Temperature Gradients and Clear-Air Turbulence Probabilities

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ABSTRACT

From the end of October 1973 to the beginning of January 1974, Continental Airlines operated one of its Boeing 747 aircraft with special instrumentation for the study of clear-air turbulence (CAT). The observations were compared with satellite-derived radiance gradients, conventional temperature gradients from analyzed maps, and temperature gradients obtained from a Rosemount total air temperature sensor on the plane. The results led to the following conclusions:

1) In regions of weak gradients of temperature or of CO_2 band radiance, the probability of CAT is extremely small.
2) CAT probabilities are significantly higher over mountains than flat terrain.
3) Even over mountains the probability of CAT is greatly increased by large gradients of temperature or radiance.
4) Satellite radiance gradients appear to discriminate between CAT and no CAT better than conventional temperature gradients over flat lands, whereas the reverse is true over mountains—although the differences between the two techniques are not large over mountains. Since most of the flights over flat terrain were flown over the Pacific Ocean, the result, if significant, may suggest that conventional temperature gradients over regions of sparse data are not as accurate as temperature gradients which can be inferred from satellites.
5) Temperature gradients obtainable from aircraft temperature sensors are not correlated with CAT statistics.

1. Introduction

When jet aircraft were generally introduced, it was believed that flight would be smooth and comfortable, above the "weather." Instead, turbulence was encountered frequently, sometimes in cirrus clouds, but often in clear air. This clear-air turbulence (CAT) is particularly annoying because there is no visual warning. Although such turbulence is rarely severe, it can be uncomfortable, and, in a few cases, has led to injuries of passengers and crew.

Attempts have been made to deal with the CAT problem in three ways: first, ideally, instruments have been suggested which, when carried on the plane, would signal the existence of CAT to the pilot before the CAT area was entered. Such attempts have usually been unsuccessful, but experimentation is continuing. Second, other planes in the area often report CAT regions which can be avoided by planes traversing the area later. This method is quite practical, provided the flight density is high. Third, many synoptic indicators of CAT have been sought but only with limited success. Usually, such indicators are obtained from synoptic maps.

In this report a study is described which related CAT probability to variables inferred directly from satellite reports. Of course, the advantage of making use of such data is that they are available world-wide, without the necessity of relying on radiosonde observations, which are scarce in many parts of the world.

In earlier work on the relation between CAT and synoptic variables, the CAT data were subjective (relying on pilot reports). They tend to be unreliable, both because different pilots react differently, and because the location is uncertain. For the project summarized in this report, quantitative turbulence data were available, though only for a relatively short time, and for a single Boeing 747 plane, operating between Los Angeles and Chicago, or between Los Angeles and Honolulu. This plane carried, in addition to the normal instrument box, a special instrument designed by Meteorology Research Incorporated, to measure turbulent dissipation, a quantity determined from the intensity of high-frequency turbulent wind fluctuations. In addition, an observer rode in the back of the plane and recorded, at frequent intervals, the subjective "feel" of the ride. Finally, all data were recorded on a special recorder, made available through the National Center of Atmospheric Research through the kind interest of Dr. Douglas Lilly. The plane belonged to Continental Airlines, and the project was generally directed by Mr. Paul Kadlec, Director of Meteorology of the airline.

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TABLE 1. Summary of flights used in the analysis.

