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NATIONAL RESEARCH COUNCIL OF CANADA

AERONAUTICAL REPORT
LR-551

STRATOSPHERIC TURBULENCE AND TEMPERATURE GRADIENTS MEASURED BY AN RB-57F

Coldscan Flights 57 to 92

BY
J.I. MacPHERSON AND E.G. MORRISSEY
NATIONAL AERONAUTICAL ESTABLISHMENT

OTTAWA
OCTOBER 1971

NRC NO. 12318

86

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SUMMARY

Through most of the period from January 1969 to June 1971, a USAF RB-57F high altitude weather reconnaissance aircraft has carried special NRC instrumentation to measure and record stratospheric turbulence and horizontal temperature gradients encountered on routine flights at altitudes from 40,000 to 65,000 feet. The main purpose of this cooperative program, named "Coldscan", was to collect data on atmospheric conditions at altitudes to be flown by the supersonic transports. Eighty-eight missions were flown covering over 136,000 nautical miles, the major portion being over central and western United States, the Pacific Ocean south of Panama, and on proposed SST routes off the east coast of North America. This is the third Coldscan data report and includes a summary of the results of all 88 flights. Data are presented on the correlation between measured stratospheric turbulence and horizontal temperature gradients, on the altitude and geographical distributions of the turbulence and temperature change encounters, and on the positions of the recorded incidents relative to the jet stream. Part 2 of the report gives detailed accounts of a selection of 15 events from Flights 57 through 92 that showed significant temperature gradients or light to moderate turbulence. These presentations include time histories of the recorded variables, flight tracks showing event positions, and meteorological analyses.

TABLE OF CONTENTS

PART 1

TABLE OF CONTENTS (Cont'd)

Page

PART 2

TABLE OF CONTENTS (Cont'd)

Page

PART 2 (Cont'd)

TABLE OF CONTENTS (Cont'd)

Page

PART 2 (Cont'd)

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STRATOSPHERIC TURBULENCE AND TEMPERATURE GRADIENTS MEASURED BY AN RB-57F

Coldscan Flights 57 to 92

INTRODUCTION

Coldscan was a co-operative stratospheric turbulence project involving the National Aeronautical Establishment and the Atmospheric Environment Service of Canada and the USAF 58th Weather Reconnaissance Squadron. An RB-57F aircraft (Fig. 1), capable of sustained flight above 60,000 feet, was fitted with a unique NRC-developed event recorder and instrumentation system designed to record incidents of turbulence and horizontal temperature gradients encountered on routine stratospheric flights. The aims of the program were to collect data on atmospheric conditions at altitudes to be flown by the supersonic transports, to attempt to relate the nature and severity of each recorded incident to geographical position and meteorological conditions, and to investigate the relationship between stratospheric turbulence and mesoscale horizontal temperature gradients.

Between January 1969 and June 1971, the instrumentation was successfully operated on 88 flights covering 136,000 nautical miles at altitudes from 40,000 to 65,000 feet. This is the third NRC report presenting data collected on these flights, and it follows the same format as the previous two - that is, Part 1 summarizes the results of all of the flights while Part 2 presents detailed accounts of 15 of the more significant incidents recorded in Flights 57 through 92. References 1 and 2 present data on Flights 2 to 18 and 19 to 56 respectively, and include analyses of a total of 35 encounters with stratospheric turbulence or strong temperature gradients. As in Part 2 of this report, these detailed accounts include time histories of the recorded parameters, route maps showing the geographical positions of the recorded incidents, and discussions of the meteorological conditions contributing to the events.

Most of the first 57 flights of the program (Ref. 1 and 2) were round-trip missions flown out of Albuquerque, New Mexico, therefore only about 1/10 of the flight miles were over ocean. To make the data more representative of conditions likely to be experienced by the supersonic transports on mainly over-water routes, 15 of the final 31 flights were operated from Dover AFB, Delaware, over segments of three of the proposed SST routes out of New York. Most of these flights were flown along a thousand mile leg of the transatlantic route during January and February, a time when there is above-average jet stream activity in this area. Ten of the events selected for detailed presentation in Part 2 were recorded during these flights. Flight-mile data for all 88 flights of the project now show a more balanced distribution over the three types of terrain, flatland (38%), mountains (34%), and ocean (28%).

During the 2½ years existence of Project Coldscan, the NAE-instrumented RB-57F was flown not only in the 88 routine Coldscan missions, but also in two special programs, the 1970 Colorado Lee Wave Experiment and the 1971 Roughrider Thunderstorm Project. The first of these was organized by the National Centre for Atmospheric Research at Boulder, Colorado. Several aircraft working separate altitude bands recorded atmospheric data on co-ordinated passes across a 100-mile leg of the Rocky Mountains during periods of forecast lee wave activity. The

RB-57F covered the 40,000 to 65,000 foot band, and on several days encountered waves similar to those reported in References 1 and 2. On occasion, even more severe activity was measured (Refs. 3 and 4). In Roughrider, a National Severe Storms Laboratory project, the RB-57F overflew thunderstorms while taking high-quality photographs and recording turbulence and temperature data on the NAE instrumentation. Twenty flights were flown during April, May, and June of this year over thunderstorms in Oklahoma and northern Texas. Many instances of light to moderate turbulence and large temperature gradients similar to those of Flight 87 (Part 2) were recorded during these Roughrider flights. For various operational reasons, few of the 88 normal Coldscan flights occurred during the summer months, so the overall turbulence statistics reported include a below-average number of encounters with turbulence over thunderstorms. The directed nature of the Roughrider flights precludes their use in this report on the Coldscan data, but future reports by the NAE and the National Severe Storms Laboratory will present data collected on these flights.

Data Acquisition and Analysis

The main feature of the NRC turbulence instrumentation package and memory recorder installed in the RB-57F is that it continually scans the incoming data but records only when significant parameter changes occur. A complete description of the system and its operation is given in Reference 5.

The NRC instrumentation is operated by the aircraft navigator on routine operational and training flights at altitudes above 40,000 feet. No attempt is made to deliberately encounter areas of turbulence or temperature change. To allow the navigator to perform his other duties, the instrumentation is highly automated, based on the NRC memory recorder. This 7-channel FM magnetic tape recorder has a 2-minute tape loop in addition to its 5-hour reel for permanent storage. Flight data are continuously recorded on the tape loop whenever the aircraft is above 40,000 feet and simultaneously scanned by exceedance detectors for parameter fluctuations exceeding preset levels. Whenever an exceedance is detected, the tape reels are actuated for the transfer of data from the loop to the storage tape. The two minutes of recorded data prior to the exceedance are retained, along with the exceedance, as long as it persists, plus the two minutes of data following the incident. The recorder reels can be initiated by any or all of the following exceedances:

(i) change in total temperature ≥ 2.5°C within a 30-second period;
(ii) vertical acceleration increment ≥ 0.35 g;
(iii) rate of change of indicated airspeed ≥ 5 knots/second.

Every stored incident is identified by a coded digital clock time superimposed on one of the recorded signals. For each exceedance the navigator logs the digital clock time, along with geographical position, altitude, aircraft weight, doppler winds, autopilot mode, and his comments concerning intensity of turbulence and local weather conditions.

Completed tapes with the navigators' data logs and maps are sent to the NAE for analysis. On tape playback, each recorded encounter is assigned a chronological flight and event number based on the coded time pulses and the information written on the data logs. Continuous time records of static (ambient) temperature are calculated by analogue computer, using the airspeed and altitude signals to correct the total temperature for the increment due to kinetic heating. This computation includes corrections to the indicated airspeed for position error and compressibility. The computed static temperature signal is recorded on 14-channel magnetic tape along with the original seven channels of data, all matched low-pass filtered with the 3 db point at 4 cycles/second. A voice channel is included on this data storage tape to record flight and event numbers as well as comments from the navigators' logs.

For each event, chart recorder traces are then prepared showing simultaneous time histories of total temperature, static temperature, indicated airspeed, normal acceleration, pitch and roll attitude, and coarse- and fine-scale altitude. These are carefully analyzed to determine the nature of each exceedance and to select the more significant events for detailed meteorological analysis. At this stage, many events are eliminated from further serious consideration. Examples are those with g exceedances due to control inputs, or total temperature changes caused by intentional large changes in airspeed. For those events selected for detailed meteorological analysis, copies of the traces and all other data describing each event are sent to the Forecast Research Section, Research and Training Division, Atmospheric Environment Service.

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PART 1

1.0 SUMMARY OF RESULTS - FLIGHTS 2 TO 92

Table 1 summarizes the flight data for the 88 Coldscan missions flown between January 31, 1969 and June 9, 1971. Data from Flights 2 to 56 are shown in totalled form since these were detailed in the equivalent tables in References 1 and 2. Flights 63 to 67 have been omitted because of an instrumentation problem during these flights.

In the 88 project missions, 136,000 nautical miles were flown in 392 hours of flight, 332 of those above 40,000 feet. The geographical areas covered by these flights are shown in Figure 2 by the superimposed ground tracks of all 88 flights, many legs of which were flown on numerous occasions. For the over-water routes, the frequency of round trips is indicated by the numbers beside the flight tracks.

An "event" is defined as any activation of the permanent storage reels of the memory recorder, either by the automatic detection of any of the three exceedances listed above or by manual initiation by the navigator. The recorded length of an event may be as short as four minutes or, when there are continuous exceedances, the recorder will operate until two minutes after the final exceedance. The longest event recorded on a routine Coldscan flight has been 19 minutes. A total of 419 events has been recorded during the 88 project flights, slightly more than one for every hour of flight. During level flight there were 88 events with a static temperature change greater than 2.5°C within 30 seconds and 41 events with turbulence with at least one vertical acceleration increment in excess of 0.35 g. Only 14 of these events had both the turbulence and the temperature change.

Considerably more than half of the 419 events had neither turbulence nor the minimum 2.5°C within 30 seconds change in static temperature during level flight. Most of these events were g exceedances caused by pilot or autopilot control inputs: many were temperature change exceedances during climbs and descents near the tropopause; and a large number were total temperature changes caused solely by substantial changes in airspeed.

1.1 Duration of Turbulence

The duration of turbulence for each encounter is defined as the period during which there were continuous high-frequency excursions of the accelerometer trace not associated with control inputs, with at least one spike in excess of 0.35 g. For the RB-57F this corresponds to a derived gust velocity of about 8 ft/sec. It is important to remember that all references to turbulence events, turbulence patches, etc. mentioned in this report are based on this definition.

In the 88 Coldscan missions, a total of 107 minutes of turbulence was measured during cruise, representing 0.53 percent of the time flown above 40,000 feet. This frequency of encounter is lower than that reported for the HI-CAT flights, even though most of the Coldscan flights were flown in geographical areas where the HI-CAT data showed the highest percentages of miles flown in moderate turbulence (Fig. 39 of Ref. 6). The HI-CAT flights were directed into areas of anticipated turbulence and thus represent an overestimate of the amount of turbulence that would be expected on routine airline-type flights.

The 0.53 percentage of time in turbulence is a lower figure than the 0.72 percent reported in Reference 2 for the first 57 flights of the Coldscan project. This decrease in the overall proportion of flight time spent in turbulence can be attributed to the recent generally smooth flights off the east coast of North America, where in 15 flights only one incident of 0.35 g turbulence occurred.

Table 2 shows the distribution of the lengths of the 41 measured patches of stratospheric turbulence. They varied from a minimum of two nautical miles to a 47 nautical mile maximum about an average of 17 nautical miles.

1.2 Altitude Distribution of Events

Figure 3 illustrates the altitude distribution of the recorded incidents and the hours of cruise flight. The incidence of stratospheric 0.35 g turbulence exhibits a peak in the 50,000-foot band of 0.6 encounters per 1,000 nautical miles, about twice the frequency of occurrence measured at the other altitudes. Percentage of time in turbulence displays a similar peak at 50,000 feet with a generally decreasing trend at higher altitudes.

The question raised by these results is whether this peak in the turbulence encounters per mile is real or the result of some bias in the data. The major portion of the Coldscan turbulence events occurred over mountainous terrain in conditions of strong winds conducive to the generation of lee waves. If these waves were prevalent at all levels in the lower stratosphere, then the favouring of a particular flight level would be expected to bias the data by indicating a higher frequency of turbulence encounters at this altitude. A closer examination of the altitude distribution data has revealed that this is a partial explanation of the observed peak at 50,000 feet, that is, 50,000 feet was a level that was flown more often over mountains than over other terrains. (Thirty-five percent of all-terrain flight miles were flown in the 5,000-foot band centred at 50,000 feet, but over mountainous terrain, 51 percent of the flight miles were flown at this level.) Nevertheless, the bias in the data does not entirely explain the peak at 50,000 feet in Figure 3, for of the turbulence incidents measured over mountains, over 60 percent were in the 50,000-foot band. The HI-CAT data also indicates a possible increase in the occurrence of turbulence in their 50,000- to 55,000-foot band (Ref. 7). Further evidence of this possibility was found during participation in the 1970 Colorado Lee Wave Experiment where the RB-57F sometimes encountered considerable turbulence between 50,000 and 53,000 feet at times when little or no turbulence was experienced at all other levels. Consequently, even with the bias in the data removed, there is appreciable evidence of an increase in the frequency of occurrence of turbulence in the 50,000-foot area, particularly over mountainous terrain.

In a recent summary of Russian research into high level turbulence, Buldovskij (Ref. 8) reported a similar maximum of turbulence encounters at 50,000 feet over mountainous terrain in the USSR. He related this maximum to the tropical tropopause which, although less pronounced than the polar tropopause in the lower middle latitudes, is frequently sufficiently strong to affect the stability and wind shears near 50,000 feet. Most of the over-mountain portions of the flights flown during Coldscan were made over the southwestern United States where the effects of the northern extension of the tropical tropopause were probably sufficiently strong to influence the statistics of turbulence encounters.

Figure 3 also shows the altitude distributions of the frequency of occurrence of events with static temperature changes of two magnitudes, those greater than 2.5°C within 30 seconds and those in excess of 5°C within one minute. The events with the larger temperature change are a subset of those with the minimum 2.5°C within 30 seconds change. The largest excursion from these fairly uniform distributions occurs at the 60,000-foot level for the smaller temperature change category. The increased frequency of occurrence here may be due in part to a bias in the data similar to that discussed above. In this case 60,000 feet was an altitude slightly favoured in winter flights off the east coast of North America at a time when above-average jet stream activity existed in the area. On the average, the RB-57F experienced events with temperature changes in excess of 2.5°C within 30 seconds ($3\frac{1}{2}$ nautical miles) about once every 1,300 nautical miles. In approximately one-third of these cases the temperature change exceeded 5°C within one minute.

1.3 Terrain Effects

Although only 34 percent of the flight miles were flown over mountainous terrain, 64 percent of the turbulence encounters and 54 percent of the events due to temperature change occurred over or within 30 nautical miles to the lee of mountains. Figure 4 shows the distribution by terrain type of the flight miles, turbulence incidents, and events with temperature change. Data are plotted on the basis of encounters per 1,000 nautical miles, where the term "encounter" refers to a single recorded event containing at least one, but possibly several exceedances.

The effect of terrain on tropospheric turbulence has been documented by Clodman et al (Ref. 9). The correlation between stratospheric turbulence and the underlying terrain also seems to be significant, and the wave-like form of the temperature data accompanying many of the turbulence events suggests that the coupling mechanism is via gravity waves. Most of the larger amplitude temperature changes (>5°C within one minute) occurred over or to the lee of high mountains orientated normal to a strong tropospheric jet stream. This type of situation almost always causes lee waves at several levels in the atmosphere.

Figure 4 shows a fairly high incidence of temperature changes over the ocean. Most of the ocean data were recorded during the east coast phase of the Coldscan program. The flights were made in an area where storm development and associated jet stream activity were much above the global average. Since most of the temperature changes have been attributed to gravity waves originating from these disturbances, the higher frequency of occurrence over the ocean compared with flatland is probably not typical of the global relationship. However, the occurrence of fewer cases of turbulence over the ocean is very significant since most flights were made under meteorological conditions well suited to the generation of turbulence.

1.4 The Influence of the Jet Stream

The position of each event was plotted on the 300 mb analyses prepared by the Atmospheric Environment Service. The distance between the event position and the closest jet stream was measured and its position north or south of the jet stream noted. The flight path was then divided into sections dependent upon the distance from the jet. From these data the number of events per 1,000 nautical miles was computed for two-degrees-of-latitude bands and the results presented in Figure 5. In order to remove the effects of the relatively small sample, both the number of events and flight distances were smoothed using a six-degrees-of-latitude triangular weighting function before dividing to obtain the number of events per 1,000 miles.

The results clearly demonstrate that the jet stream has a strong influence on stratospheric temperature changes and turbulence. Seventy percent of the events occurred within 240 nautical miles of the jet core, and the frequency of event occurrence decreased rapidly with increasing distance from the jet.

It is interesting to compare the results for all Coldscan missions (Fig. 5) with those obtained for only Flights 2 to 56 (Fig. 10 of Ref. 2). Both distributions show a secondary peak south of the jet. Although this may have been a result of thunderstorms over the Gulf of Mexico, the low flight mileage and small number of events in this latitude band suggest that this peak should not be considered significant. The only significant difference between the distributions is in the position of the primary maximum. The earlier data indicated that the maximum was south of the jet core, whereas, when the entire Coldscan data set is used, it coincides with the jet stream position. This reflects the differing mechanisms by which the jet stream affects the lower stratosphere. The major portion of the earlier data set was accumulated at lower latitudes when the effect of the jet was via mountain waves. In the warm sectors south of the jet stream the wind direction remains more or less constant with height, a condition more suited to the formation of lee waves than the backing or veering with height usually encountered north of a jet stream. At northern latitudes, the gravity waves are usually associated with anticyclonic curvature of the jet stream and such waves usually propagate from the northern side of the jet stream. Much of the flight distance during Flights 57 to 92 was off the east coast of the United States and Canada and so many of the events resulted from jet stream induced gravity waves. This change in geographical location together with the stronger jet streams caused the apparent shift in the maximum of encounters per unit distance.

Further investigations into the role of the jet stream and its application to forecasting will be made based on the entire Coldscan data set and reported separately in a later paper.

1.5 Horizontal Temperature Gradients

Figure 6 shows the changes in static (ambient) temperature encountered in Flights 2 through 92 versus the distance over which the changes took place. Most of the larger rates of change of temperature shown in this figure are from events discussed in the second part of this report and References 1 and 2. Many of these larger temperature gradients were concluded to be associated with mountain waves. Several events are represented by more than one point in Figure 6, since each half cycle of a wave in the temperature trace contributed a point to the plot.

The maximum rate of change of temperature encountered in a routine undirected Coldscan mission was 7°C in 0.45 nautical miles at 45,000 feet (Flight 87 see Part 2). However, temperature changes considerably more severe than this have been measured by this system during participation in the 1970 Colorado Lee Wave Experiment. Some of the temperature changes measured over the Rocky Mountains in that program were 8°C in 0.23 nautical miles at 62,000 feet, 20°C in seven nautical miles at 57,000 feet, and 6°C in 0.06 nautical miles at 53,000 feet. These and other incidents will be reported more fully in the results of the 1970 Colorado Lee Wave Experiment.

The temperature changes of Figure 6 have been replotted in Figure 7 categorized by the type of terrain over which the changes were measured. It is clear from this illustration that the major portion of all the temperature changes recorded in the project as well as all those of the largest magnitude (>10°C) were encountered over mountainous terrain. This does not diminish the significance of those temperature fluctuations experienced over flatland and ocean, for although none exceeds 8.5°C in magnitude, the gradients or rates of change of temperature are comparable to those measured over mountains. On the diagram for flatland, for example, six temperature changes are shown with gradients in excess of 5°C per nautical mile, including the one with the largest rate of change of temperature measured in the entire Coldscan program. Three of these changes were recorded during Event 5 of Flight 87 above 40,000-foot thunderstorms associated with a cold front lying across Oklahoma. Although the other three were recorded at 60,000 feet over flatland more than 60 nautical miles downstream of the Sangre de Cristo Mountains, they may still have been caused by mountain waves. (Event 6, Flight 42, Ref. 2.)

In the design and operation of supersonic engine inlets, both the gradient and magnitude of temperature changes likely to be experienced in the atmosphere are important. To this end, then, Table 3 presents the distribution of the gradient versus the magnitude of all 211 temperature changes from Figure 6.

1.6 Correlation Between Turbulence and Horizontal Temperature Gradients

An important objective of Project Coldscan was to collect data on the correlation between turbulence and horizontal temperature gradients in the stratosphere. The results of this analysis for the 88 flights covering 136,000 nautical miles are shown in Figure 8. In the interpretation of these results the threshold levels used in the Coldscan instrumentation must be kept in mind, for the aims of the project were primarily to investigate turbulence and temperature gradients of a magnitude that may affect SST operations. The minimum rate of temperature change to activate the recorder, for example, represents a gradient of almost $\frac{3}{4}$°C per nautical mile.

The correlation data are presented on Venn diagrams in which the areas of the circles are proportional to the number of events with turbulence and temperature change. The overlapping areas represent those events that are common to both sets, that is, containing both the turbulence and the temperature change. Figure 8(a) shows the correlation between those events with the minimum level of turbulence and temperature change required to actuate the recorder. Fourteen of the 41 events (34%) with turbulence of at least 0.35 g peak intensity displayed the temperature change, while only 16 percent of the 88 events with the minimum temperature change contained 0.35 g turbulence. The other diagrams of Figure 8 show that the correlation improves when higher levels of turbulence or greater temperature gradients are selected. Nevertheless, even when considering the 13 turbulence events of at least moderate intensity (>0.5 g) and the 31 events with temperature change in excess of 5°C within one minute, the correlation is still relatively poor, (Fig. 8(d)). If a clear air turbulence detection device had been giving turbulence warnings based on remotely sensing 5° per minute temperature gradients ahead of the aircraft, it would have correctly predicted seven cases of turbulence of at least moderate intensity However, six turbulence encounters with acceleration increments exceeding 0.5 g would have occurred without warning. Furthermore, there would have been 24 false alarms, i.e., cases with either no turbulence at all or light turbulence less than 0.5 g in peak intensity.

1.7 Concluding Remarks

Data from the 88 Coldscan flights have shown that light to moderate stratospheric turbulence (derived gust greater than 8 ft/sec) occurred about 0.5 percent of the time above 40,000 feet, tended to be concentrated over mountains near tropospheric jet streams, and had an above average frequency of occurrence at 50,000 feet. The percentage of time flown in moderate and severe turbulence was lower than that reported for the HI-CAT flights. The Coldscan figures are more representative of the frequency of turbulence encounter to be expected in routine airline flights at these altitudes.

More frequent, and perhaps more important in SST operations, were the encounters with temperature waves and horizontal temperature gradients exceeding 2.5°C in three nautical miles. These averaged 0.8 encounters per 1,000 nautical miles, tended to show a peak in their distribution at 60,000 feet, and were associated with 0.35 g turbulence only 1/6 of the time. Although the largest temperature changes (gradients exceeding 5°C per nautical mile) have been recorded only over land, a considerable number of temperature changes with gradients up to this level have been measured on SST routes of the east coast of North America.

The correlation between stratospheric turbulence and horizontal temperature gradients improves somewhat with the level of turbulence and temperature change considered. Nevertheless the poor correlation shown by these results does not offer much promise of a successful stratospheric clear air turbulence detector based on remotely sensing horizontal temperature gradients ahead of the aircraft.

TABLE 1

COLDSCAN SUMMARY - FLIGHTS 2 TO 92

Flight	Date 1970-71	Cruise Alt. × 1,000 ft	Flight Hours		Nautical Miles	Total Number of Events	Number of Events During Cruise			Duration of Turbulence min
			Total	Above 40,000 ft			With Static Temp. Change ≥ 2.5°C in 30 sec	With Turbulence	With Both Temp. Change and Turbulence	
1 to 56*			238.4	199.2	82,230	259	54	36	13	86.0
57	Sep. 29	55 & 60	4.38	3.86	1,565	2				
58	30	55 & 59	6.00	5.35	1,970	1				
59	Oct. 1	45	4.45	3.45	1,110	2				
60	2	60 & 64	5.15	4.37	2,125	5	1			
61	6	60	4.47	3.74	1,565	6	1			
62	17	63 & 65	5.75	4.90	2,185	3				
67	Nov. 13	54 - 57	6.75	5.62	2,330	10	3			
68	Jan. 10		.27		75	0				
69	12	50	1.77	1.32	300	0				
70	13	59 - 63	6.48	5.78	2,340	10	3			
71	14	60 - 65	6.33	5.78	2,340	10	5			
72	15	55 & 62	6.32	5.64	2,340	11	2			
73	18	60 & 62	5.88	5.18	2,130	3	1			
74	19	43	1.15	.49	300	0				
75	20	60 & 64	5.82	5.10	2,080	9	4	1		5.6
76	21	55 & 62	6.38	5.70	2,340	8	1			
77	Feb. 4	55 & 64	5.55	4.82	2,020	5	1			
78	6	55 - 64	5.98	5.46	2,380	3				
79	8	55 - 64	4.90	4.22	1,800	5				
80	9	60 - 64	3.83	3.16	1,450	7				
81	10	60 - 64	5.75	4.42	1,800	6				
82	11	57 - 65	6.16	5.23	2,400	7				
83	12	60 - 65	5.20	4.63	1,950	11	5			
84	16	45	5.33	4.55	1,540	5				
85	Mar. 17	45	3.25	2.65	970	2	1			
86	Apr. 15	45	4.88	4.12	1,720	5	1	2		5.2
87	20	45	3.48	2.82	1,140	9	4	2	1	9.7
88	21	45	4.75	4.15	1,650	4				
90	May 24	45 & 50	6.98	6.42	2,520	1				
91	28	50 & 55	6.10	5.30	2,300	4				
92	June 9	55	4.55	4.12	1,500	6	1			
88 Flts			392.4	331.6	136,460	419	88	41	14	106.5

* See References 1 and 2.

