Meteorological Variables vs CAT in the Stratosphere: A Statistical Approach

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Areas of CAT encountered between 12 and 20 km alt on 46 flights of the XB-70 airplane over the western United States are related to measured (wind, temperature, etc.) and derived (vorticity, advection of temperature, time rates-of-change of variables, etc.) synoptic meteorological parameters. Relative frequency distributions of these parameters associated with CAT and non-CAT areas are considered for the 300-, 200-, and 100-mb levels. The meteorological parameters are shown to be associated with CAT and non-CAT areas in the stratosphere when selected limits of the variables were exceeded. The results were partially verified by a small sample of independent YF-12A aircraft data. The frequency distributions of the time rate-of-change of several variables for CAT and non-CAT areas, e.g., the lapse rate of temperature between 100 and 200 mb, were different although the distributions of the variables were not different. The results suggest that probable areas of CAT and non-CAT encountered by a supersonic airplane in the stratosphere over the western United States can be determined from synoptic-scale data. A possible procedure for forecasting CAT in the stratosphere over the western United States is suggested.

Introduction

MOST measurements of turbulence made by aircraft have been at altitudes below 12 km and at subsonic speeds. Turbulence data were obtained between 1965 and 1967 from the supersonic XB-70 airplane during about 50 flights while cruising at altitudes generally between 12 and 20 km over the western United States. The XB-70 was a large airplane with a flexible structure that caused it to be sensitive to turbulence. Much of the data has been discussed by Kordes and Love,[1] and presented by Ehernberger.[2]

Relatively little is known about the relationships between synoptic meteorological parameters and clear air turbulence (CAT) in the stratosphere, particularly as high as 15-20 km. Some relationships based on meteorological parameters measured by, or derived from, rawinsonde data are examined in this paper. The analysis was carried out at the 100-, 200-, and 300-mb levels for all XB-70 flights. These levels encompassed the flight altitudes on most of the days, and on the other days the flight altitudes usually did not exceed the 100-mb level by more than 2 or 3 km.

In this paper, it was assumed that synoptic meteorological conditions represented by the 100-, 200-, and 300-mb levels would indicate large-scale processes in which stratospheric perturbations suitable for the formation of CAT occur. When CAT forms, it may be advected away from its source region (Moore and Krishnamurti)[3] into a region where the large-scale conditions are not necessarily favorable for its production or continued existence. Thus, one should not expect a perfect relationship between CAT and local values of atmospheric parameters. Rather, it seems more likely that a greater degree of success could be expected when average synoptic meteorological conditions over an area are associated with CAT observed within the area. In addition, it is known that the intensity of CAT may vary considerably over horizontal distances of a few kilometers and vertical distances of less than 1 km.

The present research differs from much of the previous research in that areas of CAT of any intensity, as well as those without CAT, are associated with the distribution of average values of measured, derived, time rate-of-change of synoptic meteorological quantities, and combinations of these parameters. Intuitively, it seems that it should be easier to distinguish between areas with CAT and those without CAT than between different degrees of intensity within an area. Also, if a critical range of values of a parameter exists, it should be possible to isolate it from the statistical distributions of the parameters.

Background

The large-scale processes associated with CAT may be related directly or indirectly to many parameters obtained from rawinsonde data. Some of these parameters are: vertical and horizontal wind shear, static stability, vertical motion, deformation, various stability indices, Richardson's number, vertical gradient of kinetic energy, vorticity, and others (Scorer,[4] Badgley,[5] Lumley and Panofsky,[6] Colson and Panofsky,[7] Moore and Krishnamurti,[3] Endlich,[8] Ball,[9] Powell,[10] Colquhoun and Bourke,[11] Kronebach[12] and others). CAT is frequently encountered in small-scale sloping baroclinic layers of limited vertical and sometimes horizontal extent where conditions are favorable for small gradient Richardson numbers (Delay and Dutton,[13] and Dutton[14]); however, forecasts of CAT must usually be made from synoptic-scale data. The number of studies relating CAT to synoptic meteorological parameters is large. Because of space limitations, the results of only a few pertinent publications are considered here. Further information may be found in a summary report by Veazey,[15] and in a compilation of papers edited by Pao and Goldburg.[16]