Date	Time (h:min)	Route	Indicated altitude (m)	Pressure (mb)
1973				
October 27	15:36–18:57	Los Angeles–Chicago	11 885, 12 480	195, 180
29	16:48–19:48	Los Angeles–Chicago	11 290	215
29	21:17–24:39	Chicago–Los Angeles	11 875	195
30	17:45–19:23	Los Angeles–Chicago	11 280, 12 475	240, 180
30	22:09–25:32	Chicago–Los Angeles	10 655	240
31	22:44–26:11	Chicago–Los Angeles	11 875	195
31	16:33–19:42	Los Angeles–Chicago	11 245	220
November 6	21:32–24:56	Los Angeles–Honolulu	9 455	285
14	1:33– 5:02	Honolulu–Los Angeles	11 305	215
14	21:23–24:54	Los Angeles–Honolulu	10 670	240
23	21:16–24:13	Los Angeles–Honolulu	10 670	240
25	1:16– 3:22	Honolulu–Los Angeles	10 050	265
29	21:51– 1:12	Los Angeles–Honolulu	10 670	240
December 10	21:20–24:44	Los Angeles–Honolulu	10 670	240
12	1:22– 3:49	Honolulu–Los Angeles	10 065	260
12	21:50–25:18	Los Angeles–Honolulu	10 670	240
13	20:02–22:50	Honolulu–Los Angeles	11 278	215
14	3:30– 6:33	Los Angeles–Honolulu	10 670	240
14	20:03–23:37	Honolulu–Los Angeles	11 280	215
14	3:39– 7:06	Los Angeles–Honolulu	10 770	235
17	19:36–23:03	Honolulu–Los Angeles	10 060	260
19	7:53– 9:24	Los Angeles–Honolulu	10 670	240
19	19:44–21:59	Honolulu–Los Angeles	10 060	260
21	3:59– 7:14	Los Angeles–Honolulu	10 815	230
21	19:54–22:48	Honolulu–Los Angeles	11 280	215
22	20:22–23:23	Los Angeles–Chicago	11 280	215
23	1:07– 4:15	Chicago–Los Angeles	11 890	195
27	3:29– 6:55	Los Angeles–Honolulu	10 670	240
28	3:58– 7:18	Los Angeles–Honolulu	10 685	240
29	22:01– 1:22	Los Angeles–Honolulu	10 670	240
31	1:37– 4:25	Honolulu–Los Angeles	11 285	215
1974				
January 2	21:50–25:05	Los Angeles–Honolulu	10 670	240
3	19:52–23:00	Honolulu–Los Angeles	11 280	215
5	21:50–23:30	Los Angeles–Honolulu	10 670	240
7	0:45– 4:11	Honolulu–Los Angeles	10 065	260
7	21:21–23:39	Los Angeles–Honolulu	10 670	240
8	18:17–21:45	Los Angeles–Honolulu	10 670	240
9	0:57– 3:48	Honolulu–Los Angeles	11 290	215
10	9:25–12:50	Honolulu–Los Angeles	11 275, 11 890	215, 195

After some trial flights, routine measurements began late in October 1973. Unfortunately, the shortage of jet fuel caused Continental Airlines to take the plane out of service on 10 January 1974. Thus, only 39 flights produced satisfactory records. Nine of these flights crossed the Rocky Mountains, six of which were flown on three successive days in October. Hence, the total sample is small, and the results may be affected by peculiarities of the particular months during which the plane operated. Moreover, since the results are statistical, they are strictly valid only in the region of the flight path. Still, it was possible to segregate flights over high mountains from flights over plains and ocean with differences which are probably statistically significant.

A preliminary case study of five flights suggested that the direct dissipation measurements made by the MRI instrument were the most reliable indicators of turbulence intensity, as they were most consistent with subjective comfort of the observer. Vertical accelerations and air speed fluctuations were also considered but showed frequent large excursions in smooth flight, suggesting instrumental difficulties. In fact, a later analysis of all records showed no significant correlation between MRI index, on the one hand, and variances of air speed and airplane acceleration, on the other. The correlation between comfort index and MRI index was 0.6. Details of the flights are shown in Table 1. Note that there is some tendency for the oceanic flights to have been flown at lower altitudes than the land flights. This may have biased the results very slightly.