TABLE 2

DISTRIBUTION OF LENGTHS OF TURBULENCE ENCOUNTERS

Length of Turbulence Patch Nautical Miles	Number of Cases
< 5	4
5 to 9.9	13
10.0 to 19.9	10
20.0 to 29.9	6
30.0 to 39.9	3
40.0 to 49.9	5
> 50	0

TABLE 3

DISTRIBUTION OF TEMPERATURE GRADIENTS VERSUS MAGNITUDES OF THE CHANGES

		Change in Static Temperature - deg. C.							
		2.2-3.9	4.0-5.9	6.0-7.9	8.0-9.9	10.0-11.9	12.0-13.9	14.0-15.9	Totals
Temperature Gradient - °C/nautical mile	0.7- 1.9	84	33	10	4	2	2	1	136
	2.0- 3.9	24	22	5	3	1			55
	4.0- 5.9	5	5	2	1				13
	6.0- 7.9	1	3	1					5
	8.0- 9.9								0
	10.0-11.9			1					1
	12.0-13.9								0
	14.0-15.9			1					1
	Totals	114	63	20	8	3	2	1	211

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FIG I THE RB-57F

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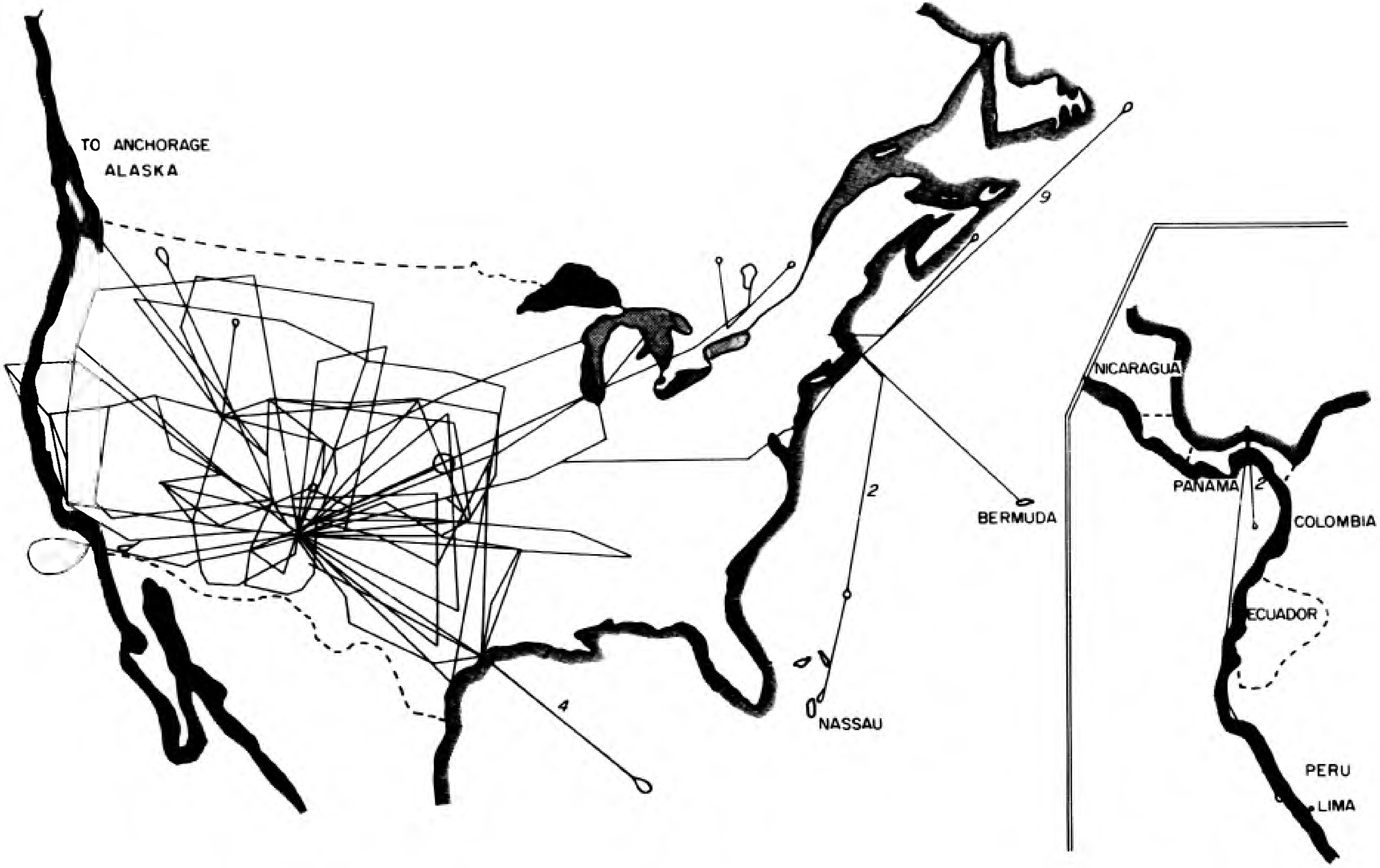

FIG 2 GEOGRAPHICAL AREAS OF COLDSCAN FLIGHTS 2 TO 92
31 JAN 1969 - 9 JUNE 1971

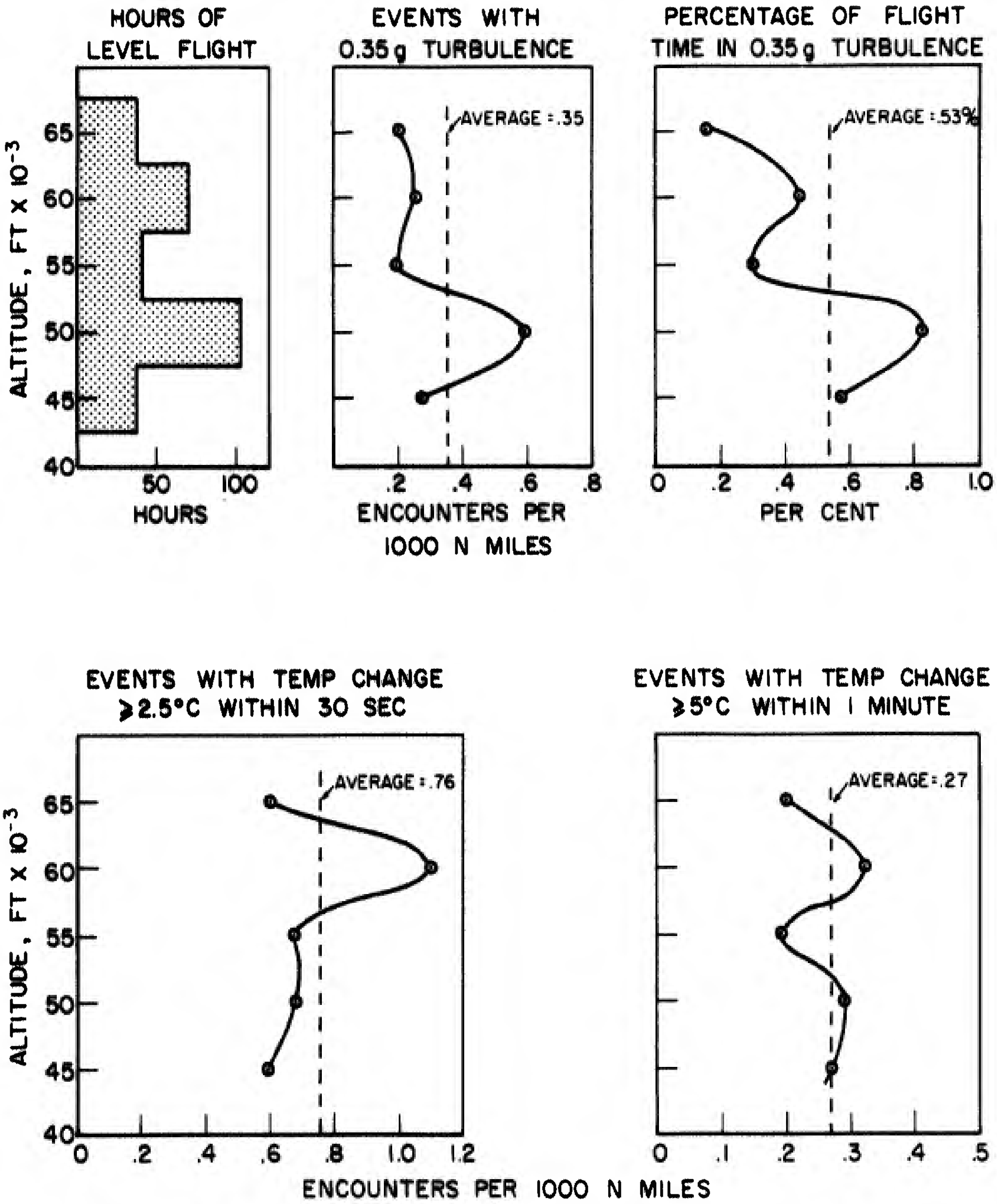

FIG 3 DISTRIBUTION OF TURBULENCE AND TEMPERATURE CHANGE WITH ALTITUDE

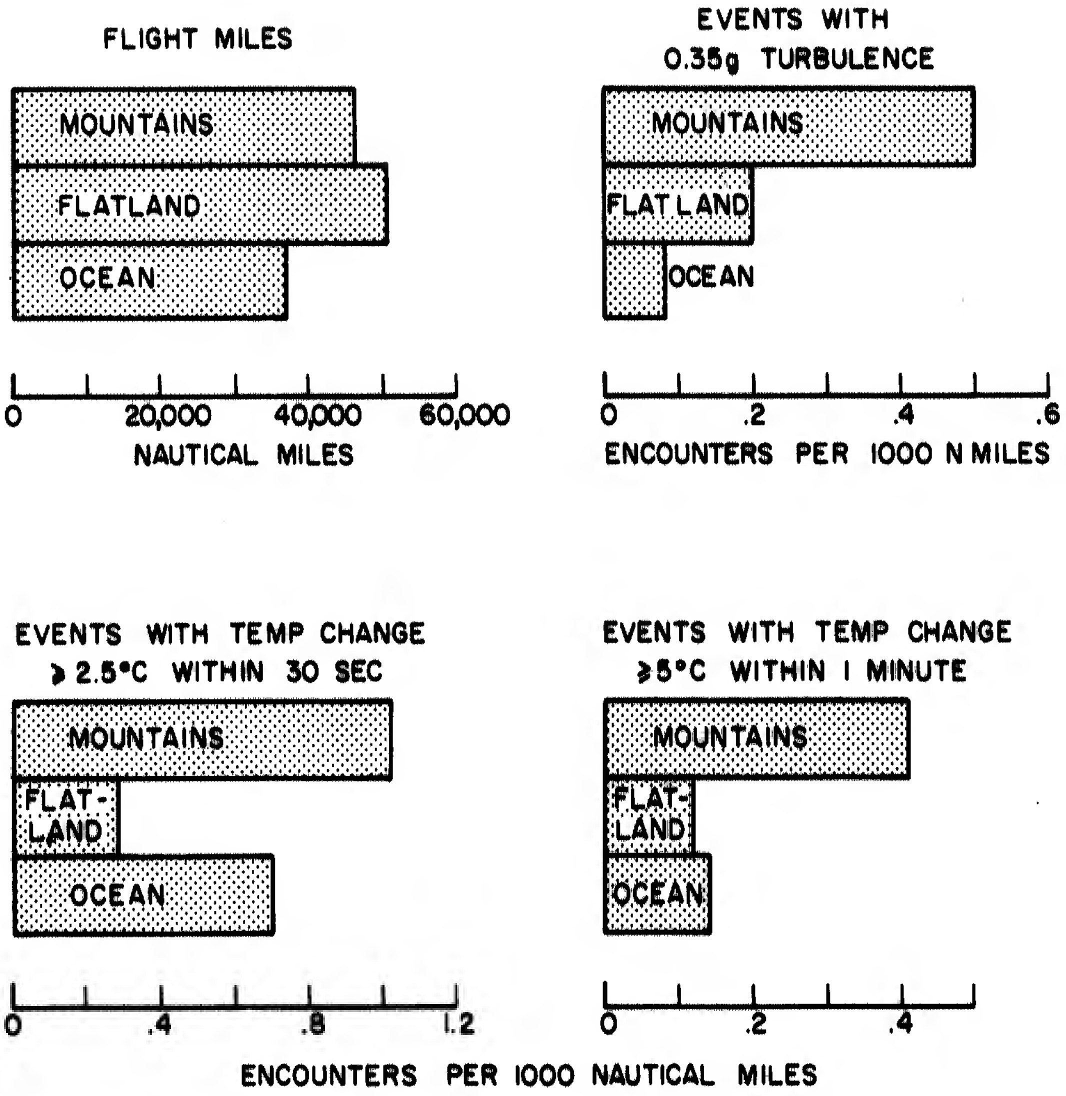

FIG 4 DISTRIBUTION OF EVENTS WITH TERRAIN

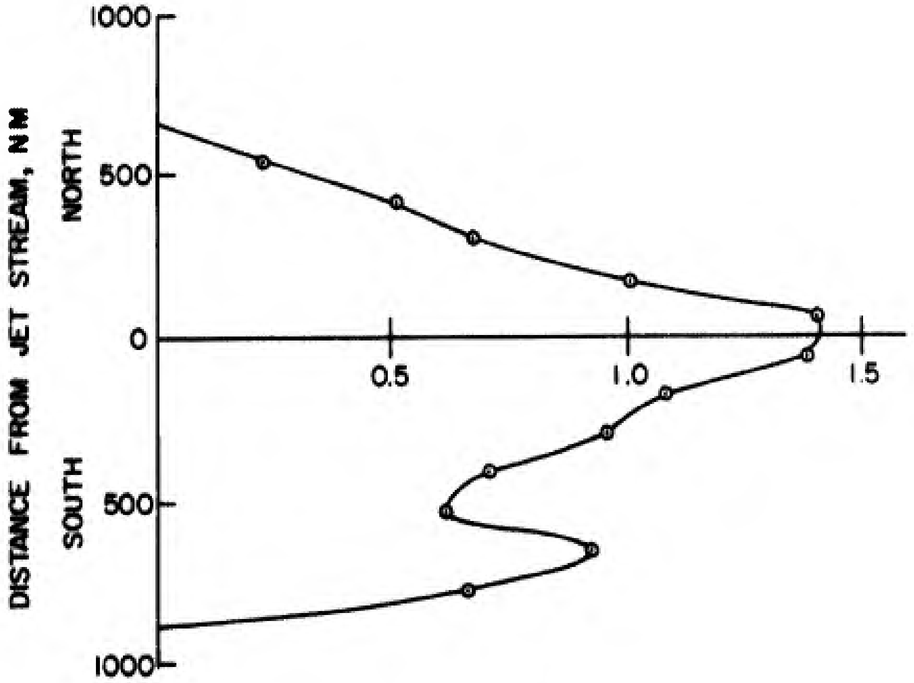

FIG 5 FREQUENCY OF EVENTS (PER 1,000 N Mi) AS A FUNCTION OF DISTANCE FROM THE 300-MB JET STREAM POSITION

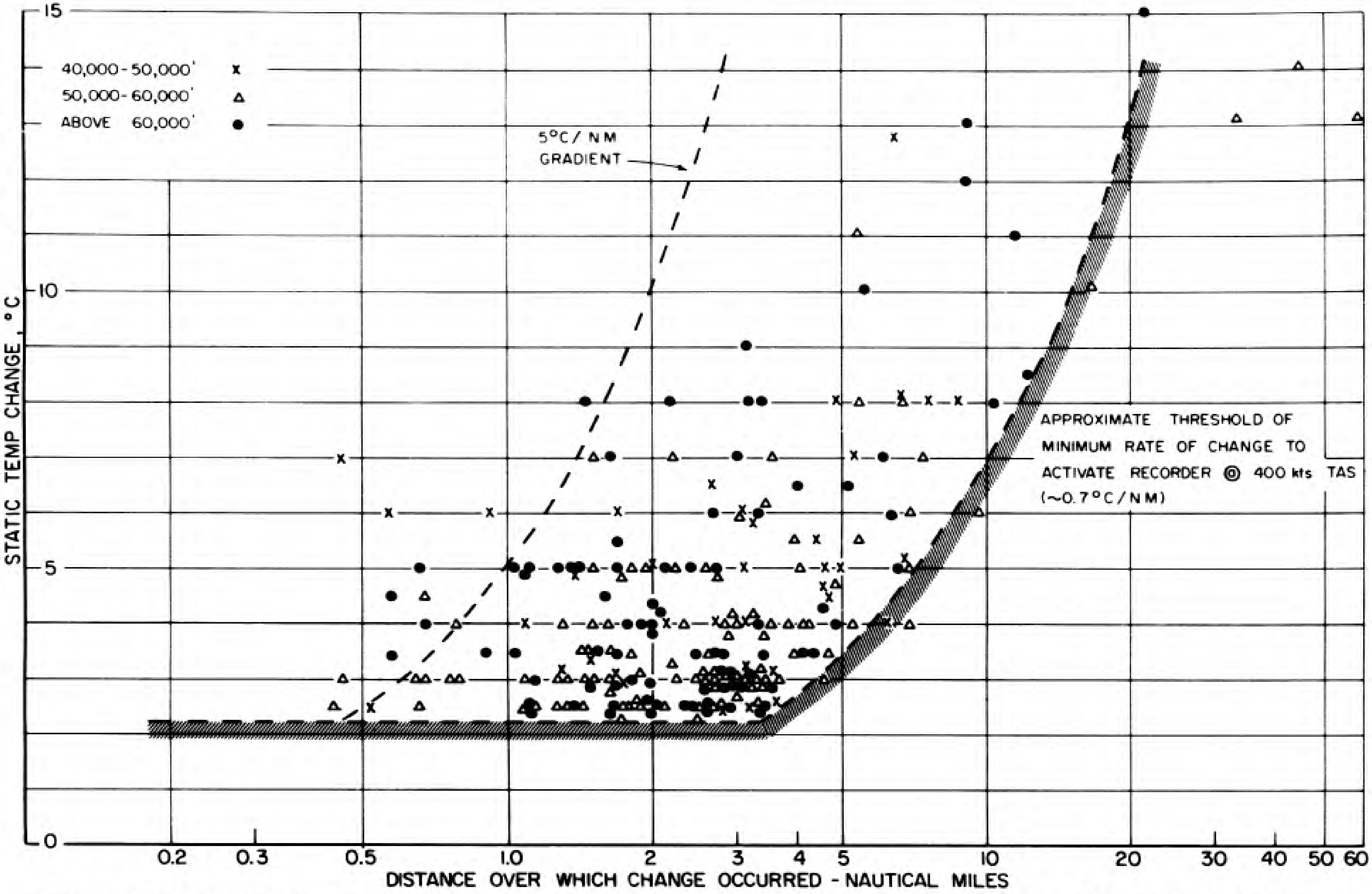

FIG 6 STRATOSPHERIC TEMPERATURE CHANGES - COLDSCAN FLIGHTS 2 TO 92 - JAN 69 TO JUN 71

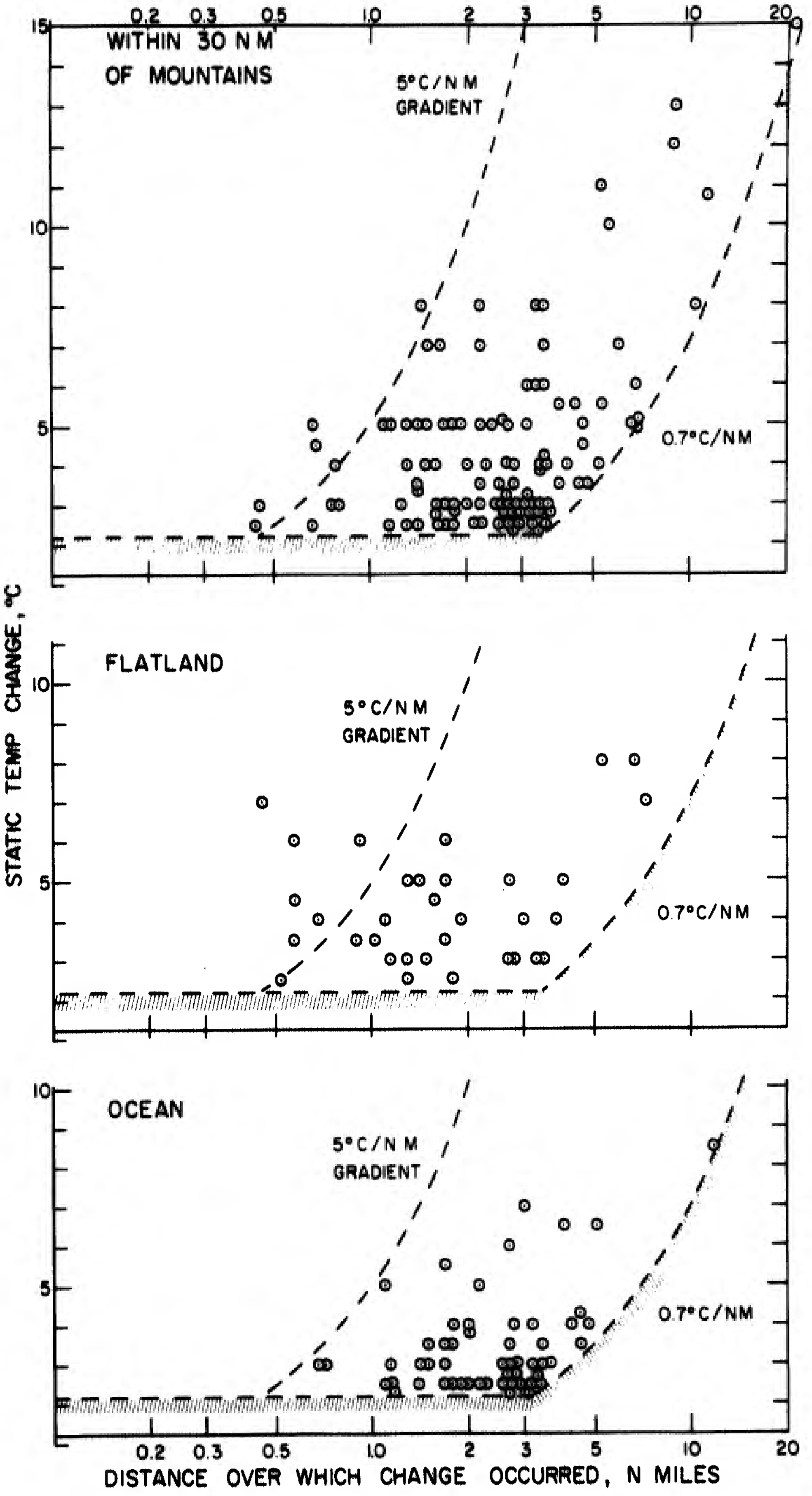

FIG 7 STRATOSPHERIC TEMPERATURE CHANGES BY TYPE OF TERRAIN

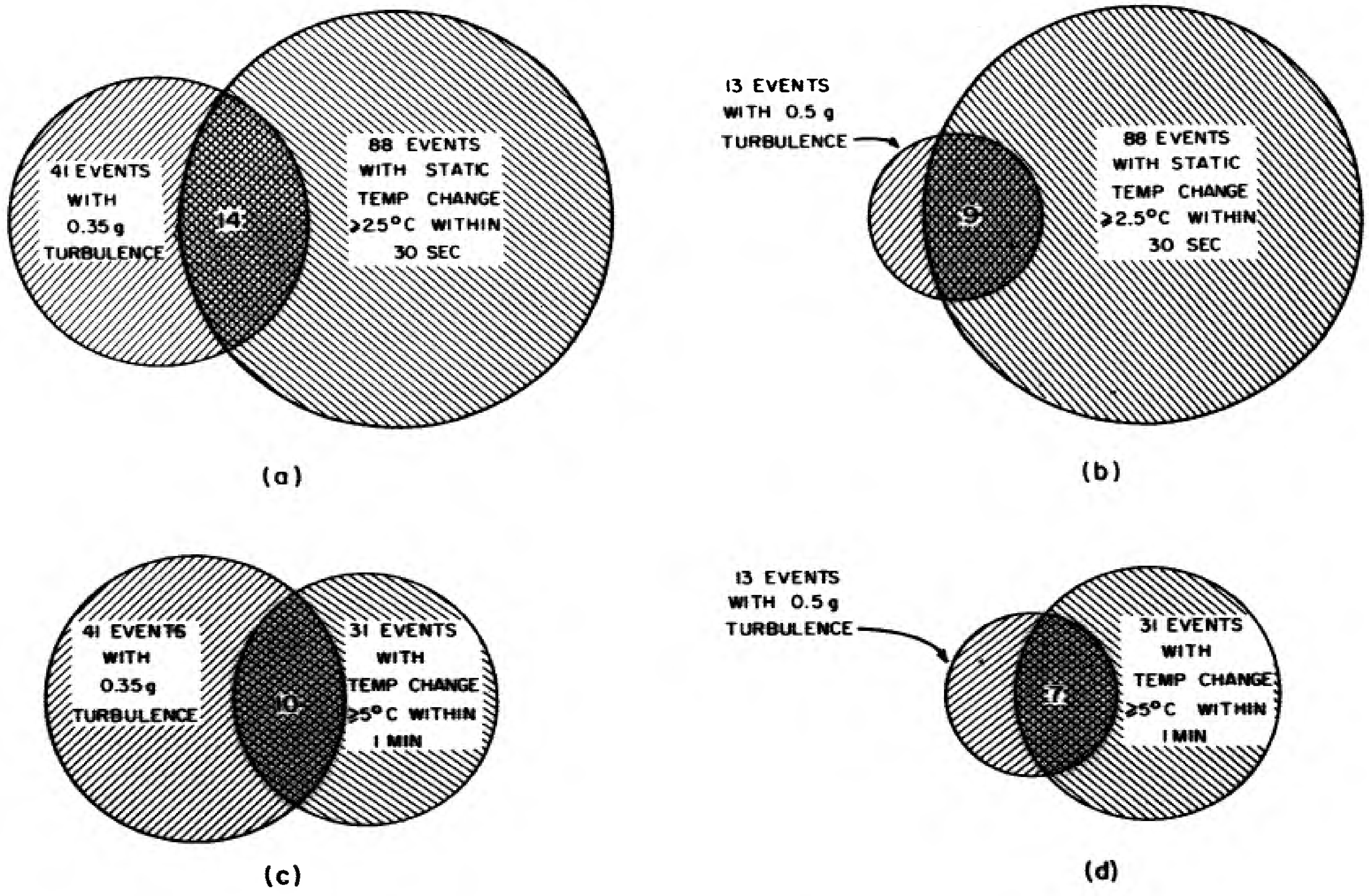

FIG 8 CORRELATION BETWEEN TURBULENCE AND TEMPERATURE CHANGE ABOVE 40,000 FEET FROM 136,000 N MILES OF FLIGHT

PART 2

2.0 SPECIAL EVENTS

Of the 419 events recorded in Project Coldscan, 35 were selected from Flights 2 to 56 for a more detailed presentation in References 1 and 2, and a further 15 from Flights 57 to 92 are analyzed in a similar manner below. The events chosen for detailed discussion are those with the most significant turbulence and horizontal temperature gradients. The data are presented in nine sections, one for each of the nine flights from which the 15 events were selected. Each section contains a discussion of the flight data and meteorological conditions, time histories of the measured parameters for each event, route maps showing event positions, and plotted and tabulated meteorological data.

The lengths of the events discussed below vary from the minimum four minutes to as long as 16 minutes. To present maximum detail, therefore, time histories are presented with scales that change from event to event, especially along the time axis. Each spike on the time scale shown below the vertical acceleration trace represents five seconds. Roll attitude is shown only when it is varying significantly. Calibration pulses occurring simultaneously on all channels are identified by "CAL" written on the altitude trace, and digital clock pulses and event marks are labelled when they appear on the roll attitude trace.

The continuous time records of static temperature were calculated by analog computer from the total temperature, altitude, and airspeed signals (corrected for compressibility and position error) using the recovery factor of 1.0 for the total temperature probe. Because the response rates for the total temperature and airspeed systems differ, high frequency fluctuations (greater than 0.5 cycles/sec) appearing on the static temperature trace during turbulence should not be considered real.

Maps accompanying each of the described incidents show the flight track as a dotted line becoming a solid black line at the position of the event. The event commences at the crossbar and ends at the arrowhead. Map scales are indicated by the 60 nautical mile spacing of the latitudes.

Each flight analyzed in this way has a table of parameters following the description of the events. The derivation of these parameters is as follows:

1. Flight Level. This is obtained from the recorded altitude trace and represents an average flight level during the event. Units are feet.

2. Terrain. This is a description of the underlying terrain in general terms (mountains, hills, plain, ocean, etc.).

3. Wavelength. The wavelength is computed from the static temperature trace and the ground speed. The component of the wavelength along the wind direction is computed and it is this value that is presented in the table. Usually an average of several waves is used unless the differences are very great, when individual values will be entered. Units are nautical miles.

4. Amplitude. This is obtained from the static temperature trace and represents half of the difference between the highest and lowest temperatures recorded during the wave. Units are degrees Celcius.

5. Vertical Velocity. This is the vertical wind velocity that a sinusoidal wave with the wavelength and amplitude computed above would have in an isothermal atmosphere. The wind speed used in this computation is usually taken from the navigation log or the closest rawinsonde ascent. The derivation of this parameter is detailed in Reference 1. The units are feet per second.

6. Distance from the Jet. This is the horizontal distance between the position of the event and the 300-mb jet stream. The 300-mb analyses used were prepared by the Central Analysis Office of the Atmospheric Environment Service. Interpolation in turn is used when either the event occurred near 0600 or 1800 Z or when the jet stream appeared to have moved rapidly. Units are nautical miles and the position of the event (north or south of the jet) is also noted.

7. Jet Max. This is the maximum speed of the jet as shown on the 300-mb analyses. Corrections and interpolation were carried out in a manner similar to that used in Paragraph 6 above. Units are knots.

8. Wind Speed. This is the wind speed at flight level obtained from the navigator's log as computed from the measured true airspeed and Doppler ground speed and drift. The units are knots.

9. Turbulence. This is approximately the peak vertical acceleration recorded for the event after the subjective removal of the portion of the acceleration that was due to high pitch rates. Units are in g's.

10. Time Difference. This is the number of hours between the event and the closest meteorological data set. Negative values denote the event occurred prior to the meteorological measurements.

2.1 Flight 61, 6 Oct. 1970 - Event 2 (Figs. 9 to 11)

The flow over the area was westerly at all levels with maximum winds of 270/80 near 40,000 feet. There appeared to be an indication of a tropical tropopause near 52,000 feet from the Albuquerque rawinsonde data (Fig. 11). Above this level the winds decreased rapidly with height at a rate between five and eight knots per 1,000 feet from 55,000 feet to 60,000 feet.

The event occurred just to the east of the Sangre de Cristo range (Fig. 10). This mountain range frequently gives rise to lee waves under westerly flows and so terrain induced gravity waves probably caused the long wave pattern on the static temperature trace (Fig. 9). The 20 nautical mile wavelength indicated in the Coldscan data is longer than the lee wavelength because the flight path was not parallel to the wind. The actual lee wavelength would have been about 15 nautical miles. The relatively high shear at this level could have been sufficiently modified by the gravity waves to cause Kelvin-Helmholtz instability waves. These waves in turn could have caused the rapid changes in temperature encountered near the start of and two-thirds of the way through the event.

Event Data

Event number	2
Flight level (ft)	60,000
Terrain	Mountains
Wavelength (n. mi)	15
Amplitude (°C)	3
Vertical velocity (ft/sec)	3
Distance from jet (n. mi)	330 S
Jet maximum (kts)	110
Wind speed (kts)	30
Turbulence (g)	0.2
Time difference (hrs)	7

2.2 Flight 70, 13 Jan. 1971 - Event 1 (Figs. 12 to 16)

Event 1 of Flight 70 occurred at 59,500 feet over the Atlantic Ocean 200 miles east of Cape Breton Island (Fig. 13). This event, which included several temperature changes of 5°C, was one of three temperature change events recorded during the flight. The other two occurred 60 miles south of the Avalon Peninsula, Newfoundland, and have maximum temperature changes of 3.5°C.

The upper tropospheric synoptic situation is shown in Figure 14. The low pressure area over central Labrador was moving southeast at 20 knots, and the northern jet stream, flowing around the low pressure area, was moving northeast at 10 knots over Nova Scotia while remaining quasi-stationary south of the Avalon Peninsula.

In the lower stratosphere, the strong polar night vortex was centered over Foxe Basin at both 30 and 100 mb. At 100 mb (53,000 feet) the influence of the 300 mb low pressure area was reflected by a trough extending from Foxe Basin southeast over Labrador (Fig. 15). This troughing did not appear to extend up to the 30 mb (77,000 ft) level.

The tropopause was near 300 mb, although from the rawinsonde data there was some suggestion of a second tropopause at 130 mb (47,000 ft). This second tropopause was probably the remnant of the northern edge of the tropical tropopause.

