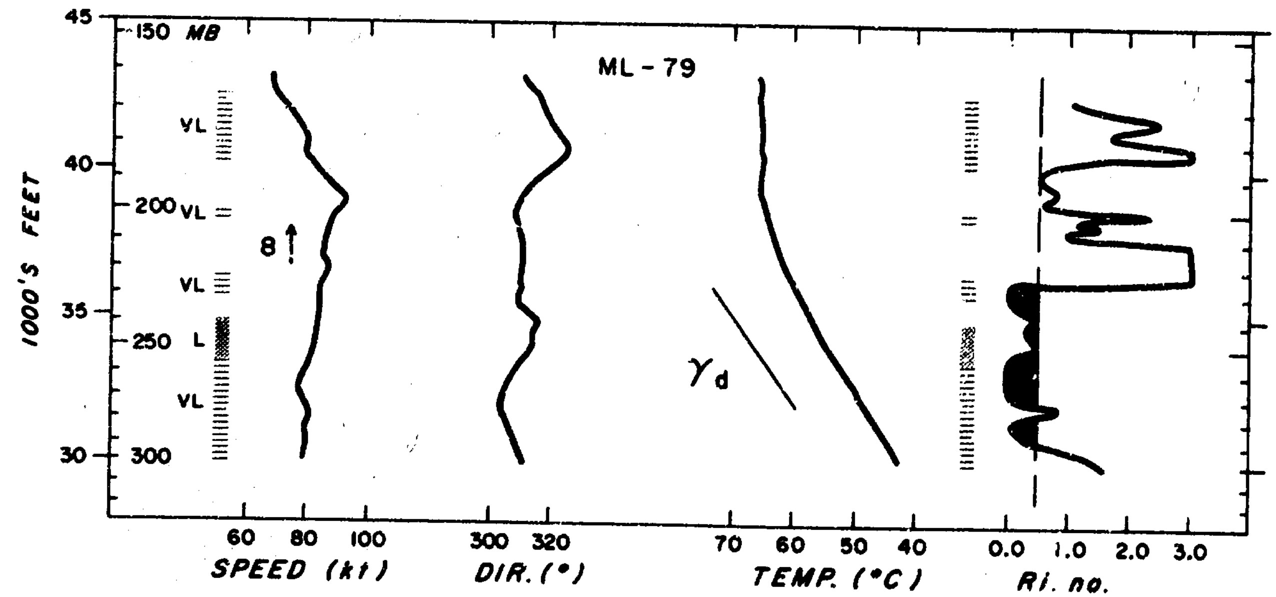

Figure 34. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Number 8

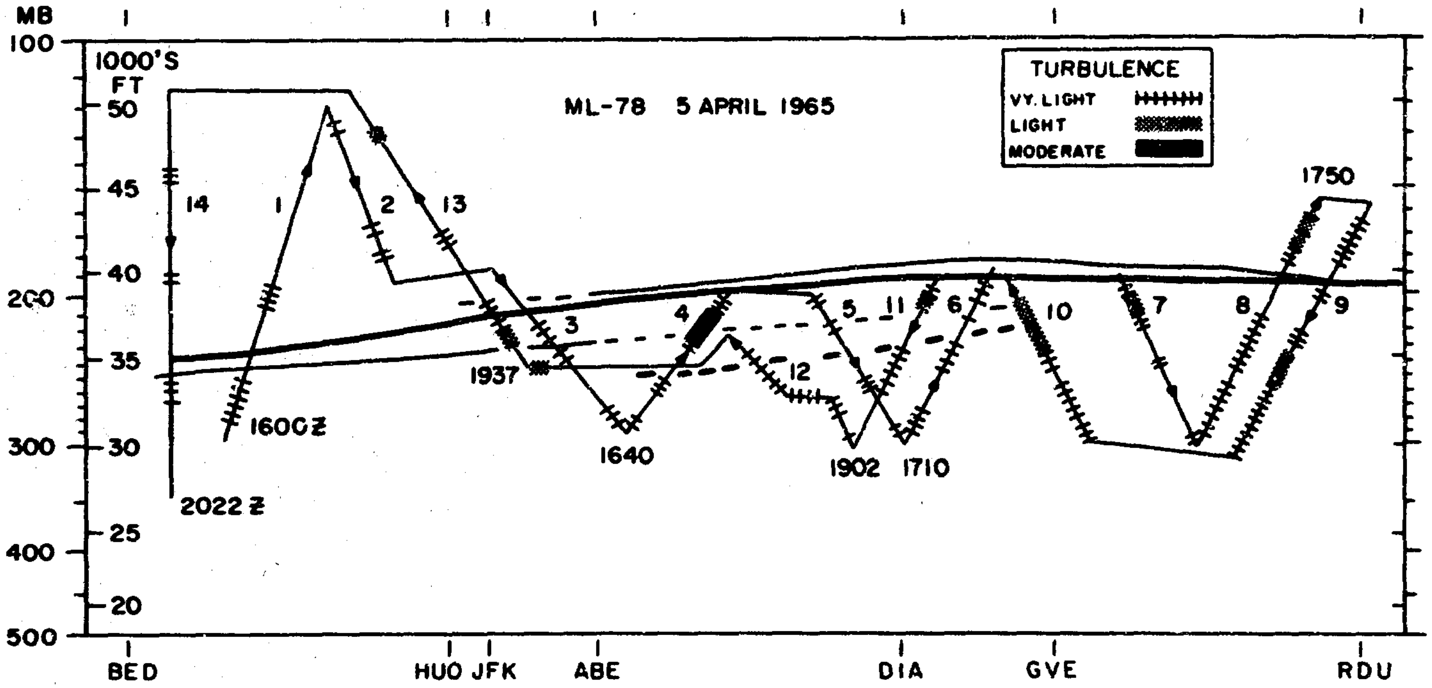

Figure 35. Flight for ML-78 From Bedford (BED) Massachusetts to Raleigh-Durham (RDU) North Carolina. Encountered CAT are shown. Heavier lines refer to tropopause and pseudo-tropopause, and numbers identify ascents and descents

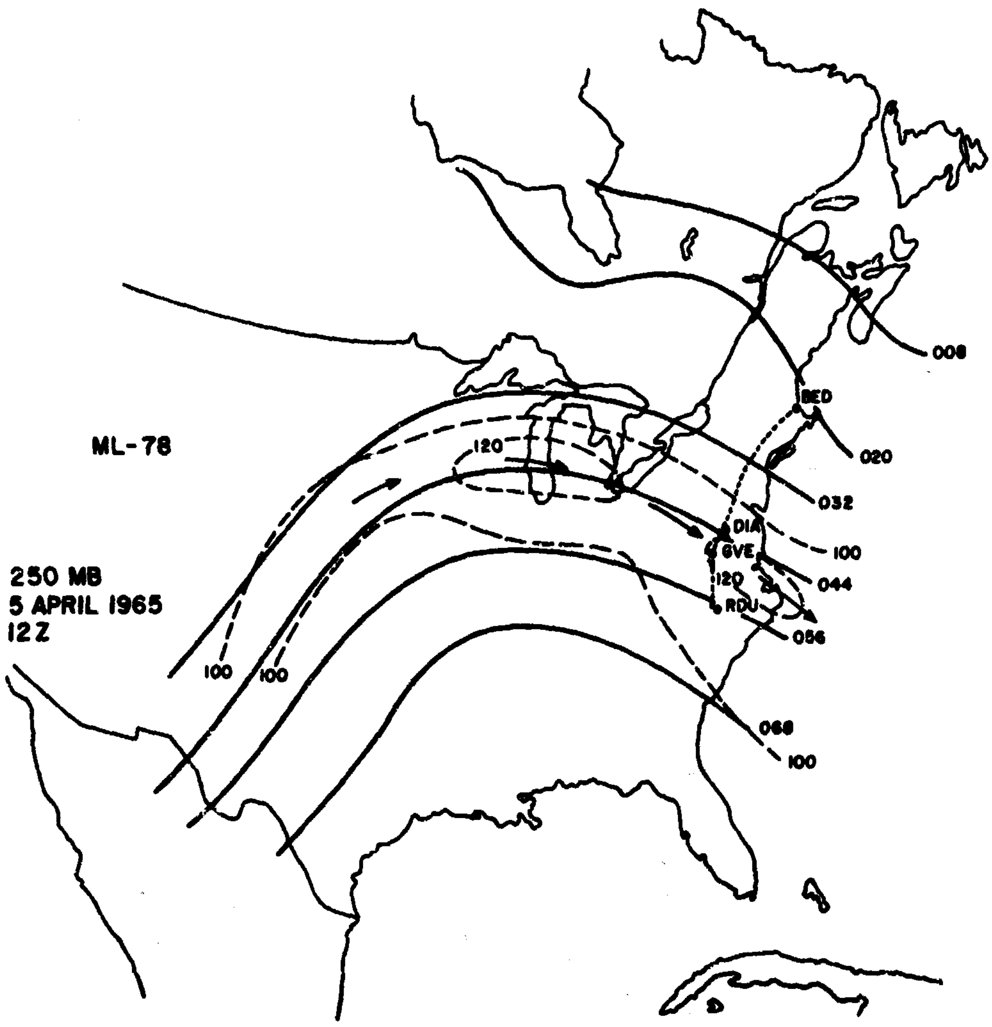

Figure 36. 250-MB Map, 5 April 1965, 12Z, Showing Height Lines and Isotachs (kt)

level of maximum wind. The winds show directional shear in the vertical across the level of maximum wind, and some high ozone is found below the tropopause.

3.2.4 RICHARDSON NUMBER CRITERION

Figures 52 through 59 show the relationship between the Richardson number and turbulence. A statistical verification using 0.5 as a critical number relative to CAT or no CAT is shown in the contingency table which follows. This criterion correctly specified CAT in 70 percent of the cases and 79 percent of the CAT cases were correctly identified. The overall hit score was 78 percent.

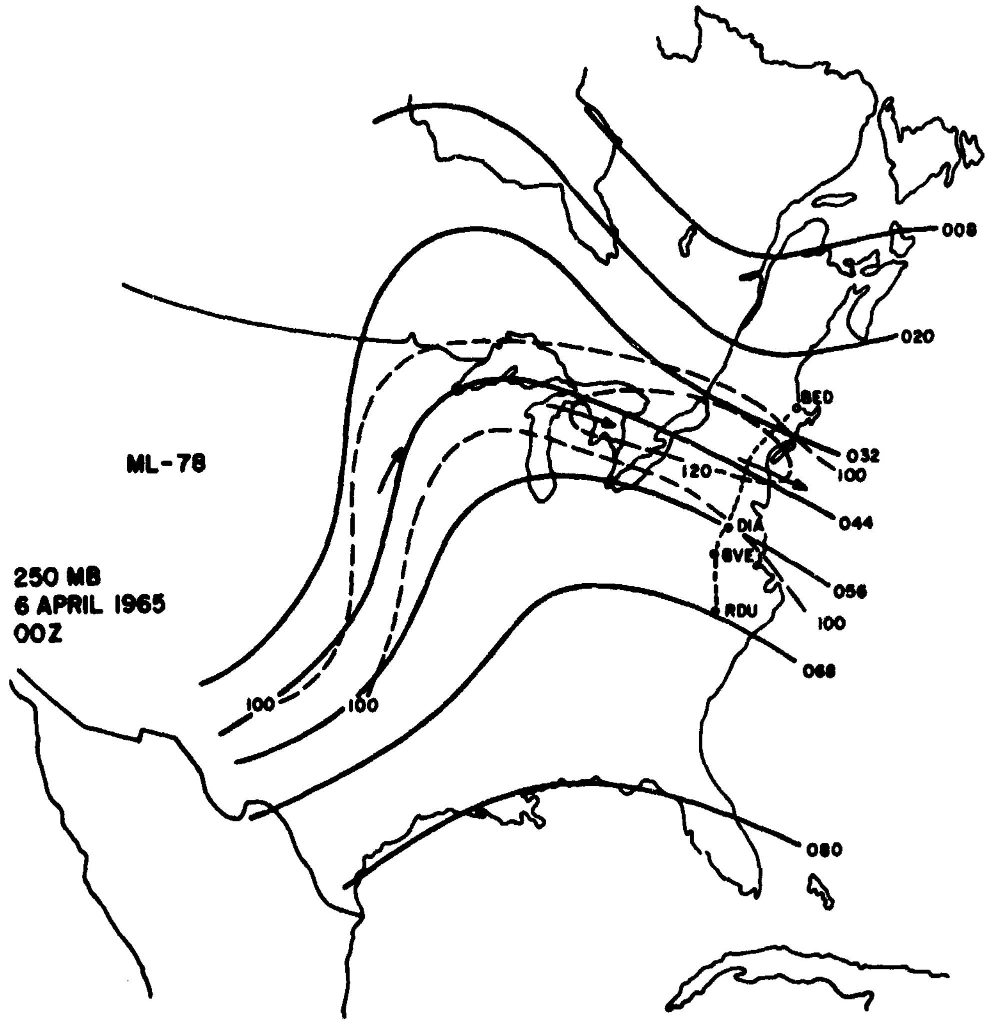

Figure 37. 250-MB Map, 6 April 1965, 00Z, Showing Height Lines and Isotachs (kt)

Table 3. Frequency of Turbulence vs Richardson Criterion of 0.5. Marginal figures in percent

	CAT	No CAT	
Ri ≤ 0.5	38	16	70%
Ri > 0.5	10	53	84%
	79%	77%	

NOTE: All Cases Percent Correct = 78

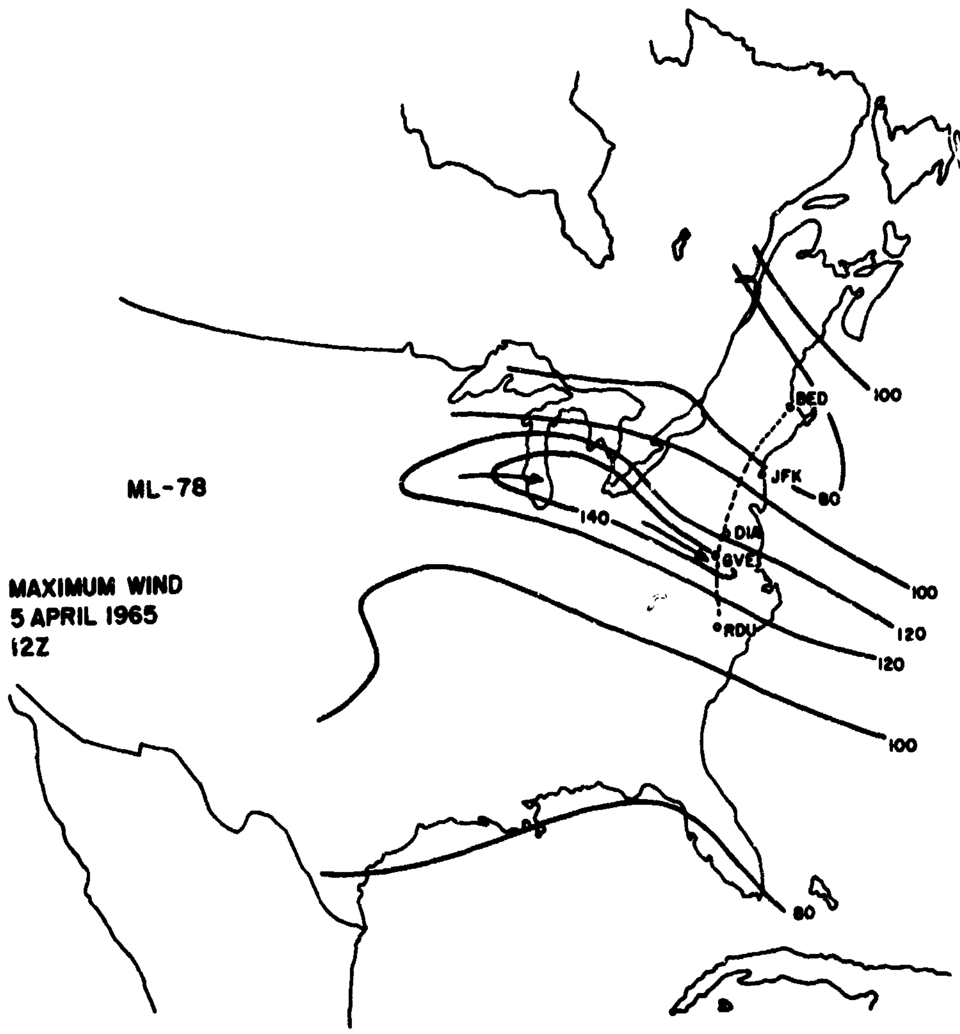

Figure 38. Maximum Wind Chart, 5 April 1965, 12Z (Isotachs in knots)

3.4 Mission ML-70 - Across a Slightly Cyclonically-Curved Northwest Jet

3. 4. 1 MISSION DESCRIPTION

Mission ML-70 probed the region between Bedford, Massachusetts (BED) and Charleston, South Carolina (CHS) 16 March 1965, 16 to 19 GMT. Five probes were made on the southbound leg, and three on the return flight. The probes were generally between 35, 000 to 46, 000 ft or 240 to 140 mb, and data from the forward and return legs were incorporated into a single set of analyses. Figure 54 shows the aircraft path, the encountered turbulence, tropopause, and pseudo-tropopause. Only a few areas of CAT were found, and some of these were located during level flight. From Figure 54 it appears that the CAT areas were of very limited extent in the transverse direction.