2. Theoretical considerations

From the available evidence, the authors have concluded that most CAT is produced by strong vertical wind shear on narrow, sloping frontal zones, sometimes called "baroclinic zones." Alternate mechanisms also exist, e.g. breaking of waves at critical layers without necesssarily strong wind shear (see Geller *et al.*, 1975). But this mechanism is judged to be less important in the regions of jet flight. Typically, strong baroclinic zones are a few hundred meters thick and a hundred km or so in horizontal width. The vertical wind shear must be strong enough to overcome the stabilizing influence of the temperature stratification; theoretically this condition requires that the Richardson number be less than 0.25. The evidence for this result, as well as the detailed mechanism of the formation of CAT, has been discussed, for example, by Dutton and Panofsky (1970).

If the baroclinic zones could be located from synoptic data, it should be possible to prepare quite accurate CAT warnings. Shapiro and Hastings (1973) have designed a method of analysis, based on potential temperature isopleths on vertical cross sections, which appears to be capable of locating the baroclinic layers. Lottes and Cahir (unpublished) at the Pennsylvania State University have prepared a program to carry on this type of analysis in real time, with very promising preliminary results. Still, such analyses are possible only every 12 hours, and temporal interpolation is a problem; further, radiosonde data over oceans and many other areas of the world are insufficient for this type of analysis. It is especially for these regions that we must consider the use of conventional analysis or satellite data.

The argument is that a strong vertical wind shear and a strong horizontal temperature gradient in a narrow zone will still be reflected in larger-than-average horizontal temperature gradients and vertical wind shears in larger areas and thicker layers. Unfortunately, the reverse is not true. If, for example, the horizontal temperature gradient is larger than average, this only implies a larger than average wind shear in a thick layer, which does not mean that a baroclinic layer exists just where the plane is flying. Hence statistics based on observations with small resolution often give essentially zero probability of CAT with weak gradients or shear, but, even with strong shear or gradients, the probabilities are only of order of 25%. The practical application of such results is that it may be possible to choose flight paths which are almost certain to be smooth, if several possible flight paths are economically reasonable.

Typical results of this sort were obtained by Woods and Panofsky (1973). They compared horizontal radiance gradients in the CO_2 band of Nimbus 4, in a channel with maximum weight at about 300 mb, with CAT probabilities.

A number of synoptic variables have been compared with each other as predictors of CAT: isobaric thickness gradients, vertical wind shears, isobaric temperature gradients, and horizontal radiance gradients. Of these four variables, the first two were rejected because their accuracies at the space and time of the flights could not be inferred with sufficient accuracy from the synoptic information. This left isobaric temperature gradients and radiance gradients. The former have the advantage that they can be obtained everywhere in the Northern Hemisphere at regular intervals, and can be interpolated relatively easily. But they become less accurate over areas of poor radiosonde coverage. The radiance gradients have the disadvantage that they cannot be determined well for many flight times, unless many more satellites are available than has been true in the past. Also, radiance gradients in cloudy areas do not represent temperature gradients. They have two advantages: one, that gradients are equally good everywhere in the world; and second, that horizontal gradients are based on measurements with the same instrument, so that instrumental or reduction errors are likely to cancel.

Therefore, in this report, CAT statistics will be compared both with satellite data and isobaric temperature analyses. The satellite data were obtained from NOAA 2, and the temperature gradients from a smoothed NMC analysis, made available from magnetic tapes stored at NCAR. In addition, an attempt was made to relate CAT statistics to gradients of temperature measured on the plane, corrected for the angle between plane trajectory and isotherms.

3. Treatment of the satellite data

Satellite data in the neighborhood of the flight paths were obtained in three channels (3, 4 and 8). Channel 4 observations were interpreted to give vertically averaged temperatures, with a weighting function given in Fig. 1. Maximum weight is given at about 400 mb, a level rather lower than desirable. Still, there is considerable weight near 200 mb, so that a shear layer near 200 mb should show up as a region of strong radiance gradients in channel 4.