The winds over the area of the events were strongest at 200 mb (Fig. 16). The aircraft Doppler winds and the rawinsonde winds both indicated a backing of the winds with height above the 200 mb level. The aircraft winds backed more and increased sharply while those measured by the rawinsonde decreased with height. As a result, the vector wind shear estimates for the area differed greatly; south at 40 knots/1,000 feet from the aircraft wind data and south at 2 knots/1,000 feet from the rawinsonde data. While it is possible that there were very large small-scale vertical wind shears in the area, it is probable that the actual wind shears were smaller than those based on aircraft data but locally larger than the rawinsonde data would suggest. Small sideslip angles and Doppler alignment errors can lead to large Doppler wind errors while having little effect on the use of the Doppler for navigation.

The static temperature changes during this event showed a wave-like variation that suggests the changes were due to local vertical motions in the air caused by wave motion. The wavelength of the larger-amplitude waves was estimated from the trace at 12 nautical miles, sufficiently long to have resulted from gravity waves. The shorter waves appear to be correlated with the pitch attitude, vertical acceleration, and indicated air speed variations. This suggests that they could have resulted from the effects of errors in indicated air speed caused by aircraft motions rather than from small-scale horizontal variations in air temperature. However, they could also have resulted, at least in part, from a set of Kelvin-Helmholtz waves growing in the shear zone as a result of local instability caused by the larger gravity waves. The mechanism for this type of development is discussed by Scorer in Reference 10.

Event Data

Event number	1
Flight level (ft)	59,500
Terrain	Ocean
Wavelength (n. mi)	12
Amplitude (°C)	4
Vertical velocity (ft/sec)	9
Distance from jet (n. mi)	250 N
Jet max (kts)	180
Wind speed (kts)	50
Turbulence (g)	0.25
Time difference (hrs)	5

2.3 Flight 71, 14 Jan. 1971 - Events 3/4, 5 and 6 (Figs. 17 to 21)

Flight 71 was flown 24 hours after Flight 70 and over the same northern SST route out of New York City. The synoptic condition had altered so little that no discussion is necessary here. However, there was a good satellite cloud photograph taken three hours prior to the events and this is shown in Figure 21. There appear to be well-organized wave clouds oriented across the jet stream direction, extending eastward from the Cape Breton Highlands several hundred miles out into the Atlantic. While these wave clouds were well below the flight level of the aircraft, they indicate that the troposphere was able to sustain wave motions over long periods. Since there were no zero-wind-speed levels reported in the rawinsonde data at least part of this wave energy could have travelled up into the lower stratosphere.

The events occurred 80 miles south-south-east of the Avalon Peninsula of southeast Newfoundland (Fig. 20). Both the Stephenville and Sable Island rawinsonde data showed wind maxima at about 60 mb (63,000 ft), while the aeroplane Doppler wind data showed the wind speed to be decreasing with height between 60,000 and 62,000 feet. The vector wind shear computed from the rawinsonde data was 4 knots/1,000 feet while that from the aircraft was 14 knots/1,000 feet. The direction of the shear differed slightly for the two methods: southwest for the rawinsonde winds and south for the aircraft data.

The wavelengths of the temperature fluctuations were much shorter on the 14th of January than on the previous day. Only Event 6 (Fig. 19) had a wavelength that exceeded the Brunt-Väisälä wavelength. For an isothermal atmosphere and a 70-knot wind, the Brunt-Väisälä wavelength is seven nautical miles. It is therefore unlikely that, in the case of Events 3/4 and 5, the temperature changes were the result of gravity waves. All these events were accompanied by large pitch attitude changes and changes in altitude. These changes were largest during the first two events. Some of the changes could have resulted from the aircraft passing through thermally-stratified layers or from a combination of this and of wave motions set up in such stratified layers. Alternatively, the vertical motions of the aircraft could have masked the true wavelength of the temperature waves.

The altitude trace for Event 5 (Fig. 18) shows several steps in the signal from one side of the plot to the other. This is a feature of the instrumentation that allows the recording of fine-scale altitude, that is, altitude is recorded by means of a sawtooth pattern that switches over for each 4,000-foot increase in altitude. In Event 5, the altitude of the aircraft was fluctuating about one of the switchover points.

Event Data

Event number	3/4	5	6
Flight level (ft)	60,000	61,000	62,000
Terrain	Ocean	Ocean	Ocean
Wavelength (n. mi)	4.5	3.3	8.5
Amplitude (°C)	3	3	3
Vertical velocity (ft/sec)	25	35	15
Distance from jet (n. mi)	250 N	240 N	240 N
Jet max (kts)	180	180	180
Wind speed (kts)	70	70	70
Turbulence (g)	-	0.1	0.1
Time difference (hrs)	6	6	6

2.4 Flight 72, 15 Jan. 1971 - Event 8 (Figs. 22 to 25)

The 15th of January was the third consecutive day on which a flight was made off the southern coasts of Nova Scotia and Newfoundland. On this flight the largest temperature change occurred 60 miles south of Halifax, Nova Scotia, somewhat farther west of event positions on the previous two flights. However, a second but smaller temperature change (3.5°C) was recorded south of the Avalon Peninsula in the same general area as the events of Flights 71 and 72.

The 300 mb analysis and jet stream positions are shown in Figure 24. Since the 13th of January the low pressure area had elongated in an east-west direction until it stretched across Canada and out into the Atlantic. As a result the flow over the Maritimes was more zonal. The flow pattern at higher levels was still governed by a deep low pressure area over Foxe Basin. Over the Maritimes the winds were stronger than average and backed slowly with height. Unfortunately neither the Sable Island nor the Stephenville rawinsonde wind data were available at the flight level on this date. The aircraft Doppler winds indicated a slight vector wind shear (2 kts/1,000 ft) from the southeast.

The temperature change again appears to have resulted from an encounter with a gravity wave. The wavelength of 14 nautical miles is sufficiently long, being twice the Brunt-Väisälä wavelength. The static temperature data suggest that the wave was one of a wave-packet or wave-train, probably the one with the largest amplitude since the others failed to trigger the event recorder. The high-frequency temperature variations mid-way along the record did not appear to be caused by aircraft motions. These perturbations may have resulted from Kelvin-Helmholtz instability waves growing in shear layers which, under the influence of the gravity wave, have become dynamically unstable.

Event Data	
Event number	8
Flight level (ft)	62,000
Terrain	Ocean
Wavelength (n. mi)	14
Amplitude (°C)	4
Vertical velocity (ft/sec)	12
Distance from jet (n. mi)	60 N
Jet max (kts)	180
Wind speed (kts)	68
Turbulence (g)	0.1
Time difference (hrs)	7½

2.5 Flight 75, 20 Jan. 1971 - Events 4 and 7 (Figs. 26 to 30)

The lower stratospheric flow pattern is shown by the 100 mb analysis in Figure 30. The events took place in an area of strong winds east of the trough extending from a low pressure area just east of James Bay south through Dover AFB. The jet stream position at 300 mb was about 200 miles northeast of the 100 mb maximum wind over the eastern United States and southeast of the Atlantic coast maximum. A jet maximum of 180 knots was centered over Bermuda.

The vertical wind shear vector for Event 4 was northeast at 10 knots/1,000 feet based on the Sable Island rawinsonde data and northwest at 10 knots/1,000 feet based on the aircraft data. This is a high vertical wind shear for these levels and is probably sufficient to give rise to turbulence. The Richardson Number was two, which is very much lower than usual for stratospheric levels. The 5.6 minutes of light to moderate turbulence was probably shear-induced. An interesting aspect of this turbulence encounter is the complete lack of temperature change, suggesting that the turbulence did not originate from wave motions.

At 63,000 feet near New York City the wind speed, reported by the navigator as 110 knots, was measured at 85 and 60 knots by the 20-1200 and 21-0000 GMT rawinsonde ascents. The nine mile wavelength of the temperature wave in Event 7 (Fig. 28) was two miles shorter than the Brunt-Väisälä wavelength based on the aircraft winds and two miles longer than that based on an average rawinsonde wind of 70 knots. Assuming that the rawinsonde data are the more representative it appears that the temperature change was caused by gravity waves originating either from the jet stream or from the mountains to the west. The shorter wave may have resulted from Kelvin-Helmholtz instability in a layer modified by the effects of the gravity wave.

Event Data

Event number	4	7
Flight level (ft)	62,000	63,500
Terrain	Ocean	Ocean
Wavelength (n. mi)	-	3 and 9
Amplitude (°C)	-	2.0 and 3.0
Vertical velocity (ft/sec)	-	25 and 15
Distance from jet (n. mi)	360 N	400 N
Jet max (kts)	180	180
Wind speed (kts)	80	70
Turbulence (g)	0.4	-
Time difference (hrs)	-6	-5

2.6 Flight 76, 21 Jan. 1971 - Event 2 (Figs. 31 to 34)

The synoptic situation at 100 mb is shown in Figure 33. The flow over New York is slightly more general than on the previous day. The vector wind shear given by the aircraft data was southeast at 5 knots/1,000 feet while the rawinsonde data gave southwest at 7 knots/1,000 feet.

The aircraft data in Figure 31 have the appearance of a single wave about eight miles in length. This is approximately equal to the Brunt-Väisälä frequency at the wind speed measured by the aircraft. However, the New York rawinsonde temperature data (Fig. 34) show a sawtooth pattern which may have resulted either from the balloon passing through a series of waves or from thermally-stratified layers. If these layers were present then the vertical motion of the aircraft shown by the altitude trace could have masked the actual wavelength of the waves. The most probable explanation for these waves is that they are gravity waves induced by the low mountains northwest of the flight path.

Event Data

Event number	2
Flight level (ft)	55,500
Terrain	Ocean
Wavelength (n. mi)	8
Amplitude (°C)	2.5
Vertical velocity (ft/sec)	14
Distance from jet (n. mi)	250 N
Jet maximum (kts)	150
Wind speed (kts)	85
Turbulence (g)	-
Time difference (hrs)	3

2.7 Flight 83, 12 Feb. 1971 - Events 3 and 5 (Figs. 35 to 39)

The 300 mb analysis (Fig. 38) shows that there was a relatively strong westerly flow in the upper troposphere and lower stratosphere over the Bahamas. The tropopause was at about 53,000 feet (Fig. 39) and the maximum winds (265/92) were reported at 40,000 feet. The vector wind shear computed from the rawinsonde data between the 48,000 and 63,000 foot levels was east-northeast at 5 knots/1,000 feet. The aircraft data indicated a much higher shear of 13 knots/1,000 feet from the southeast between 60,000 and 63,000 feet. Although errors in the aircraft winds may have caused an overestimate of the shear, there is little doubt that Event 5 occurred in an area of high vertical wind shear. Only the aircraft data were available to compute the shear for Event 3, northeast at 3 knots/1,000 feet.

Both of the events have the appearance of resulting from encounters with gravity waves (Figs. 35 and 36). The wavelength of the waves cannot be computed since the flight path was normal to the jet stream and along the crests of any waves originating with the jet or the upstream terrain. It is unlikely that the gravity waves were originated by thunderstorms as none was reported for the area on the 1800 Z surface weather chart. The satellite photographs for the area one hour before the time of the events did not show any thunderstorms or wave clouds.

Event Data

Event number	3	5
Flight level (ft)	60,500	60,500
Terrain	Ocean	Island
Wavelength (n. mi)	-	-
Amplitude (°C)	6	2.5
Vertical velocity (ft/sec)	-	-
Distance from jet (n. mi)	130 N	50 S
Jet maximum (kts)	80	80
Wind speed (kts)	45	30
Turbulence (g)	-	-
Time difference (hrs)	5	5

2.8 Flight 86, 15 Apr. 1971 - Event 2 (Figs. 40 to 43)

In this event, three minutes of light to moderate turbulence was encountered at 45,000 feet about 40 miles east of the Grand Canyon (Figs. 40 and 41). The synoptic situation is illustrated by the 300 mb analysis in Figure 42. A cold low pressure area was moving slowly southeast with the jet maximum moving southeast and rotating about the centre at a rate of 60° per 12 hours. The 1200 GMT Las Vegas rawinsonde data (Fig. 43) indicated a maximum wind speed of 80 knots, 2,000 feet below the flight level of the aircraft. The sawtooth appearance of the rawinsonde data results from the balloon traversing either lee waves with a wavelength of about six nautical miles or a series of stratified layers. Since this wavelength is somewhat short for stratospheric lee waves, it is probable that the temperature variations were stratified layers. The vertical wind shear in the more stable layers can be locally very large over short vertical distances even if the average shear is small. In this case the rawinsonde data indicate a shear of about 5 knots/1,000 feet at flight level. Since the flight data do not indicate the presence of any gravity waves it appears that the turbulence was induced by a locally high vertical wind shear.

Event Data

Event number	2
Flight level (ft)	45,000
Terrain	Flatland
Wavelength (n. mi)	-
Amplitude (°C)	2.5 rise
Vertical velocity (ft/sec)	-
Distance from jet (n. mi)	200 N
Jet maximum (kts)	130
Wind speed (kts)	50
Turbulence (g)	±0.35
Time difference (hrs)	-2

2.9 Flight 87, 20 Apr. 1971 - Events 1, 5 and 7 (Figs. 44 to 50)

The flight was made behind a cold front that had passed eastward over Albuquerque 30 hours earlier. The position of the cold frontal cloud band at 1640 GMT is clearly outlined by the satellite photograph in Figure 50. At upper levels the flow was relatively strong as shown by the 300 mb analysis (Fig. 49). The flight track was tangential to the jet stream that curved around the 300 mb low pressure area.

Event 1 occurred to the east of the southern extension of the Sangre de Cristo Range and the Manzano Mountains (Fig. 45). Lee waves have been observed over these hills on a number of Coldscan flights but not as far east as in this case. There appears to be one wave, about 60 miles in length, which was probably a gravity wave and a number of shorter waves about seven miles in length. The Brunt-Väisälä wavelength was six miles so that even the shorter temperature fluctuations were sufficiently long to have been caused by gravity waves. The Albuquerque rawinsonde data showed westerly winds from the surface to about 60,000 feet with a maximum wind of 69 knots at 38,000 feet. The wind shear was about 2 knots/1,000 feet at the flight level.

Event 7 occurred near Amarillo almost directly over the jet stream. The vertical wind shear was very small near the flight level (less than 1 knot/1,000 feet), however there were indications of the tropical tropopause at 45,000 feet. Recent Russian research has indicated that turbulence is frequently encountered near the tropical tropopause (Ref. 8). The increase in temperature recorded during the event was probably caused by the aircraft flying through the upper limits of the cold front from the lower stratosphere into the upper tropical troposphere.

Event 5 was encountered just as the aircraft flew over the western extremity of the cloud mass associated with the cold front (Fig. 50). The temperature trace has a similar appearance to the traces recorded during the over-thunderstorm flights made during the National Severe Storms Laboratory Roughrider program. It is most likely that the aircraft flew over a large cumulo-nimbus cloud and that the turbulence and temperature changes were associated with the cloud. The turbulence was sufficiently severe to make the pilot turn the aircraft through 180 degrees and head west. A comparison of the temperature, vertical acceleration, and roll attitude traces shows that the temperature fluctuations and turbulence persisted for a similar period both sides of the turn.

<u>Event Data</u>

Event number	1	5	7
Flight level (ft)	45,000	45,000	45,000
Terrain	Flatland*	Flatland	Flatland
Wavelength (n. mi)	60 and 7	-	-
Amplitude (°C)	6 and 3	8° rise	5° rise
Vertical velocity (ft/sec)	3 and 15	-	-
Distance from jet (n. mi)	40 S	100 S	10 N
Jet maximum (kts)	110	110	110
Wind speed (kts)	60	80	40
Turbulence (g)	-	0.7	0.35
Time difference (hrs)	-6	-5	-4

* 90 miles east of the southern tip of the Sangre de Cristo Range.

3.0 ACKNOWLEDGEMENTS

The writers wish to express their sincere appreciation to Col. O.A. Thomas, USAF, Pentagon, Mr. Donald Elmore of General Dynamics, and Colonels D. Wolfe, D. Campbell, G. Durden, and the many other personnel of the 58th Weather Reconnaissance Squadron, whose excellent co-operation made Coldscan possible. The pilots and navigators who flew the Coldscan missions are too numerous to mention individually, so to all the aircrew of the 58th Weather Reconnaissance Squadron we offer a special thanks.

Grateful acknowledgement is also offered to the Mechanical Engineering Division of NRC for the use of the memory recorder.

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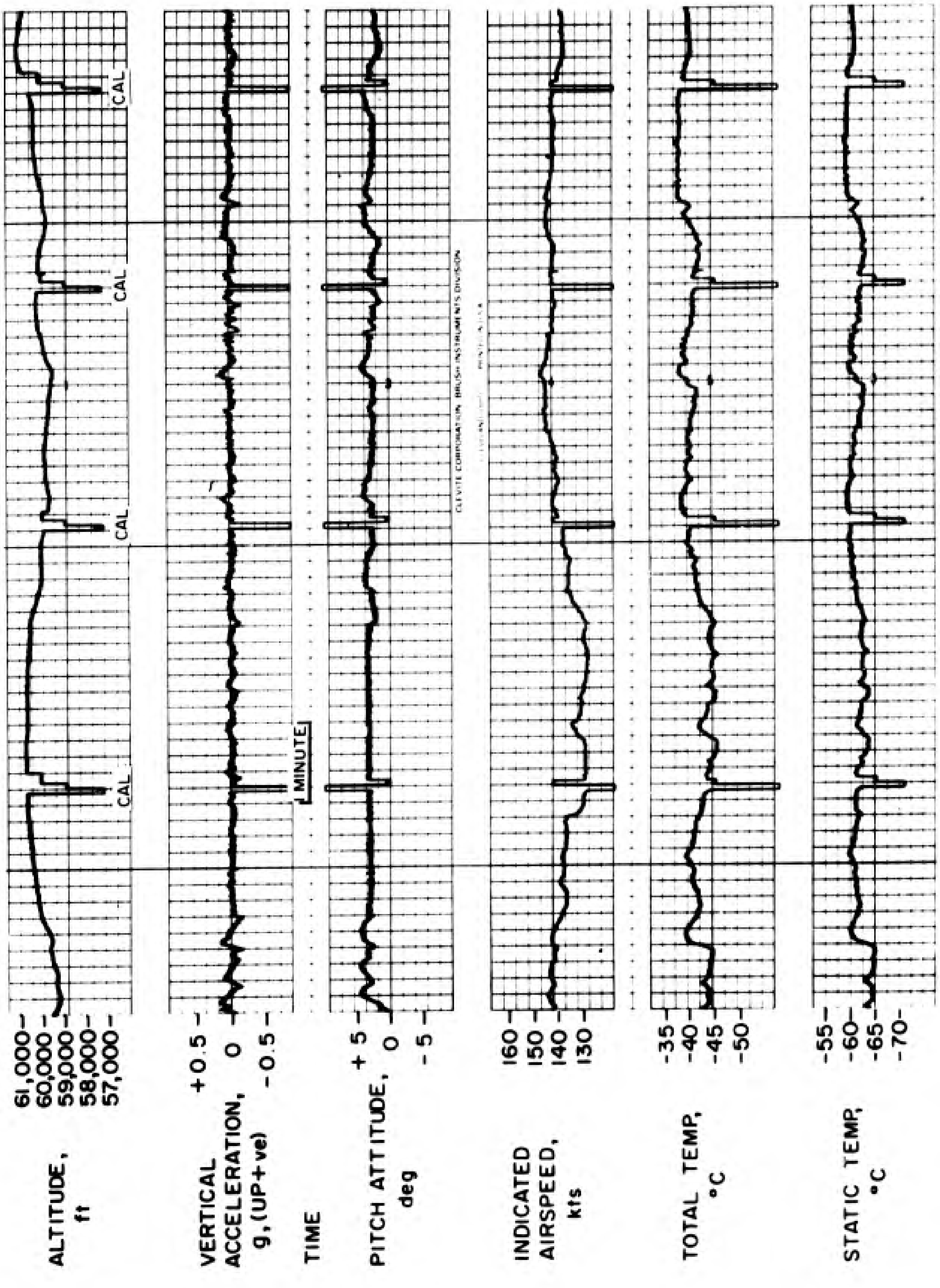