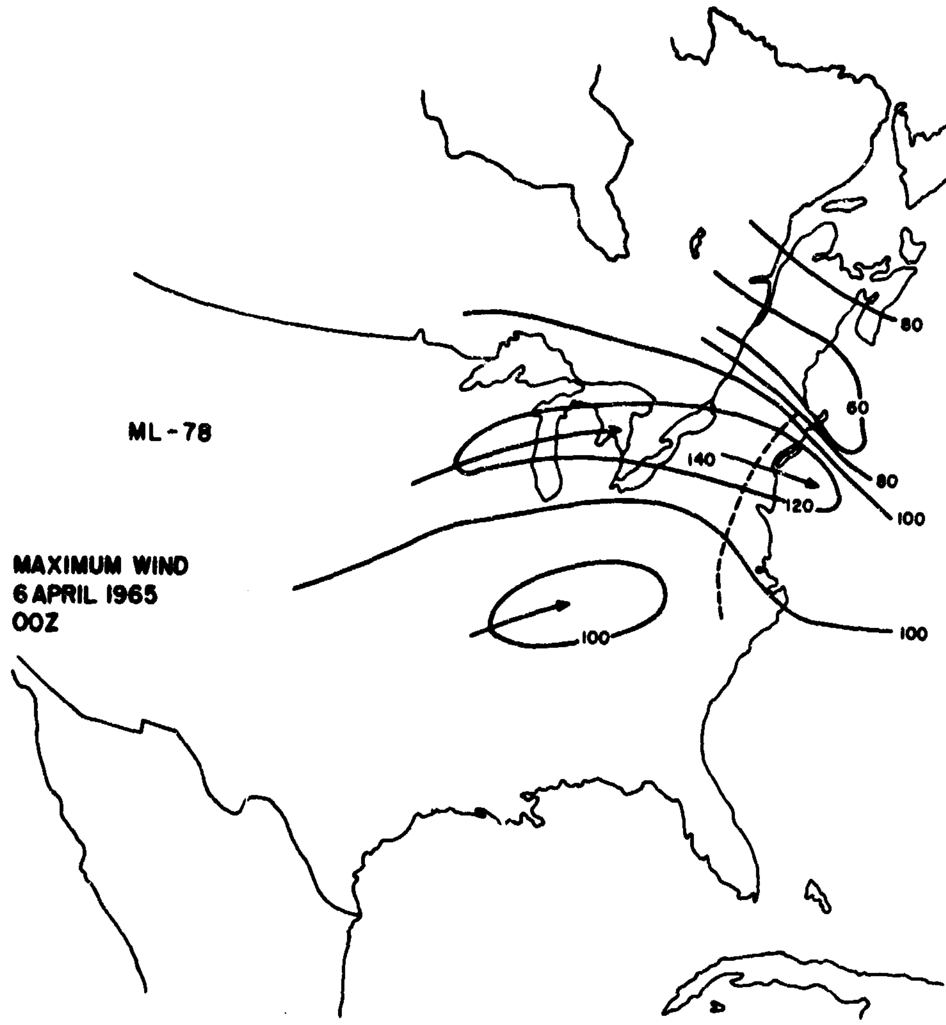

Figure 39. Maximum Wind Chart, 6 April 1965, 00Z (Isotachs in knots)

3.4.2 SYNOPTIC SITUATION

The 200-mb map for 16/12Z and the maximum wind charts for 16/12Z and 17/00Z are shown in Figures 55, 56, and 57 respectively. The flight track is across a slightly cyclonically-curved northwest flow, containing two major jet systems. The polar jet is below 30,000 ft, and the midlatitude jet is in the vicinity of 35,000 ft and shows a split structure near the Atlantic coast. Cross sections derived from the 16/02Z and 17/00Z radiosonde data are shown in Figures 58 and 59. Well-defined tropopause "breaks" are seen in connection with two jet streams.

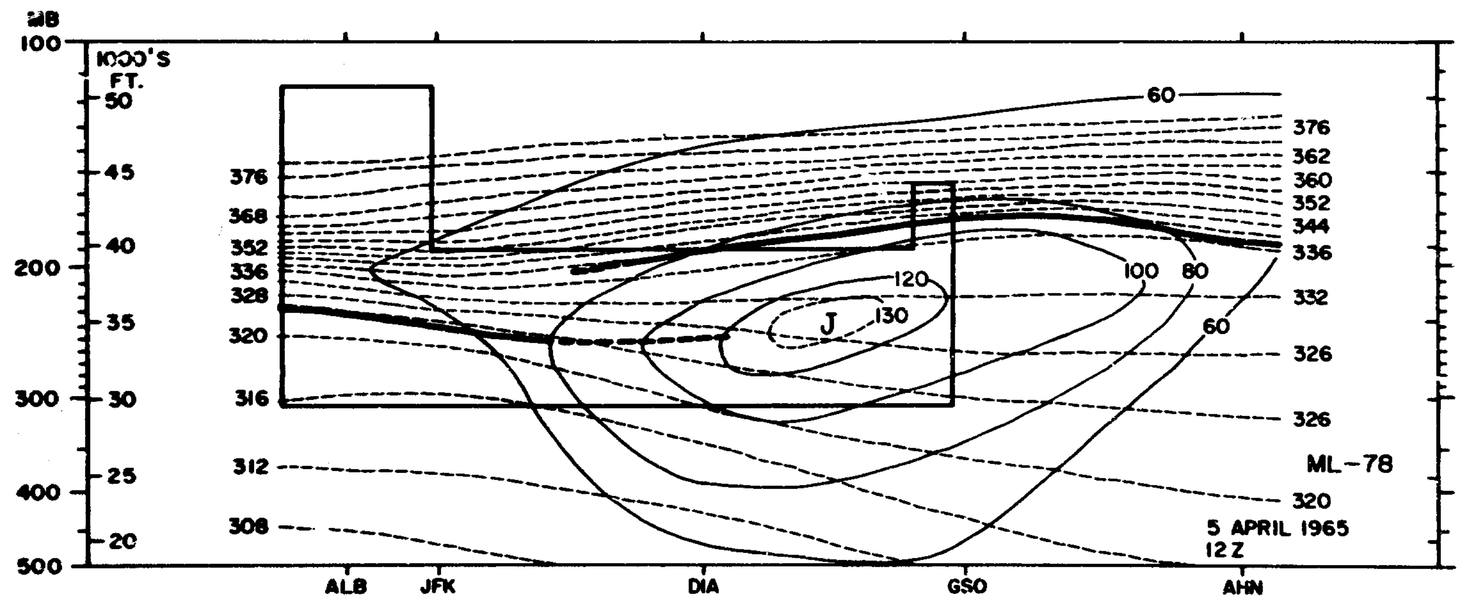

Figure 40. Vertical Cross Section From Albany (ALB) New York to Athens (AHN) Georgia, 5 April 1965, 12Z. Thin solid lines are wind speed (knots) and thin dashed are potential temperature (°K). Heavy solid lines refer to tropopause and pseudo-tropopause

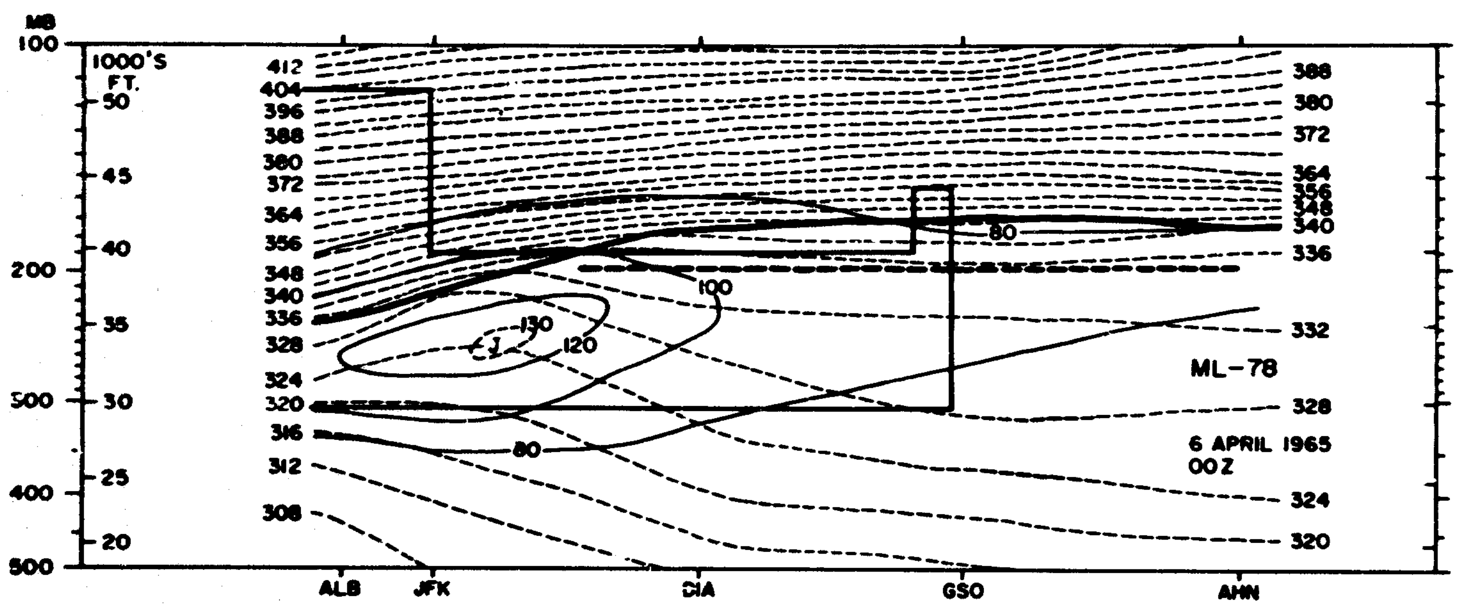

Figure 41. Vertical Cross Section From Albany (ALB) New York to Athens (AHN) Georgia, 6 April 1965, 00Z. Thin solid lines are wind speed (knots) and thin dashed are potential temperature (°K). Heavy solid lines refer to tropopause and pseudo-tropopause

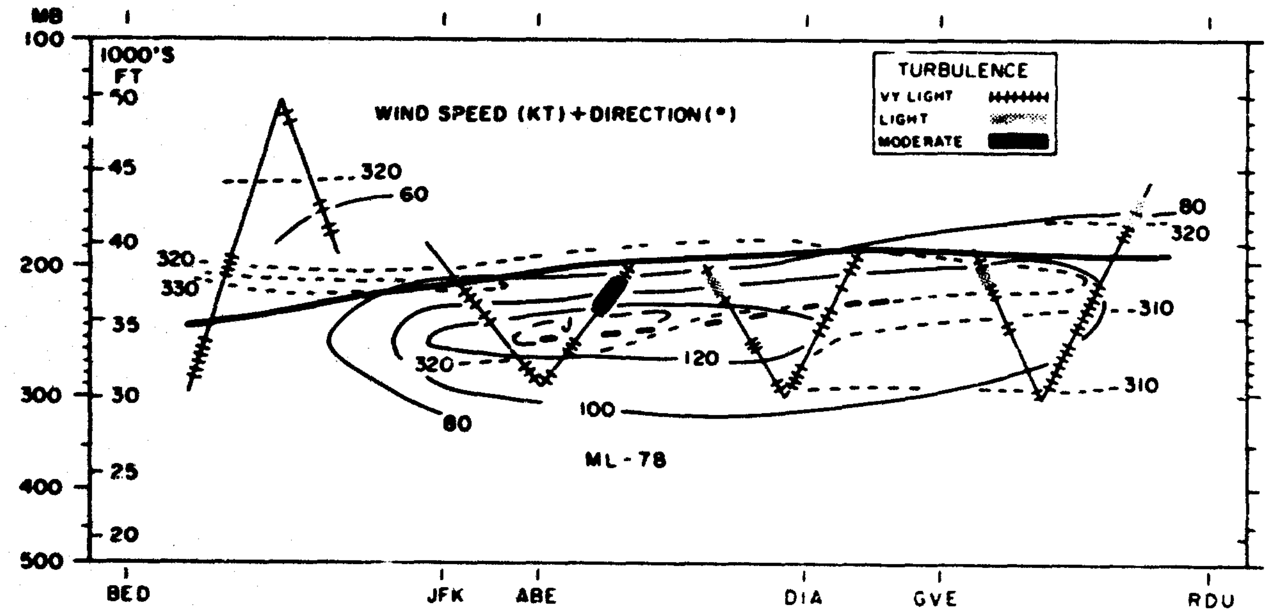

Figure 42. Cross Section of Wind Speed (Solid Lines) and of Wind Direction (Dashed Lines). Heavy lines identify tropopause and pseudo-tropopause

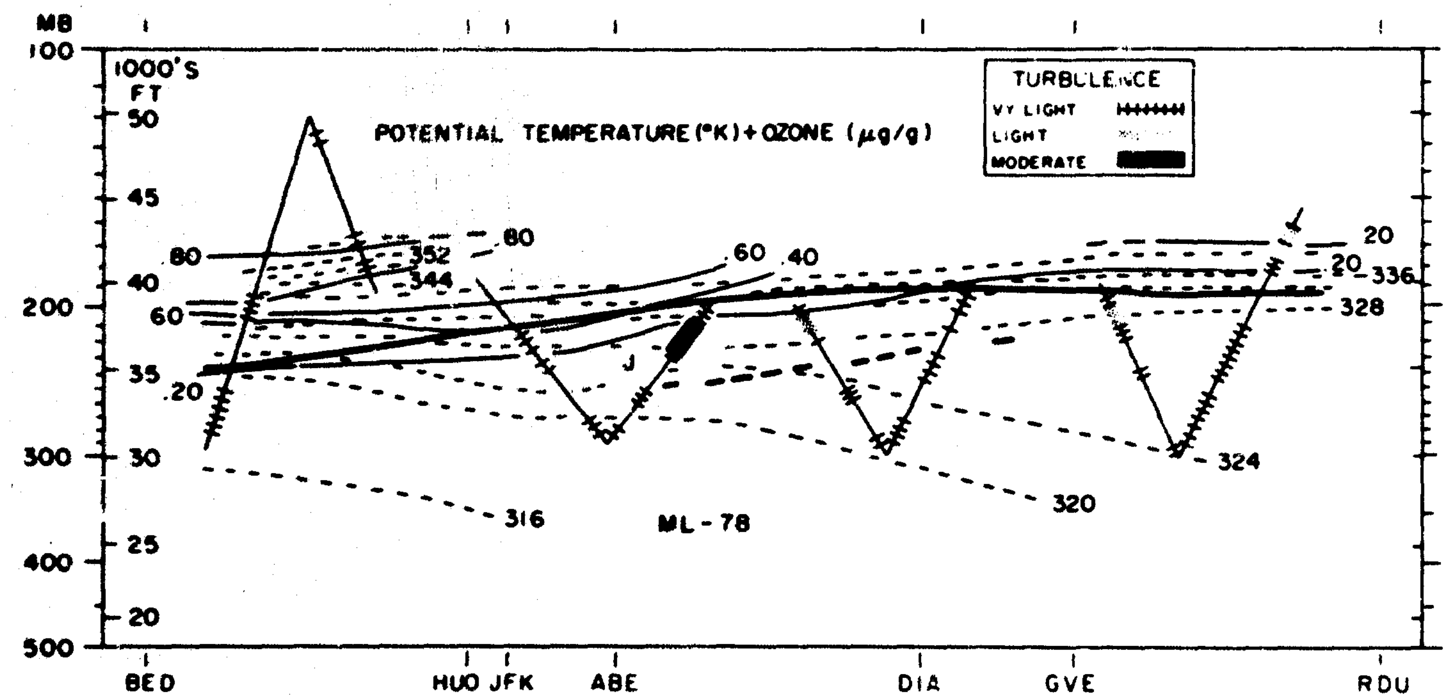

Figure 43. Cross Section of Potential Temperature (Dashed Lines) and of Ozone Mixing Ratio (Solid Lines). Conventions same as in Figure 42

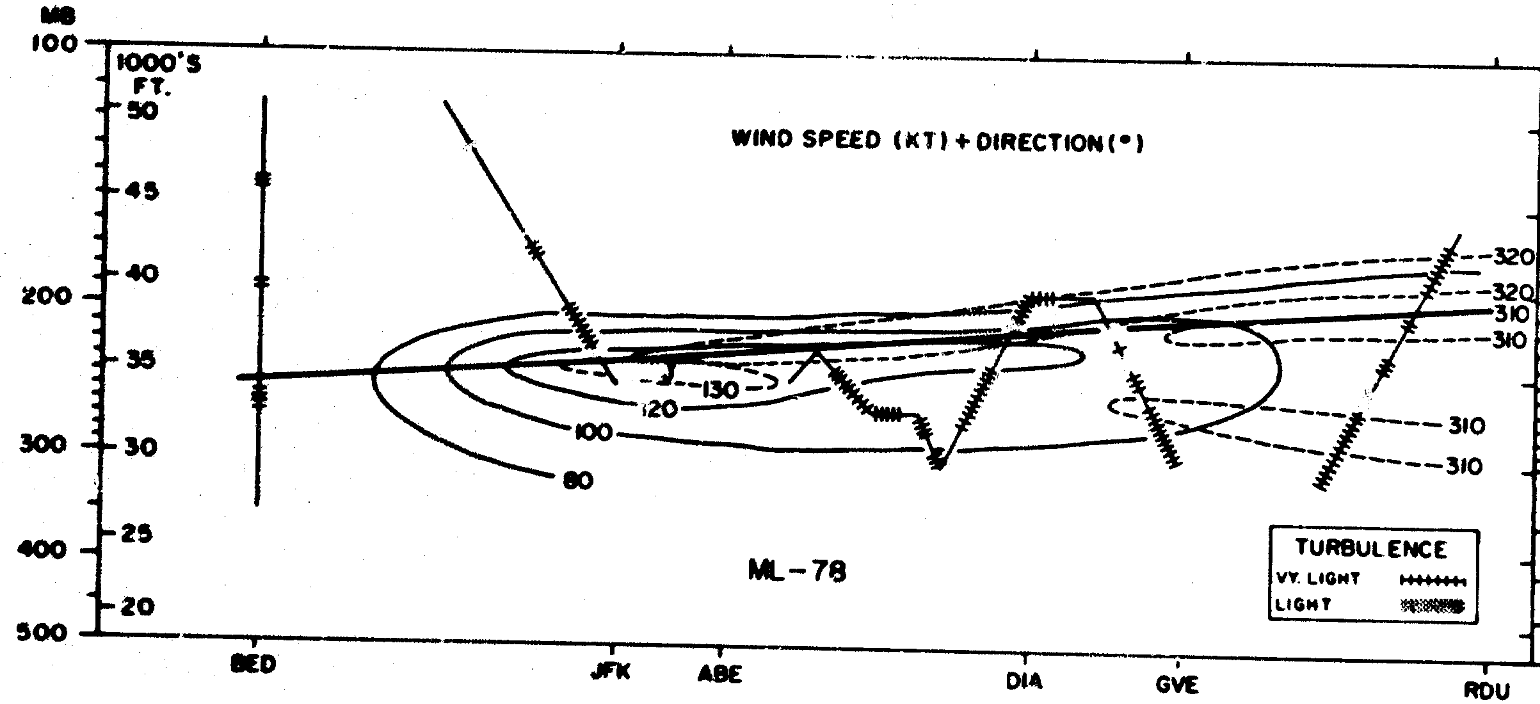

Figure 44. Cross Section of Wind Speed (Solid Lines) and of Wind Direction (Dashed Lines) on Return Flight. Heavy lines identify tropopause and pseudo-tropopause