Strong horizontal radiance gradients in channel 4 can be produced either by strong gradients in the vertically averaged temperatures, or they could signify contrasts between clouds and no clouds. Since we are interested only in the former, an attempt was made at the outset to exclude areas of high clouds from the analysis. This was done by analyzing first window radiances from channel 8. Regions of effective temperatures of less than 265 K were excluded from the further analysis. For the remaining regions, isopleths of effective temperature were drawn and smoothed.

Coincidences between satellite passes and available

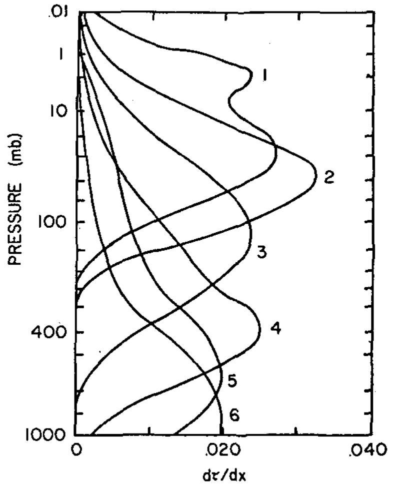

FIG. 1. VTPR CO_2 weighting functions for channels 1–6. Here τ is the atmospheric transmittance, and $x=p^{2/7}$. (From Department of Commerce's *Satellite Infrared Soundings From NOAA Spacecraft.*)

aircraft data are relatively rare. To maximize the amount of data available for comparison, without greatly deteriorating the quality of the statistical inferences, the following procedure was adopted:

1) If no satellite data were available within 4 h of flight time at any point, the data were ignored unless the movement was minimal.

2) If the time discrepancy was less than 2 h, the time difference was ignored, provided that the isotherms were expected to travel less than 1° latitude in that period. If the isotherms shifted more rapidly, the maximum time differential ignored was *equal to or less than* the time required to travel 1° latitude. In one important case, the isotherm pattern was extrapolated just beyond the region covered by the observations, so that temperature gradients at the edge of the pattern could be computed.

3) If the time differential falls between these limits, positions of radiance isopleths were interpolated between radiance maps drawn at intervals of 12 h, under the assumption that the spacing of isopleths is conservative.

The radiance gradients were divided by the sine of latitude so as to be proportional to the vertical gradient of the geostrophic wind vector. It has been shown by Zak and Panofsky (1968) that such radiance gradients represent differences between winds weighted by minus the derivative of the weight function (Fig. 1) above the maximum and the winds weighted by the derivative of the weight function below the maximum.

4. Analysis of conventional data

Smoothed NMC analyses of temperature and contour height were available at 200, 250 and 300 mb. A vertical interpolation was attempted. The maps were interpolated in time, either by simple linear interpolation, or by moving patterns at a uniform rate. Stratospheric portions were separated from tropospheric portions, as statistical relationships in those two regions are expected to be different.

Temperature gradients over 200 km were directly computed from the maps without additional smoothing, since the maps had already been smoothed sufficiently.

Temperature gradients in the stratosphere appeared to be unreasonably large. According to Hovermale (personal communication) the analyses contained an error at high levels. Hence, stratospheric NMC data were not used in the statistics.

Temperatures recorded on the plane were characterized by a great deal of high-frequency noise. Therefore, these temperatures were smoothed by averaging over three successive observations. From these smoothed temperatures, gradients over 200 km were computed. These were divided by the sine of the angle between the smoothed isotherms (on the NMC maps) and the flight paths, to yield temperature gradients normal to the isotherms.

5. Treatment of the turbulence data

After inspection of a limited data set, it was decided to treat 1 s averages as basic turbulence measurements. From these quantities, various statistics were computed over 3 min (~45 km). These included means and standard deviations of MRI dissipation (to be referred to as Q), air speed, vertical acceleration of the plane and comfort index (the subjective record of turbulence). The statistics were computed through the good offices of Mr. Erik Petersen, Danish Atomic Energy Commission, who was assigned to the project temporarily.