FIG 9 FLIGHT 61, EVENT 2

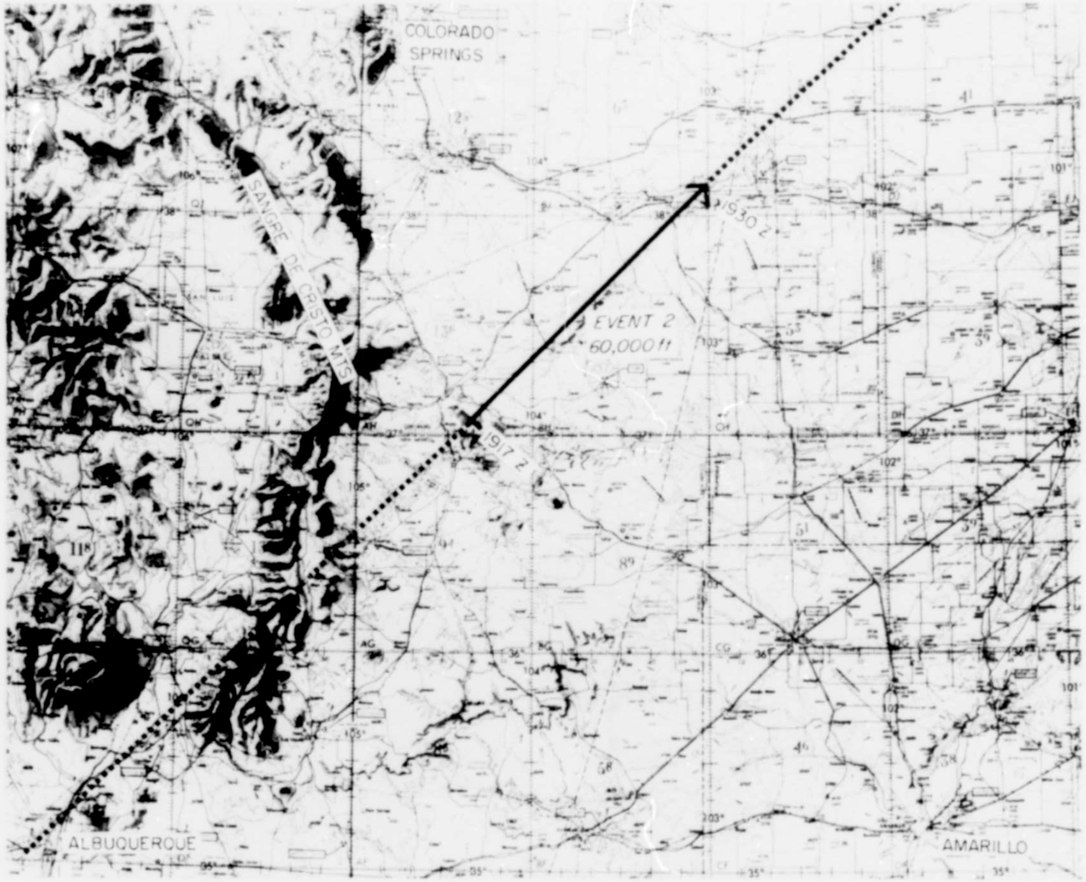


FIG 10 FLIGHT TRACK SHOWING EVENT 2 OF FLIGHT 61, 6 OCT 1970

NOT REPRODUCIBLE

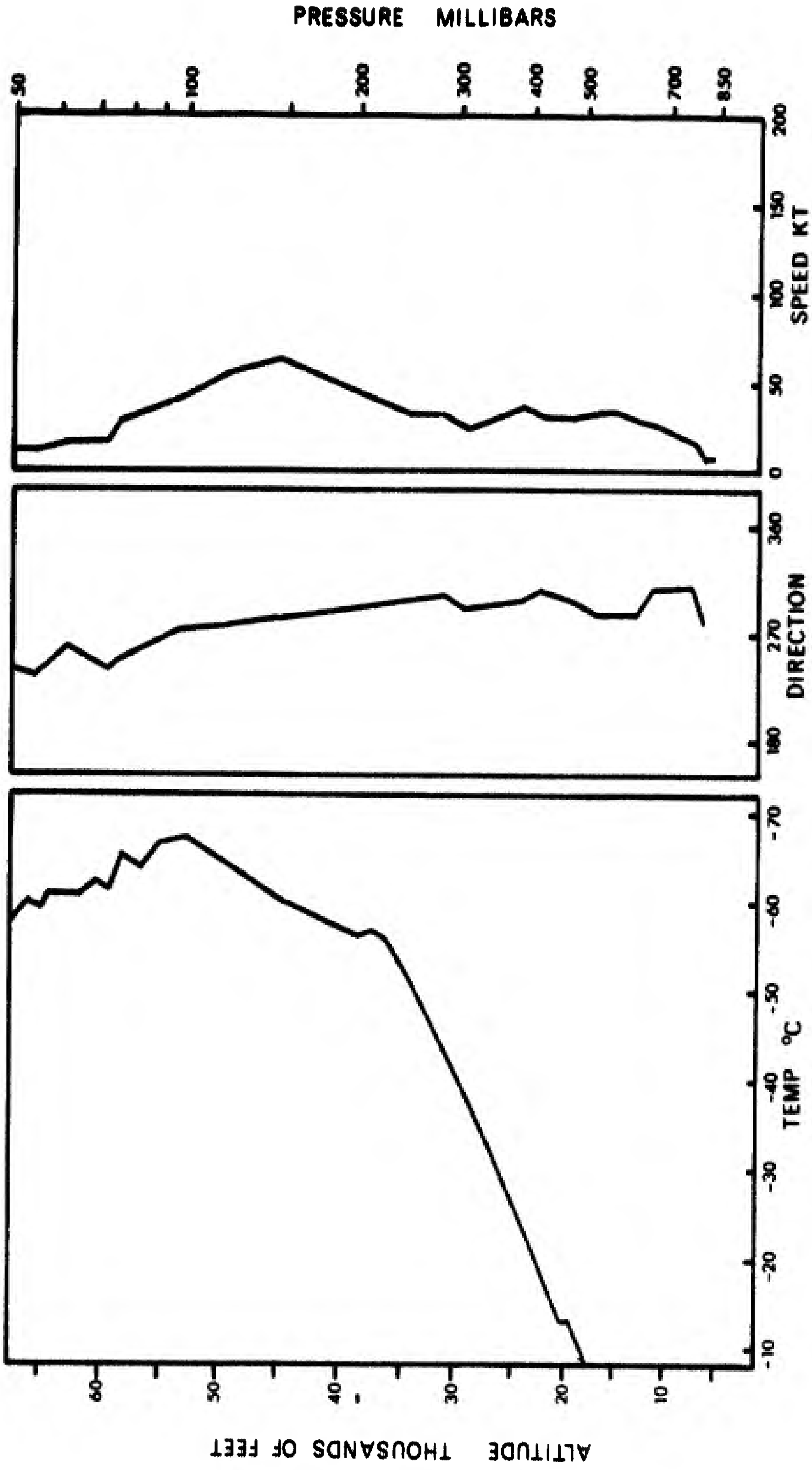


FIG II UPPER AIR DATA

ALBUQUERQUE, N. M. 1200 G.M.T. 6 OCTOBER,1970

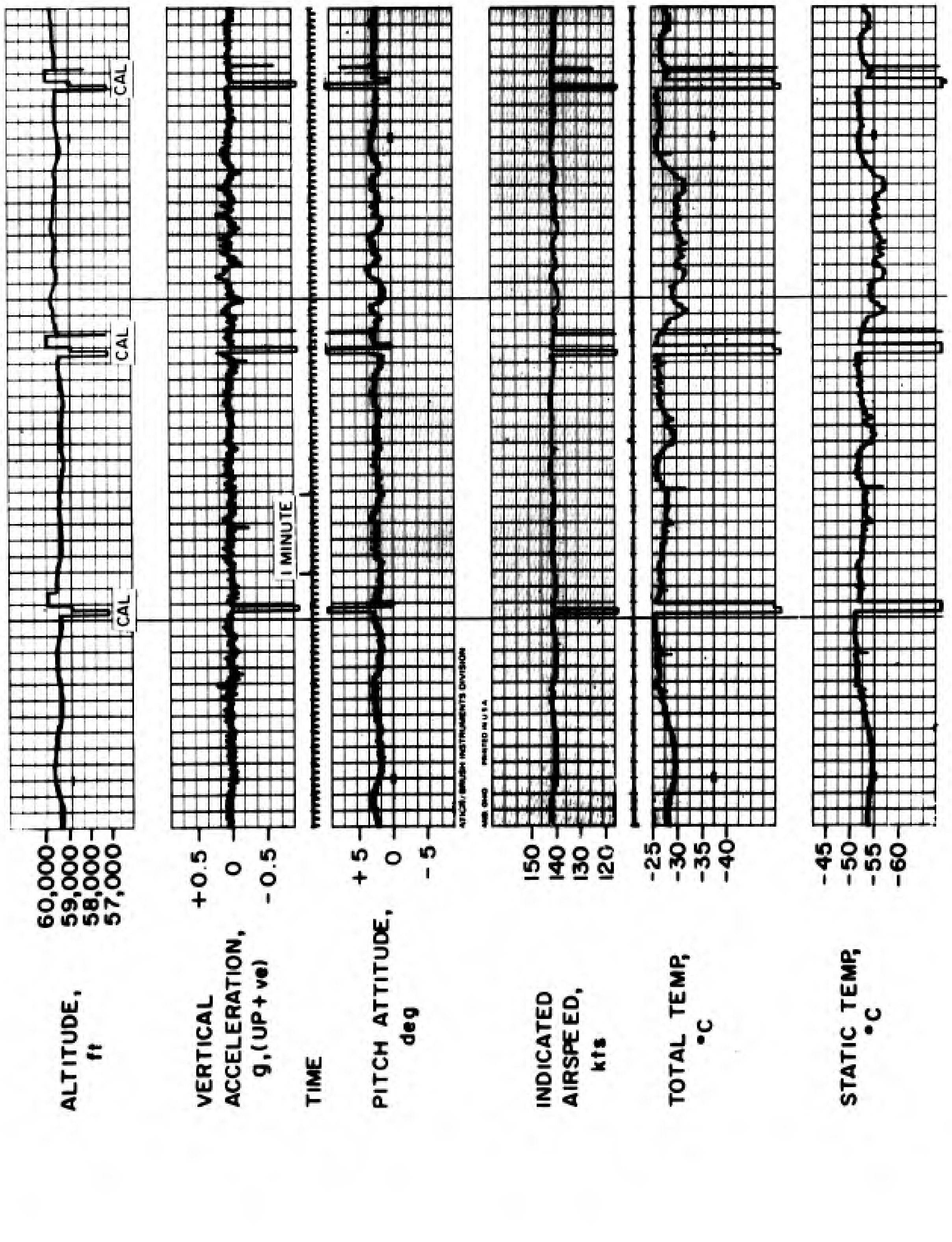
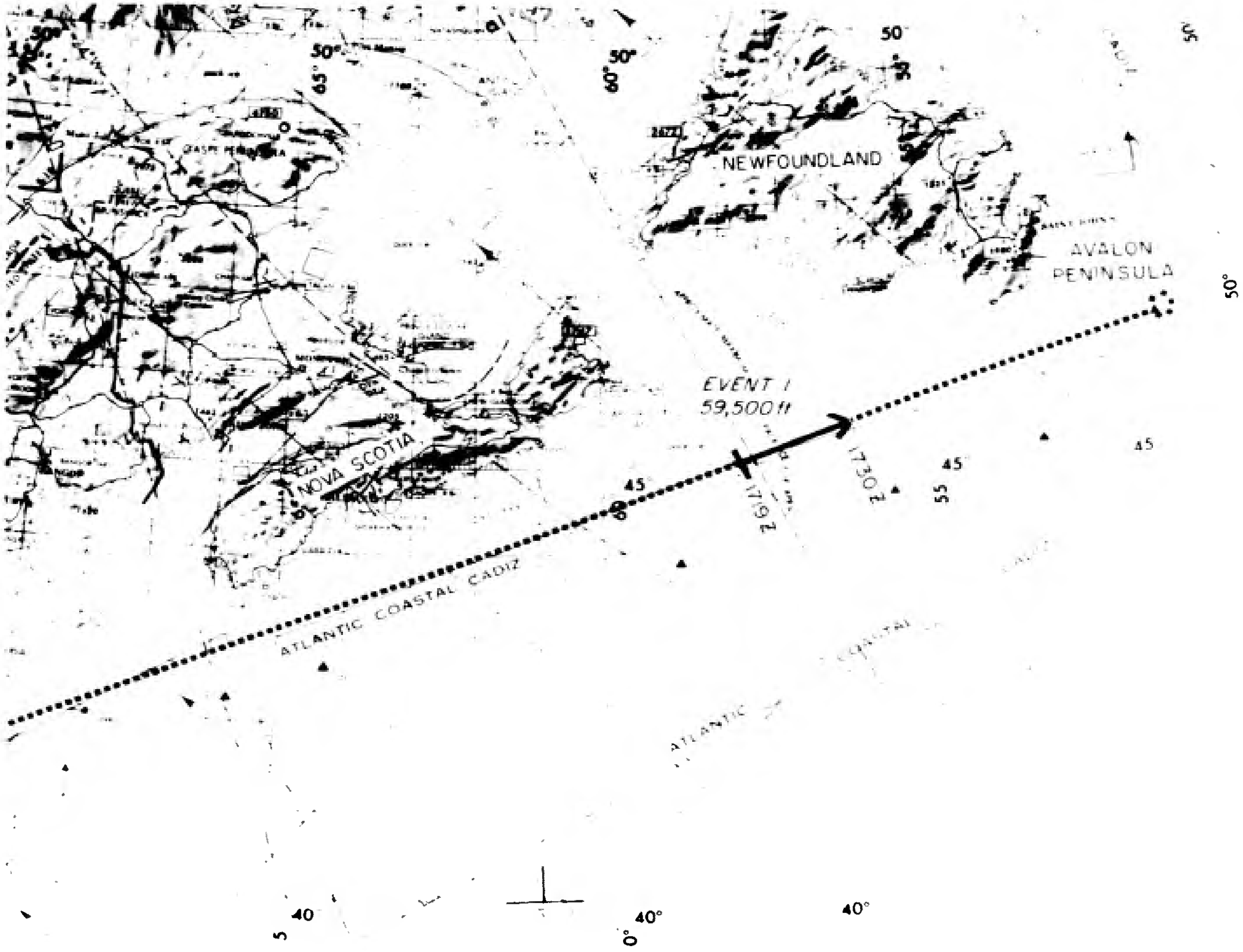