Ball,[9] in an analysis of stratospheric HICAT data, found light-to-moderate CAT to be associated with irregularities in the temperature profile which included strong inversions as well as large lapse rates of temperature. A good relationship was found between the intensity of turbulence and various representations of static stability. Also, CAT was found to be associated with large horizontal gradients of temperature. There was a tendency for the intensity of CAT to increase with vertical vector wind shear, although the relationship was not as good as that found for static stability. Other researchers (see, e.g., Ehernberger,[2] and Mitchell and Prophet[17]) also observed CAT to be associated with irregularities in the temperature profile. The fact that CAT may be associated with temperature inversions is due to an increase in vertical vector wind shear (mechanical production) resulting from a sloping baroclinic layer (Dutton and Panofsky).[18] Positive buoyancy is responsible for CAT when the lapse rate of temperature becomes large.

An analysis of project HICAT data (Waco)[19] in the stratosphere between 13.7-21.4 km revealed that CAT was associated with low Richardson numbers resulting from large

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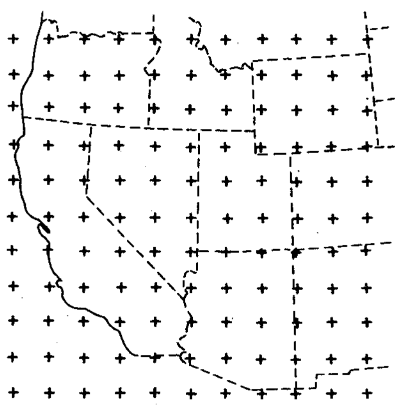

Fig. 1 Grid used in analyzing data from constant-pressure charts.

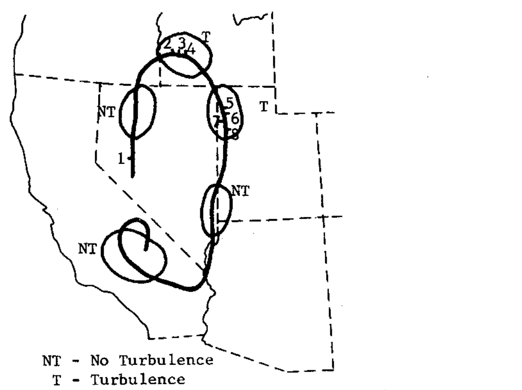

Fig. 2 An example of the classification of turbulent or nonturbulent areas for a flight made on Nov. 2, 1965 (flight track taken from Ehernberger, 1968. Numbers on flight track indicate turbulence encounters.)

decreases in temperature with height or strong vertical wind shears. When the Richardson number was <15, the ratio of turbulent to nonturbulent cases was about 4 to 1. Another analysis of HICAT data by Powell[10] measured over Australia between 200 and 50 mb showed a better relationship between CAT and the stability index defined by $V\Delta\alpha/\Delta z$ where V is wind speed, α wind direction, and z is height, than between CAT and the Richardson number (Ri). Endlich[8] found large values of $V\Delta\alpha/\Delta z$ and small values of Ri generally to be associated with CAT regions, but neither parameter appeared to be superior to the other.

A summary of results obtained from 4 five-day periods (Colquhoun)[20] indicates that the stability index defined above, vorticity, vorticity advection, and the CAT Index derived by Colson and Panosfky[7] were poor indicators of CAT. Better relationships were found between vertical wind shear and Richardson's number and CAT than between CAT and the parameters mentioned above. Kroneback[12] found the Richardson number to be a better parameter for outlining areas of expected CAT than vertical or horizontal wind shear, or vertical or horizontal gradients of kinetic energy. Richardson numbers less than 1 outlined about 40% of the reported occurrences of moderate or severe CAT. The wide range in results between CAT and the Richardson number has been summarized by Veazey.[15]

Analysis Methods

Computation of Synoptic Meteorological Parameters

Most of the flight altitudes for the XB-70 flights considered in this investigation were between the 200- and 100-mb levels. Synoptic charts were analyzed, in the usual manner, for the 300-, 200-, and 100-mb constant-pressure surfaces, and data were obtained from the analyzed charts by interpolation for each grid point shown in Fig. 1. The spacing between the grid points in this figure is approximately 158 km.