As was mentioned in the introduction, a preliminary case study had shown that the statistics of Q were best suited to describe the turbulence characteristics encountered by the plane. Quantitatively, Q is defined by

$$Q=[(\rho/\rho_0)\epsilon]^{\frac{1}{3}}, \tag{1}$$

where ρ is density, subscript 0 refers to sea level and ϵ is the rate of dissipation of energy into heat.

The output of the MRI instruments was checked qualitatively by estimating the total dissipation in the layer from 30 000 to 40 000 ft based on just the measurements during the 39 flights. This quantity is given approximately by

$$\rho_0 \Delta z \overline{Q^3}, \tag{2}$$

where Δz is the thickness of the layer and $\overline{Q^3}$ is averaged through the layer. The quantity $\overline{Q^3}$ was approximated by

$$\bar{Q}^3+3\bar{Q}\,\overline{Q'^2}, \tag{3}$$

which was evaluated over 3 min segments. Here it has been assumed that the distribution of Q in each 3 min segment is symmetrical, so that $\overline{Q'^3}$ vanishes (a prime denotes a deviation from a 3 min average). Numerically, evaluation of the terms in Eq. (2) resulted in an average dissipation between 30 000 and 40 000 ft of 0.66 W m^{-2}, in excellent agreement with independent estimates by Kung (1966) and by Trout and Panofsky (1969). Trout's data, adjusted to apply to fall and winter seasons, yield an average dissipation of 0.67 W m^{-2} in the same layer. Over the Pacific Ocean and mountains the average values for the dissipation were 0.48 and 2.2 W m^{-2}, respectively.

Although the relation between Q and a subjective description of turbulence intensity depends on the type of plane and other variables, the following categories (Table 2) are given for orientation purposes by MacCready *et al.* (1965).

The final statistical analysis was based on comparison of 200 km average Q values formed from the 3 min means with 200 km gradients of temperature or radiance.

6. Radiance gradients, temperature gradients and turbulence

Table 3 summarizes the statistical relationship between radiance gradients from channel 4 and Q values for all cases outside of clouds. The radiance gradients have been divided into four groups of approximately equal probability. The limits for the Q values divide the data into three categories corresponding to negligible, light and moderate (or stronger) turbulence, according to the recommendation of Table 2.

First, we see that 27 of the 33 cases of moderate or stronger turbulence occurred with greater than average temperature gradients; 18 of the 33 cases were associated with unusually strong radiance gradients.

If we consider the table in another way, we see that, for the strongest radiance gradients, the probability is 32% that the turbulence is light or stronger, and 15.5% that it is moderate or stronger. This contrasts with the column of weakest temperature gradients, where the corresponding probabilities are 4.5% and 0.9% respectively.

Thus, it is seen that, if it were possible to fly only in regions of weak radiance gradients, the probability of any turbulence is 5%, and that of moderate turbulence less than 1%, if we assume that the sample analyzed is representative. Whether the turbulence cases in weak temperature gradients are due to errors of analysis or by alternate mechanisms of CAT cannot be decided from the data. Recently, Geller *et al.* (1975) have suggested that "critical" levels could be responsible for some CAT. If this is correct, of course CAT could occur in regions of weak temperature gradients.

TABLE 2. Equivalence of Q values and subjective turbulence description.

Description	Q ($cm^{2/3}$ s^{-1})
Negligible	<0.8
Light	0.8– 1.9
Moderate	1.9– 4.5
Heavy	4.5–10.7
Extreme	>10.7

TABLE 3. Probability of different CAT intensities as function of temperature differences over 200 km determined from satellite channel 4 (all cases). Actual number of cases in parentheses.

