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ATMOSPHERIC TEMPERATURE GRADIENTS RELATED TO CLEAR AIR TURBULENCE IN THE UPPER TROPOSPHERE AND LOWER STRATOSPHERE

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FOREWORD

One of the requirements of this research study was to collect data on commercial jet flights that coincided, as closely as possible, to the time and ground track of XB-70 test flights. Since the test flights were conducted over the western United States, it was necessary to request authorization from several airlines for the privilege of admission to the flight deck for this purpose.

I want to express my sincere appreciation to the following airlines for granting this request and cooperating in the data collection:

Flight Operations Department of Continental Airlines, Inc.
Flight Operations Department of National Airlines, Inc.
Flight Operations Department of United Air Lines, Inc.
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ATMOSPHERIC TEMPERATURE GRADIENTS RELATED TO CLEAR AIR TURBULENCE

IN THE UPPER TROPOSPHERE AND LOWER STRATOSPHERE

By Paul W. Kadlec

SUMMARY

Clear air turbulence of various intensities, especially at altitudes between 50,000 and 70,000 feet, has been encountered on numerous occasions by the XB-70 airplane flying at supersonic airspeeds. A preliminary review of some of these data indicated that high altitude turbulence was often associated with large vertical gradients in the temperature profile. Previously, an Eastern Airlines study reported a correlation between horizontal temperature gradients and significant clear air turbulence encountered by subsonic jet aircraft. Therefore, an investigation was made to determine whether any specific patterns in the vertical temperature profile were found to be associated with horizontal temperature gradients and/or significant clear air turbulence.

From the analysis of the temperature lapse rate at subsonic cruising altitudes, it was observed that 77% of the significant turbulence at reduced airspeed occurred below the tropopause. Furthermore, the temperature at the base of the tropopause inversion was colder than standard in 70% of the cases. No clearly defined relationship was established between the 12 hour height change of the tropopause and flight conditions from this data sample. The presence of the jet stream was found to be the most common feature of the upper air pattern associated with significant turbulence.

Temperature profiles above 100 millibars (53,000 feet) indicated a relationship between temperature increases in stratospheric inversions at a rate of 1.5°C or greater per 1000 feet and significant turbulence below 41,000 feet. Also, a gradual temperature increase with altitude of approximately 1.0°C or more per 1000 feet above the highest inversion (above 100 millibars) was found to have a similar correlation to significant turbulence at lower altitudes.

Data from five XB-70 test flights were analyzed in conjunction with information compiled on coincidental commercial jet flights to further explore the temperature/turbulence relationship. Moderate turbulence was encountered on only one flight of this series. The incident was associated with a gradual temperature rise of 1.0°C per 1000 feet in the vertical temperature profile above 50,000 feet in the turbulence area. Pronounced temperature inversions in the stratosphere were also found to be present near the time of the encounter.

Valuable pilot reports from multi-levels in the atmosphere are the only source of information currently available to verify the existence of the turbulence layers.

INTRODUCTION

When the XB-70 airplane began the supersonic portion of its flight test program, clear air turbulence was encountered for the first time by a large aircraft, comparable in size to the forthcoming generation of supersonic transports. Turbulence of various intensities has been encountered during some portion of a majority of test flights over the mountainous terrain of the western United States. Forecasting the phenomenon at altitudes primarily above 50,000 feet, has been a pioneering effort for the meteorologist concerned with test flight weather briefings due to the lack of research or previous experience at these altitudes.

Although the formation and life cycle of atmospheric turbulence which is not associated with convective activity, is still not clearly understood, research efforts by the government and industry have shown notable progress towards this goal in the last decade. Endlich, McLean, Reiter (ref. 1 and 2) and many others have contributed to the fund of knowledge being compiled on this subject which is of vital interest to the entire aviation community.

Eastern Airlines also began a research program in 1960, primarily to study the effects of non-convective turbulence on the operation of jet aircraft. Data for the study were collected by a research meteorologist, riding as an extra crew member, in the cockpit of commercial and military jet aircraft. Other relevant information was extracted from aircraft flight recorders, pilot reports, and flight photographs, to further enhance the quality and quantity of the data source.