FIG 12 FLIGHT 70, EVENT 1



NOT REPRODUCIBLE

FIG 13 FLIGHT TRACK SHOWING EVENT 1 OF FLIGHT 70, 13 JAN 1971

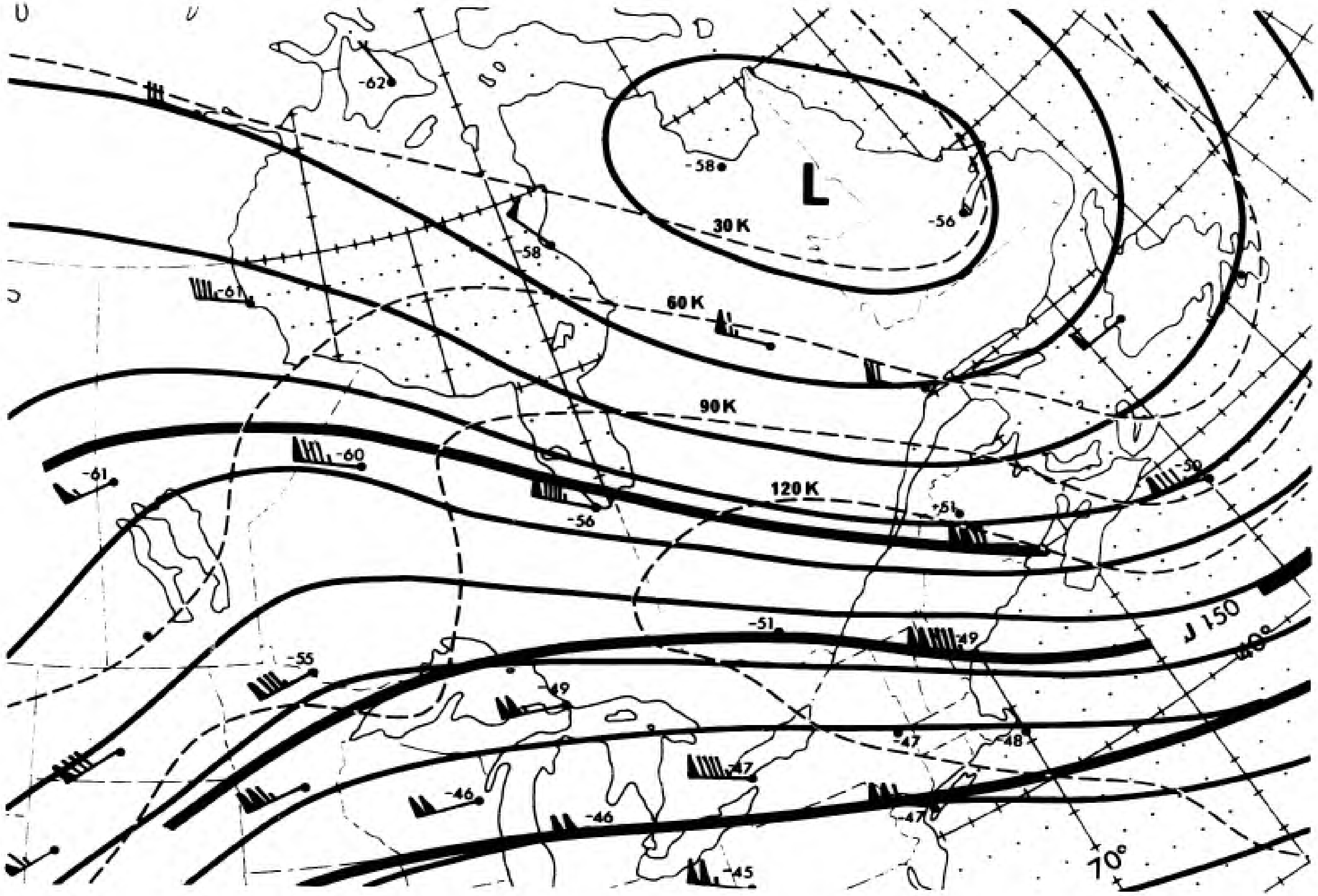


FIG 14 300 mb ANALYSIS 1200 GMT 13 JAN 1971

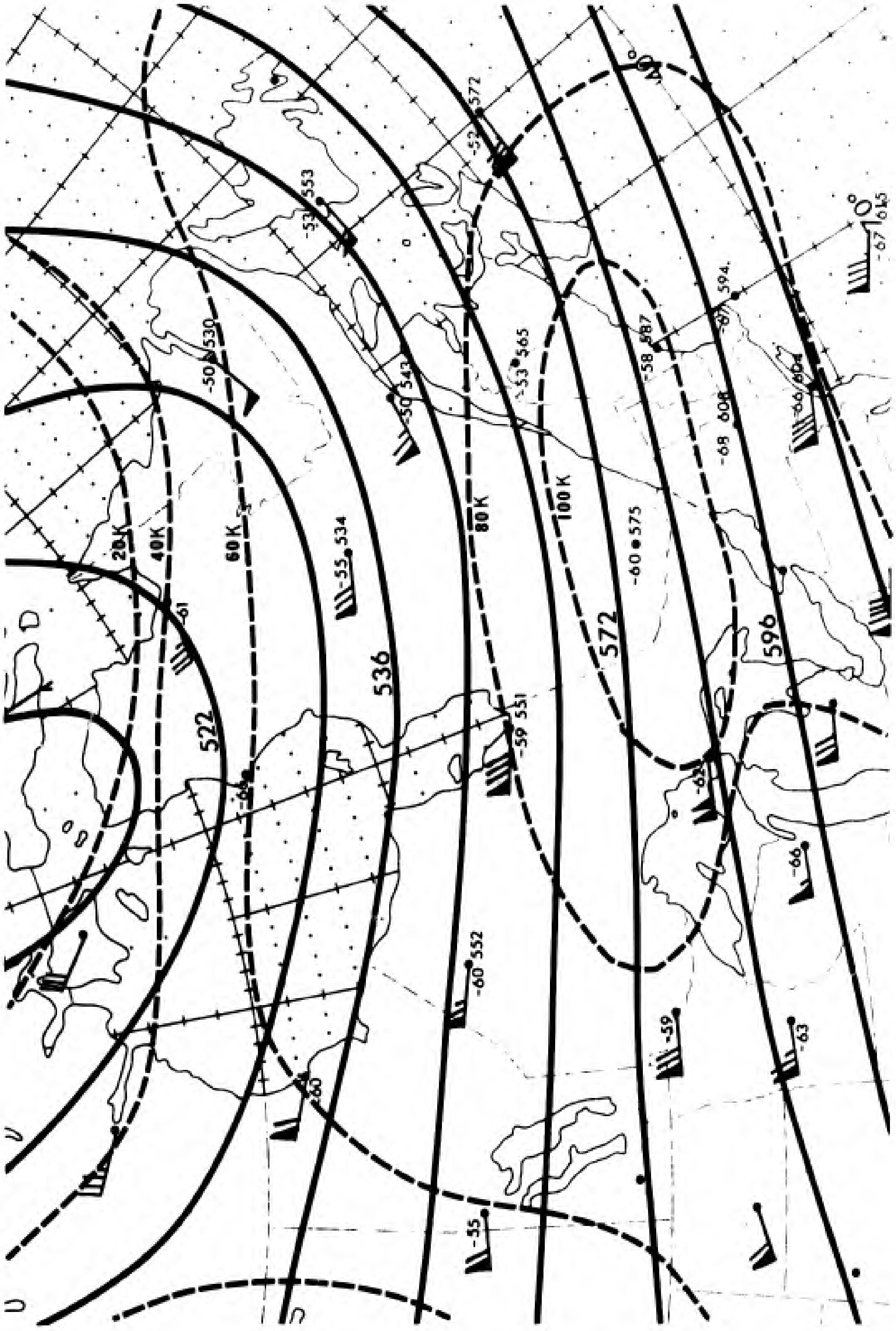


FIG 15 100 mb ANALYSIS 1200 GMT 13 JAN 1971

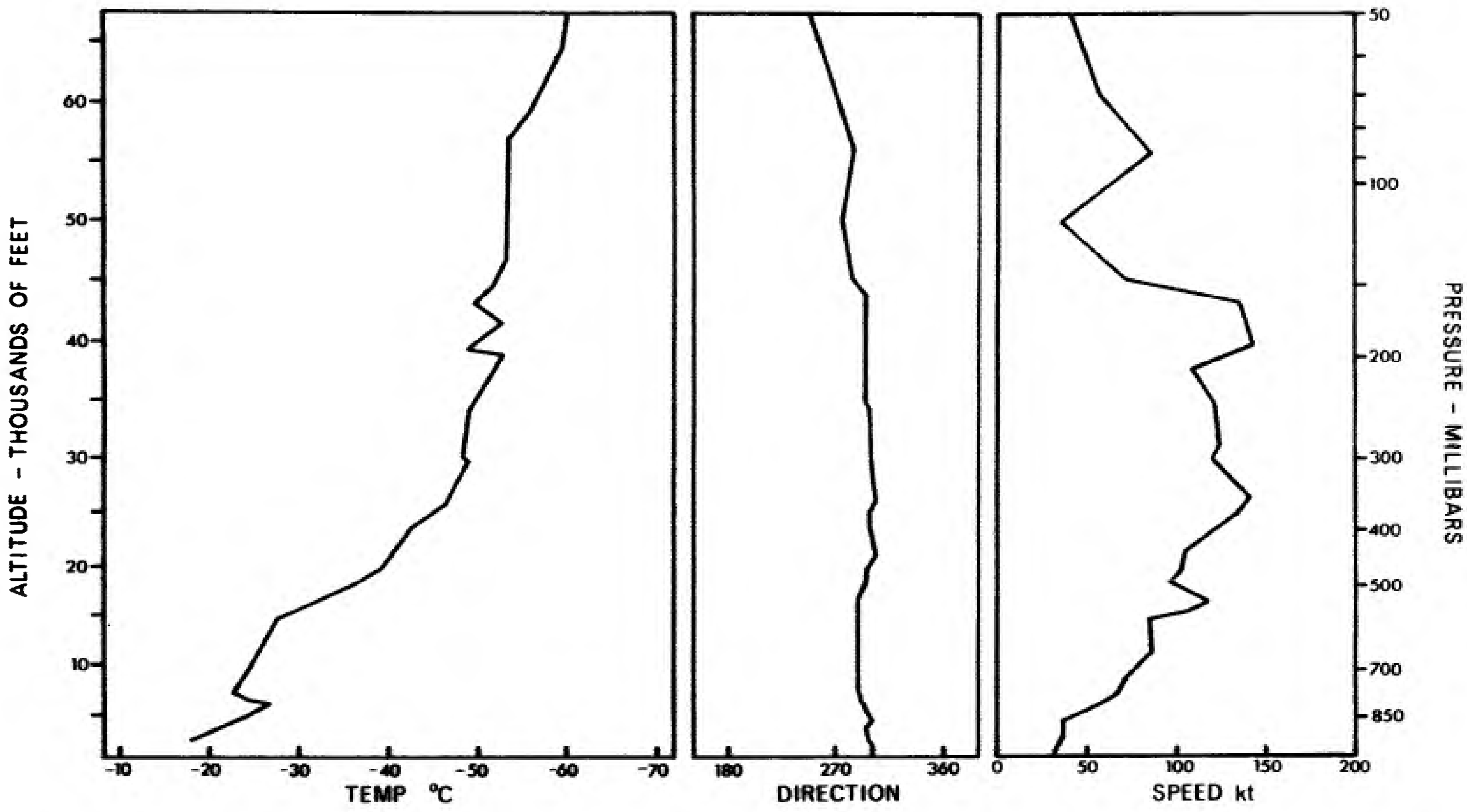


FIG. 16 UPPER AIR DATA

SABLE ISLAND, N.S. 0000 G.M.T. 14 JANUARY, 1971

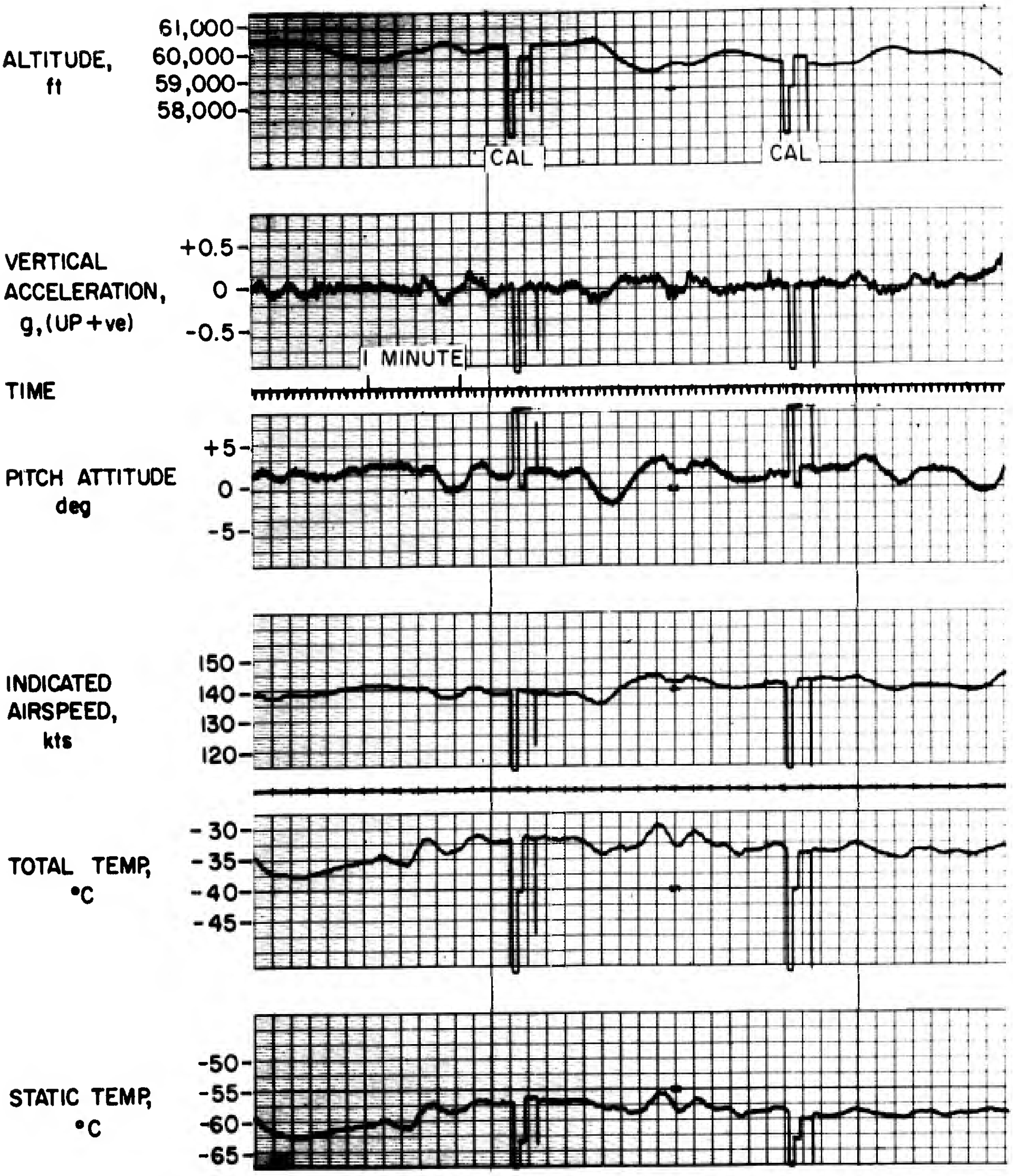


FIG 17 FLIGHT 71, EVENT 3/4

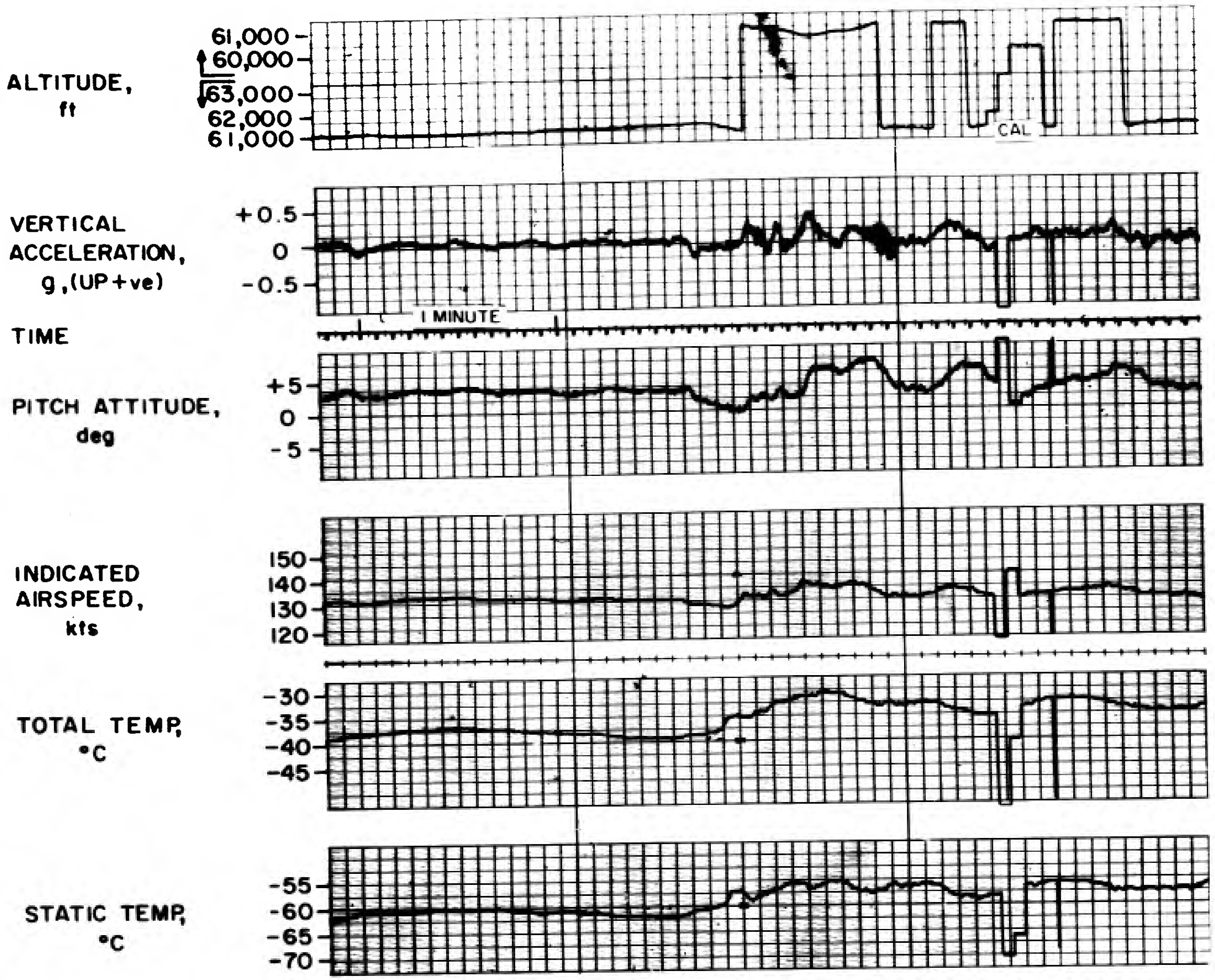


FIG 18 FLIGHT 71, EVENT 5

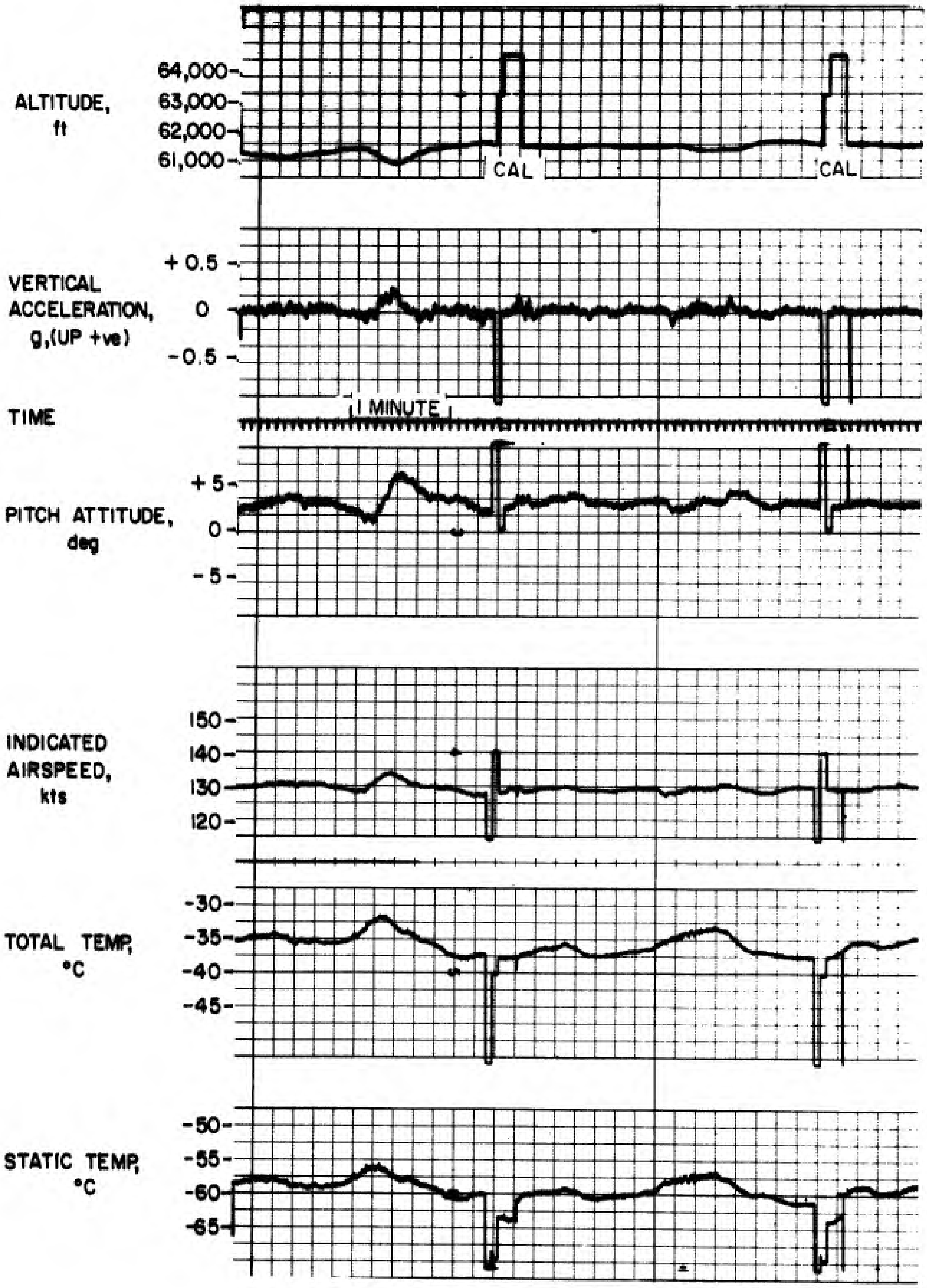


FIG 19 FLIGHT 71, EVENT 6

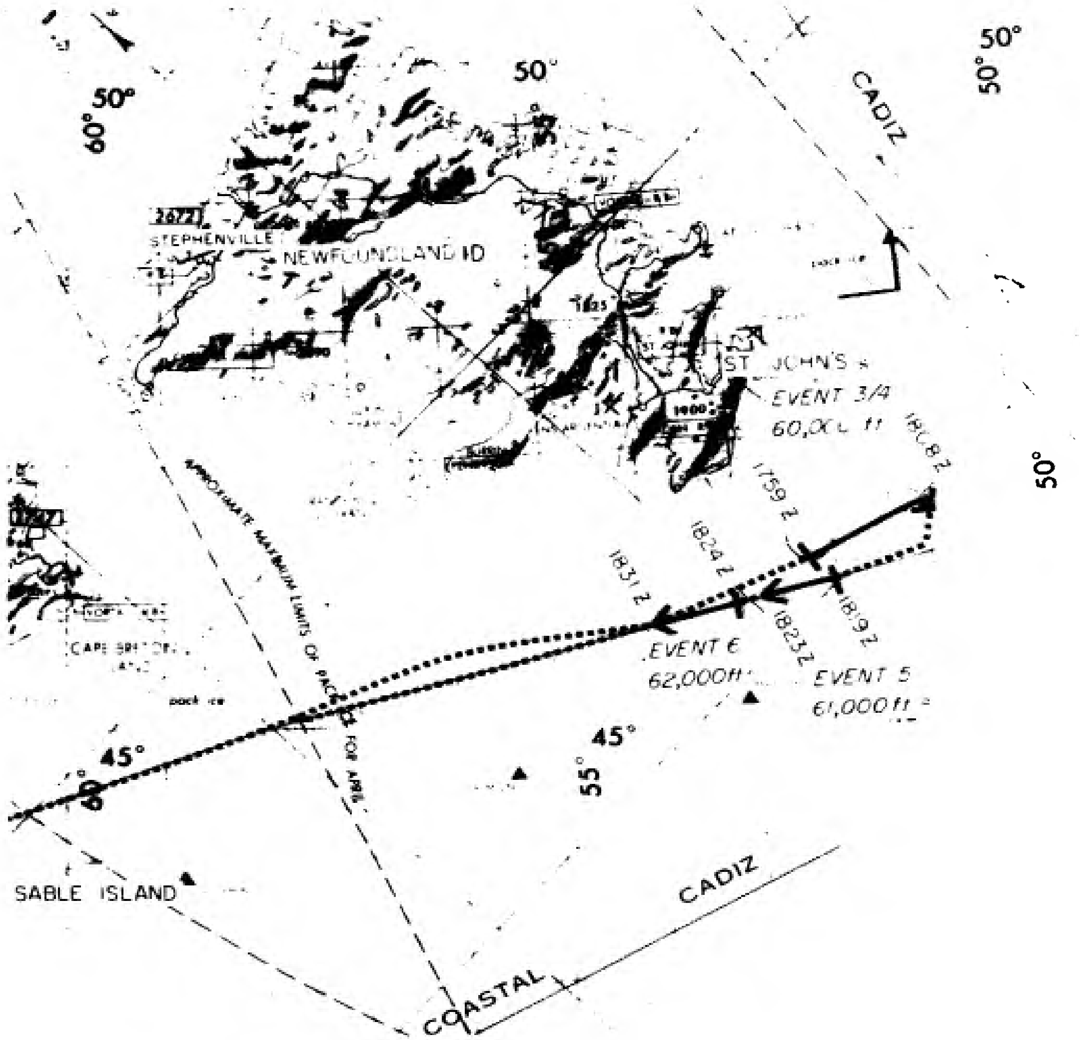


FIG 20 FLIGHT TRACK SHOWING EVENTS 3/4, 5, AND 6 OF FLIGHT 71, 14 JAN 1971

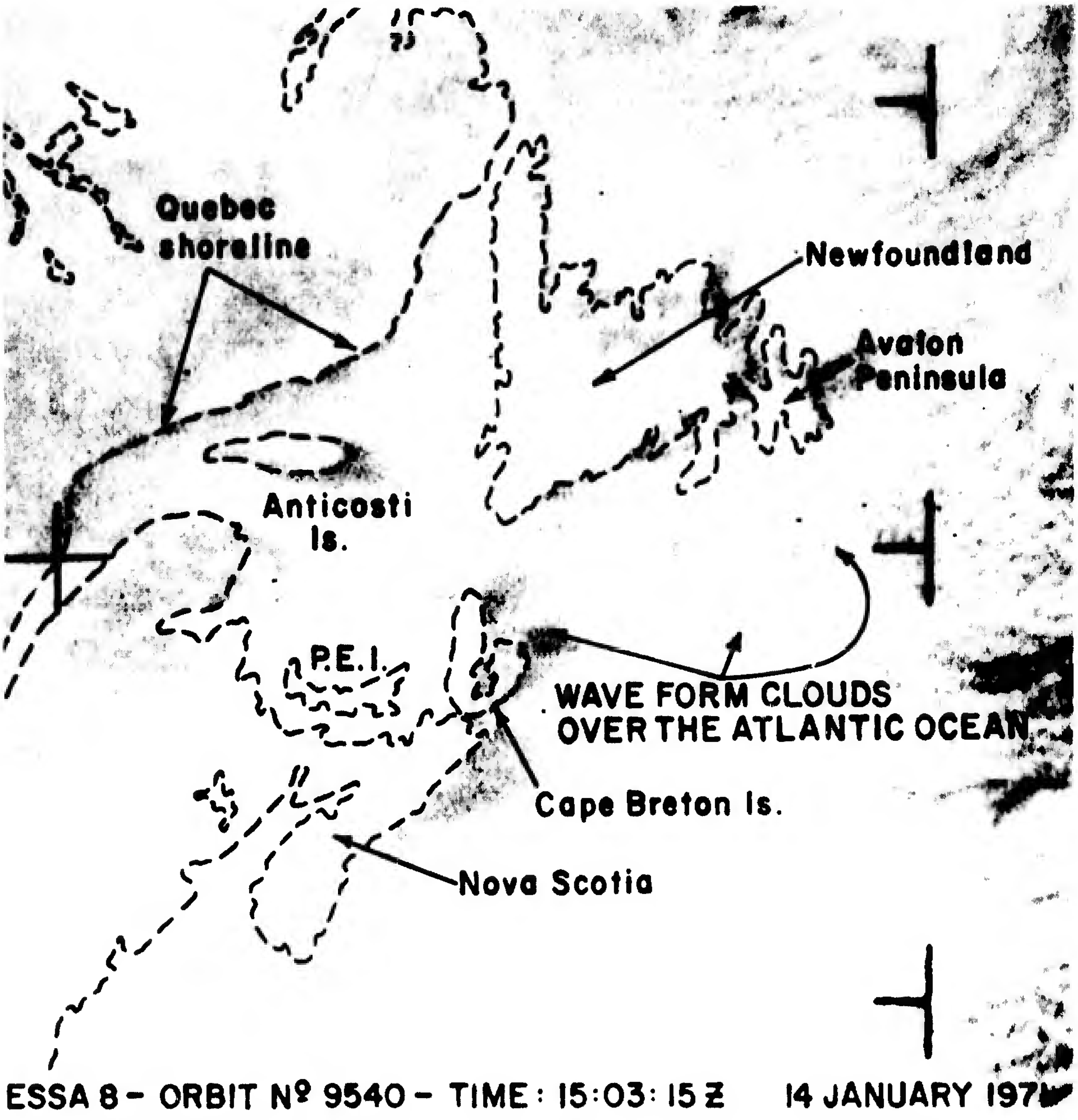


FIG 21 SATELLITE PHOTOGRAPH OF AREA OF FLIGHT 71

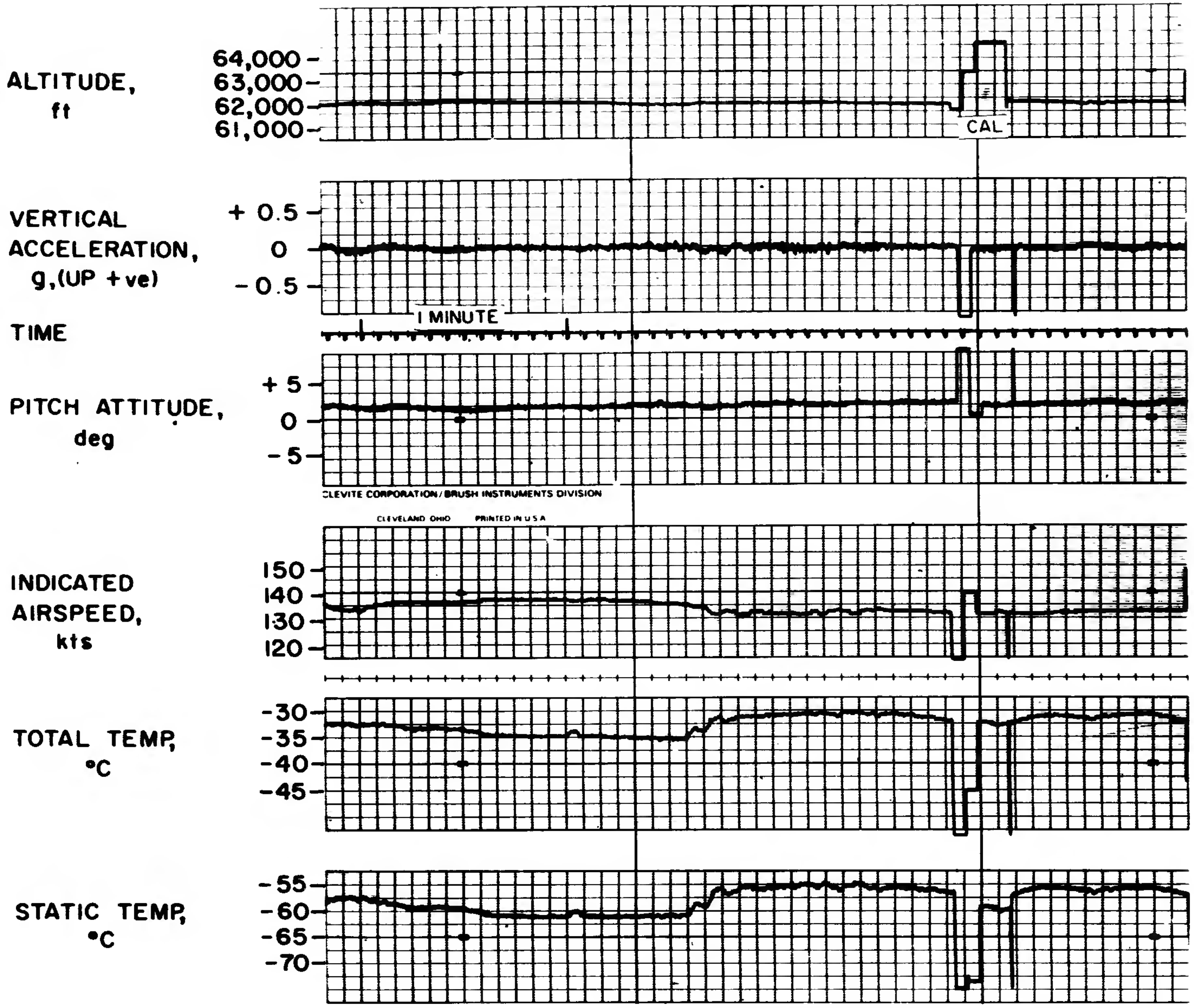


FIG 22 FLIGHT 72, EVENT 8

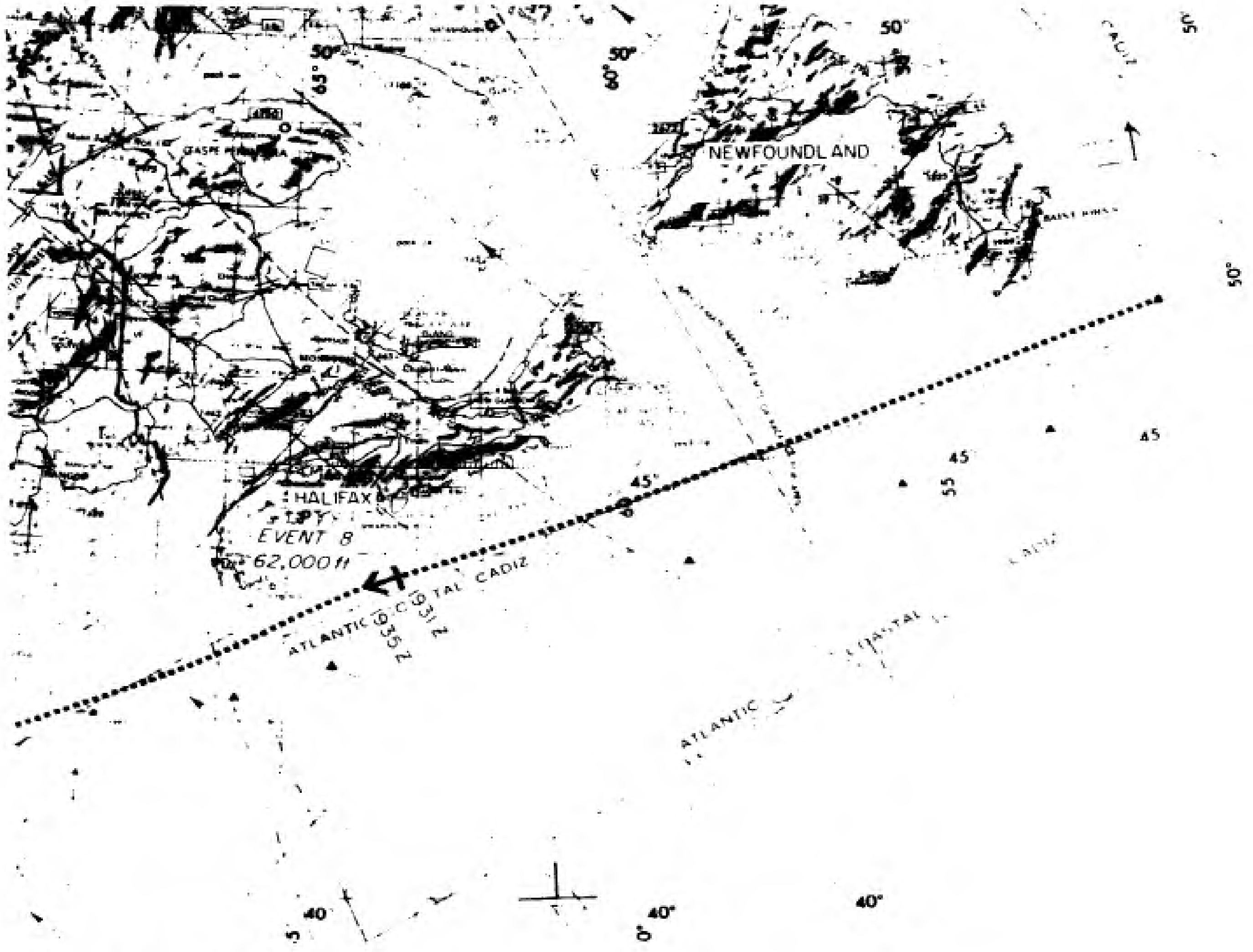


FIG 23 FLIGHT TRACK SHOWING EVENT 8 OF FLIGHT 72, 15 JAN 1971