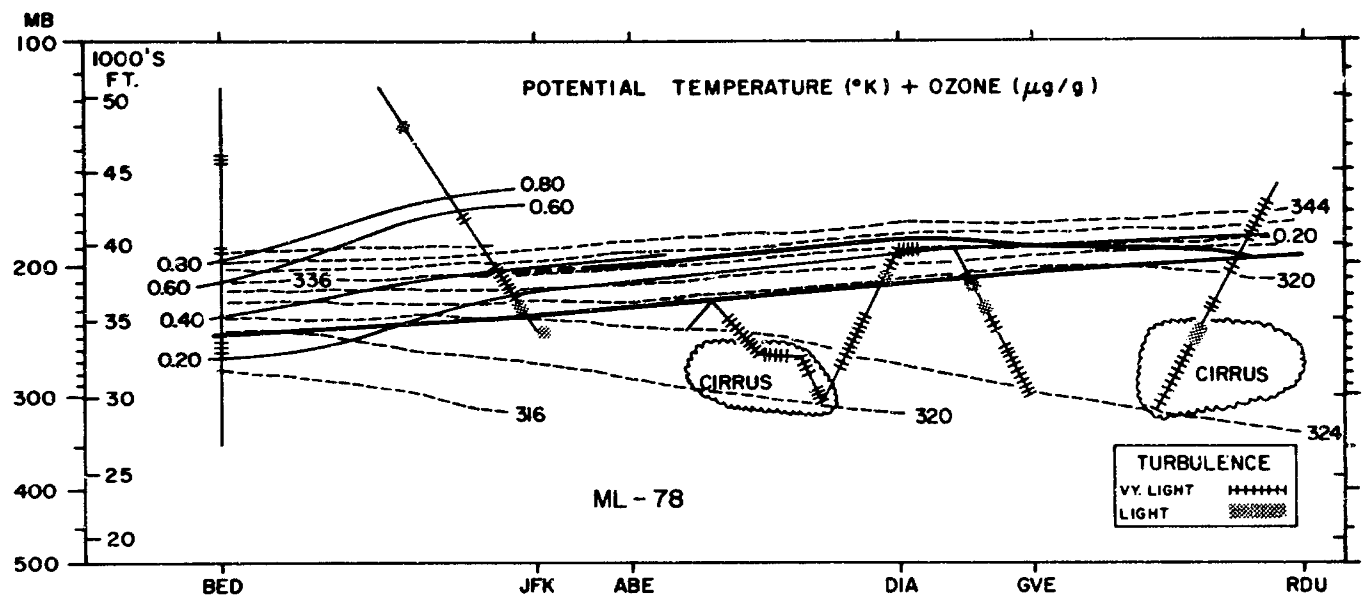

Figure 45. Cross Section of Potential Temperature (Dashed Lines) and of Ozone Mixing Ratio (Solid Lines) on Return Flight. Conventions same as in Figure 42