During the course of this research, Kadlec (ref. 3) discovered that both certain rates as well as magnitudes of horizontal temperature change were indicative of impending significant turbulence encountered by an aircraft in level flight, especially in clear skies. A rate of temperature change of 1.0°C per minute, associated with a 2.0°C total change, was determined to be the minimum useful combination of values for detecting significant turbulence by an aircraft cruising near Mach .83. Furthermore, faster rates of change and larger total amounts of change were generally indicative of a higher intensity of turbulence. These temperature criteria, related to non-convective turbulence encountered in clear skies and in cirrus clouds, were observed to occur primarily in the troposphere at jet altitudes between 20,000 and 41,000 feet.

During the XB-70 flight test program, pilot reports and data recordings of rapid horizontal temperature changes associated with clear air turbulence have also been observed on occasion. In addition, specific patterns in the vertical temperature profile have been found to be associated with the higher intensities of turbulence encountered by the XB-70, especially above 50,000 feet. Ehernberger (ref. 4) noted that vertical temperature profiles frequently had pronounced lapse or strong inversion layers in these turbulent areas.

The objective of this research study was to determine whether any specific patterns in the vertical temperature profile were found to be characteristic to cases in which certain horizontal temperature gradients and/or turbulence have been encountered by subsonic jet aircraft in clear air. Data for this portion of the study were extracted from flight records compiled by the research meteorologist on 1,100 flights, together with supporting upper air information.

Also, additional flights were made in connection with the XB-70 test flights to collect data on a commercial jet flight that coincided, as closely as possible, to the flight time and ground track of the XB-70. These comparative flights were made over the western United States during the period of April through October, 1967, to identify and locate tropospheric features which might be related to turbulence encountered by the XB-70.

DATA ACQUISITION AND EVALUATION

The primary source of data for analysis was the in-flight collection of all pertinent information available from cockpit instrumentation and visual observation of sky conditions by the research meteorologist. Detailed horizontal and vertical cross sections and a flight data log were completed during the course of each flight. Photographs of sky conditions were also taken to provide a visual reference to certain cloud patterns of interest. Pilot reports from other aircraft were recorded to provide additional information on atmospheric conditions in the area. These data were further supplemented with surface, radar, upper air, and radiosonde information relative to the time and track of the data collection flight.

Throughout the report, the term sky conditions will be used to describe the physical appearance of the atmosphere through which the aircraft is passing, indicating either clear skies or the presence of some amount of cloud cover. The term flight conditions refers to the response of the aircraft to either smooth air or turbulence of some intensity.

Since this research study was concerned with temperature and/or turbulence behavior patterns relative to supersonic aircraft operating generally above 50,000 feet, a search was made through existing data for those cases in which the subsonic flight operated in clear skies. Surface and radar charts were studied to further eliminate those cases that were associated with convective activity. The data revealed 98 cases in which the aircraft encountered horizontal temperature gradients causing a minimum temperature change of 2.0°C or more at a rate which equalled or exceeded 0.5°C per minute and/or significant clear air turbulence. Of this total, 90 cases were in clear skies with no clouds above 20,000 feet. In the remaining 8 cases, the flight was also on top of all clouds, but with some amount of cirrus below.

Radiosonde charts were plotted for all cases utilizing the Northern Hemisphere Data Tabulations Daily Bulletins, 35 mm microfilm of this same information, and teletype data. Radiosonde charts were plotted that coincided as closely as possible to both the time and the area of interest of each individual case of turbulence and/or temperature change. When the data were available, temperature, wind, and tropopause information was plotted from 500 (18,000 feet) to 10 millibars (mb) (102,000 feet). Temperature profiles from 162 radiosonde soundings in both the troposphere and stratosphere were then available for comparisons of lapse rate, tropopause and other inversions, and isothermal layers. Also, the tropopause data either 12 hours earlier, or 12 hours later than the radiosonde closest to flight time was recorded. If a flight departed within six hours after the radiosonde time, the tropopause information for the next radiosonde 12 hours later was recorded. Conversely, if a flight departed within six hours before the radiosonde time, the tropopause information from the radionsonde 12 hours earlier was noted. The vertical wind shear was also recorded for each Rawin station, with the information available from the Maximum Wind and Shear Analysis Chart prepared by the National Meteorological Center.