The following parameters were computed from 1200 GMT data for each grid point shown in Fig. 1 at each constant-pressure surface or as noted: Richardson number (200-100 mb), vector horizontal wind shear, lapse rate of temperature (200-100 mb), vector horizontal wind shear, lapse rate of temperature (200-100 mb), advection of relative vorticity, advection of temperature, temperature, CAT index (200-100 mb), zonal wind component, meridional wind component, scalar wind speed, relative vorticity, absolute vorticity, coriolis effect (βv), contour heights, vertical vector wind shear (200-100 mb), advection of absolute vorticity, horizontal gradient of temperature, and the time rate-of-change of each of these parameters over the 12-hr period encompassing each flight. Finite-difference approximations were used to evaluate each of these parameters. All derivatives in the horizontal plane were evaluated over a distance of $2\Delta x$ where Δx is the spacing between grid points, while those in the vertical direction (Richardson number, lapse rate of temperature, CAT Index, and vertical vector wind shear) were evaluated from data at the 100- and 200-mb levels (vertical distance ≈ 5km). The 300-mb data were not used in the evaluation of vertical derivatives because the tropopause was generally between 300 and 200 mb so that the gradients between these levels were not representative of stratospheric conditions. In the horizontal plane, the computed values were associated with the midpoint of the interval or array of points used in the computations. A

Table 1 Frequency distributions[a] of the height of the 300- and 200-mb surfaces associated with turbulent and nonturbulent areas

a) 300 mb

Areas	$H_{300} \times 10^2$ m: ≤87.9	88.0-88.9	89.0 89.9	90.0-90.9	91.0-91.9	92.0-92.9	93.0-93.9	94.0-94.9	95.0-95.9	96.0-96.9	≥97.0
Turbulent	0(0)	2(2)	5(5)	9(10)	20(21)	13(14)	20(21)	17(18)	7(7)	1(1)	0(0)
Nonturbulent	0(0)	2(3)	1(1)	6(8)	13(17)	14(18)	8(10)	19(24)	12(15)	3(4)	0(0)

b) 200 mb

Areas	$H_{200} \times 10^2$m: ≤114.9	115.0-115.9	116.0-116.9	117.0-117.9	118.0-118.9	119.0-119.9	120.0-120.9	121.0-121.9	≥122.0
Turbulent	1(1)	6(6)	8(9)	16(17)	14(15)	20(21)	16(17)	8(9)	5(5)
Nonturbulent	2(3)	2(3)	4(5)	10(13)	17(22)	7(9)	16(21)	11(14)	9(12)

[a]Percentage frequencies in parentheses. Number of areas: With turbulence—94; without turbulence—78.

Table 2 Empirical probabilities expressed in percent of CAT associated with synoptic meteorological variables beyond limits where frequency distributions differed for CAT and non-CAT encountered by the XB-70 airplane in the stratosphere.