NOT REPRODUCIBLE

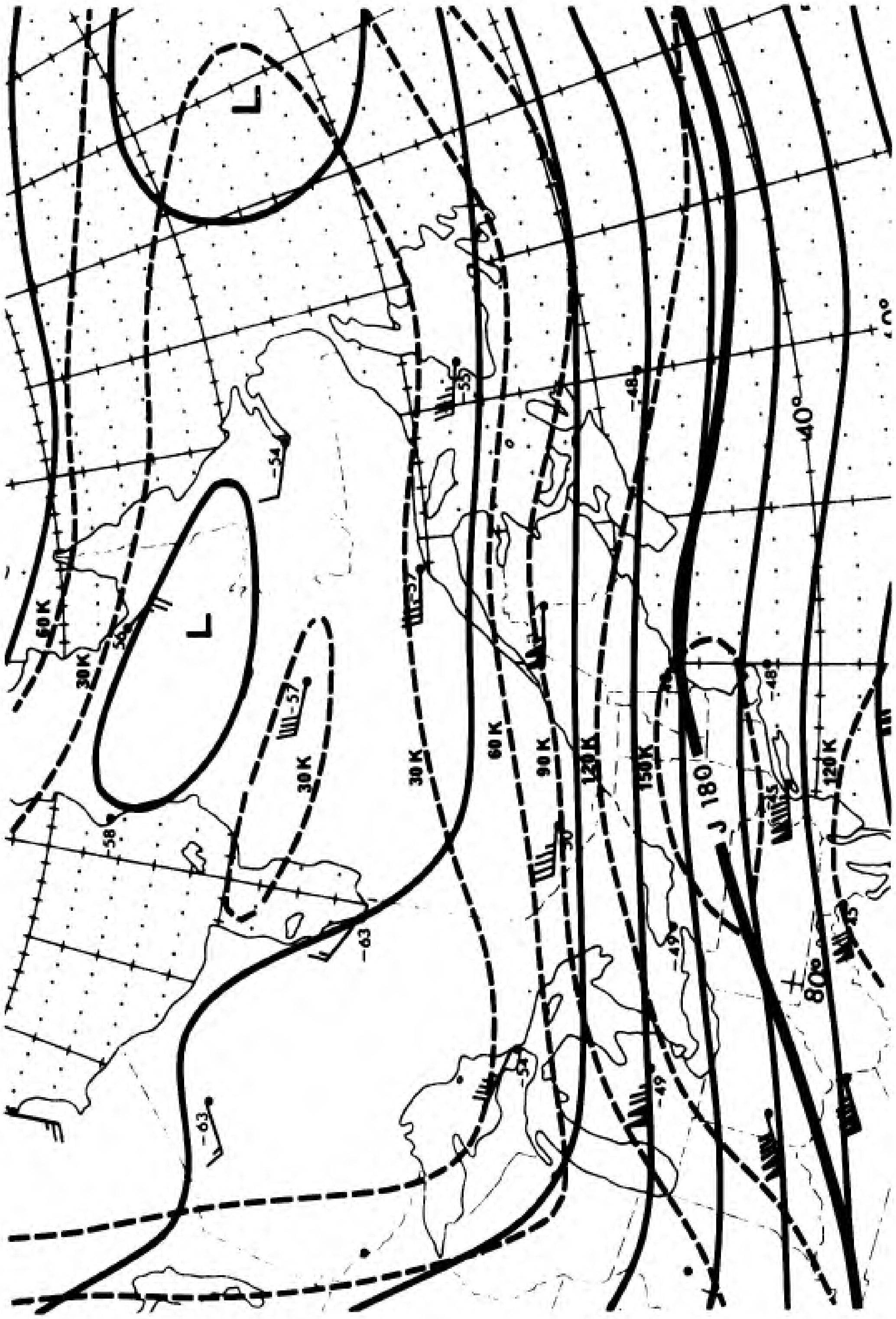


FIG 24 300 mb ANALYSIS 1200 GMT 15 JAN 1971

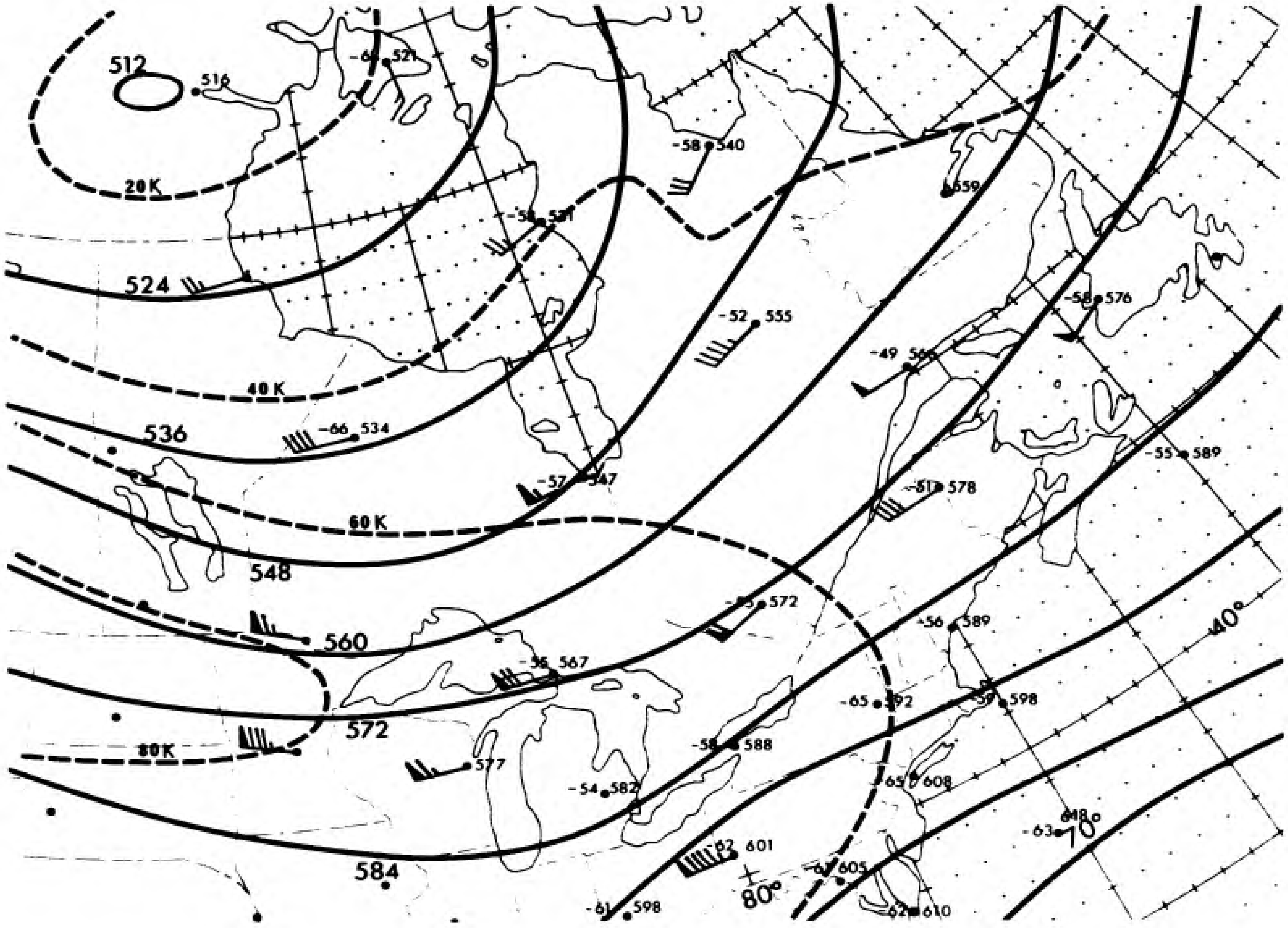


FIG 25 100 mb ANALYSIS 1200 GMT 15 JAN 1971

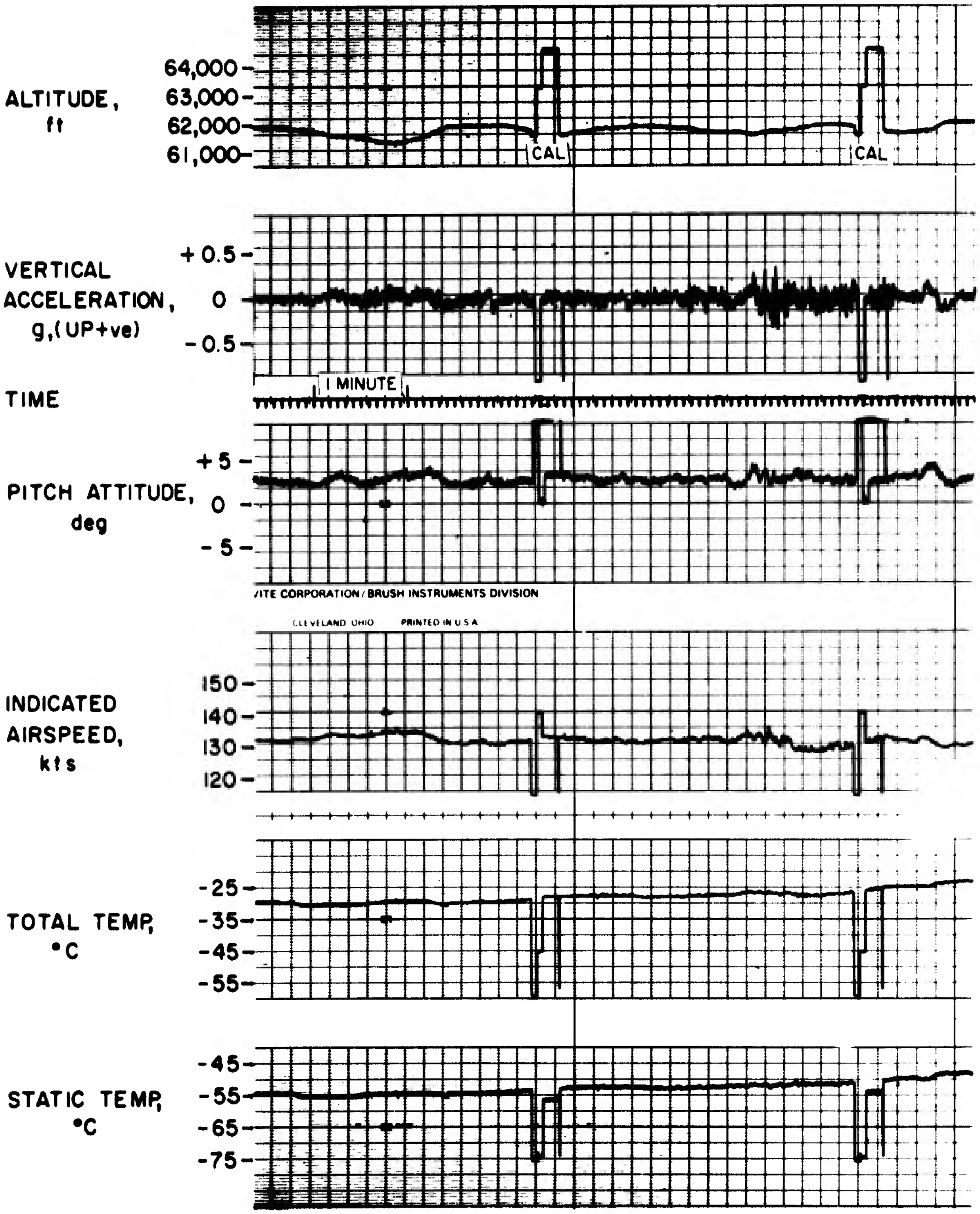


FIG 26 FLIGHT 75, EVENT 4

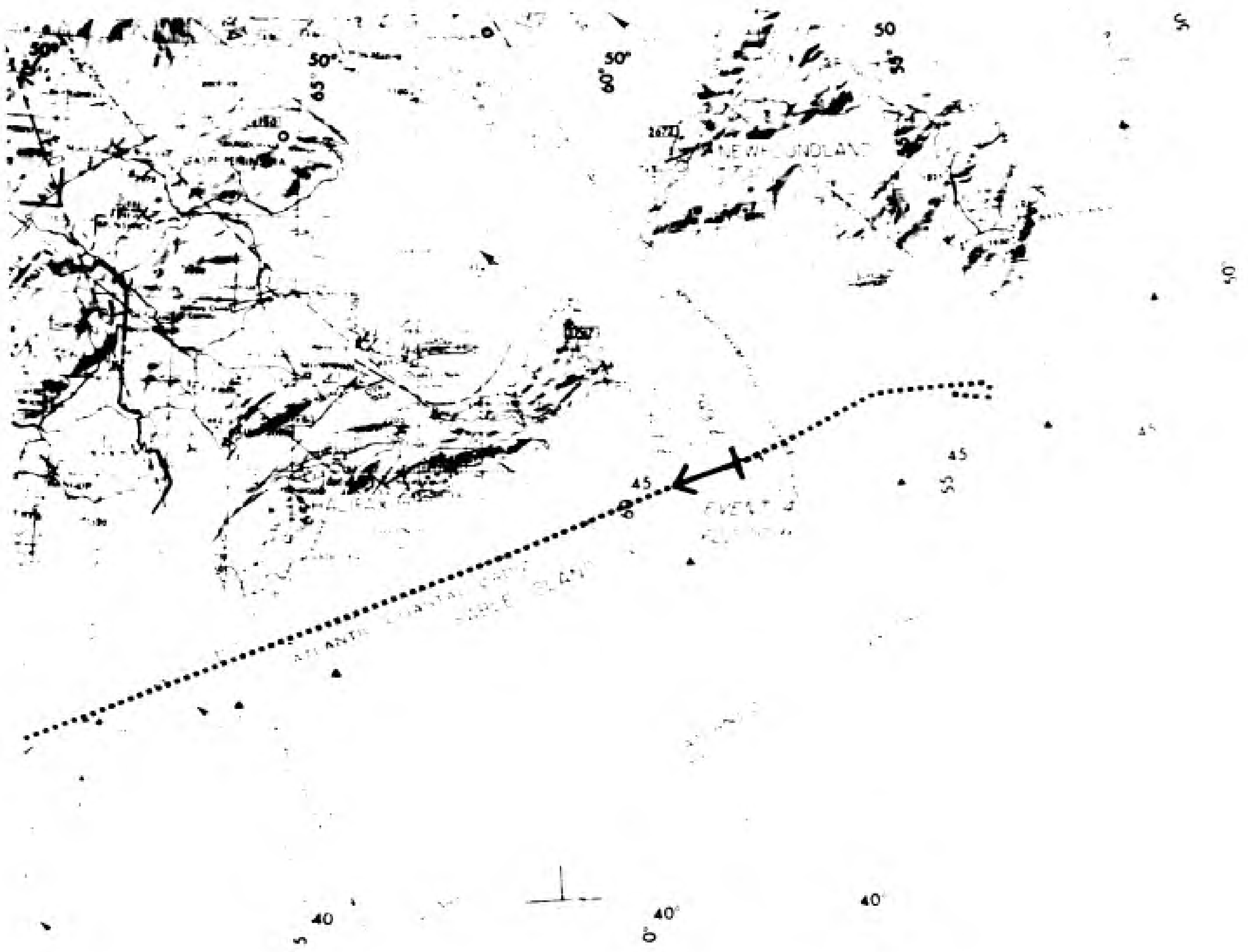


FIG 27 FLIGHT TRACK SHOWING EVENT 4 OF FLIGHT 75, 20 JAN 1971

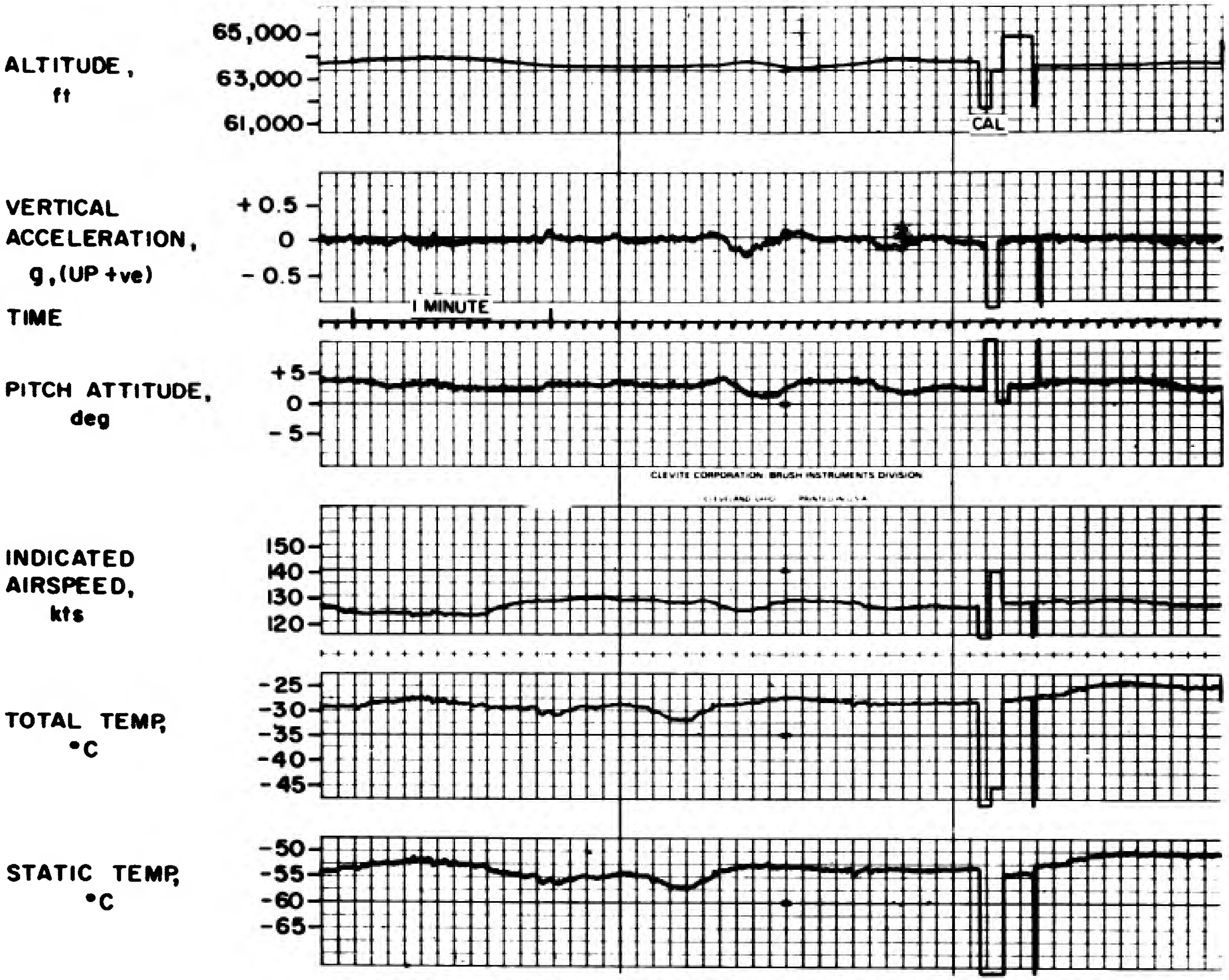


FIG 28 FLIGHT 75, EVENT 7

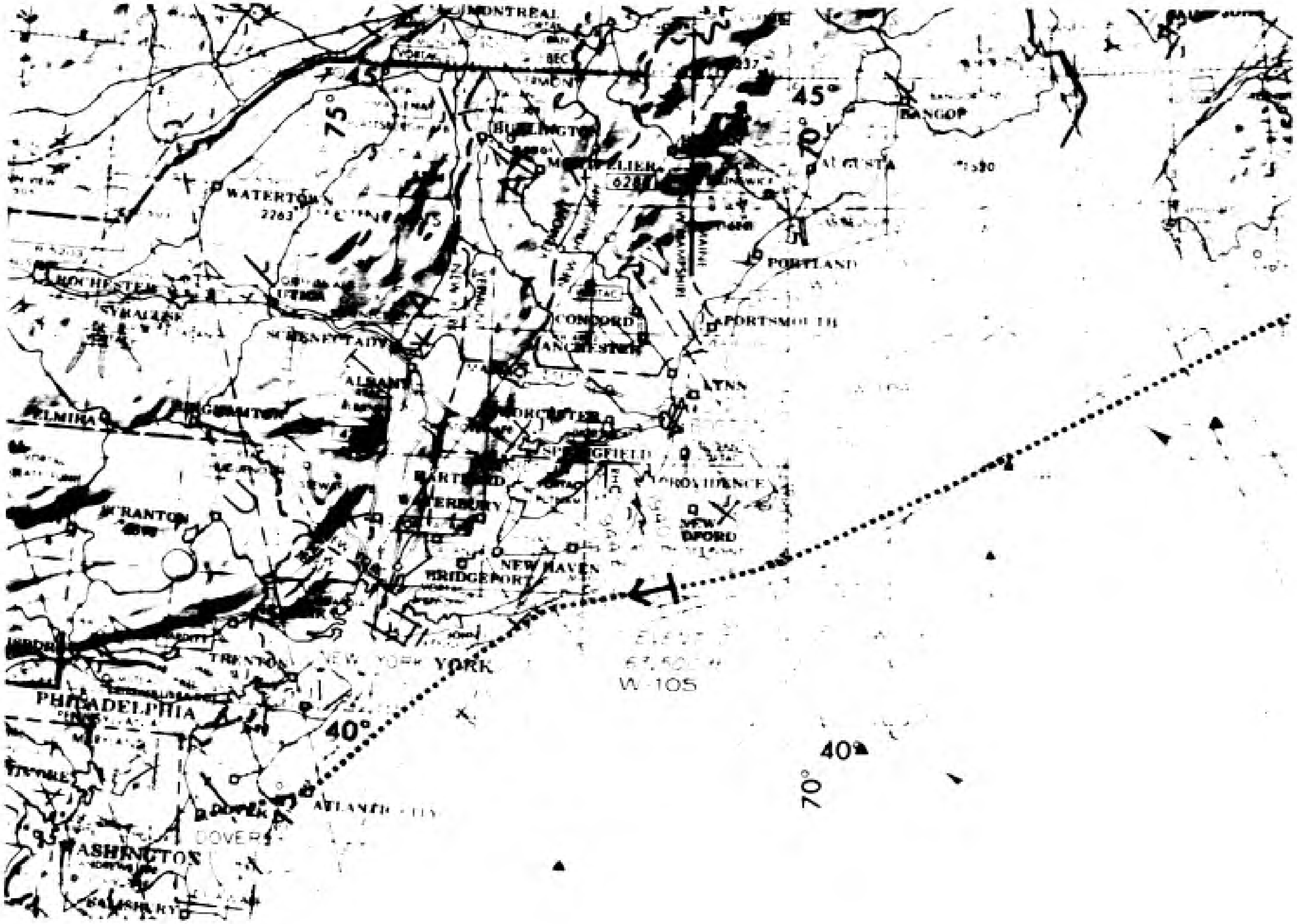


FIG 29 FLIGHT TRACK SHOWING EVENT 7 OF FLIGHT 75, 20 JAN 1971

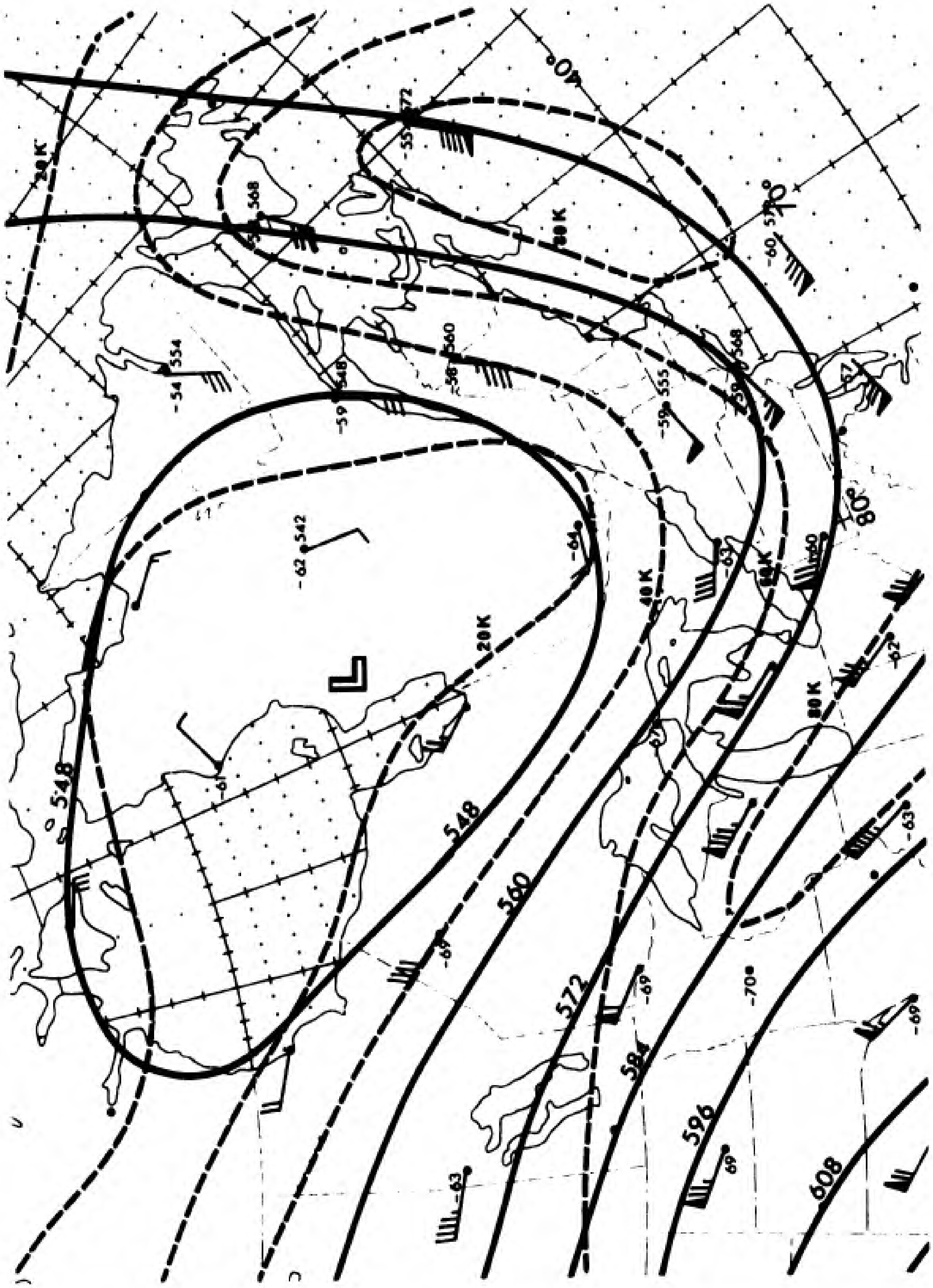


FIG 30 100 mb ANALYSIS 1200 GMT 20 JAN 1971

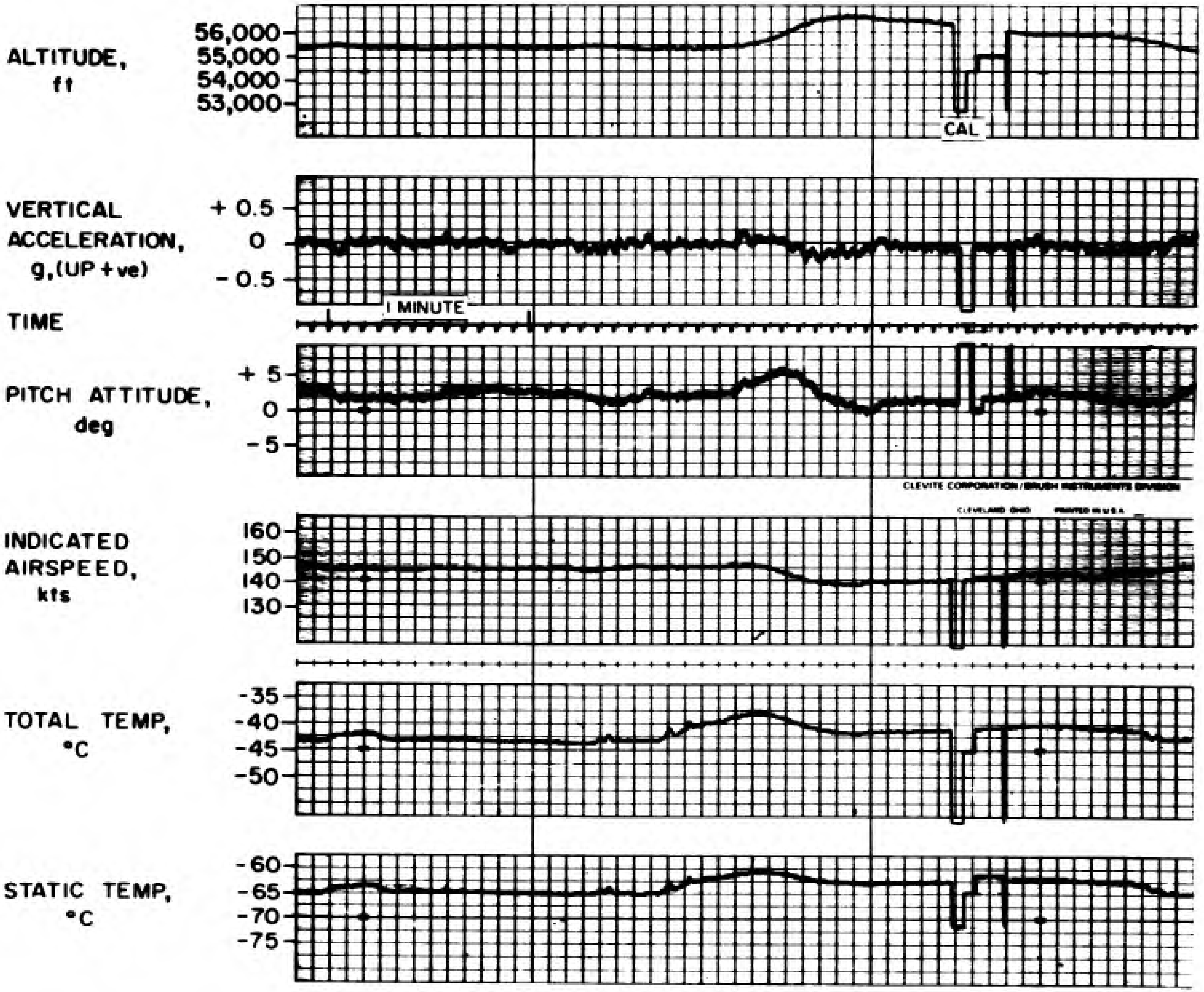


FIG 31 FLIGHT 76, EVENT 2

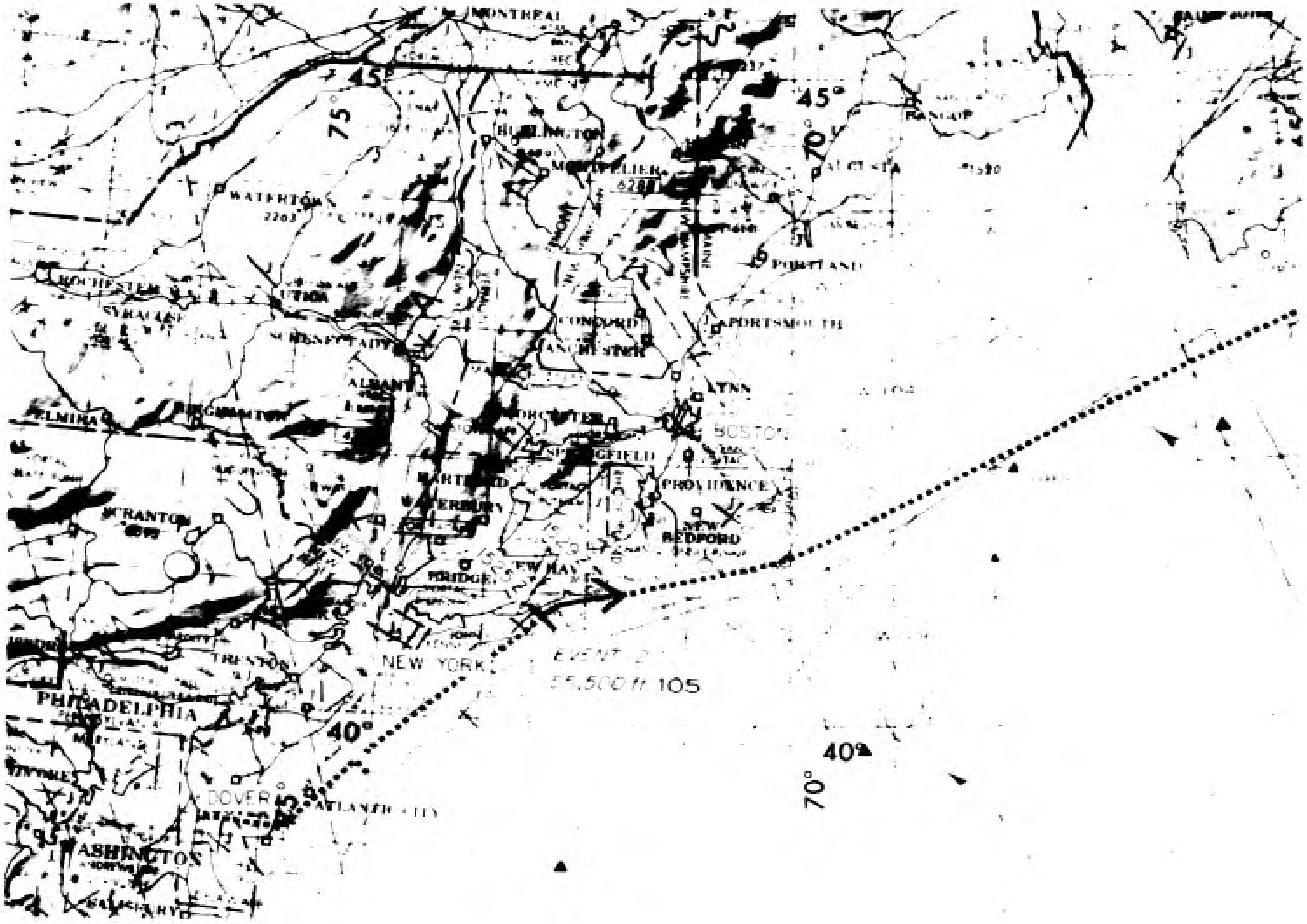


FIG 32 FLIGHT TRACK SHOWING EVENT 2 OF FLIGHT 76, 21 JAN 1971

NOT REPRODUCIBLE

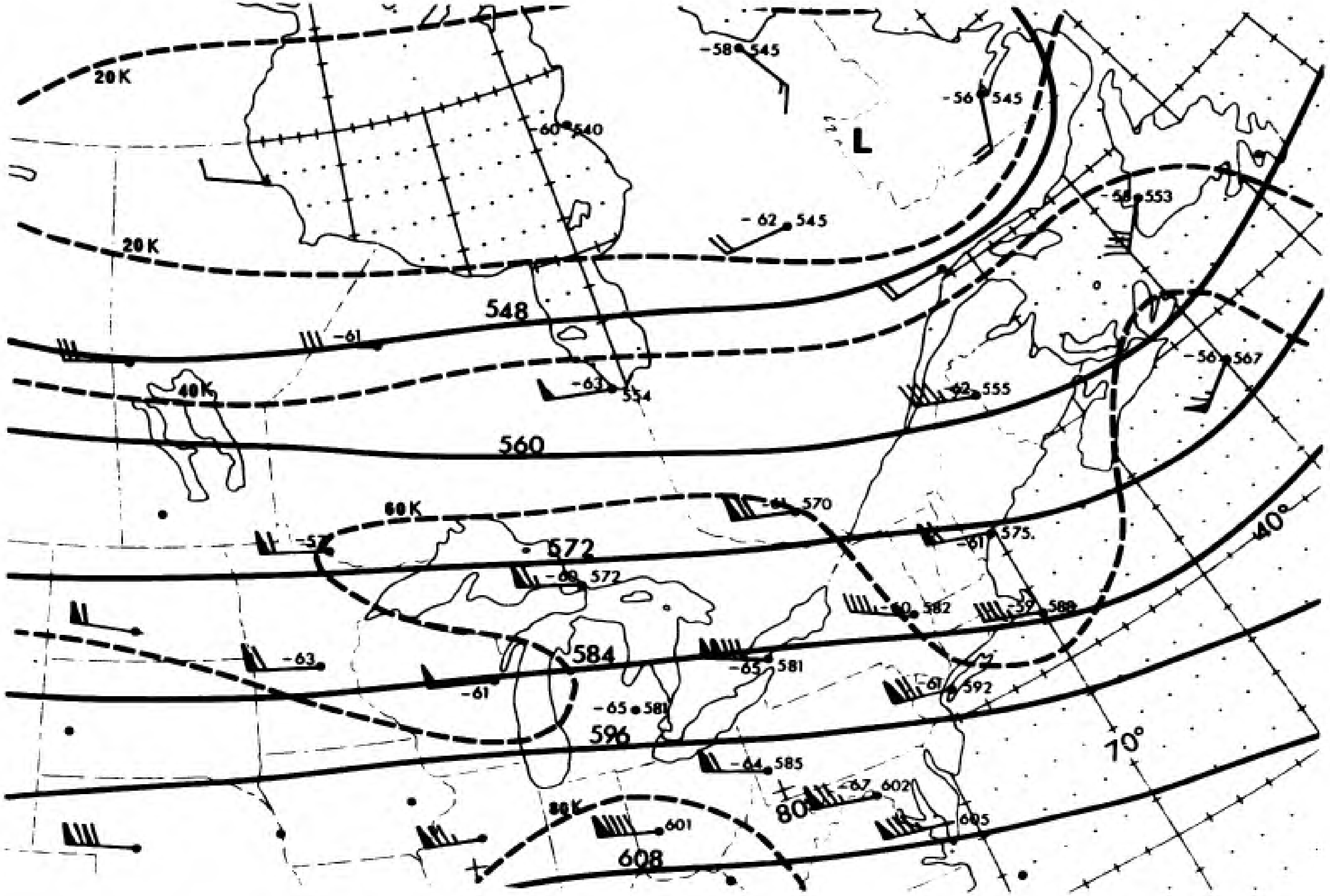


FIG 33 100 mb ANALYSIS 1200 GMT 21 JAN 1971

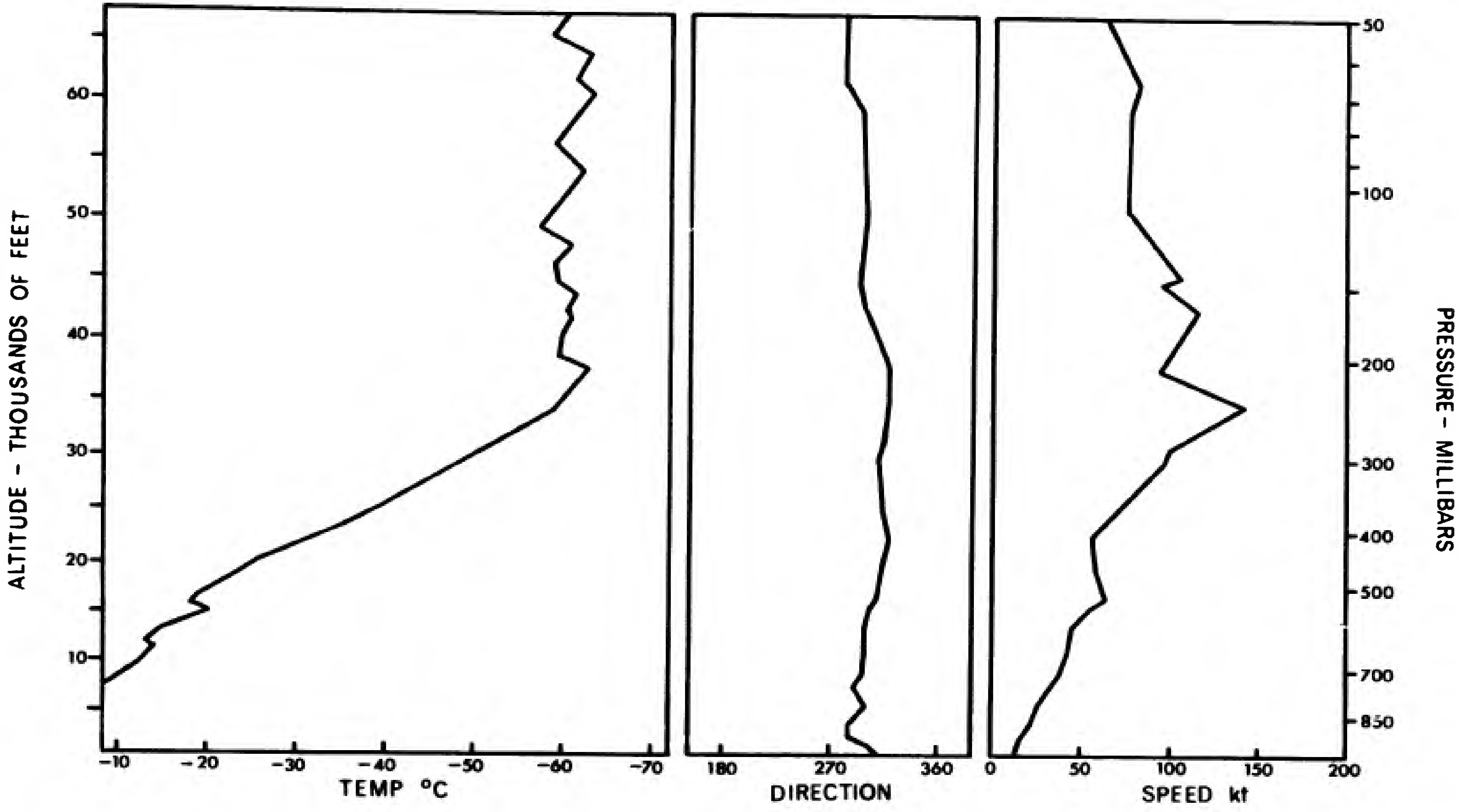


FIG. 34 UPPER AIR DATA

JOHN F. KENNEDY AIRPORT, N. Y.