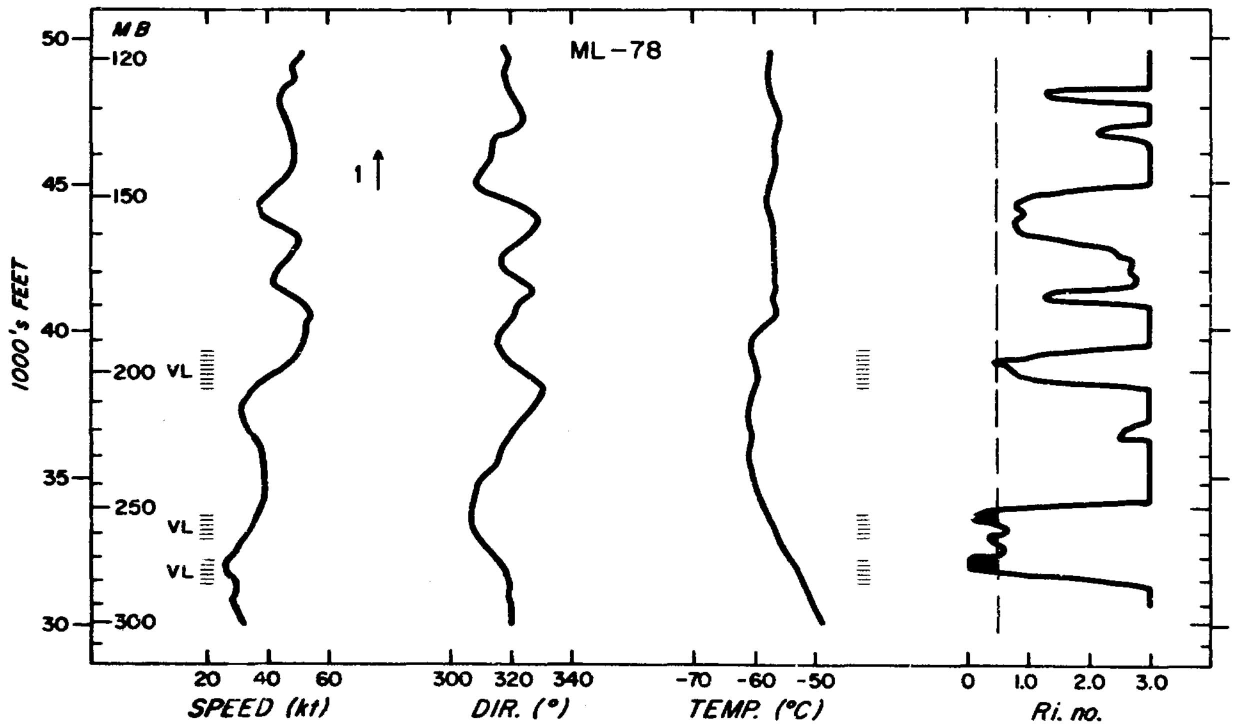

Figure 46. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Number 1

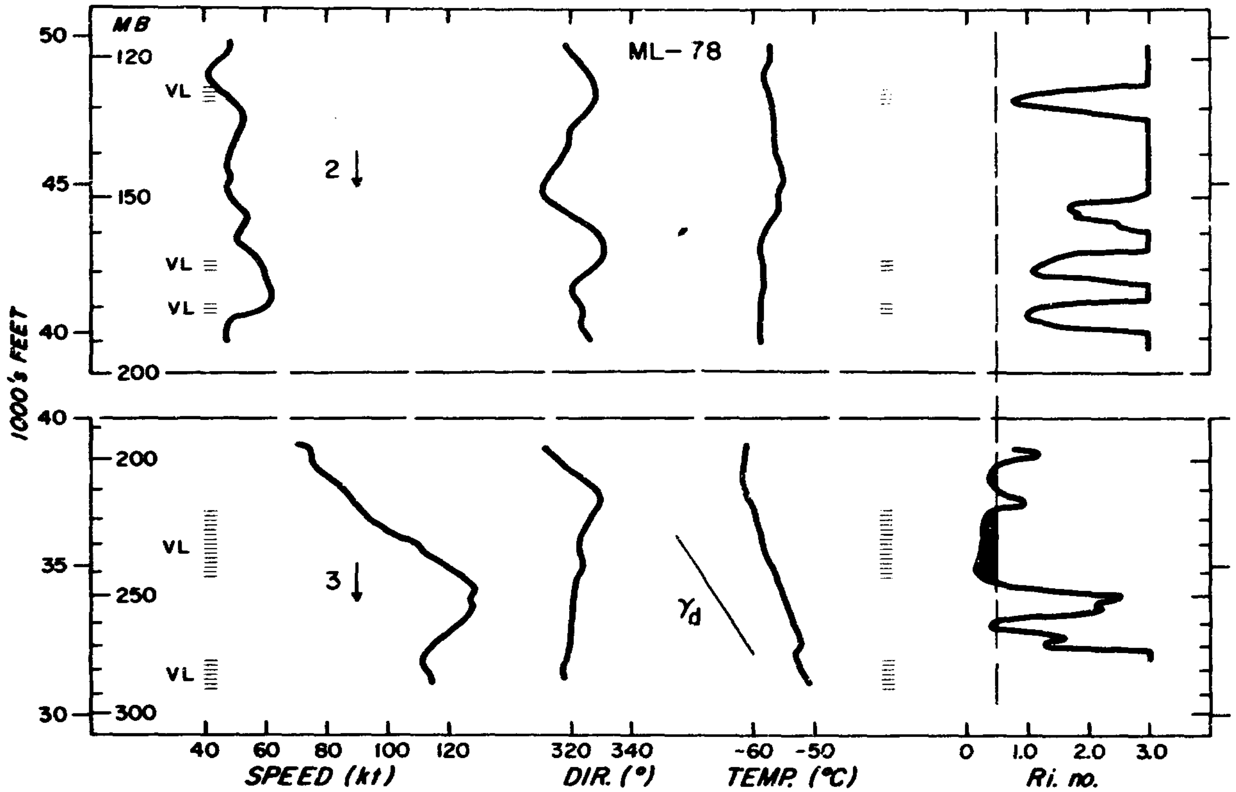

Figure 47. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Numbers 2 and 3

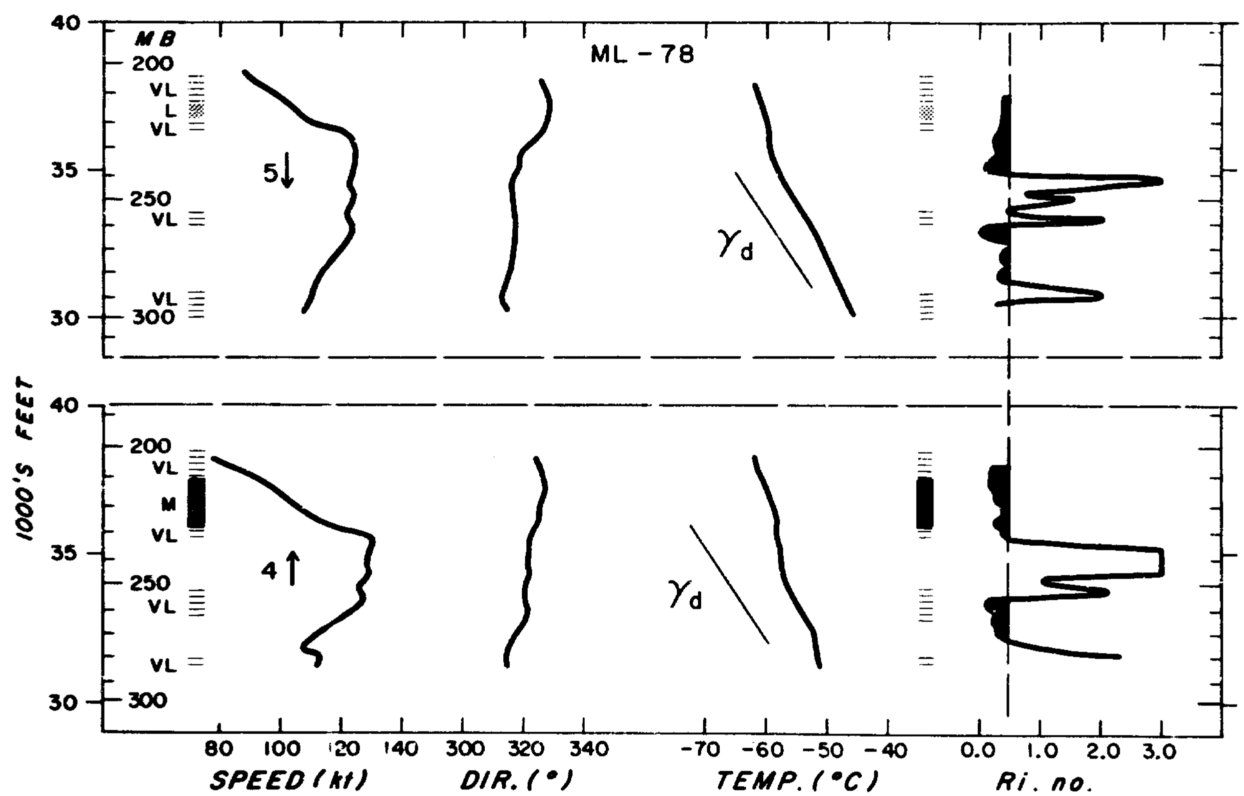

Figure 48. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Numbers 4 and 5

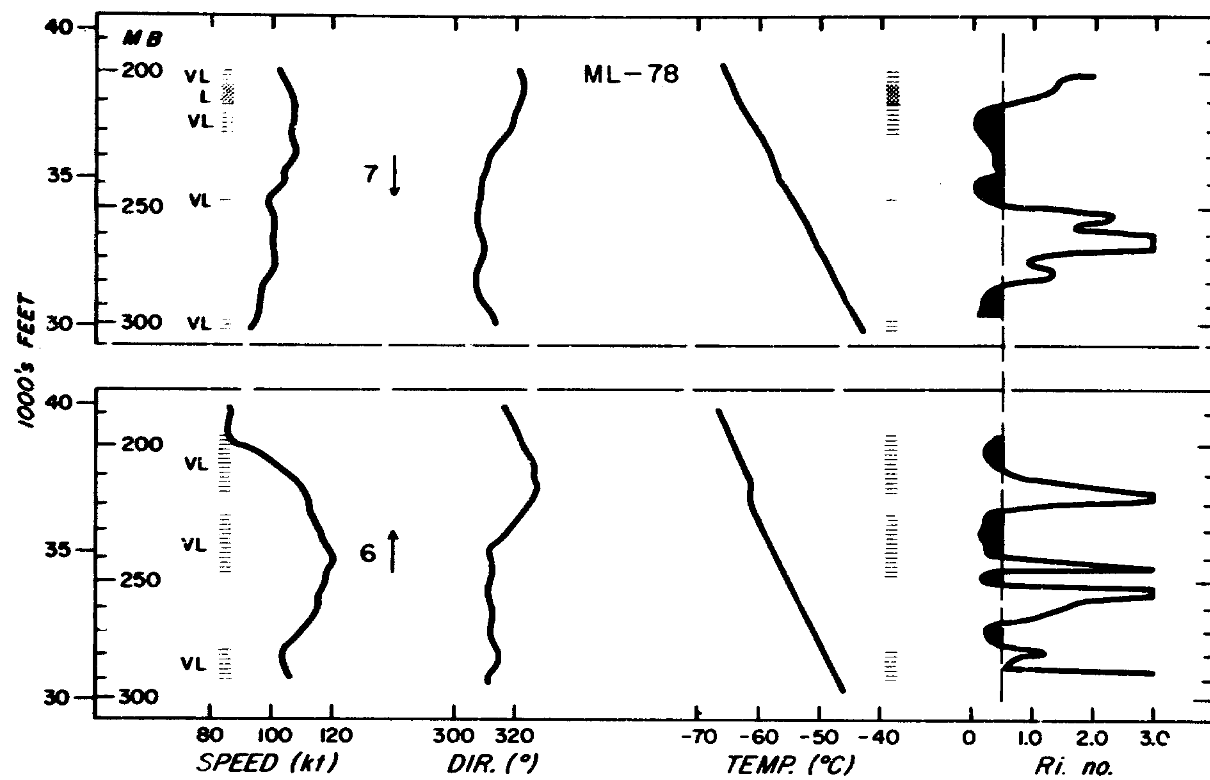

Figure 49. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Numbers 6 and 7

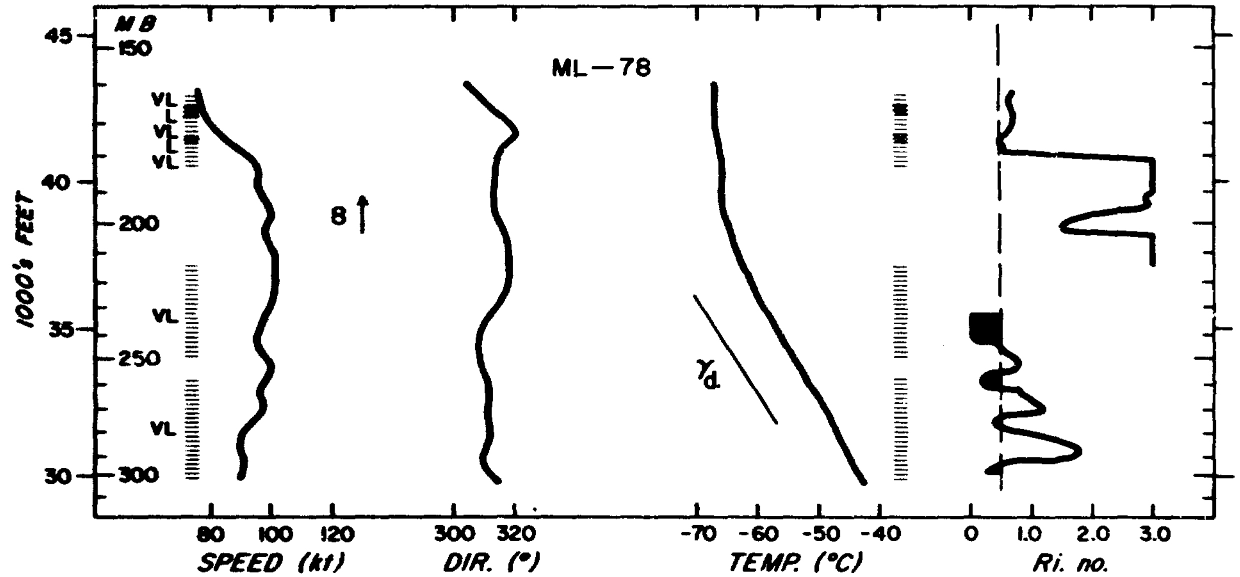

Figure 50. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Number 8

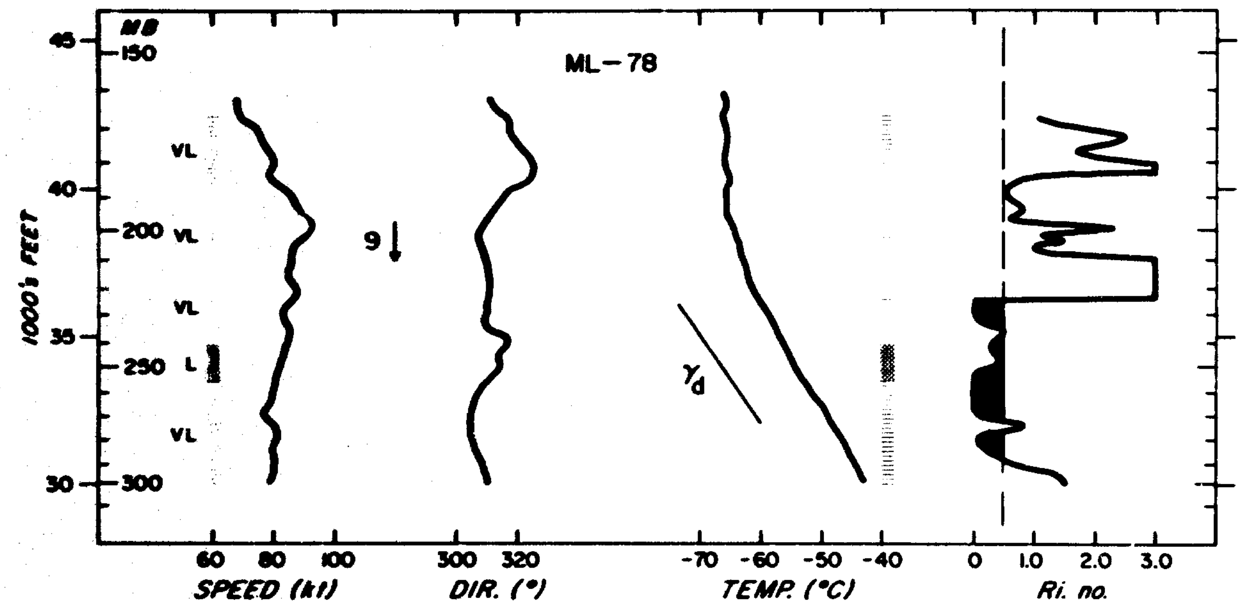

Figure 51. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Number 9

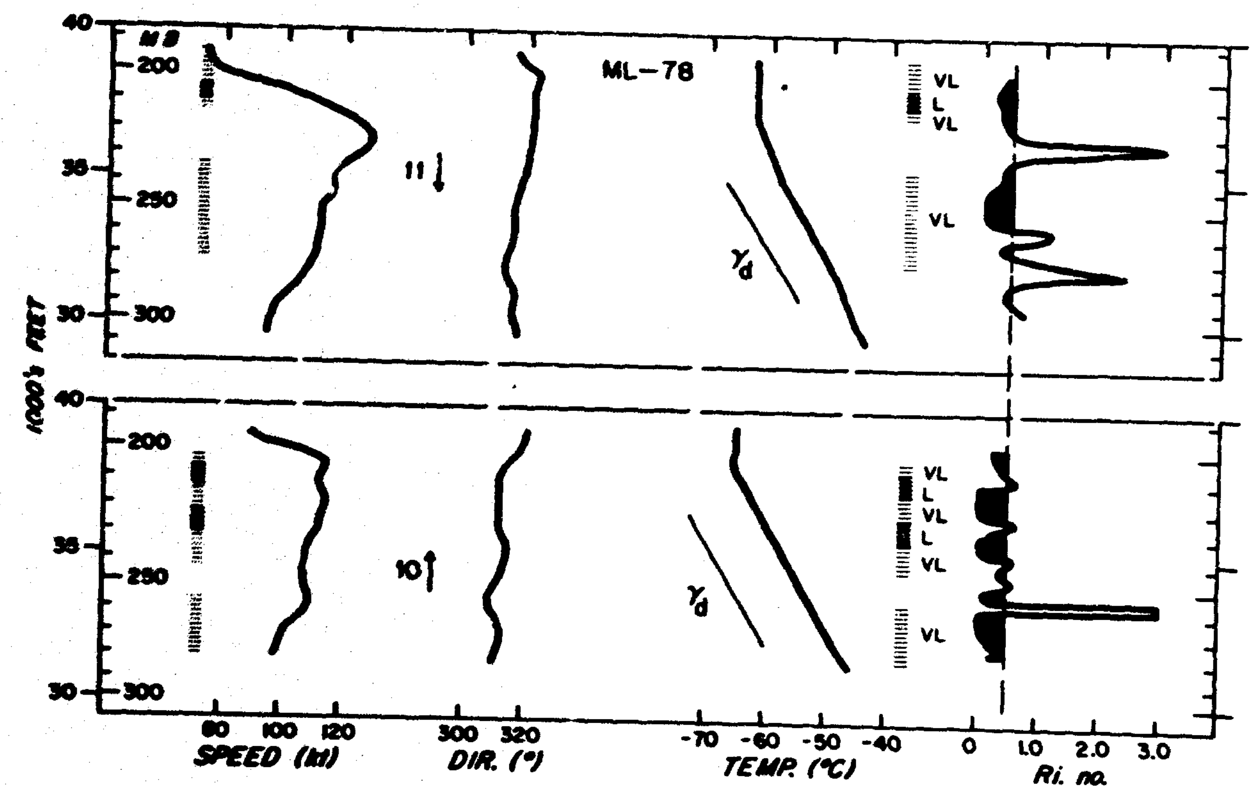

Figure 52. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Numbers 10 and 11

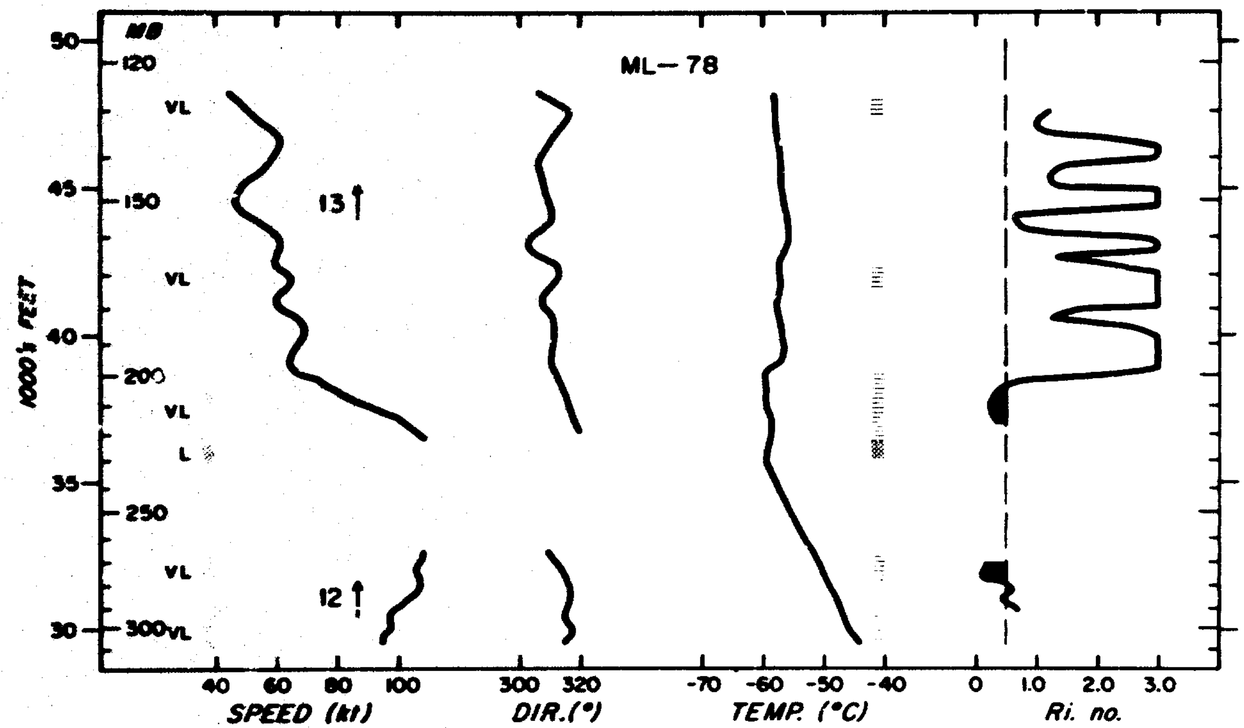

Figure 53. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Numbers 12 and 13

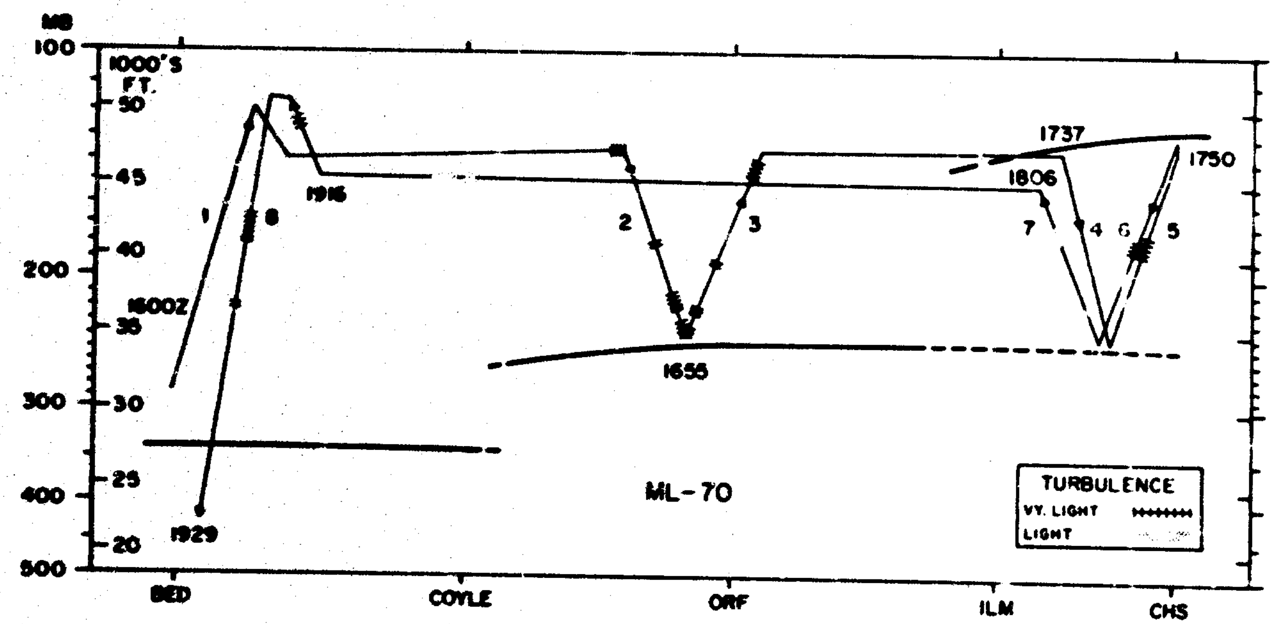

Figure 34. Flight ML-70 From Bedford (BED) Massachusetts to Charleston (CHS) South Carolina. Encountered CAT are shown. Heavier lines identify tropopause and pseudo-tropopause, and numbers identify ascents and descents, and time (GMT) shown at few points

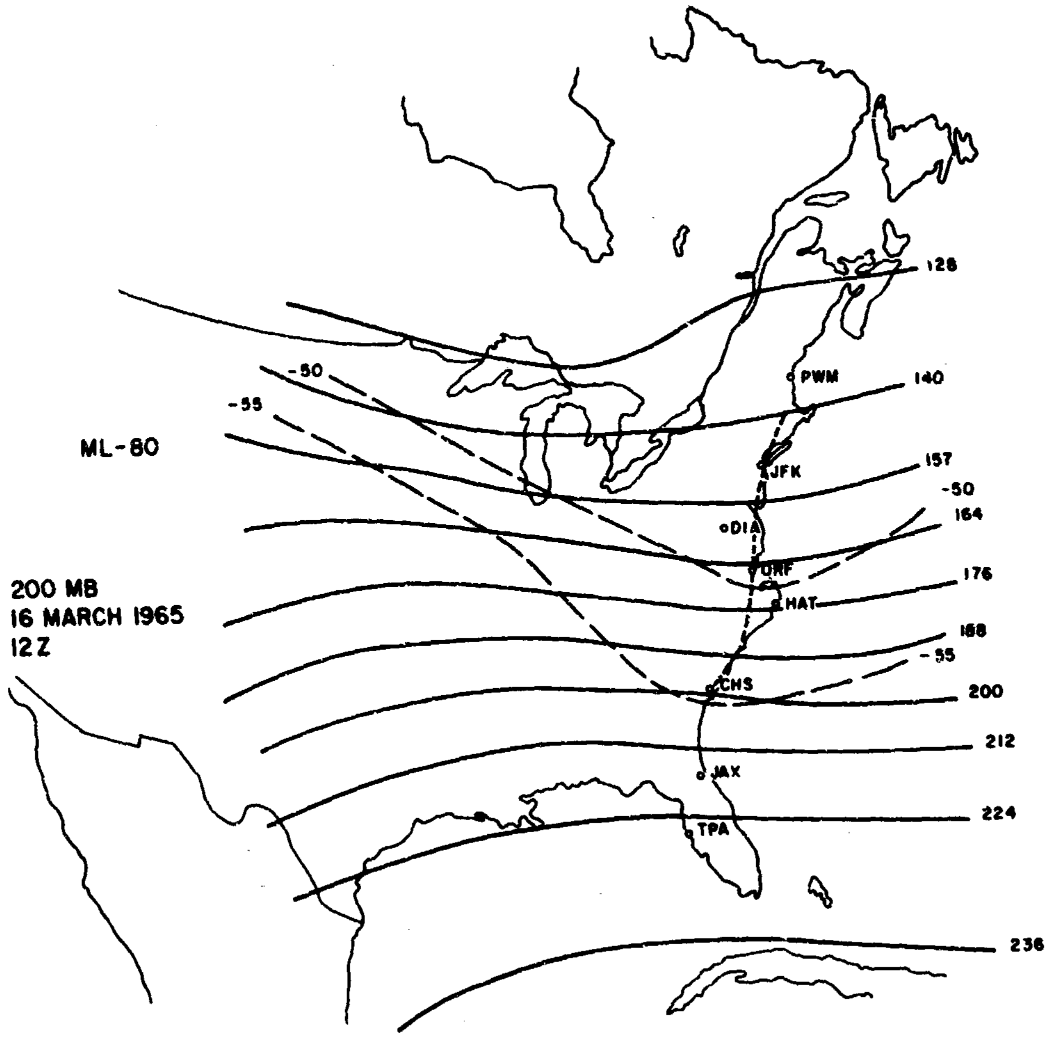

Figure 55. 200-MB Map, 16 March 1965, 12Z

3.4.3 MESOSCALE STRUCTURE

The mesoscale structures of wind speed and and wind direction are shown in Figure 60, and of potential temperature and ozone in Figure 61. Profiles of wind, temperature, and the Richardson number are presented in Figures 62 through 66. The two "break" regions noted in the RAOB cross sections are also clearly defined in the mesoscale data. Most of the aircraft data were obtained in the region of the midlatitude "break." Two sets of ascents and descents, comprising four probes, were made close together in space and time in the "break" area above the midlatitude jet. In view of the spacing of these probes, it was decided

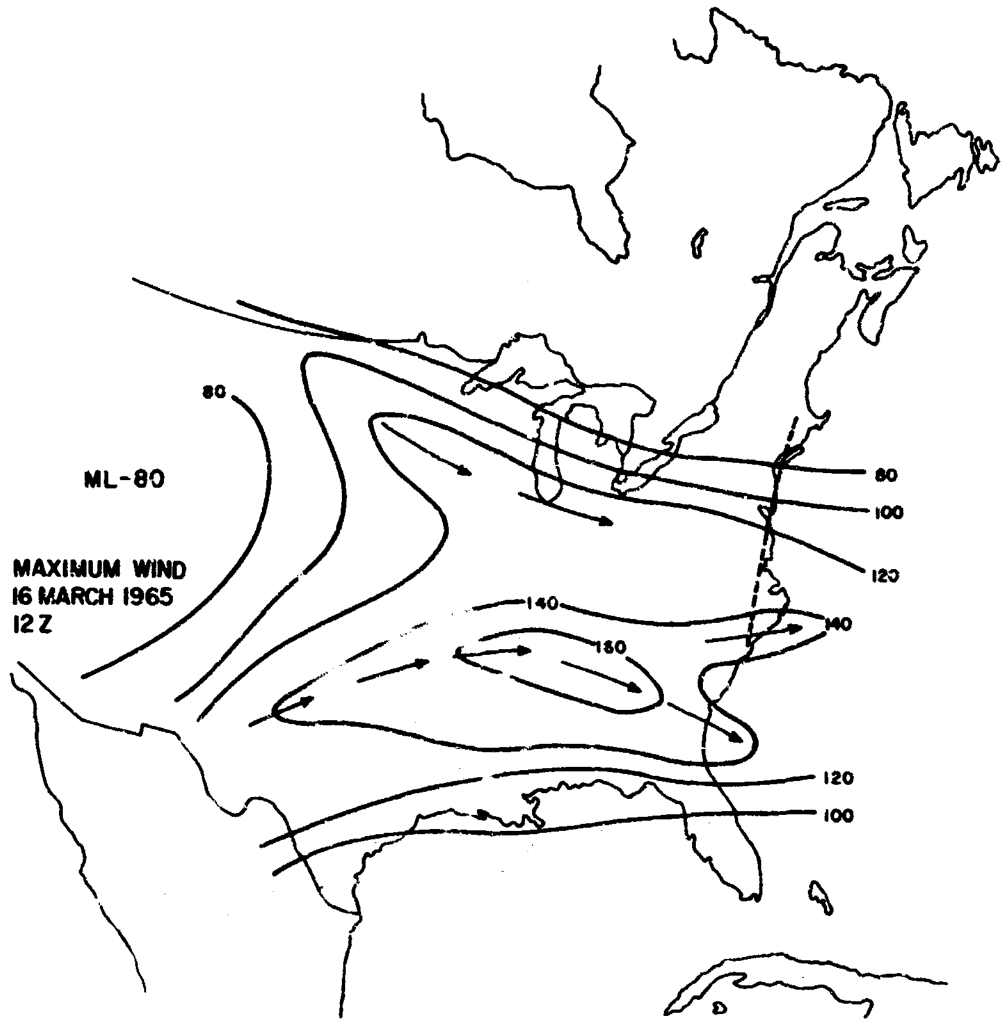

Figure 56. Maximum Wind Map, 16 March 1965, 12Z (Isotachs in knots)

to combine probe number 4 with 7, and number 5 with 6. This averaged data were used in the cross sections. There were only very small differences in the ozone and temperature data between the separate probes in a given pair. However, the wind variations, especially the speed component, were suspiciously large. The averaged data were used in the analyzed cross sections. The implied vertical wind shears are quite small, and the stabilities are moderate. These conditions, which would be unfavorable to the development of CAT, are in qualitative agreement with the aircraft observations of very little turbulence. The ozone data are interesting in that it shows high amounts below the tropopause in the ILM-CHS sector.