Parameter	Limit	Percent verification
	300 mb	
Zonal wind speed (u)	$\geq 20\,\mathrm{m\,sec^{-1}}$	70(43/61)
Scalar wind speed (V)	$\geq 30\,\mathrm{m\,sec^{-1}}$	79(37/47)
Relative vorticity (ξ)	$< -5\times10^{-5}\,\mathrm{sec^{-1}}$	69(20/29)
Advection of temperature ($-\vec{V}\cdot\vec{\nabla}T$)	$< -10^{-4}\,{}^\circ\mathrm{C\,sec^{-1}}$	82(14/17)
Advection of relative vorticity ($-\vec{V}\cdot\vec{\nabla}\xi$)	$< -3\times10^{-9}\,\mathrm{sec^{-2}}$	77(17/22)
Magnitude of vector horizontal wind shear $\lvert\partial\vec{V}/\partial n\rvert$	$\geq 4.5\times10^{-5}\,\mathrm{sec^{-1}}$	71(17/24)
Local temperature change ($\partial T/\partial t$)	$< 0^\circ\mathrm{C\,sec^{-1}}$	68(28/41)
Local scalar wind change ($\partial V/\partial t$)	$< -1.6\times10^{-4}\,\mathrm{sec^{-2}}$	74(23/31)
Magnitude of local temperature advection change $\lvert\partial(-\vec{V}\cdot\vec{\nabla}T)/\partial t\rvert$	$> 2.0\times10^{-9}\,{}^\circ\mathrm{C\,sec^{-2}}$	69(35/51)
	200 mb	
Zonal wind speed (u)	$\geq 20\,\mathrm{m\,sec^{-1}}$	66(51/77)
Meridional wind speed (v)	$< -10\,\mathrm{m\,sec^{-1}}$	67(36/54)
Scalar wind speed (V)	$\geq 30\,\mathrm{m\,sec^{-1}}$	75(39/52)
Local height change ($\partial H/\partial t$)	$< -5\times10^{-4}\,\mathrm{m\,sec^{-1}}$	76(19/25)
Local scalar wind speed change ($\partial V/\partial t$)	$< -1.6\times10^{-4}\,\mathrm{sec^{-2}}$	64(16/25)
Coriolis effect (βv)	$< -1.6\times10^{-10}\,\mathrm{sec^{-2}}$	63(42/67)
	100 mb	
Zonal wind speed (u)	$> 12\,\mathrm{m\,sec^{-1}}$	63(52/83)
Absolute vorticity (η)	$> 1.2\times10^{-4}\,\mathrm{sec^{-1}}$	75(24/32)
Horizontal vector wind shear ($\partial\vec{V}/\partial n$)	$> 1.5\times10^{-5}\,\mathrm{sec^{-1}}$	67(12/18)
Local horizontal wind shear change ($\partial\vec{V}_n/\partial t$)	$< -2.0\times10^{-10}\,\mathrm{sec^{-2}}$	70(31/44)
Magnitude of local relative vorticity change $\lvert\partial\xi/\partial t\rvert$	$\geq 3.0\times10^{-10}\,\mathrm{sec^{-2}}$	65(43/66)
	100-200 mb	
Richardson number (R_i)	≤ 30	64(45/70)
Vertical vector wind shear ($\partial\vec{V}/\partial Z$)	$\geq 5.0\times10^{-3}\,\mathrm{sec^{-1}}$	73(27/37)
Local vertical wind shear change ($\partial\vec{S}/\partial t$)	$> 10^{-7}\,\mathrm{sec^{-2}}$	83(15/18)
Magnitude of local lapse rate change $\lvert\partial\gamma/\partial t\rvert$	$\geq 2.0\times10^{-8}\,{}^\circ\mathrm{C\,m^{-1}\,sec^{-1}}$	72(21/29)
Magnitude of local CAT Index change $\lvert\partial I/\partial t\rvert$	$> 4.0\times10^{-2}\,\mathrm{sec^{-1}}$	81(21/26)

scalar analysis was performed for each parameter, and the flight track of the aircraft superimposed to make it possible to associate average values of synoptic meteorological parameters with turbulent and nonturbulent areas.

Specifications of Turbulent and Nonturbulent Areas for Each Flight

Segments along each XB-70 flight track of 100-200 km in length in turbulent and nonturbulent air were selected with the centers of the segments separated by about the same or greater distances. Average values of meteorological variables were extracted from the analyzed fields corresponding to each segment of the flight track. Only those areas were selected which definitely fell into one category or the other. Single turbulence encounters of small lateral extent were not classified as turbulent, and neither were they included in the nonturbulent categories. An example of turbulent and nonturbulent areas for one flight is shown in Fig. 2. Using this method, there were 94 turbulent and 78 nonturbulent areas defined and used in this study.