1200 G.M.T. 21 JANUARY, 1971

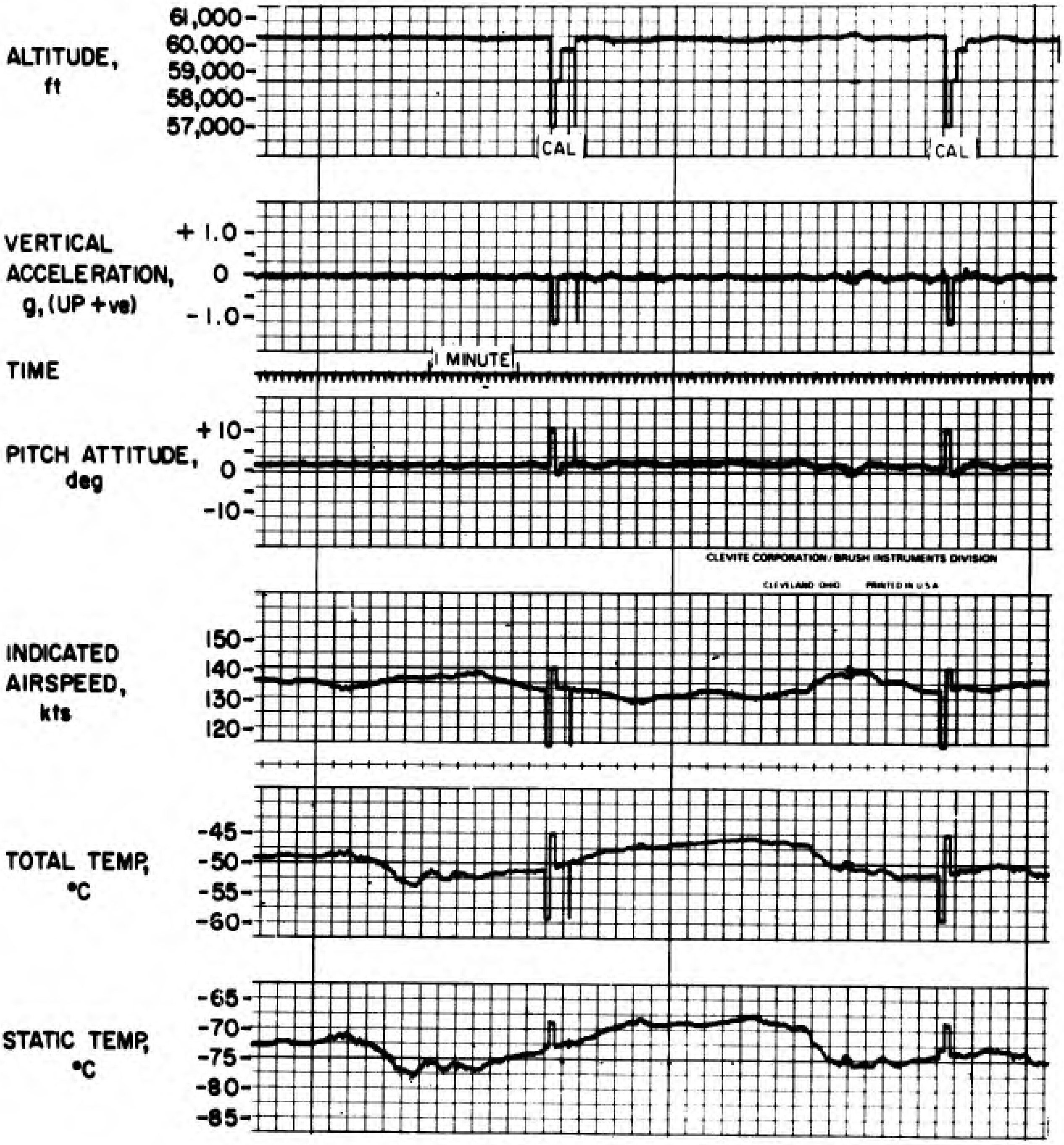


FIG 35 FLIGHT 83, EVENT 3

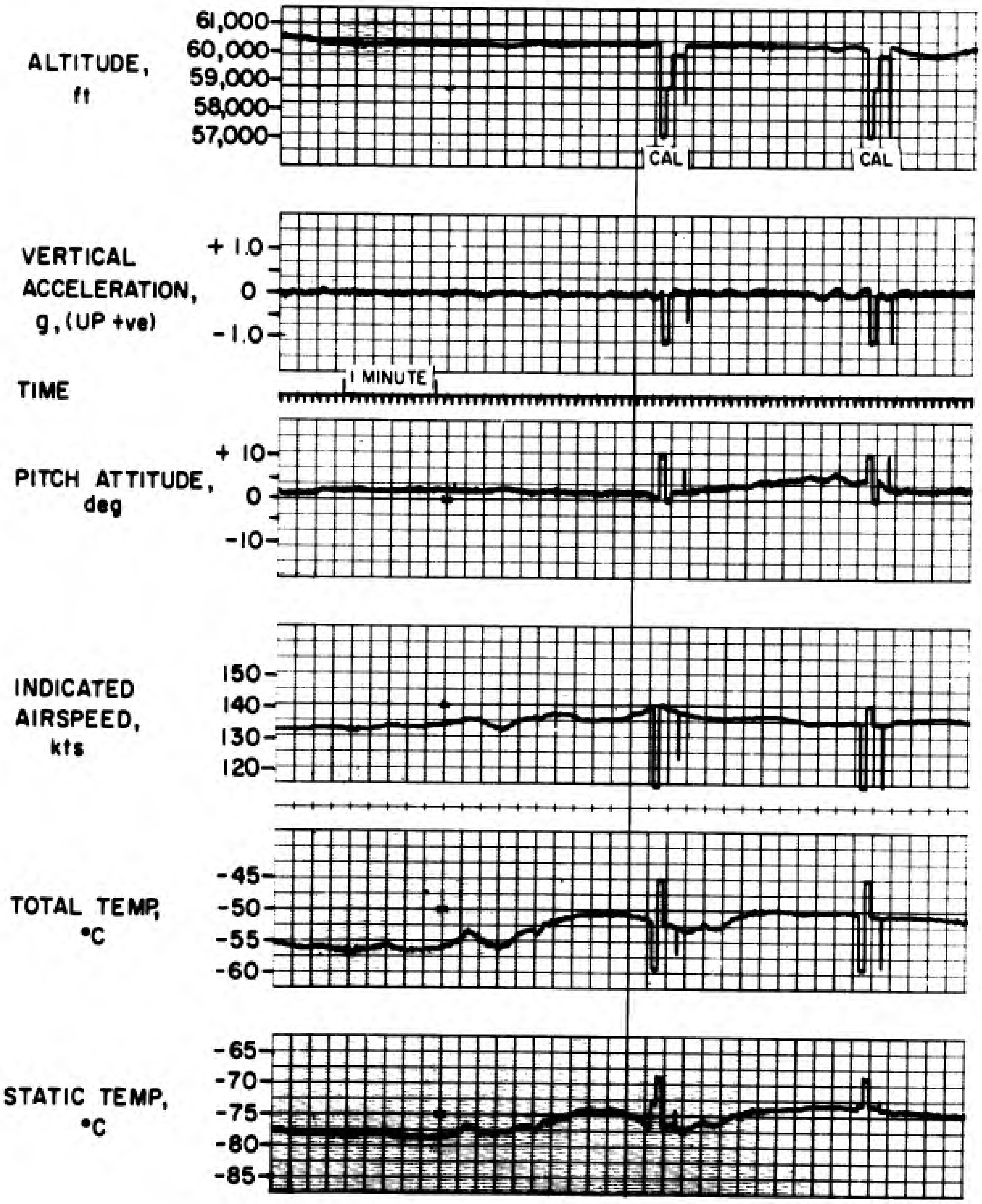
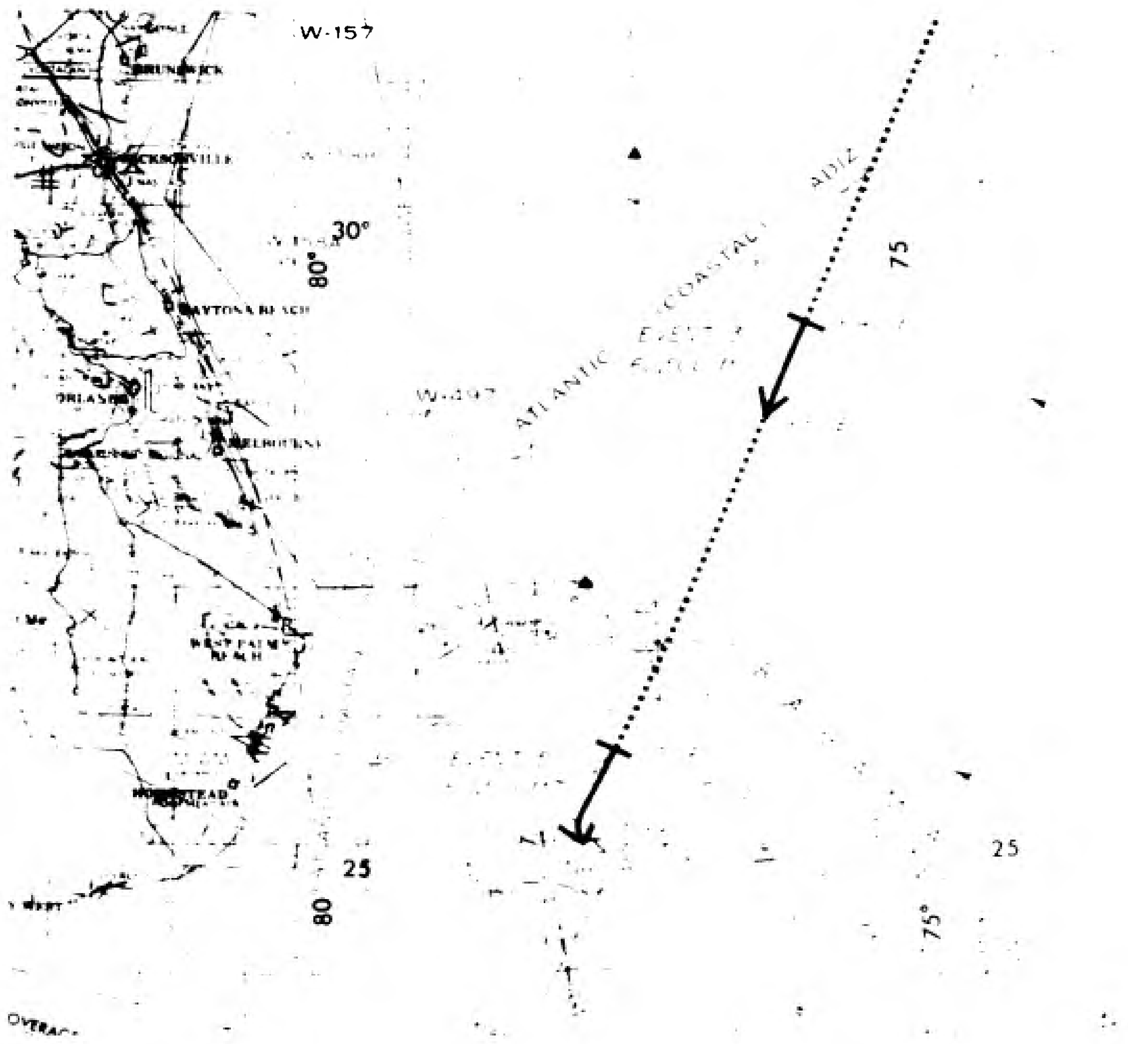