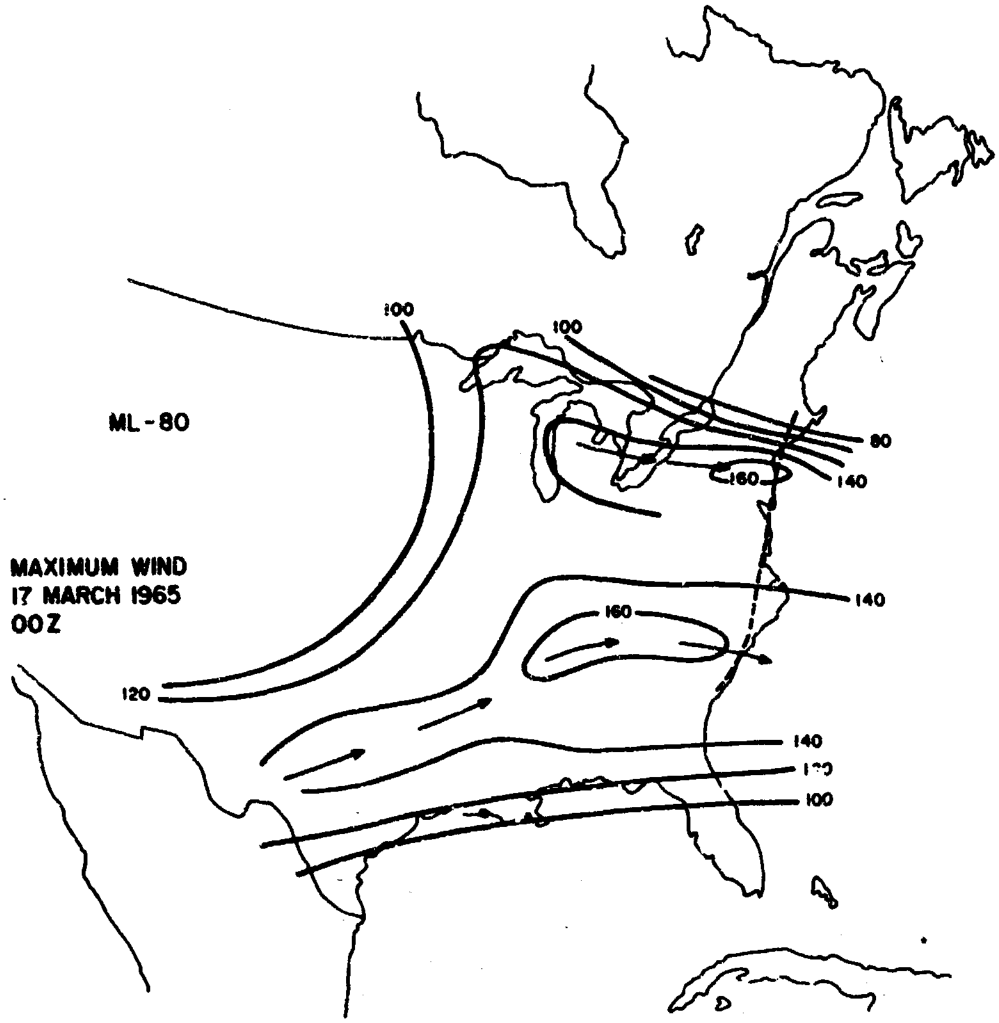

Figure 57. Maximum Wind Map, 17 March 1965, 00Z (Isotachs in knots)

3.4.4 RICHARDSON NUMBER CRITERION

Figures 62 through 66 show the relationship of the Richardson number to turbulence. A statistical verification of 0.5 as a critical number relative to CAT or no CAT is shown in the contingency table which follows. This is based only on data from probes 2, 3, 4, and 8 because of uncertainties in the rest of the data. There were only five cases of CAT and four of these were correctly specified by the criterion. The overall hit score was 92 percent.

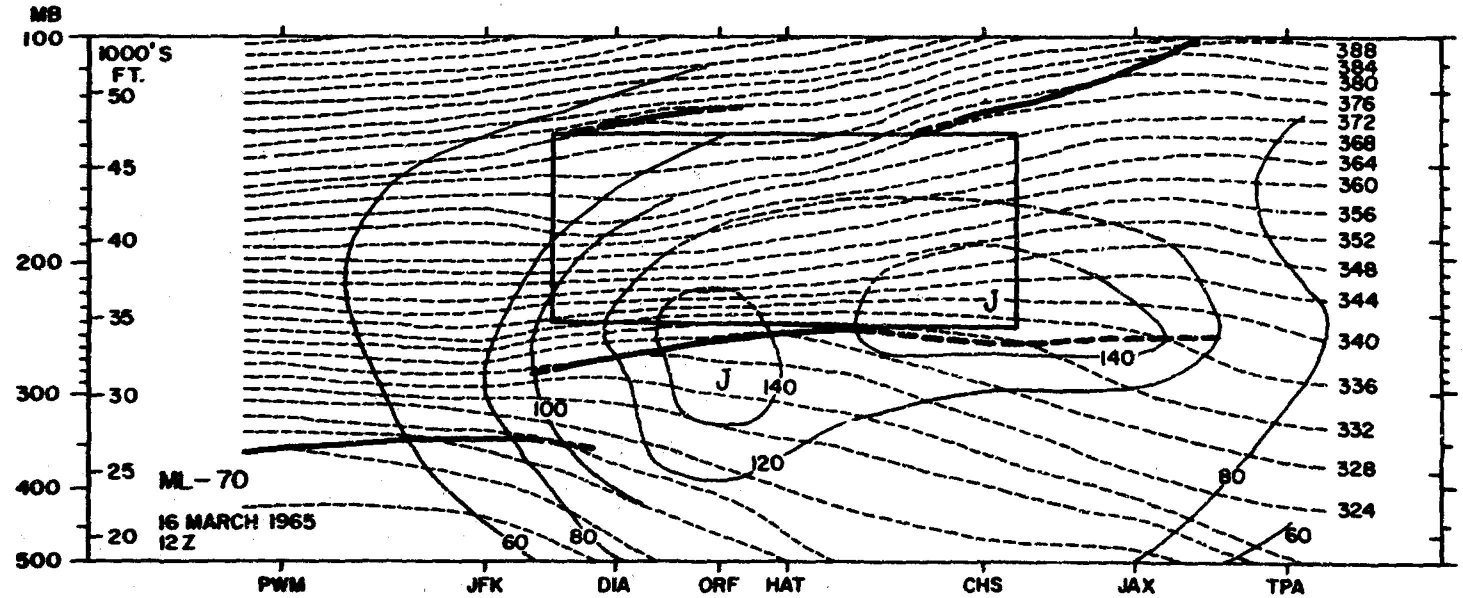

Figure 58. Vertical Cross Section From Portland (PWM) Maine to Tampa (TPA) Florida, 16 March 1965, 12Z. Thin solid lines are wind speed (knots) and thin dashed potential temperature (°K). Heavy lines identify tropopause and pseudo-tropopause

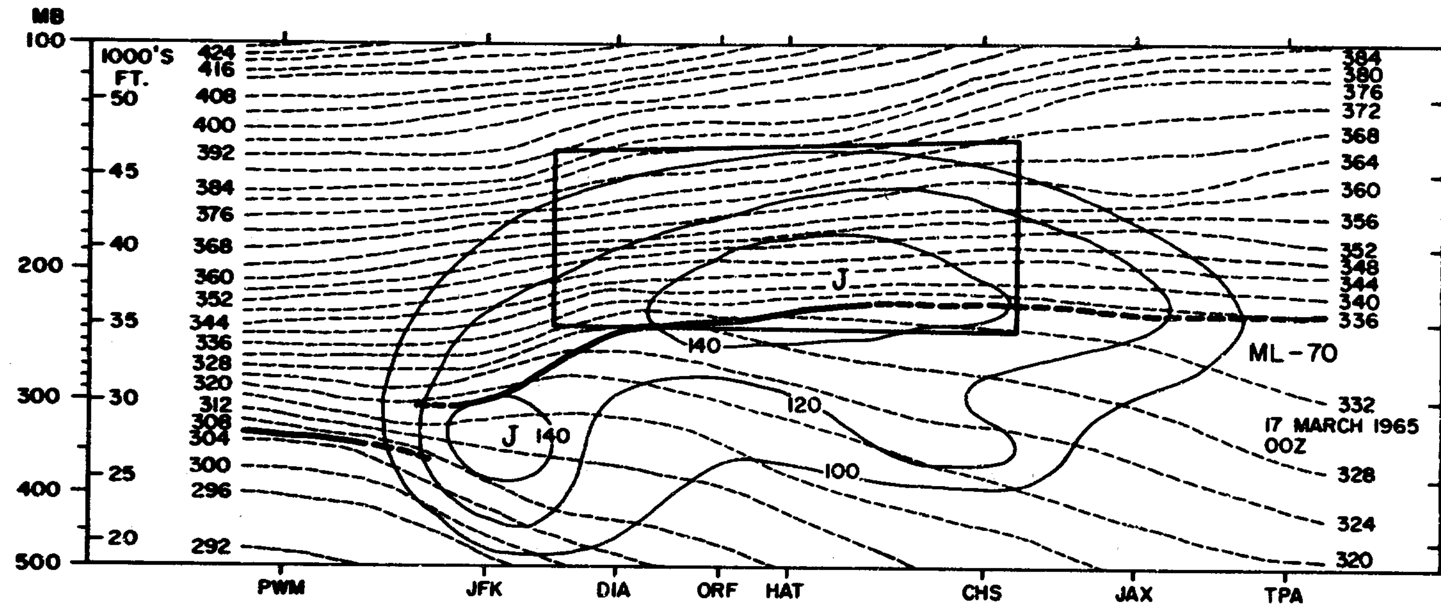

Figure 59. Vertical Cross Section From Portland (PWM) Maine to Tampa (TPA) Florida, 17 March 1965, 00Z. Thin solid lines are wind speed (knots) and thin dashed potential temperature (°K). Heavy lines identify tropopause and pseudo-tropopause

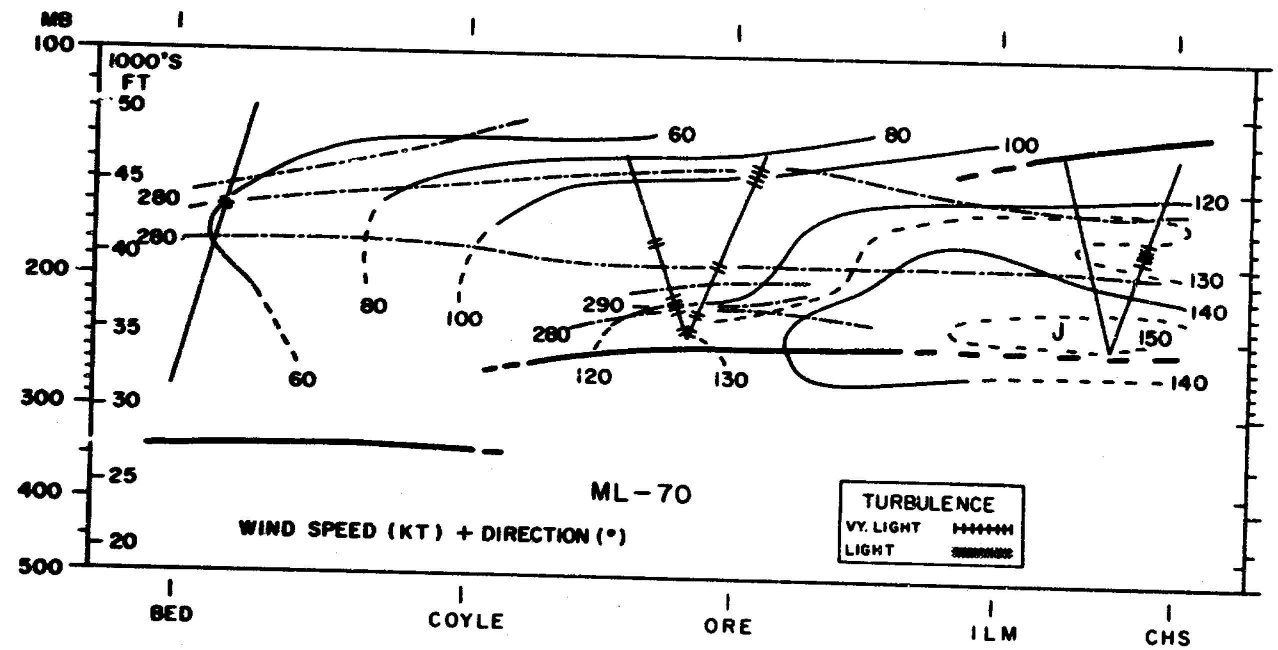

Figure 60. Cross Section of Wind Speed (Solid Lines) and Wind Direction (Dashed Lines). Heavy lines identify tropopause and pseudo-tropopause

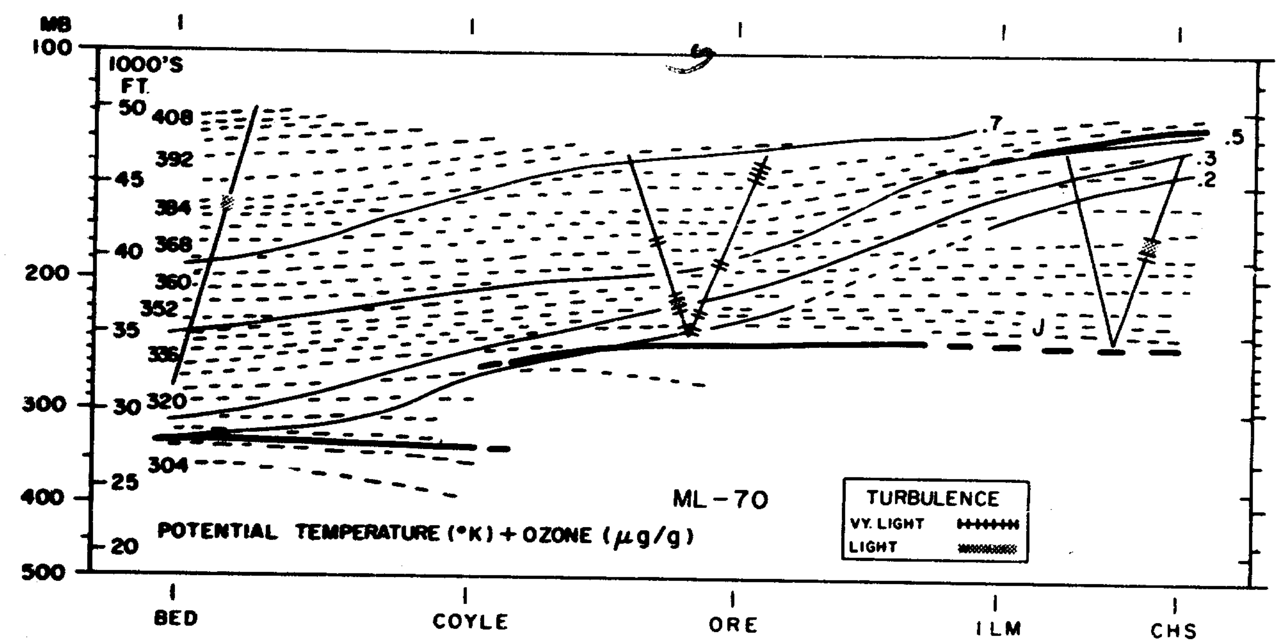

Figure 61. Cross Section of Potential Temperature (Dashed Lines) and Ozone Mixing Ratio (Solid Lines). Conventions same as in Figure 60