The number of CAT and non-CAT areas selected was not based on the probability of individual occurrences of CAT nor on the percentage of time the airplane was in CAT. Even within a CAT area turbulence was patchy and usually encountered several times. The degree of intensity of turbulence was not considered in the specification of areas.

Frequency Distributions of Synoptic Meteorological Parameters Associated with Turbulent and Nonturbulent Areas

For each turbulent and nonturbulent area the average values of the synoptic meteorological parameters listed previously were determined from the data obtained for the 300-, 200-, and 100-mb levels regardless of the flight altitude of the XB-70. Frequency distributions of these variables were prepared for the turbulent and nonturbulent areas in terms of absolute frequencies, which represent the number of times turbulent or nonturbulent areas occurred for a given class interval of the variable, and the corresponding percentage frequencies, which represent the percentage of all turbulent or nonturbulent observations falling within the class interval. An example of the frequency distributions is shown in Table 1 for heights of the 200- and 300-mb levels.

The frequency distributions associated with turbulent and nonturbulent areas were analyzed for each variable to determine intervals of each variable by inspection over which the two frequency distributions differed. Except near the tails of the distributions, most of the ranges encompassed two or more class intervals of the variable. These distributions form the basis for establishing the association between turbulent and nonturbulent areas and meteorological parameters.

Results

Empirical Probabilities for the Occurrence of CAT

The variables whose distributions differed for CAT and non-CAT conditions, the limit beyond which the distributions differed, and the percent verification for CAT when the stated limits were exceeded are shown in Table 2. In the percent verification column, the numbers in parentheses represent the number of times CAT occurred when the variable exceeded the stated limit divided by the total number of times the limit was exceeded. Only those variables are shown for which the percent verification exceeded approximately 60% and included about 10% or more of the total observations. Because of the relatively small data sample, sampling fluctuations could account for some of the observed differences in the frequency distributions and, therefore, any one variable should not be used alone as a criterion for forecasting CAT. A forecasting procedure is suggested in the following section.

Many of the parameters presented in Table 2 appear in theories of CAT or indicate the presence of vertical motion which is known to be a key factor in setting up conditions favorable for CAT. For example, the Richardson number, vertical vector wind shear, and horizontal vector wind shear appear in various forms of the eddy energy equation. Parameters such as the advection of temperature, local temperature change, coriolis effect, and the advection of vorticity are related to vertical motion. The remaining parameters appearing in Table 2 may either be related to those appearing in the theories or indicative of vertical motion. Notably absent in Table 2 is the lapse rate of temperature, although it appears in the Richardson number, and the CAT Index although it is related to the vertical vector wind shear. It may be significant to note that the time rate-of-change of several variables appear in the table and that these parameters distinguish between CAT and non-CAT conditions to about the same extent as the more familiar parameters appearing in turbulence theories.

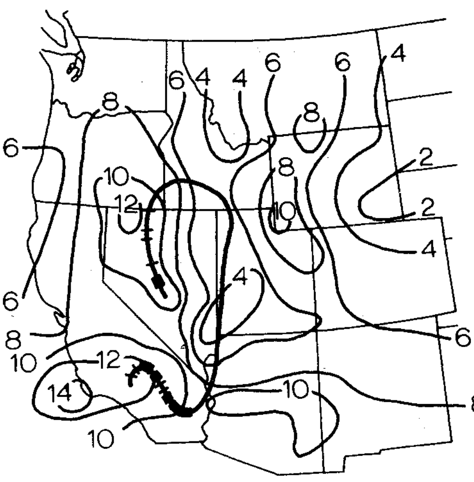

Fig. 3 Analysis of the number of parameters exceeding specified limits for Oct. 16, 1965. The flight track of the XB-70 shows where turbulence was encountered.