	$\Delta T/\sin\varphi$ (°C)				
	<1	1–1.3	1.4–1.8	$\geqslant 1.9$	Total
$Q<0.8$	95.5 (106)	82.1 (110)	75.4 (92)	68.1 (79)	(387)
$0.8\leqslant Q<1.9$	3.6 (4)	14.2 (19)	17.2 (21)	16.4 (19)	(63)
$Q\geqslant 1.9$	0.9 (1)	3.7 (5)	7.4 (9)	15.5 (18)	(33)
Total	(111)	(134)	(122)	(116)	(483)

Channel 3 radiance gradients discriminate less well between flights with and without turbulence than Channel 4 radiances, as seen in Table 4. The reason is presumably that most of the weight in channel 3 is placed on stratospheric regions which frequently have temperature gradients with signs opposite to tropospheric gradients, where most of the flights took place.

Table 5 shows the relation between CAT statistics and temperature gradients over oceans and flat lands, as obtained from channel 4 satellite data and from the NMC analysis. The vast majority of the observations in Table 5 come from flights over oceans.

To save space, and to get larger numbers into each box, the categories of temperature gradients have now been reduced to three, again with nearly equal probability in each temperature gradient category.

Inspection of the table shows that radiance gradients obtained from satellites are superior to temperature gradients obtained from the NMC charts for the periods and flights here analyzed. Since the different pieces of information are not independent of each other, a rigor-

TABLE 4. Probabilities of different CAT intensities as functions of temperature differences over 200 km determined from satellite channel 3. Actual number of cases in parentheses.

	$\Delta T/\sin\varphi$ (°C)			
	<0.8	0.8–1.1	$\geqslant 1.2$	Total
$Q<0.8$	80.2 (134)	82.5 (118)	78.0 (135)	(387)
$0.8\leqslant Q<1.9$	12.0 (20)	8.4 (12)	17.9 (31)	(63)
$Q>1.9$	7.8 (13)	9.1 (13)	4.0 (7)	(33)
Total	(167)	(143)	(173)	(483)

TABLE 5. Probability of different CAT intensities over ocean and flatlands as function of temperature differences over 200 km determined from channel 4 radiance gradients, and from NMC analyses in the troposphere. Actual numbers of cases in parentheses.

	Satellite $\Delta T/\sin\varphi$(°C)				NMC troposhere $\Delta T/\sin\varphi$(°C)			
	<1.1	1.1–1.6	$\geqslant 1.7$	Total	<1.7	1.7–2.5	$\geqslant 2.6$	Total
$Q<0.8$	95.0	82.5	73.3		90.0	82.8	79.9	
	(115)	(104)	(88)	(307)	(504)	(365)	(353)	(1222)
$0.8\leqslant Q<1.9$	4.1	17.5	20.0		8.8	13.8	18.3	
	(5)	(22)	(24)	(51)	(49)	(61)	(81)	(191)
$Q\geqslant 1.9$	0.8	—	6.7		1.3	3.4	1.8	
	(1)	(0)	(8)	(9)	(7)	(15)	(8)	(30)
Total	(121)	(126)	(120)	(367)	(560)	(441)	(442)	(1443)

ous test regarding the "significant" differences of the two sets of data has not been made. Yet, qualitatively, it seems plausible that the differences are real. For example, for the satellite data, 8 of the 9 cases of moderate turbulence occur with the largest temperature gradients; the NMC temperature gradients discriminate less well. Again, according to the satellite data, the probability of any turbulence is only 5% in weak temperature gradients; in the corresponding NMC category, the probability is 10%. In strong temperature gradients the probability of CAT is 27% according to satellite data, and 20% according to conventional data. It is tentatively suggested that this apparent superiority of satellite data over oceans is due to lack of radiosondes in oceanic areas and consequently imprecise analysis.

Table 6 contains the same type of information as Table 5, but over mountains. Comparison of the two tables shows that CAT is more probable over mountains than over flat terrain, a fact shown also by some other studies. The probability of CAT over mountains is particularly great in strong temperature gradients: 42% according to the satellite data, and 48% according to conventional observations. Even with small temperature gradients, CAT probability is considerable over mountains. Altogether, NMC temperature gradients seem to discriminate slightly better between CAT and no CAT than satellite radiance gradients, presumably because over the Rockies conventional data are plentiful.