FIG 36 FLIGHT 83, EVENT 5



NOT REPRODUCIBLE

FIG 37 FLIGHT TRACK SHOWING EVENTS 3 AND 5 OF FLIGHT 83, 12 FEB 1971

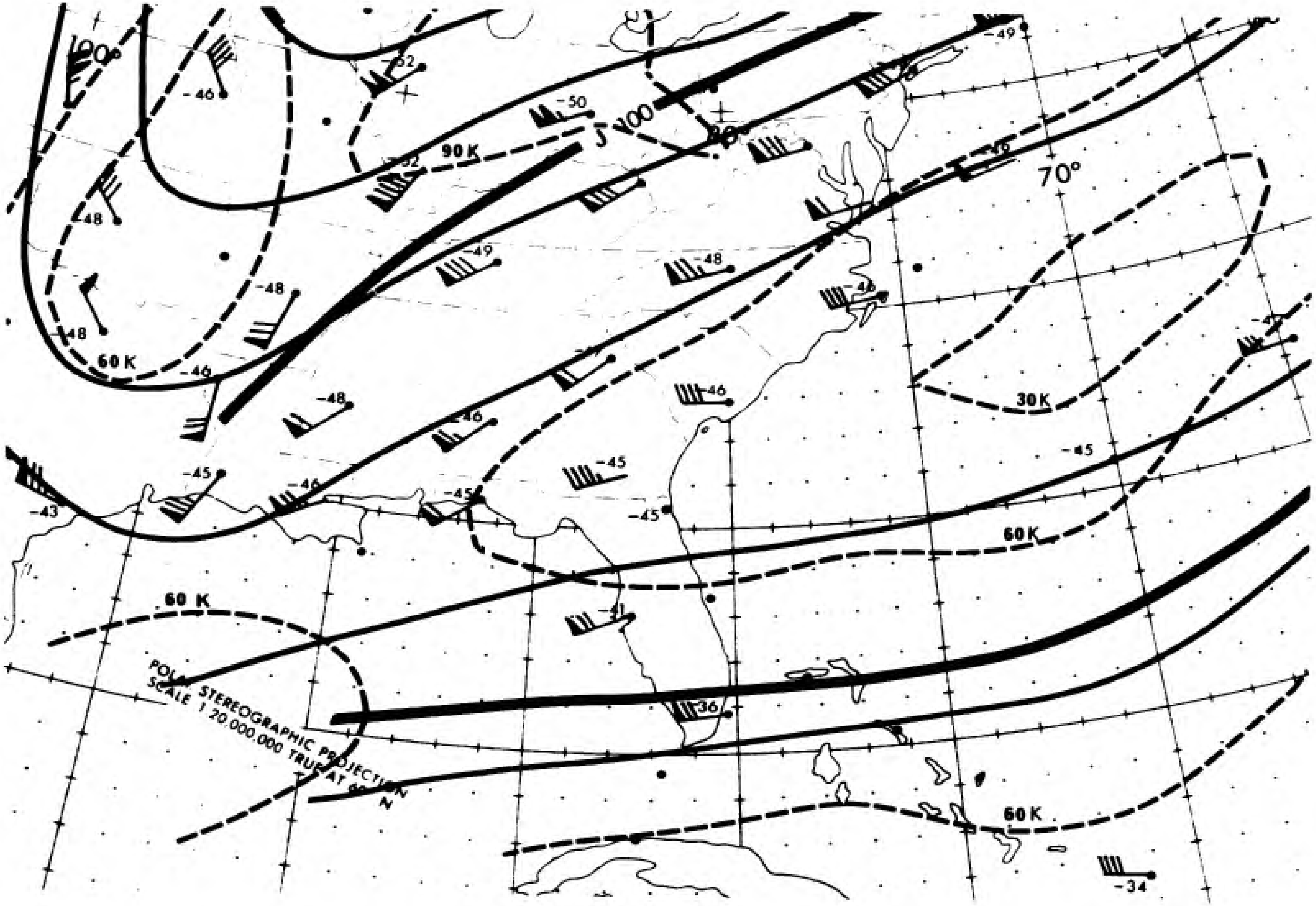


FIG 38 300 mb ANALYSIS 1200 GMT 12 FEB 1971

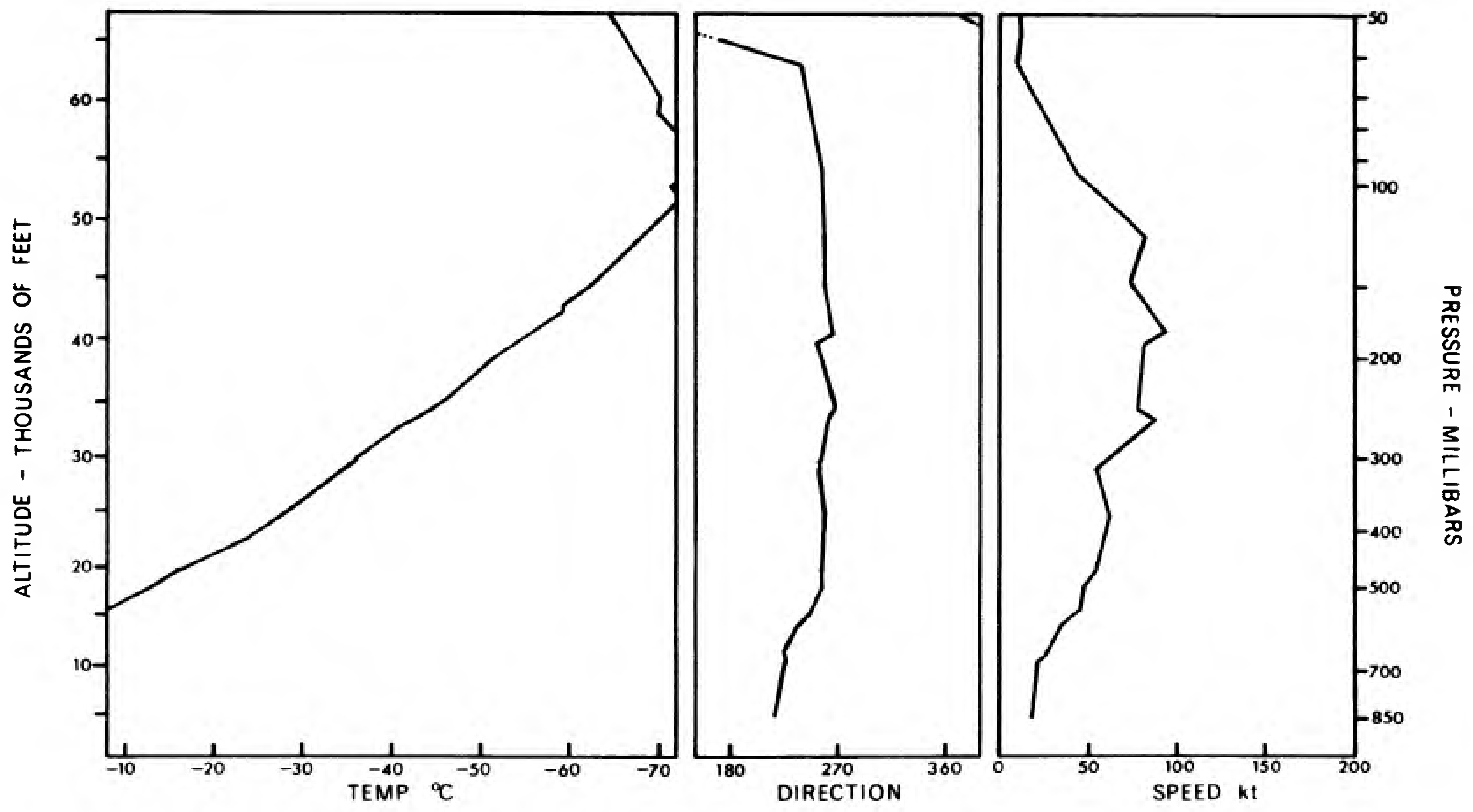


FIG. 39 UPPER AIR DATA

MIAMI, FLORIDA 1200 G.M.T. 12 FEBRUARY, 1971

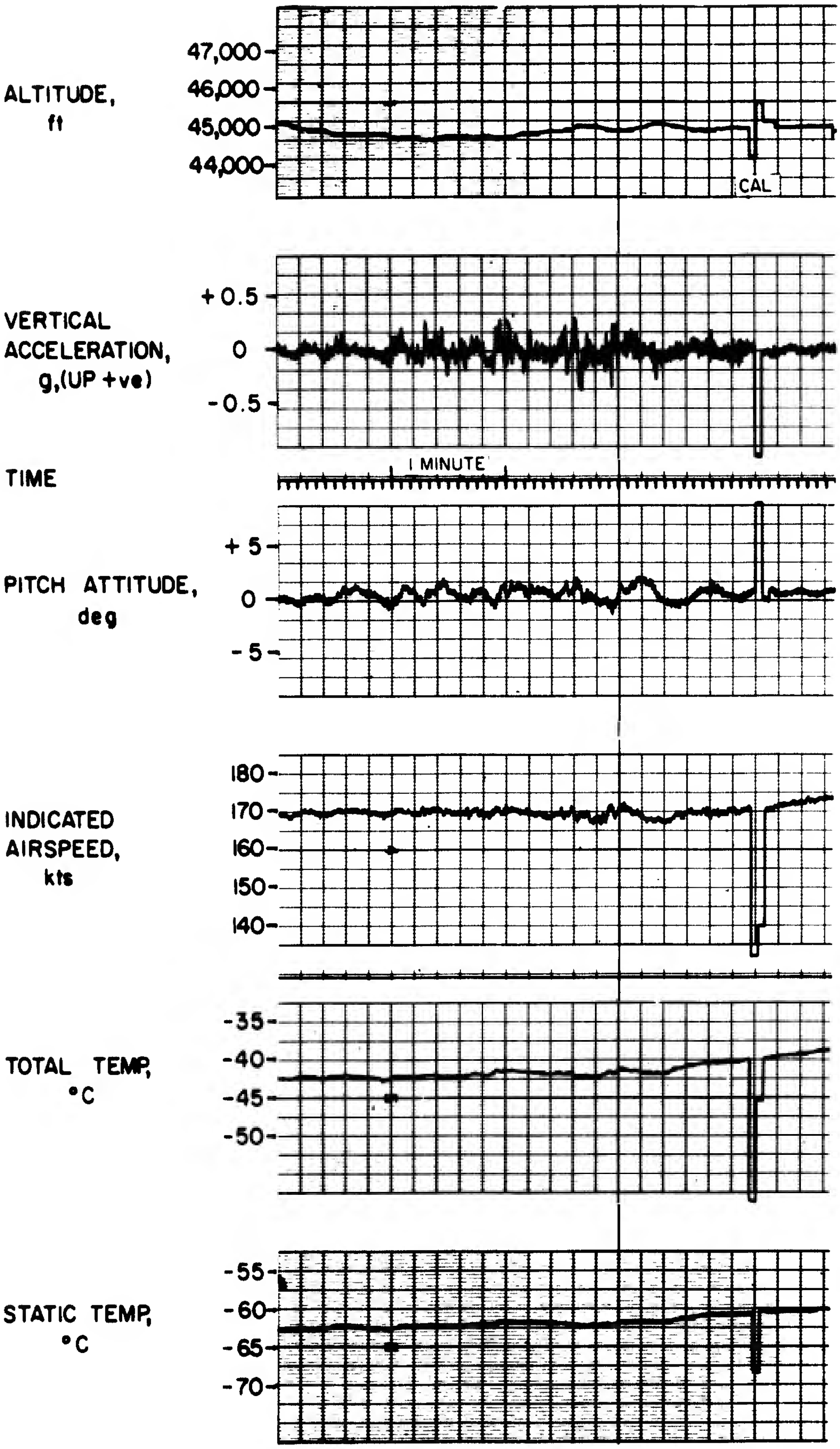


FIG 40 FLIGHT 86, EVENT 2

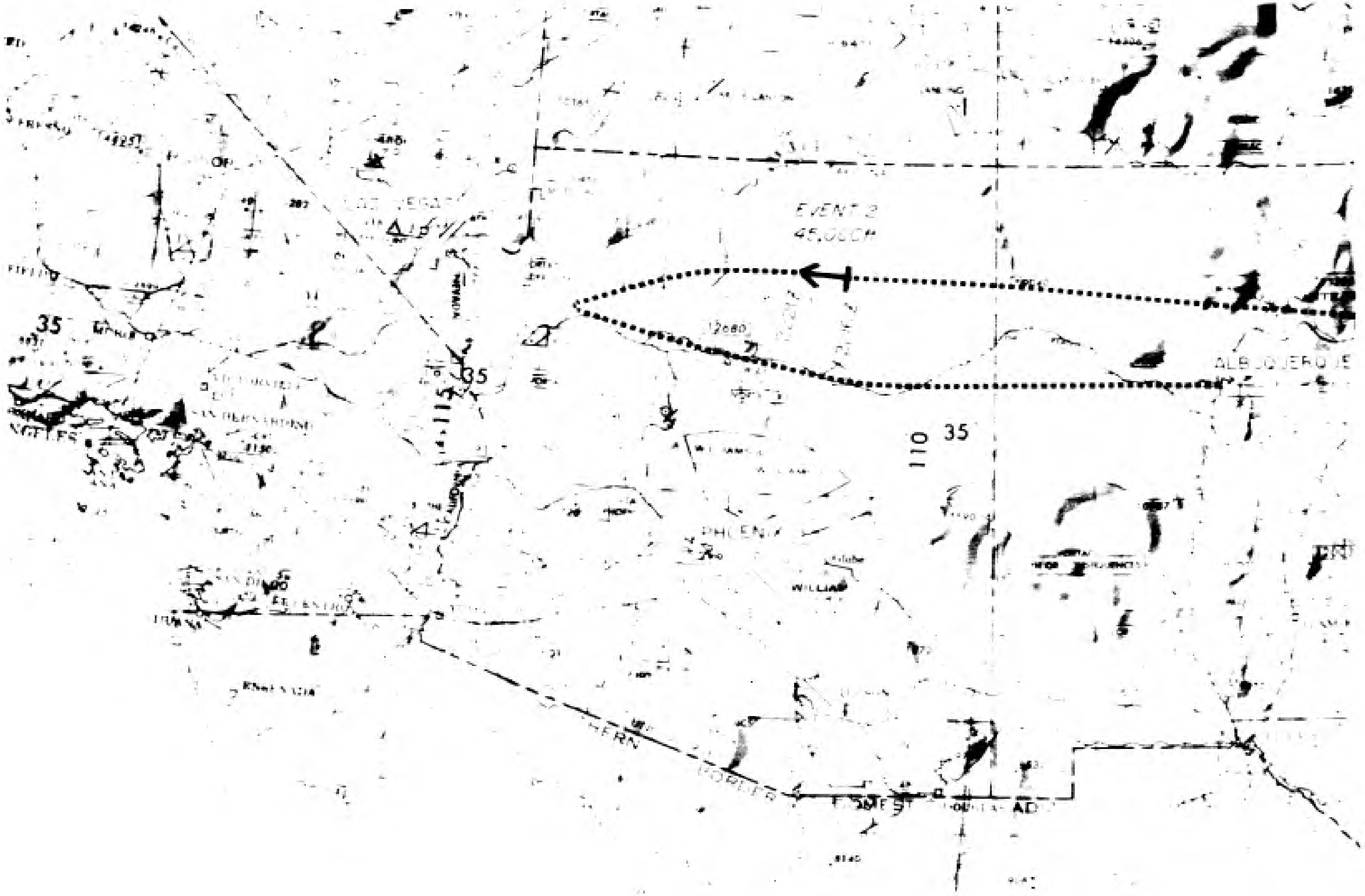


FIG 41 FLIGHT TRACK SHOWING EVENT 2 OF FLIGHT 86, 15 APR 1971

NOT REPRODUCIBLE

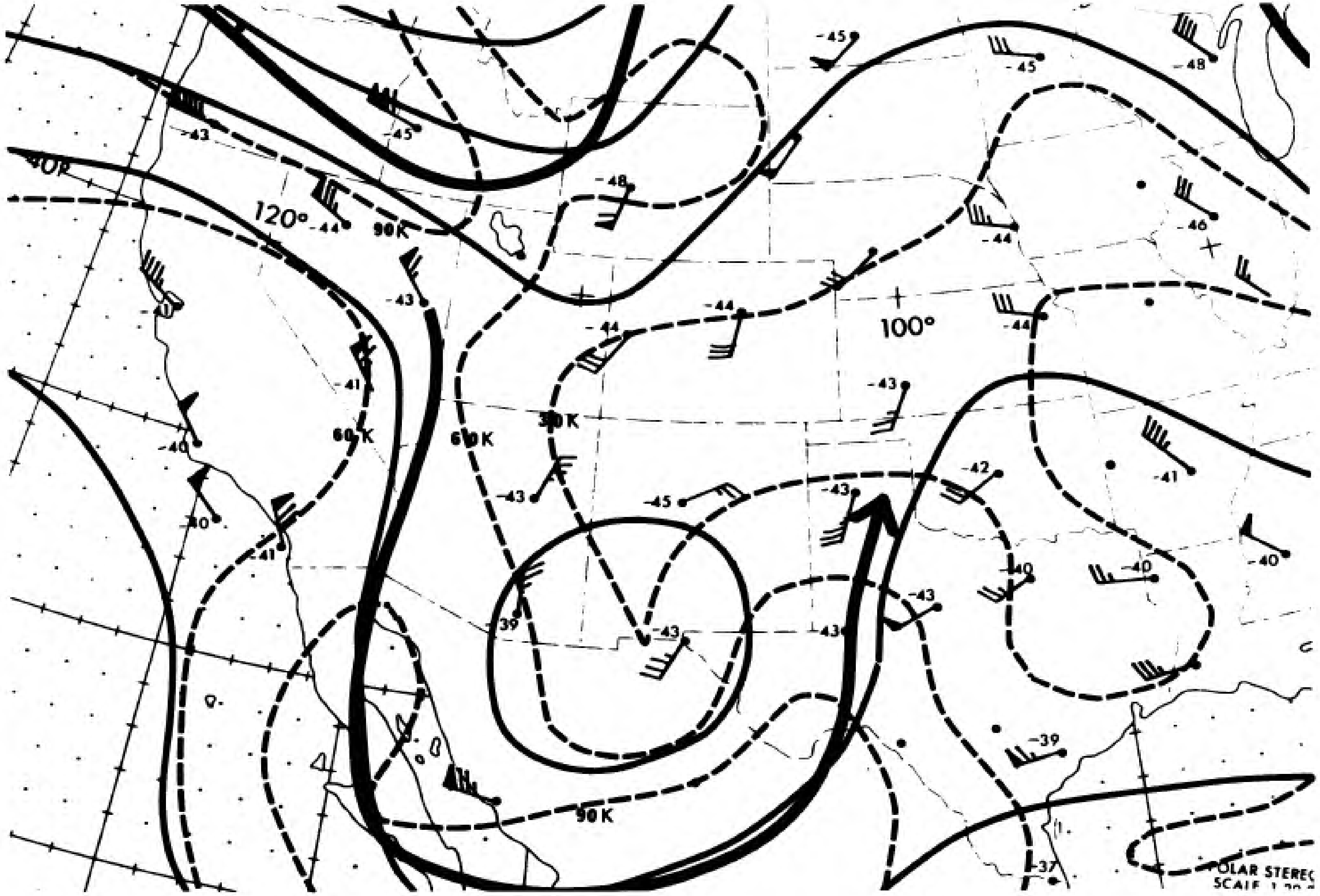


FIG 42 300 mb ANALYSIS 0000 GMT 16 APRIL 1971

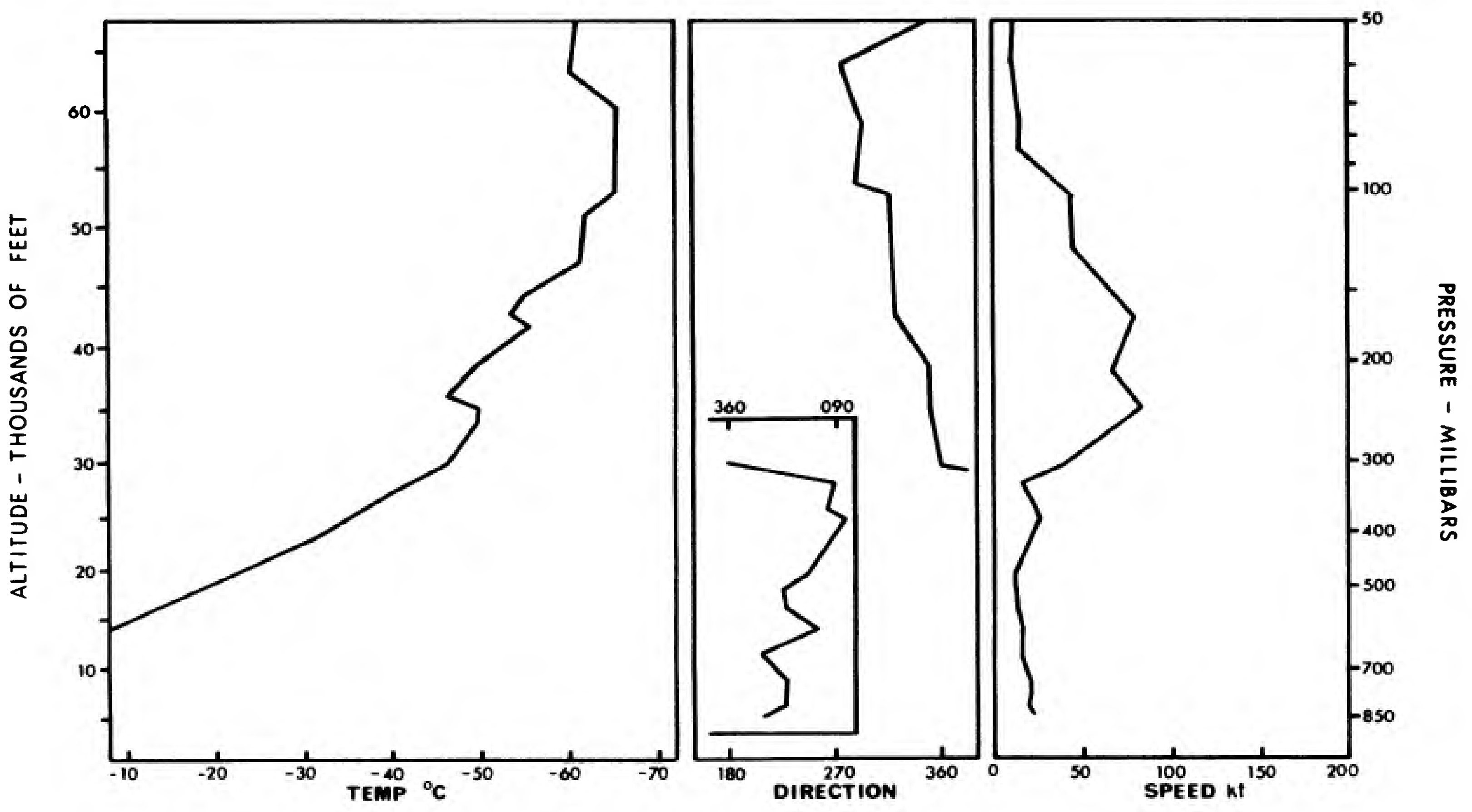


FIG. 43 UPPER AIR DATA

LAS VEGAS, NEVADA 1200 G.M.T. 15 APRIL, 1971

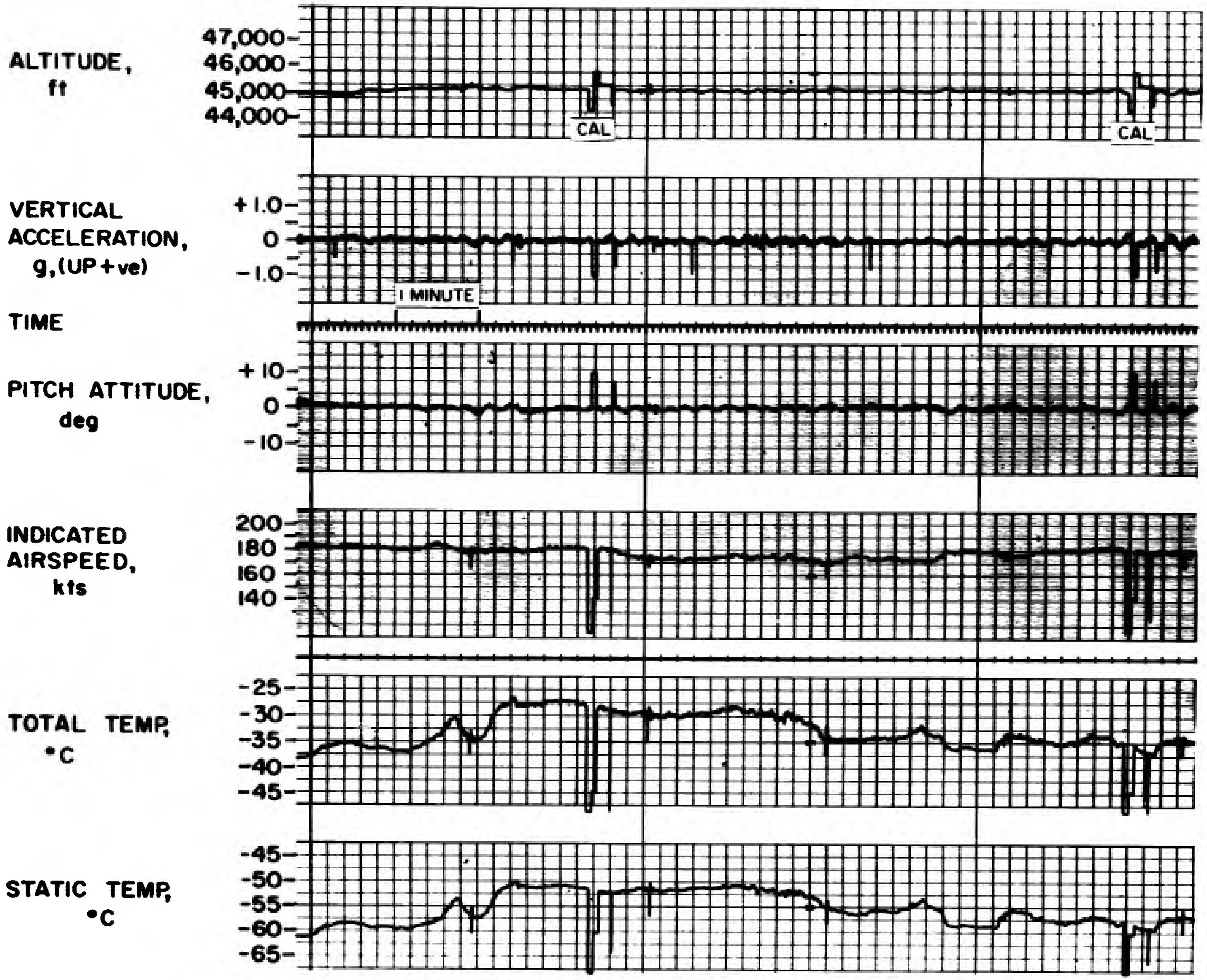


FIG 44 FLIGHT 87, EVENT I

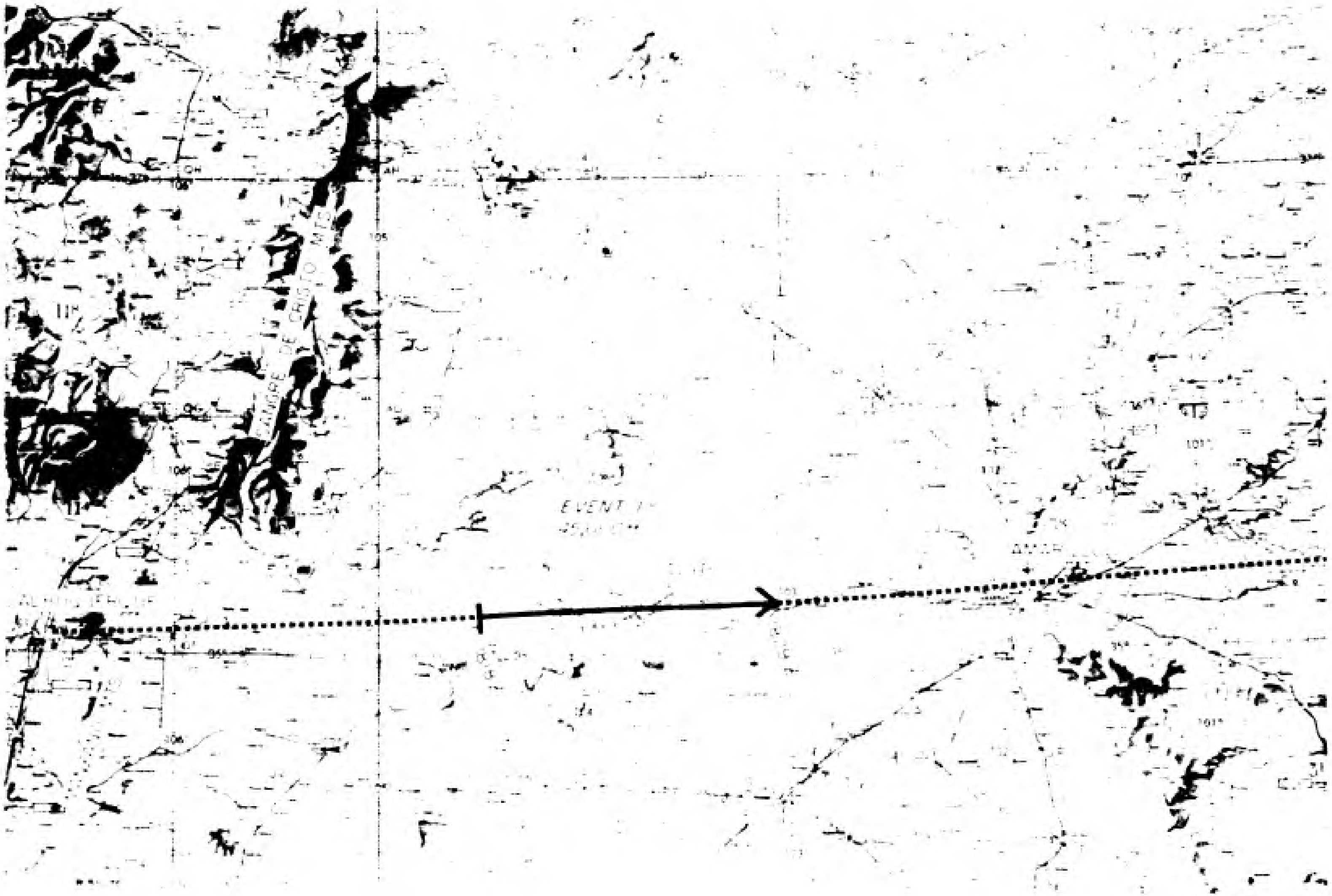


FIG 45 FLIGHT TRACK SHOWING EVENT 1 OF FLIGHT 87, 20 APR 1971

NOT REPRODUCIBLE

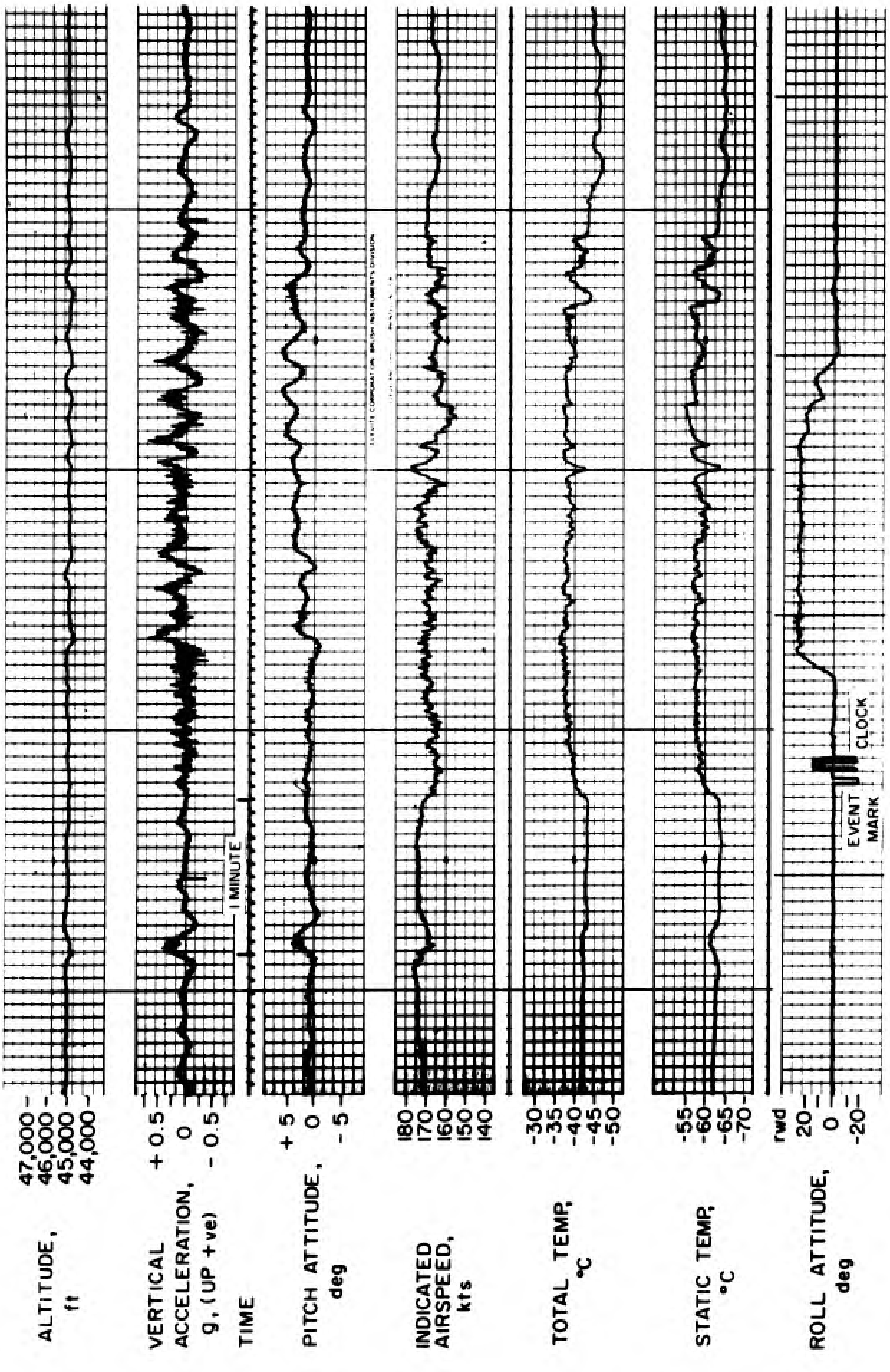


FIG 46 FLIGHT 87, EVENT 5

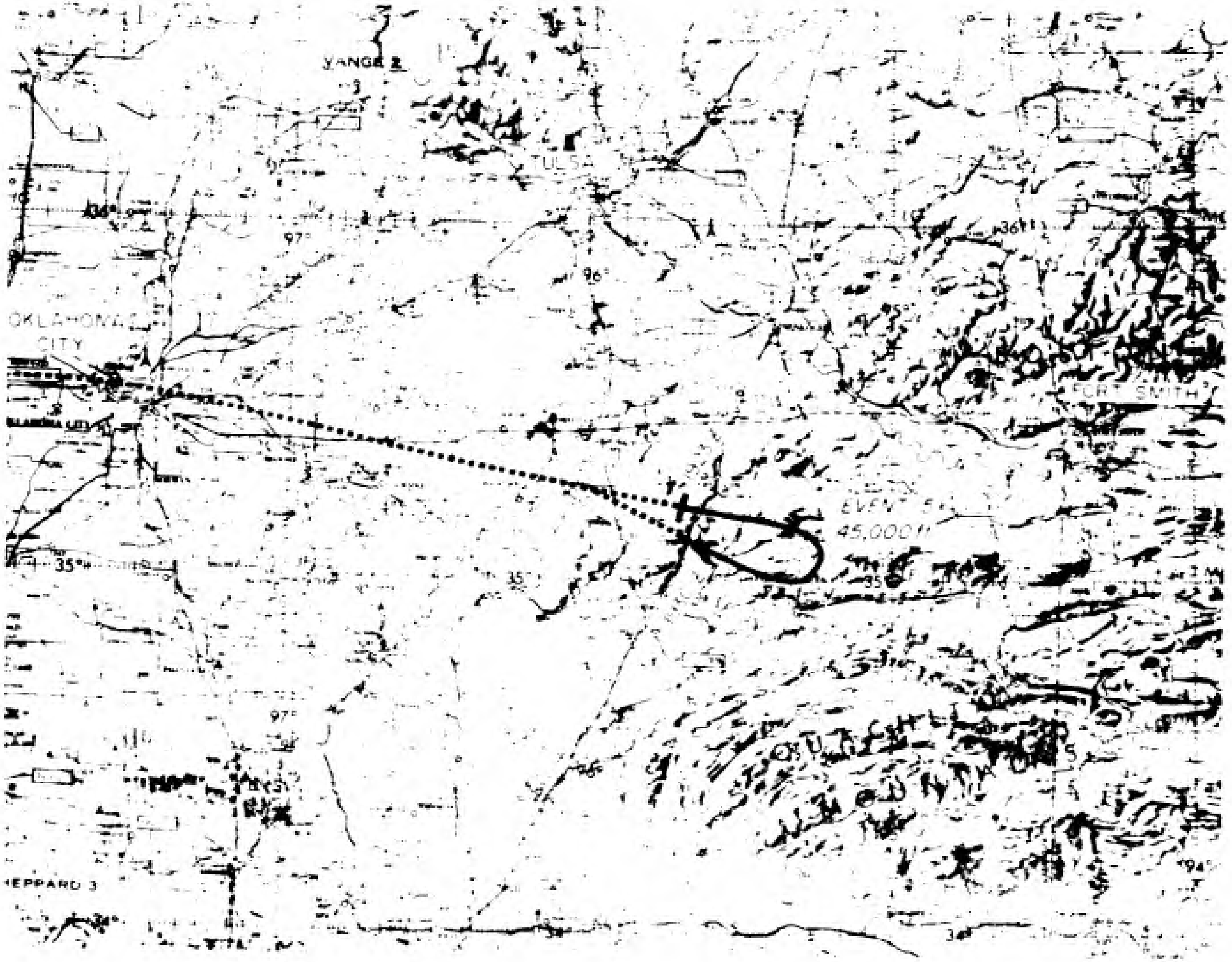


FIG 47 FLIGHT TRACK SHOWING EVENT 5 OF FLIGHT 87, 20 APR 1971

NOT REPRODUCIBLE

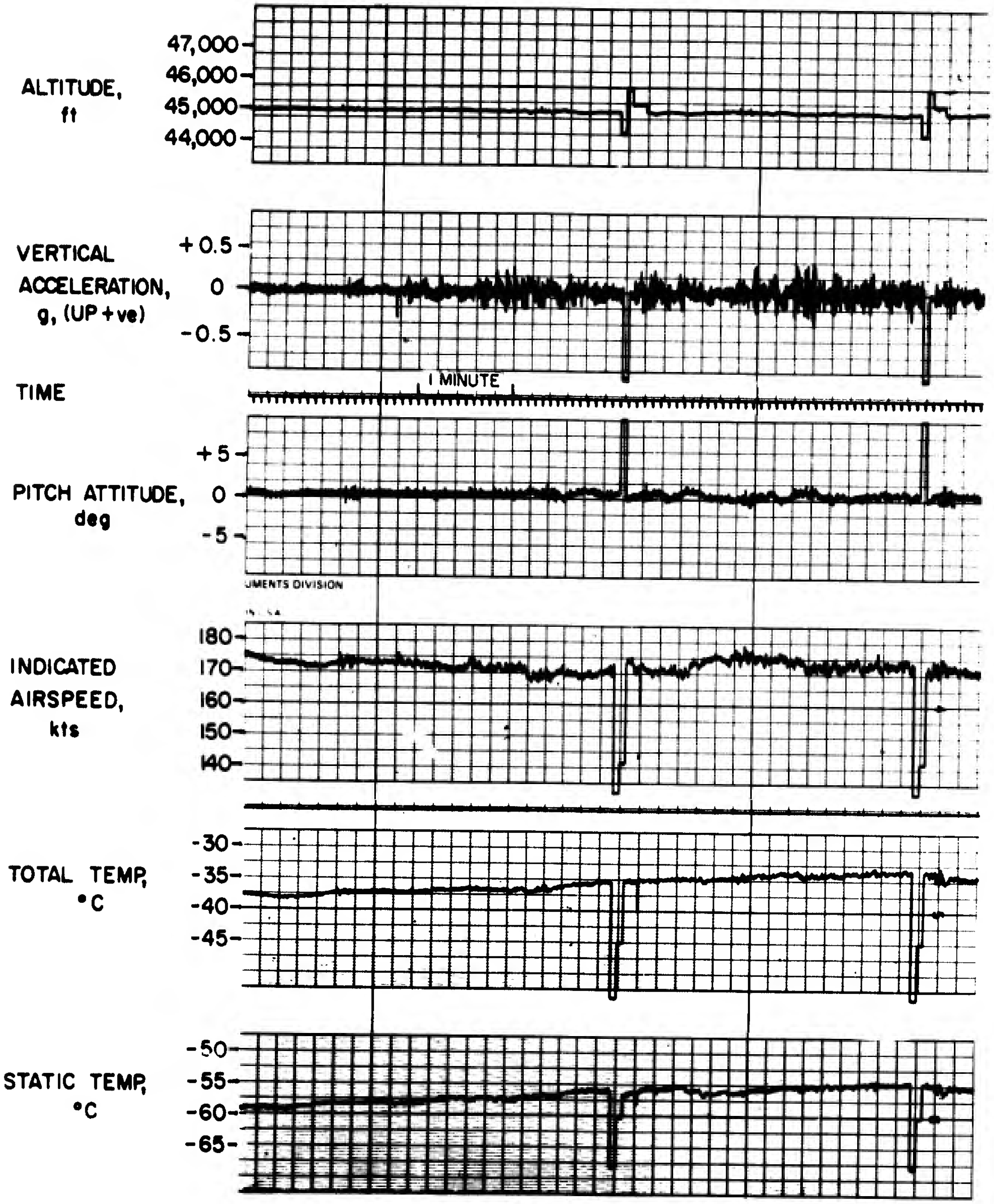


FIG 48 FLIGHT 87, EVENT 7

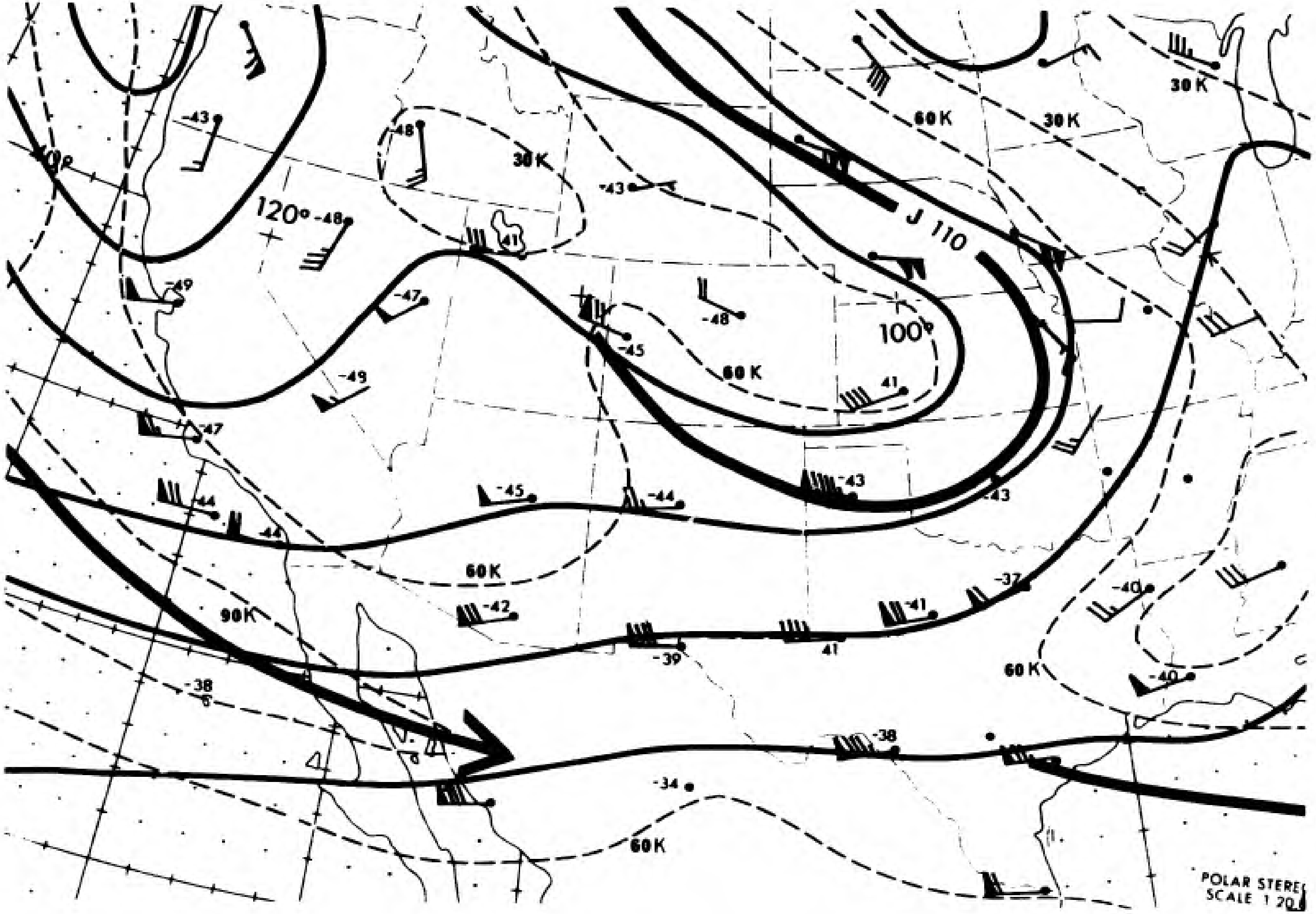
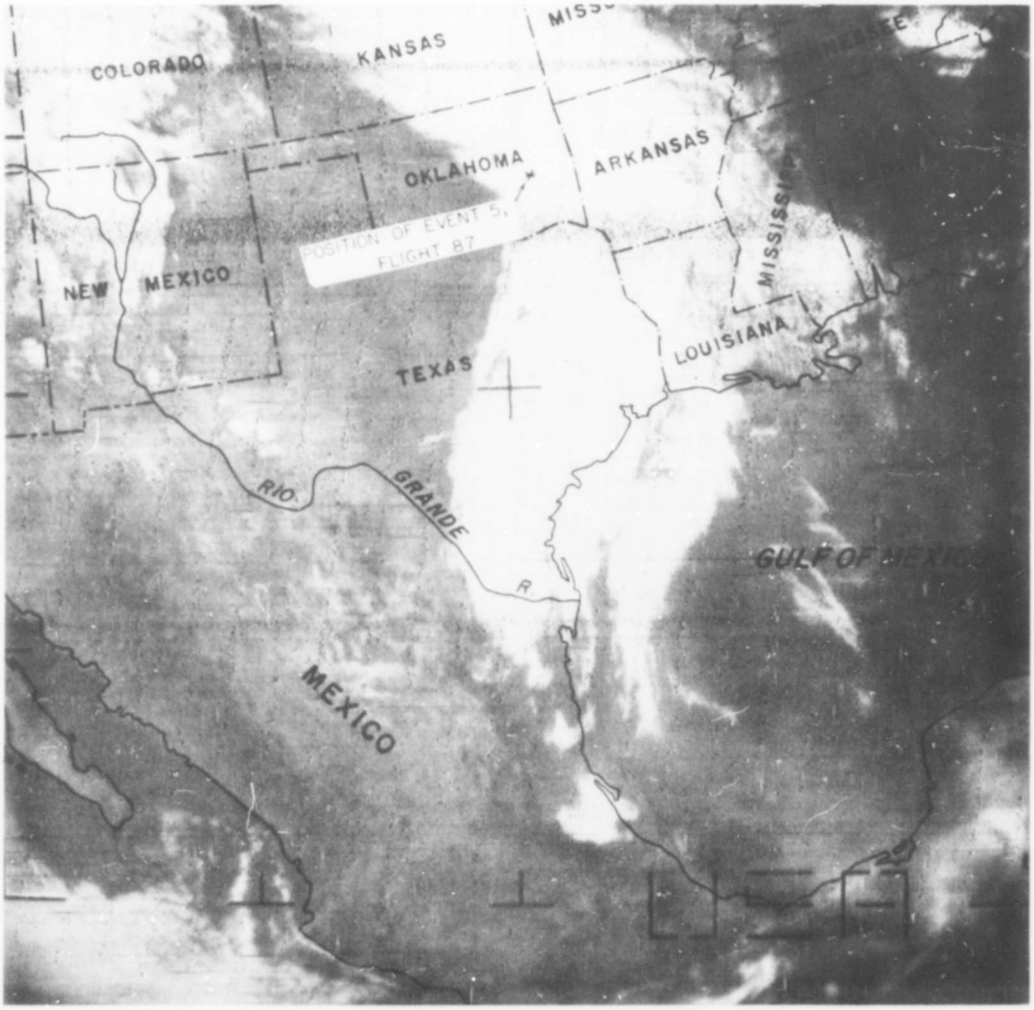


FIG 49 300 mb ANALYSIS 0000 GMT 21 APRIL 1971

NOT REPRODUCIBLE



ESSA 8 - ORBIT Nº 10746 - TIME: 16:40:53 Z - 20 APRIL 1971

FIG 50 SATELLITE PHOTOGRAPH 3 HOURS PRIOR TO EVENT 5 OF FLIGHT 87