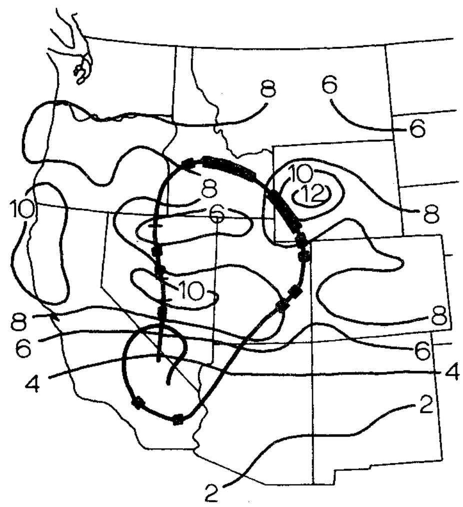

Fig. 4 Analysis of the number of parameters exceeding specified limits for Jan. 3, 1966. The flight track of the XB-70 shows where turbulence was encountered.

Verification of Results

An abundance of clear-air turbulence data in the stratosphere above 40,000 ft does not exist. There are some data available, however, from about 20 flights of the YF-12A airplane flying in the same general area and altitudes of the XB-70. Meteorological parameters associated with CAT and non-CAT areas for these flights were computed in the same manner as those for the XB-70 data, but because of the small sample size (about 20 areas each of CAT and non-CAT) it was not possible to establish frequency distributions as was done for the XB-70 data. Instead, the results obtained from the XB-70 were checked as follows using YF-12A data. The number of parameters which exceeded the limits presented in Table 2 associated with CAT and non-CAT areas were counted at each pressure level and for the 100-200-mb layer. It was found that when CAT occurred there were more limits exceeded than when CAT did not occur. The average number which was exceeded when CAT occurred for all layers was about 10 as compared to about 6 for the non-CAT areas. In addition, it was found that the number of parameters whose limits were exceeded near the flight altitudes was generally greater by a factor of 2-to-3 as compared with those in non-CAT areas. For example, when the flight level was between 100 and 200 mb the number of parameters whose limit was exceeded at 200 mb and between 100 and 200 mb was about 8-to-10 as compared with 2-to-6 when CAT did not occur. There were cases when these results were not obtained, but in these cases CAT was observed nearby (generally within 300 km).

Suggested Forecasting Procedure

A suggested procedure for using the XB-70 results to forecast CAT is as follows. Evaluate the parameters in Table 2, count the number of parameters exceeding the stated limits and prepare charts showing the areal distribution of these numbers. Some indication of the altitude where the CAT would be expected can be estimated by comparing the relative number of limits exceeded at the 300-, 200-, and 100-mb levels.

Examples of this procedure for two XB-70 flights are shown in Figs. 3 and 4. These figures contain isopleths drawn for the number of limits exceeded for variables presented in Table 2, and the flight tracks of the airplane showing where turbulence was encountered. The parameters were evaluated showing where turbulence was encountered. The parameters were evaluated from rawinsonde data encompassing the flight time. In both figures, most turbulence was encountered in regions where the number of limits exceeded is about 8 or more, and smooth flight conditions in regions of 6 or less. With the exception of the extensive turbulence encounter over Idaho in Fig. 4, the turbulent regions were encountered in or near regions where the maximum number of limits were exceeded. These results not only support the suggested forecasting procedure, but also the conclusions reached above from the YF-12A data. For both flights there was generally a greater percentage of exceedances near the flight altitude than below it, but additional research is needed before conclusions can be reached regarding the expected altitude of turbulence.

Conclusions

Frequency distributions prepared from synoptic meteorological parameters at 300, 200, and 100 mb associated with turbulent and nonturbulent areas encountered by the XB-70 airplane in the stratosphere (12-20 km), show that turbulence occurs more frequently than nonturbulence when the parameters exceed certain values. Most of the variables which distinguish between CAT and non-CAT conditions are those appearing in turbulence theories or are indicators of vertical motion which is known to be a key parameter in leading to conditions favorable for CAT. Fortunately, it is possible to evaluate most if not all the parameters from available synoptic data, thus making it possible to use the results to forecast CAT. The results obtained from the XB-70 data were verified by independent YF-12A data although the data sample was too small to reach definite conclusions on the basis of frequency distributions.

A suggested procedure for forecasting CAT based on the number of exceedances of limits of specified variables was verified for two flights of the XB-70 airplane. This procedure gives the geographical location of CAT regions.

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