A tentative conclusion suggested by Tables 5 and 6 is that, in regions of good conventional coverage, conventional temperature gradients are better indicators of CAT than radiance gradients; the reverse is true in regions of poor conventional coverage. It should be remembered, however, that the statistics in Table 5 were based on data obtained during very few days.

A two-dimensional contingency table (Table 7) was also constructed, with both channel 3 and channel 4 as predictors of CAT. Table 7 shows that in regions of large channel 4 radiances, the probability of turbulence was larger for the category of smallest channel 3 gradients. In regions of large values in both channel 3 and 4, the probability of turbulence was sharply reduced.

A possible explanation of these results is that when radiance gradients are large in channel 4 but small in channel 3, the large vertical wind shear occurs near the flight level; but if radiance gradients are large in channel 3 and 4, it is most likely that the strong radiance gradients occur above flight level, or that weaker gradients are spread through a thick layer.

Table 8 shows CAT statistics in relation to temperature gradients determined from the temperature sensor on the plane corrected for the angle between the flight trajectory and the isotherms. Apparently, there is no clear relation between CAT probability and temperature gradient. For example, the probability of negligible turbulence is independent of the temperature gradient, and the probabilities of light or moderate turbulence

TABLE 6. As in Table 4 except over mountains.

	Satellite $\Delta T/\sin\varphi$(°C)				NMC troposphere $\Delta T/\sin\varphi$(°C)			
	<1.4	1.4–1.8	$\geqslant 1.9$	Total	<1.8	1.8–2.3	$\geqslant 2.4$	Total
$Q<0.8$	77.3	66.7	58.3		88.9	77.1	52.4	
	(34)	(22)	(21)	(77)	(32)	(27)	(22)	(81)
$0.8\leqslant Q<1.9$	11.4	15.2	5.6		2.8	14.3	14.3	
	(5)	(5)	(2)	(12)	(1)	(5)	(6)	(12)
$Q\geqslant 1.9$	11.4	18.2	36.1		8.3	8.6	33.3	
	(5)	(6)	(13)	(24)	(3)	(3)	(14)	(20)
Total	(44)	(33)	(36)	(113)	(36)	(35)	(42)	(113)

TABLE 7. Two-dimensional contingency table based on both channels 3 and 4 as predictors of turbulence. The number without parenthesis is the probability of Q values >1.5. The number in parenthesis is the number of cases in each category.

	$\Delta T/\sin\varphi$(°C)			
	<1.1	1.1–1.6	$\geqslant 1.7$	Total
$\Delta T/\sin\theta < 0.8$°C	0	1.7	34.9	
	(66)	(58)	(43)	(167)
0.8°C $\leqslant \Delta T/\sin\theta < 1.2$°C	2.9	14.3	10.5	
	(35)	(70)	(38)	(143)
$\Delta T/\sin\theta \geqslant 1.2$°C	0	5.7	14.3	
	(36)	(53)	(84)	(173)
Total	(137)	(181)	(165)	(483)

show no clear relation to this variable. This result is due, at least in part, to the large-amplitude erratic short-period temperature variations, and due to often small angles between flight path and isotherms.

TABLE 8. Probability of CAT of different intensities as function of temperature gradient over 200 km determined from aircraft thermometer, corrected for angle between flight path and isotherms. Actual number of cases in parentheses.

	$\Delta T/\sin\varphi$(°C)			
	<1.2	1.2–2.4	$\geqslant 2.5$	Total
$Q<0.8$	85.9	86.6	84.4	
	(432)	(354)	(412)	(1198)
$0.8 \leqslant Q < 1.9$	12.9	10.3	14.3	
	(65)	(42)	(70)	(177)
$Q \geqslant 1.9$	1.2	3.1	1.2	
	(6)	(13)	(6)	(25)
Total	(503)	(409)	(488)	(1400)

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