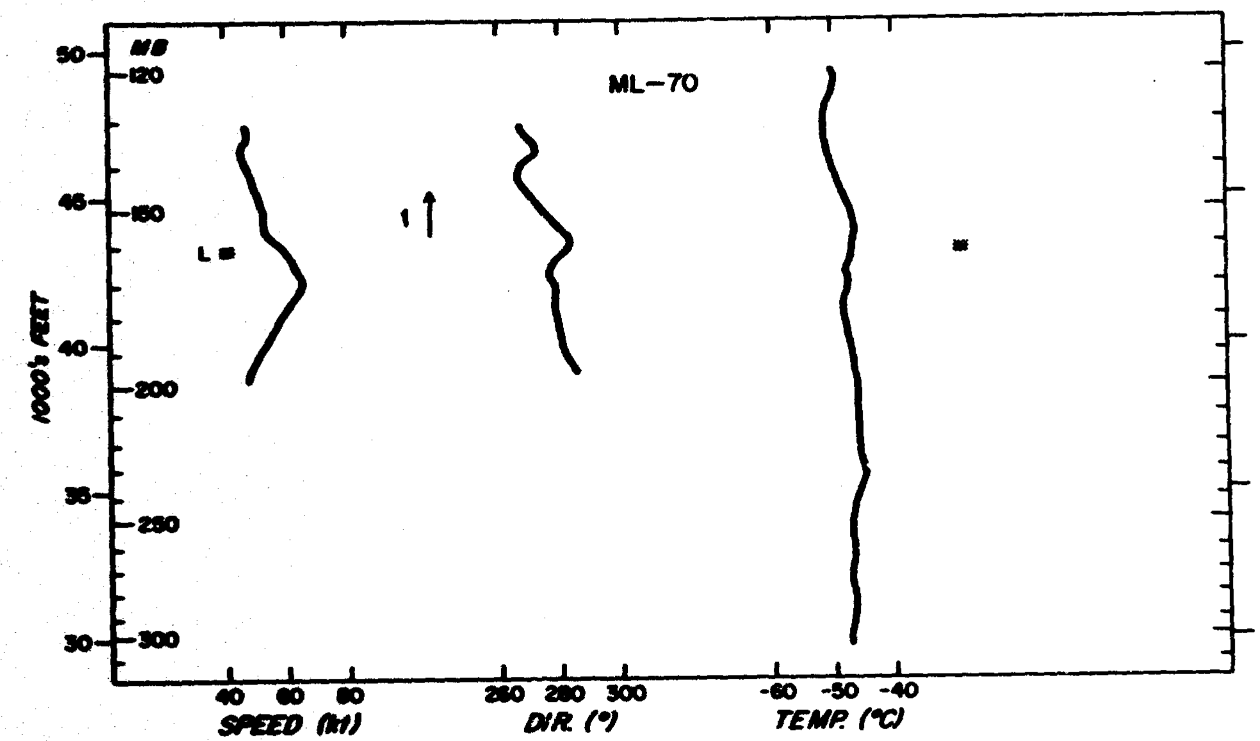

Figure 62. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Number 1

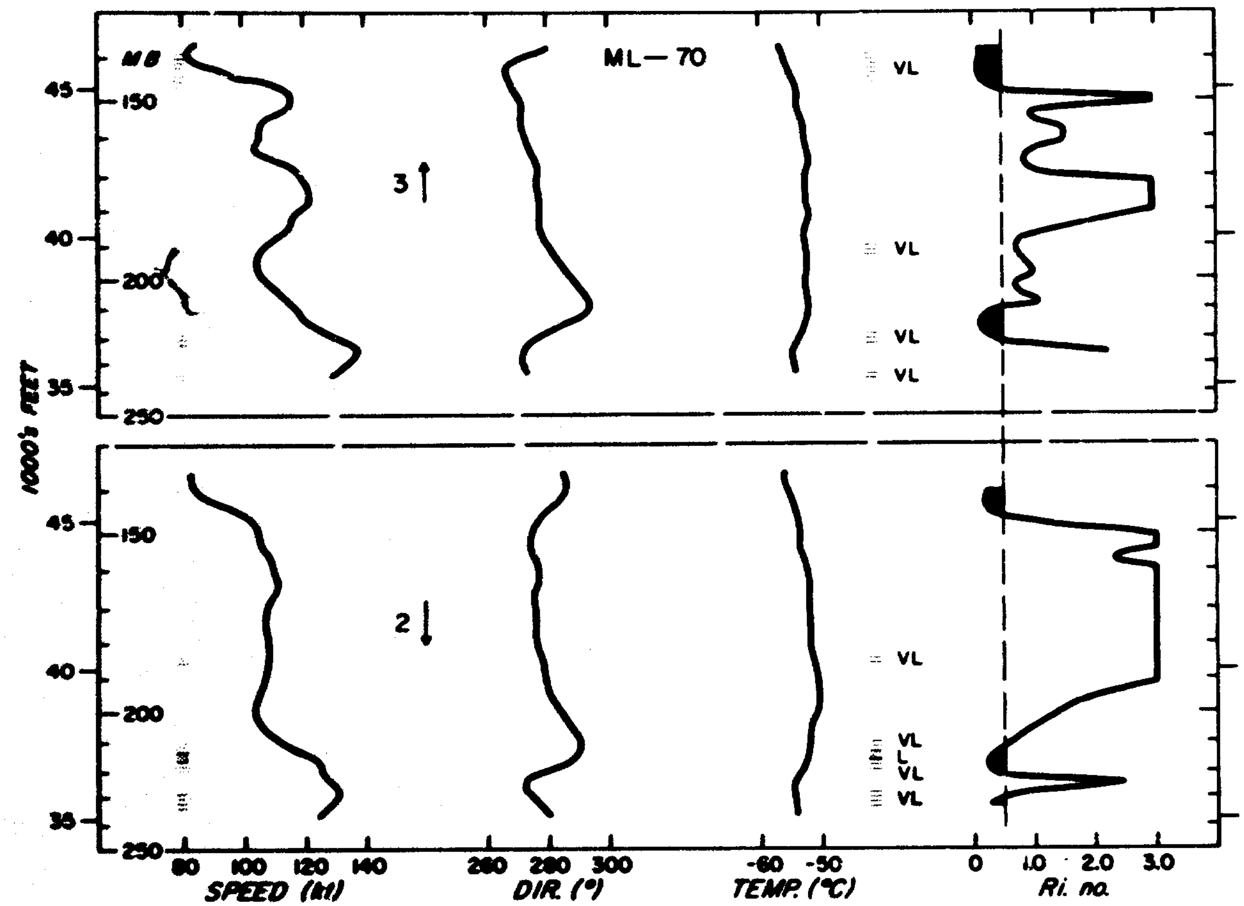

Figure 63. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Numbers 2 and 3

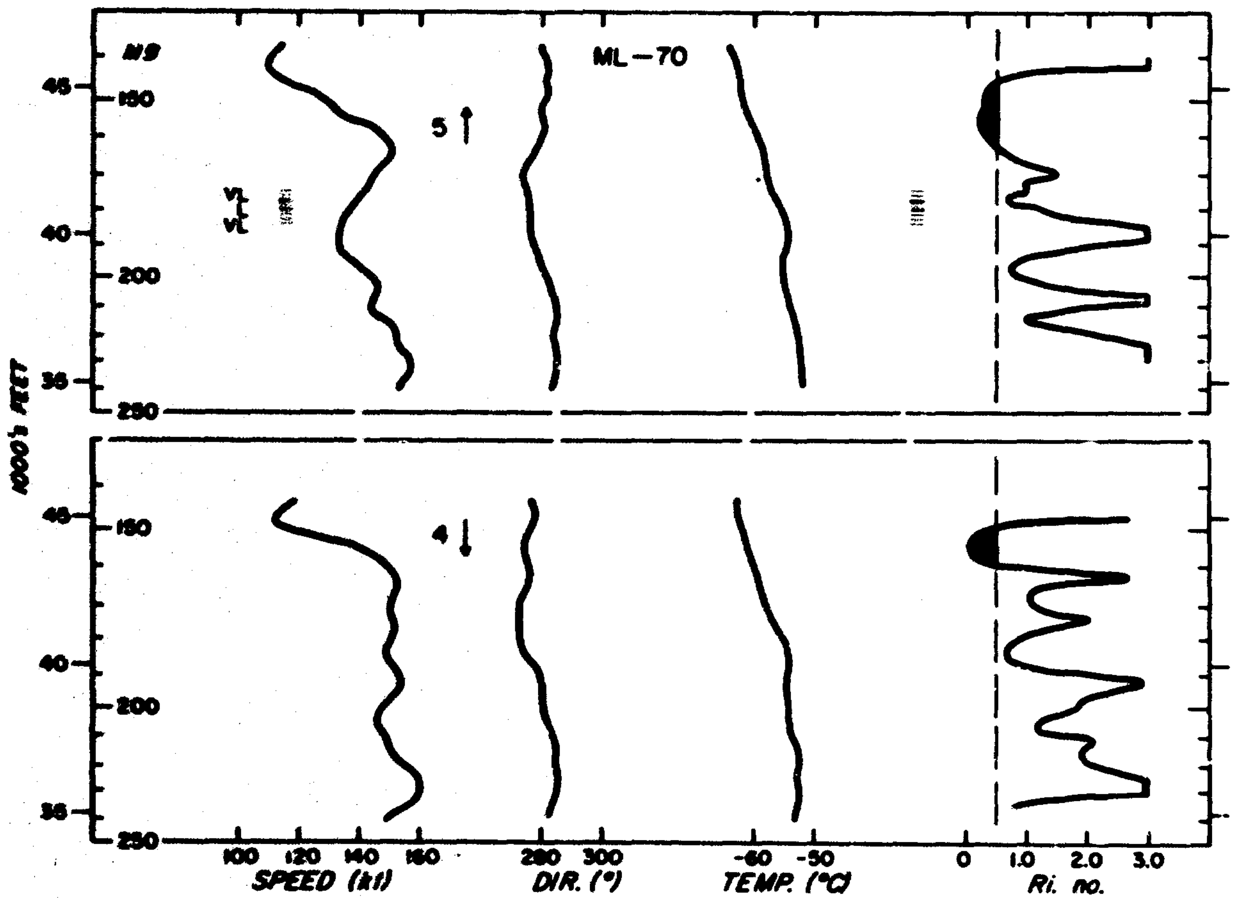

Figure 64. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Numbers 4 and 5

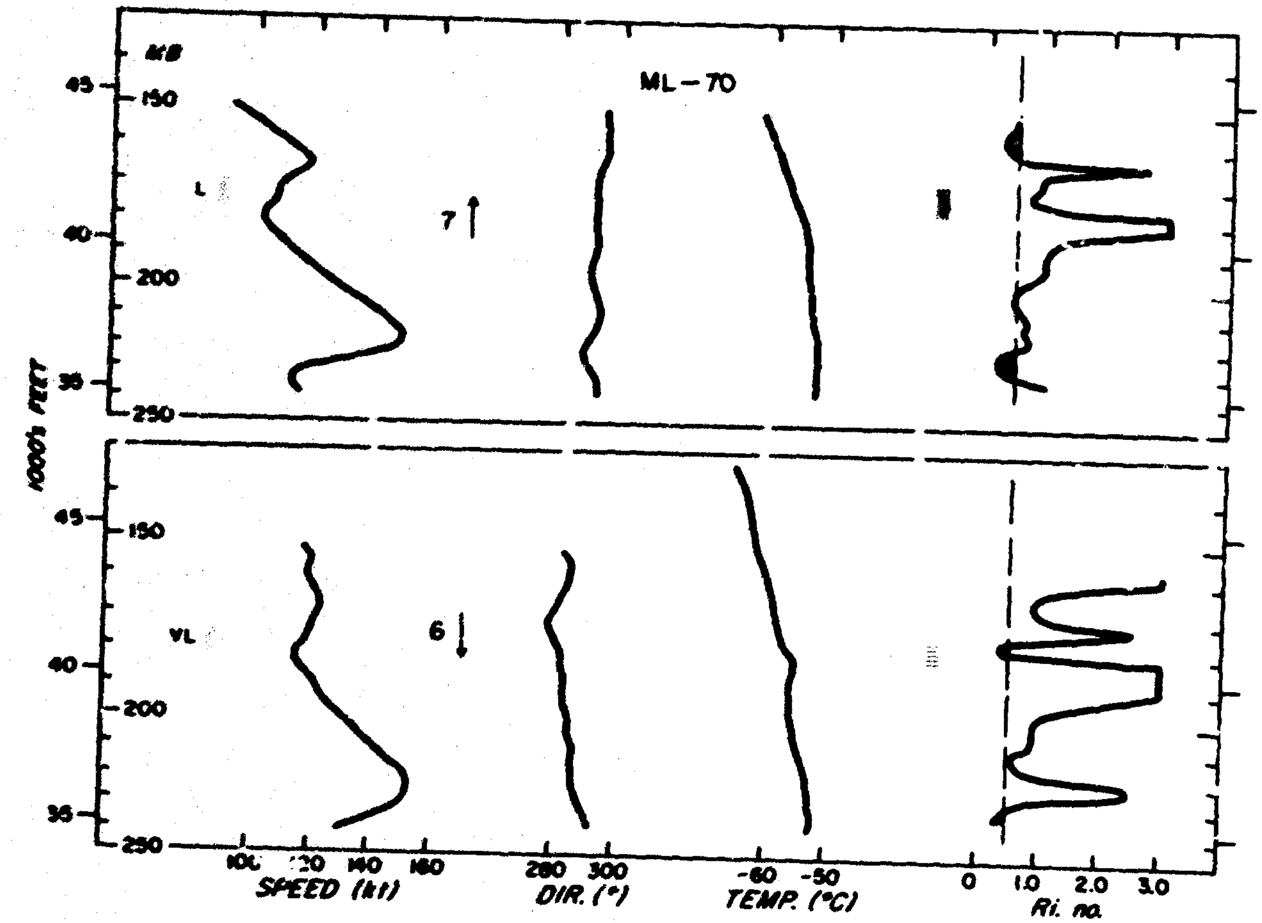

Figure 83. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Numbers 6 and 7

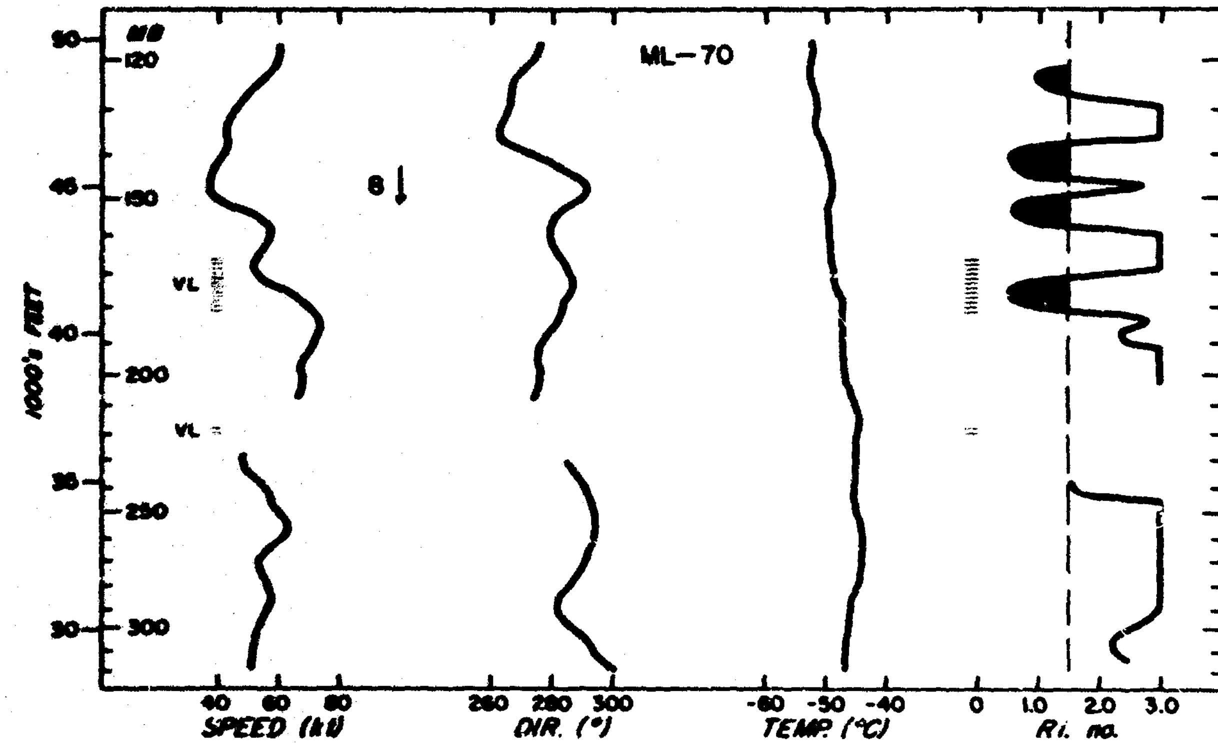

Figure 66. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Number 8

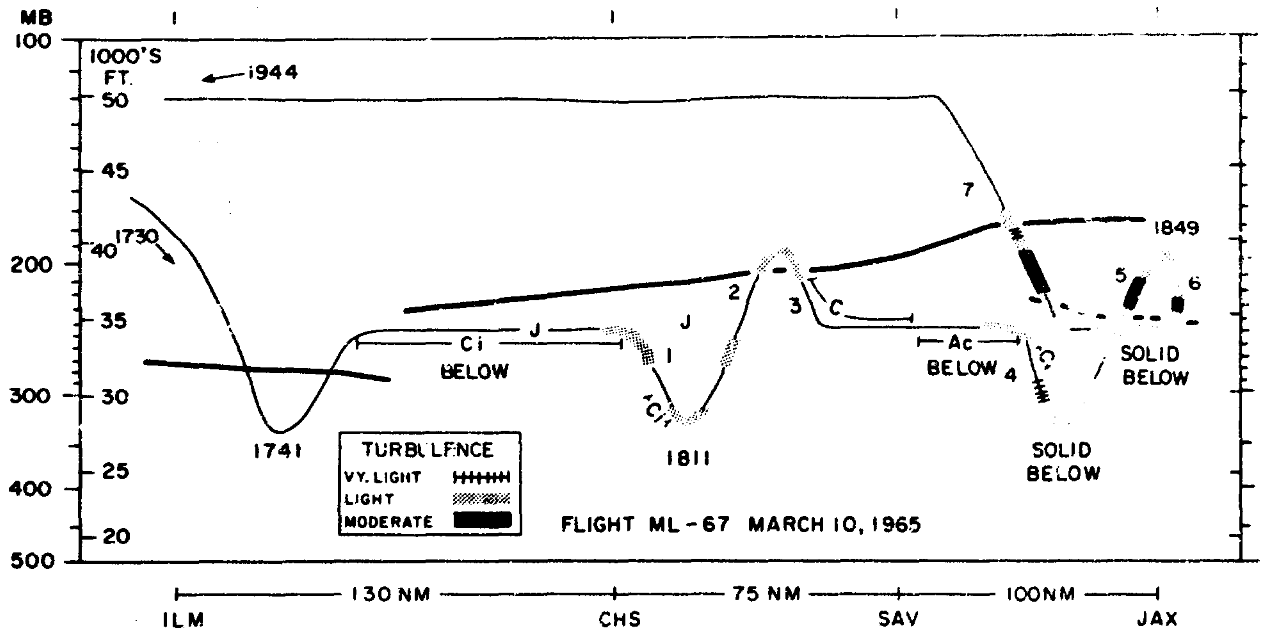

Figure 67. Flight ML-67 From Bedford (BED), Massachusetts to Jacksonville (JAX), Florida. Encountered CAT are shown. Heavier lines identify tropopause and pseudo-tropopause, and numbers refer to ascents and descents. Time (GMT) shown at a few points. Clouds below aircraft in clouds shown by —C—

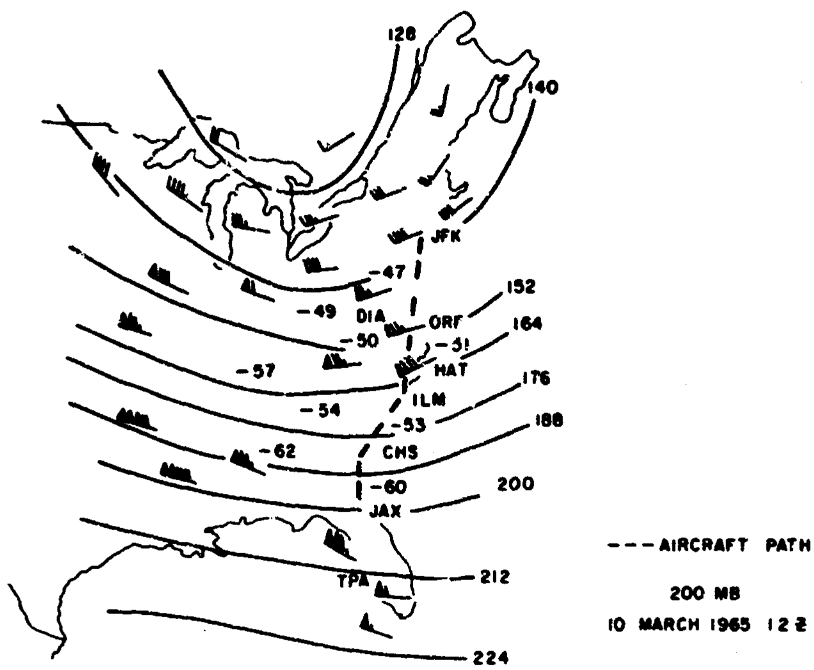

Figure 68. 200-MB Map, 10 March 1965, 12Z

Table 4. Frequency of Turbulence vs Richardson Criterion of 0.5. Marginal figures in percent

	CAT	No CAT	
Ri ≤ 0.5	4	3	57%
Ri > 0.5	1	40	98%
	80%	93%	

NOTE: All Cases Percent Correct = 92

3.5 Mission ML-67 - Across a Cyclonically-Curved Northwest Jet

3.5.1 MISSION DESCRIPTION

Mission ML-67 was flown 10 March 1965, between Bedford, Massachusetts, (BED) and Jacksonville, Florida (JAX), and the area of interest was between Wilmington, North Carolina (ILM) and Jacksonville. The aircraft was in this area from 1440 to 1900 GMT and probed between 30,000 to 40,000 ft, or 300 to 200 mb. Figure 67 shows the aircraft path, the encountered turbulence, tropopause, pseudo-tropopause, and the cloudiness at and below flight level. North of Charleston, South Carolina (CHS) the track was free of

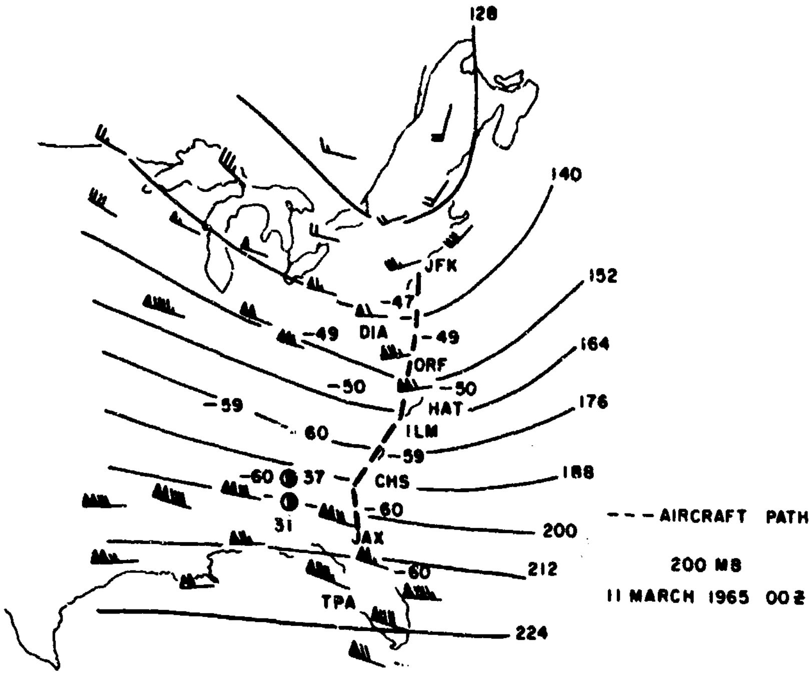

Figure 69. 200-MB-Map, 11 March 1965, 00Z Moderate CAT

CAT. Portions of the flight were in cirrus clouds, and a considerable part of the track was flown above solid layers of clouds.

3.5.2 SYNOPTIC SITUATION

The 200-mb and the maximum wind charts for 10/12Z and 11/00Z are shown in Figures 68, 69, 70 and 71. The area probed was slightly west of the upper level trough and in the exit region of the jet. Wind speeds in the core were as high as 200 kts at 00Z. The jet was displaced northward during the 12-hour period 10/12Z to 11/00Z, and along the east coast, the jet moved from the vicinity of Jacksonville to near Charleston. A cross section based upon the 11/00Z radiosonde data is presented in Figure 72. Two jets, each associated a marked tropopause "break," are shown. This mission probed the region around the southern jet.

3.5.3 MESOSCALE STRUCTURES

The mesoscale structures of wind speed and potential temperature are shown in Figure 73, and wind direction and ozone in Figure 74. The position of the jet core and the tropopause profile are in good agreement with these features as they were shown in the 11/00Z data in Figure 72. Vertical profiles of wind speed, wind direction, temperature, and the Richardson number are shown in Figures 75, 76, and 77

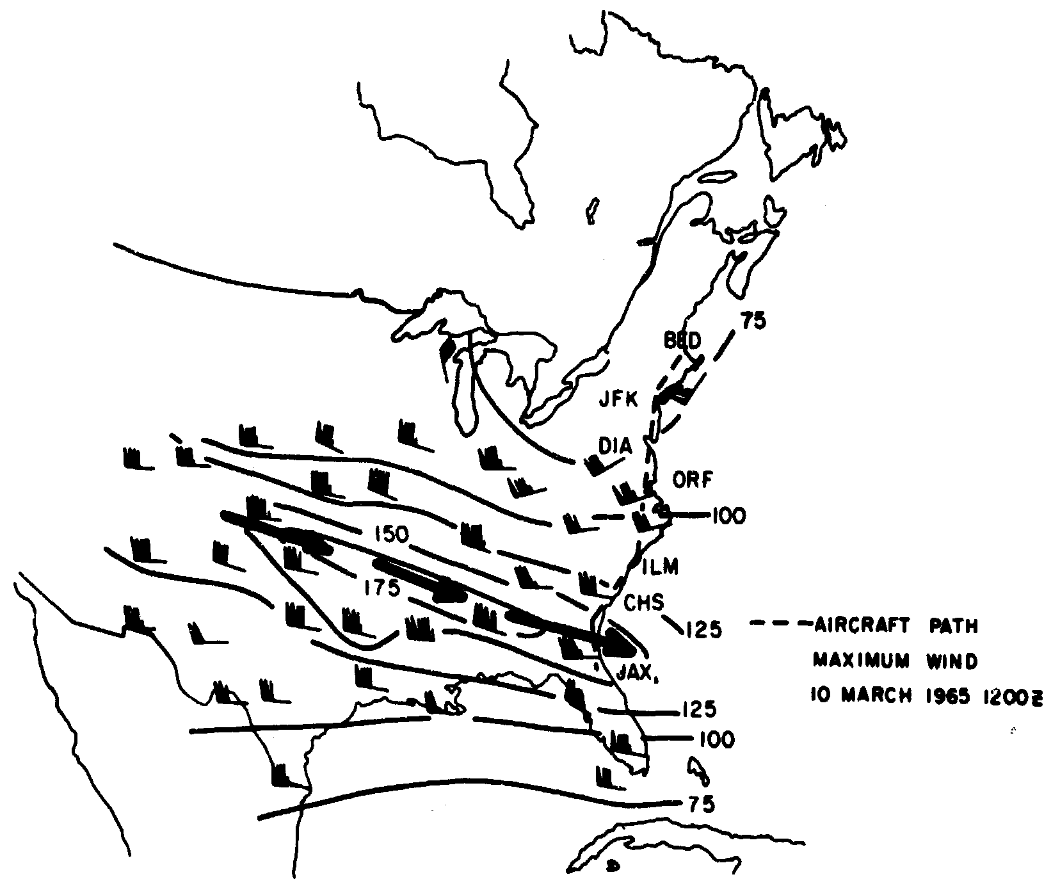

Figure 70. Maximum Wind Map, 10 March 1965, 12Z (Isotachs in knots)

for probes 1, 2, 4, 5, and 7. The wind data in probes number 3 and 6 were not usable.

A striking feature in this case is the absence of CAT on the cold or cyclonic side of the jet. It should be noted, however, that probing on the cyclonic side was limited to the vicinity of Wilmington where the vertical wind shear was apparently very weak. No turbulence was noted in the pronounced tropopause "break" area south of Wilmington. Also no CAT was encountered along most of the constant-level track southward to near Charleston. This is not surprising, since the level track closely follows the level of maximum wind. The suggestion that there was no turbulence on the cyclonic side of jet was supported by reports from the commercial airlines. Figure 69 contains commercial reports near map time, and two cases of moderate were noted at 31,000 and 37,000 ft upstream from Charleston and Jacksonville.

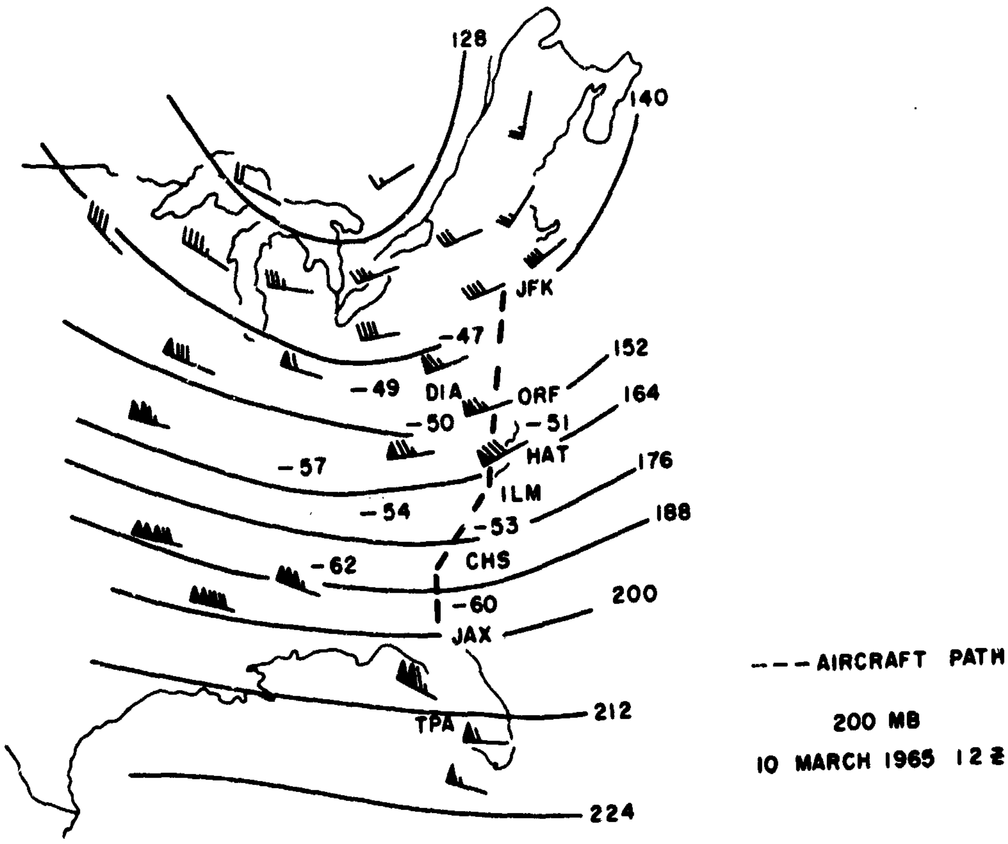

Figure 71. Maximum Wind Map, 11 March 1965, 00Z (Isotachs in knots)

Areas of CAT were found below and above the level of maximum wind, and at two places the turbulence penetrated into the stratosphere. The more intense and extensive areas of CAT were located above the level of maximum wind in the SAV-JAX sector. From spatial and temporal continuity considerations, it is reasonable to assume there was an extensive broad layer of turbulent air above the wind maximum. As can be seen in Figure 73, most of the turbulent layer is in a region of low stability and sandwiched between the tropopause and a shallow stable layer below.

3.5.4 RICHARDSON NUMBER CRITERION

From Figures 75 and 76, it is clear that there are a number of CAT areas in layers of small wind shear and low stability, such as in probes 4 and 5. CAT in regions of high stability and strong shear are seen at top of probe number 2. A statistical verification of 0.5 as a critical number relative to CAT or no CAT is shown in the contingency table which follows.

About 70 percent of the CAT cases were correctly specified by the Richardson criterion, and the overall hit score was 71 percent.

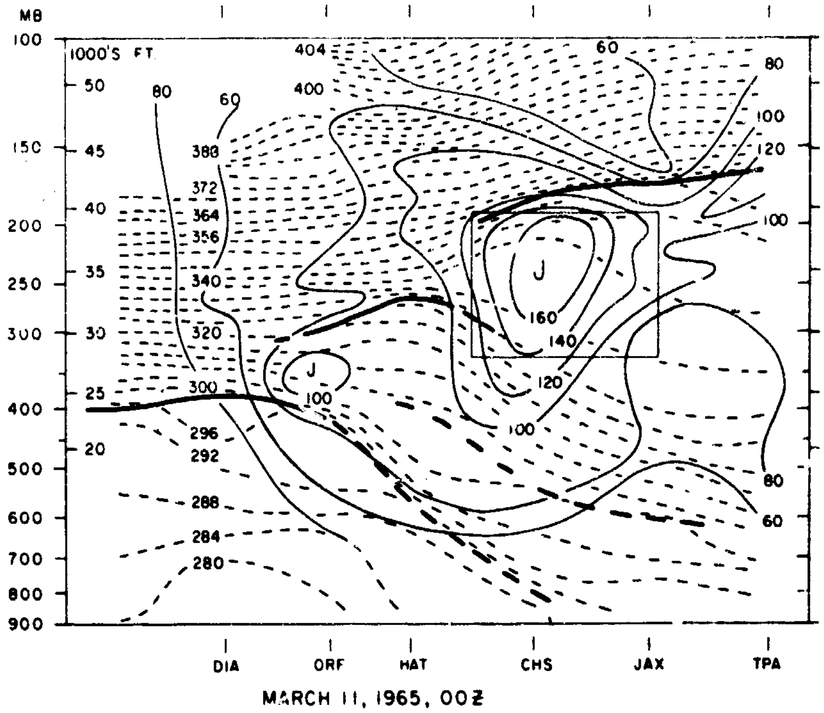

Figure 72. Vertical Cross Section From Washington (DIA) D.C. to Tampa (TPA) Florida, 11 March 1965, 00Z. Thin solid lines are wind speed (knots) and thin dashed are potential temperature (°K). Heavy lines identify tropopause and pseudo-tropopause

Table 5. Frequency of Turbulence vs Richardson Criterion of 0.5. Marginal figures in percent

	CAT	No CAT	
Ri ≤ 0.5	18	6	75%
Ri > 0.5	8	16	67%
	69%	73%	

NOTE: All Cases Percent Correct = 71

4. SUMMARY

The clear air turbulence encountered by our missions occurred largely in association with a jet stream. CAT (including light and more intense) was more extensive in a lateral direction above the level of maximum wind than below that level, and

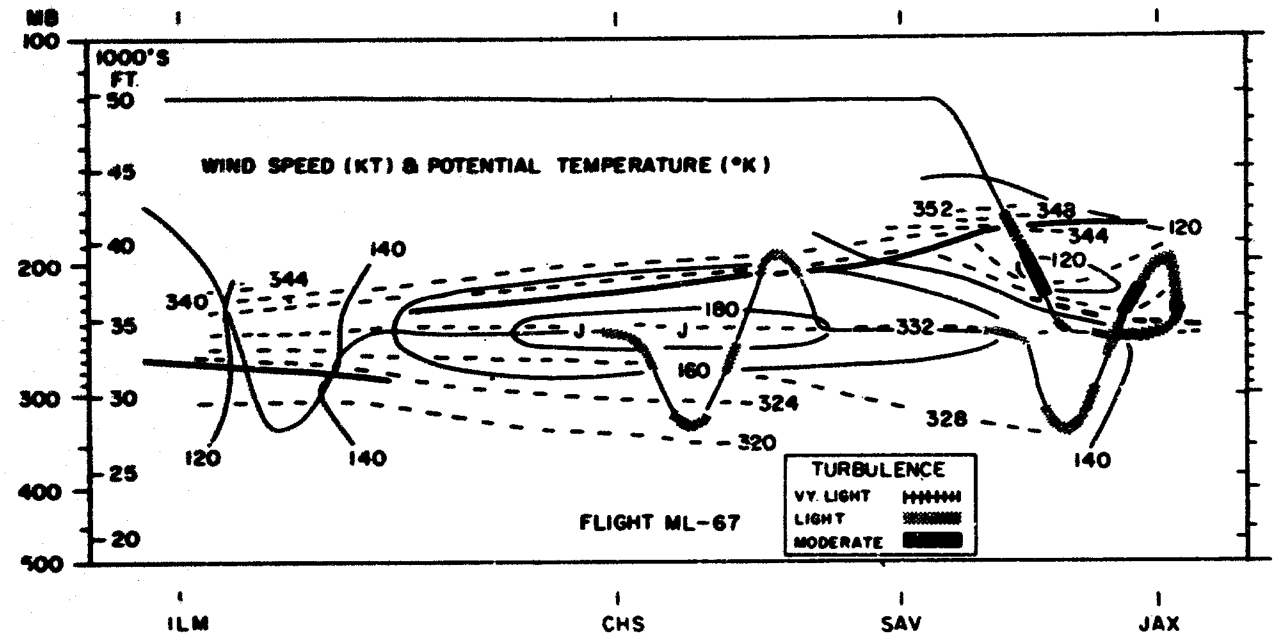

Figure 73. Cross Section of Wind Speed (Solid Lines) and of Potential Temperature (Dashed Lines). Heavier lines identify tropopause and pseudo-tropopause

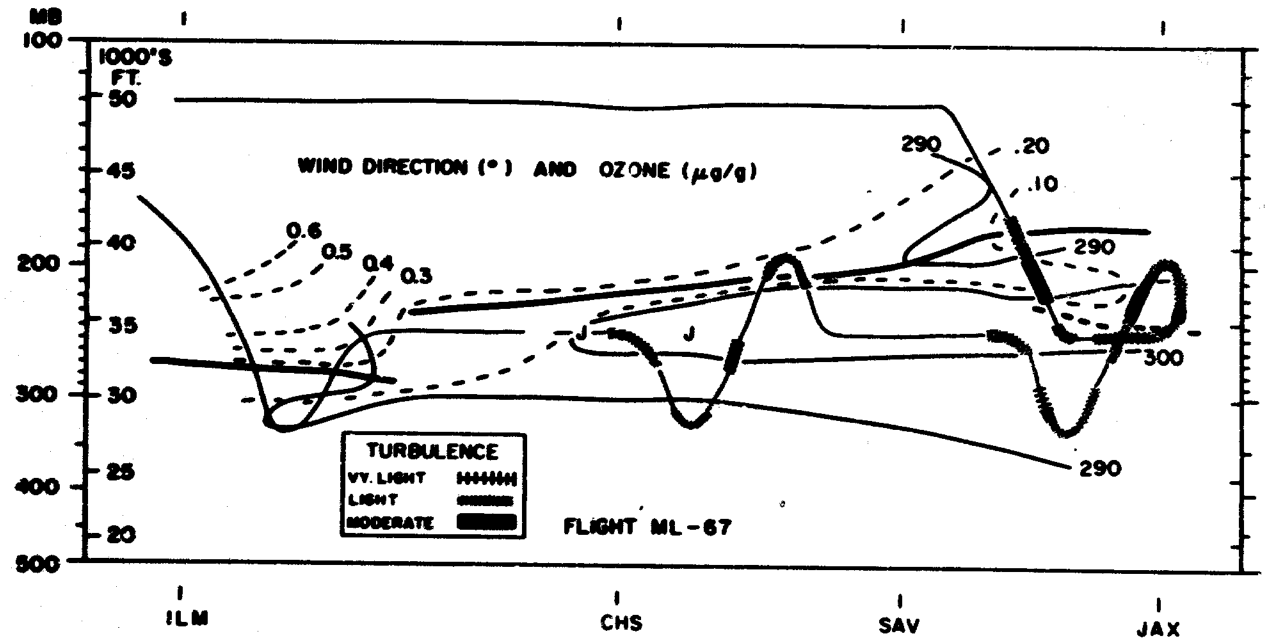

Figure 74. Cross Section of Wind Direction (Solid Lines) and of Ozone Mixing Ratio (Dashed Lines). Conventions same as in Figure 73

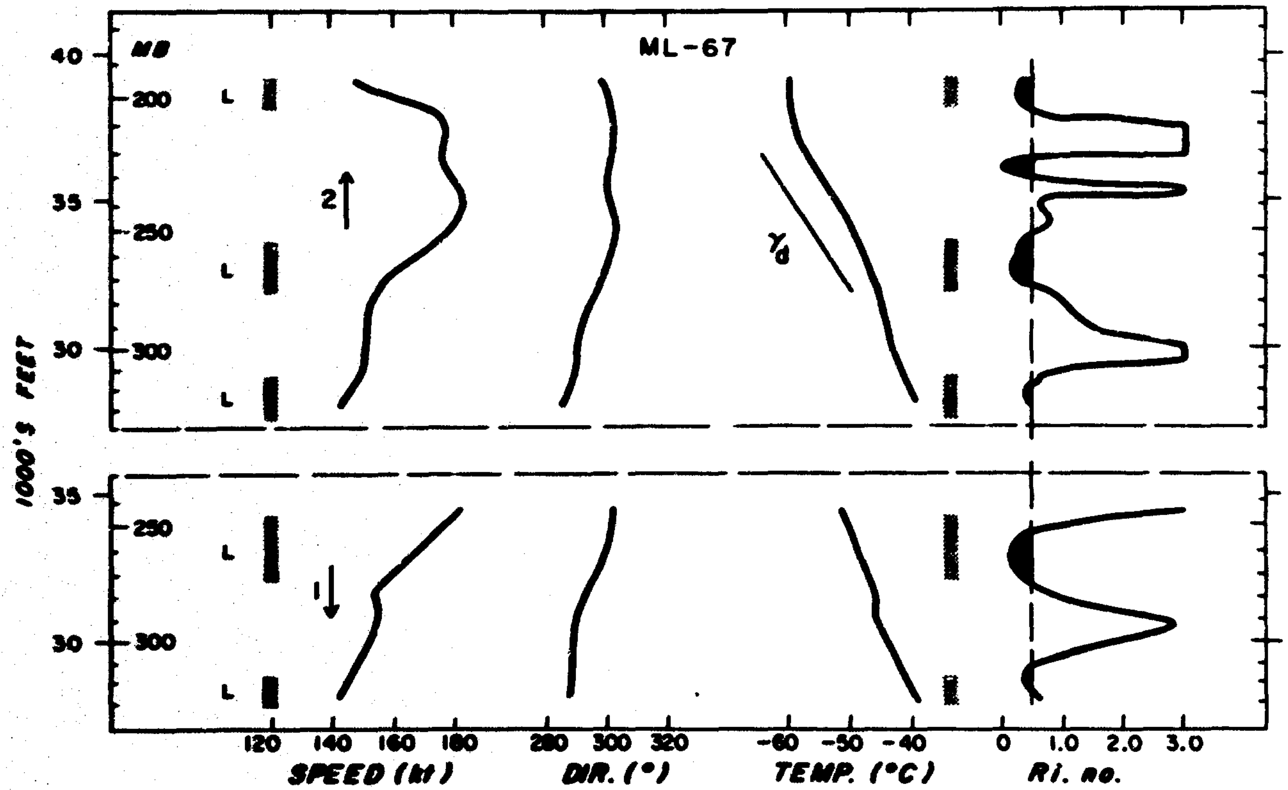

Figure 75. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Numbers 1 and 2

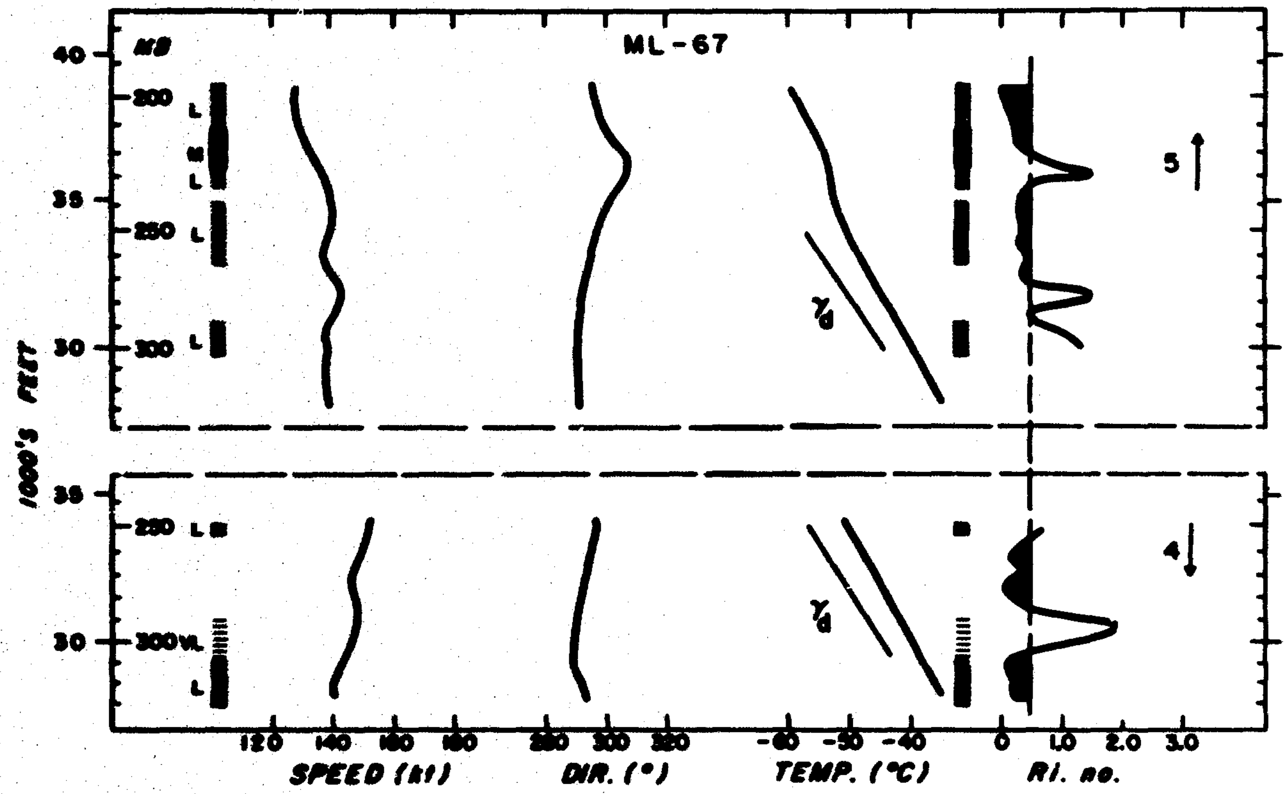

Figure 76. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Numbers 4 and 5

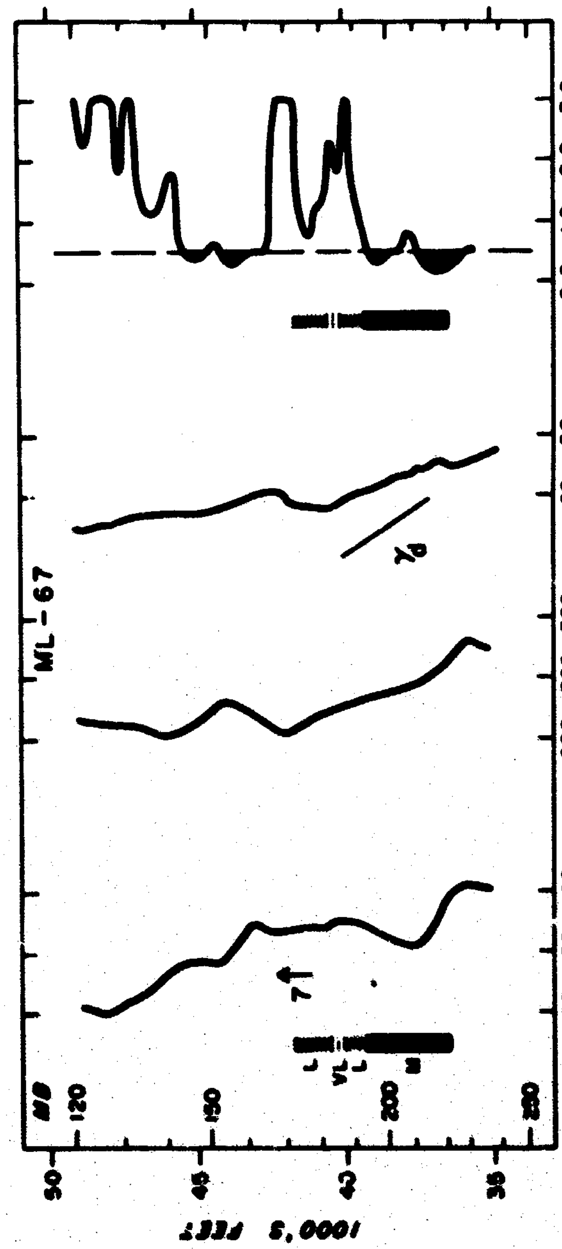

Figure 77. Vertical Profiles of Wind, Temperature, and Richardson Number for Probe Number 7

there was little turbulence at the level of minimum vertical wind shear. The importance of the vertical wind shear as an energy source for the turbulence was evident. Above the level of maximum wind, the CAT was most frequent in the tropopause "break" region, extending from over the jet and into the cyclonic side of the flow. While the turbulent regions extended up to 300 miles in cross-wind direction and 7000 or 8000 ft in the vertical, the areas of moderate or greater intensity were very patchy in the horizontal, and the vertical extent was generally well under 2000 ft. In one mission, extensive CAT, including a fair amount of moderate was found on the anticyclonic side of the jet. There was widespread thick alto-cumulus cloud layers below flight level and some cirrus cloud layers at flight level. The vertical wind shear was small, but when combined with low stability, the resulting Richardson number was small or favorable for CAT generation. In nearly every case of moderate or more severe CAT, the base of this activity was located at the top or within a stable layer, and the activity extended upwards into a region of low stability.

The verification of the Richardson criterion for the five missions were combined into one table as shown below. There are 439 cases in all, and CAT was correctly specified about 70 percent of the time. The hit score for all the CAT and no CAT cases was 80 percent. It should be pointed out that the criterion did not appear to be able to discriminate moderate CAT from light, or even from the very light CAT, which was at least a 1000-ft thick.

Table 6. Frequency of Turbulence vs Richardson Criterion of 0.5 for the 5 Missions. Marginal figures in percent

	CAT	No CAT	
Ri ≤ 0.5	105	44	71%
Ri > 0.5	44	246	85%
	71%	85%	

NOTE: All Cases Percent Correct = 80

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Hq AFCRL, OAR (CRH) United States Air Force Bedford, Massachusetts 01730	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Mesoscale Structure of the Atmosphere in Regions of Clear-Air Turbulence
Volume I

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Scientific Report. Interim.

5. AUTHOR(S) (Last name, first name, initial)

PENN, Samuel and PISINSKI, Thomas A.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 1967	93	5

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) AFCRL-67-0115 AFSG No. 190
b. PROJECT AND TASK NO. 8628-10	
c. DOD ELEMENT 62405394	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFCRL-67-0115
d. DOD SUBELEMENT 681000	

10. AVAILABILITY LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Hq AFCRL, OAR (CRH) United States Air Force Bedford, Massachusetts 01730

13. ABSTRACT

The mesoscale structure of the atmosphere in regions of Clear-Air Turbulence (CAT) is investigated by means of aircraft observations of wind, temperature, and ozone obtained in the upper troposphere and in the lower stratosphere. Analysis from five CAT missions are shown, including vertical cross sections normal to flow patterns and also detailed vertical "soundings" of wind, temperature, and the Richardson number. A verification is obtained at intervals of 1000 ft between the occurrence of CAT and a Richardson criterion of 0.5. Over 70 percent of the 149 CAT cases are correctly specified by the criterion.

Unclassified
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14. KEY WORDS	LINK A		LINK B		LINK C	
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Clear-Air Turbulence						
Aircraft Data						
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