Notations were made concerning the presence of certain identifiable features from the upper air charts that were in proximity to the temperature and/or turbulence event. These included jet streams, troughs, ridges, closed lows, converging, and zonal flow patterns.

Temperature profiles above 100 mb (53,000 feet) were also examined to determine lapse rate, secondary tropopause and inversions, isothermal layers, and other behavior patterns which could be related to high altitude turbulence. However, no verifying pilot reports from aircraft above 41,000 feet were available to associate these temperature patterns with flight conditions.

Since April 1967, five additional data collection flights made in connection with XB-70 test flights provided a new source of valuable information for a comparative analysis. Reports of flight conditions from altitudes above 41,000 feet encountered by the XB-70 were made available by the National Aeronautics and Space Administration. Tape recordings of pilot comments and vertical acceleration data from the XB-70 flights were reviewed to obtain information pertinent to the research study.

RESULTS

Since flight conditions encountered by both subsonic and supersonic aircraft were of primary concern in this report, the analysis of all data was directed toward determining which aircraft and atmospheric parameters would indicate either smooth air or some degree of clear air turbulence. Flight conditions were divided into six categories: smooth or very light chop, light chop or turbulence, and light to moderate chop or turbulence at cruising airspeed; light chop or turbulence, light to moderate chop or turbulence, and moderate chop or turbulence at reduced airspeed.

Reducing airspeed is the first and often the quickest method available to the flight crew to minimize the effects of turbulence. Normally a reduction in airspeed to maintain Mach .80 or 280 knots indicated airspeed, whichever is lower, is the desired airspeed for turbulence penetration. However, it is a target speed rather than a limiting value. It has been observed that a reduction from cruising to turbulence penetration airspeed will in effect reduced the reported turbulence by one intensity category.

Table 1 reveals the first comparison between flight conditions and average horizontal temperature data. The division of cases with regards to flight conditions in the table is as follows:

<u>Cruising Airspeed</u>

Smooth - Very Light Chop	56 cases
Light Chop	19 cases
Light - Moderate Chop	1 case

<u>Reduced Airspeed</u>

Light Chop	13 cases
Light - Moderate Chop	8 cases
Moderate Chop	1 case

TABLE 1. RELATIONSHIP BETWEEN FLIGHT CONDITIONS AND HORIZONTAL TEMPERATURE GRADIENTS

AVERAGE HORIZONTAL TEMPERATURE GRADIENTS

	AVERAGE RATE OF TEMPERATURE CHANGE °C/MIN	AVERAGE TOTAL TEMPERATURE CHANGE °C
CRUISING AIRSPEED		
Smooth - Vry. Lt. Chop	0.6°C/Min.	2.9°C
Lt. Chop	0.7°C/Min.	2.9°C
Lt. - Mdt. Chop	0.7°C/Min.	4.0°C
REDUCED AIRSPEED		
Lt. Chop	0.9°C/Min.	4.0°C
Lt. - Mdt. Chop	0.9°C/Min.	3.1°C
Mdt. Chop	0.9°C/Min.	5.0°C

The average rate of temperature change increased as the turbulence intensity increased in a characteristic pattern. The same general relationship applied to the average total change in temperature.

These data, recorded on subsonic aircraft in clear skies, revealed that horizontal temperature gradients which produce a change of at least 3.0°C at an average rate of 0.9°C per minute were associated with significant turbulence. The total amount of temperature change of 2.0°C per minute at a rate of 1.0°C as reported previously was associated with significant turbulence events that occurred in both clear skies and jet stream cirrus.

It has also been observed that there is no apparent relationship between the occurrence of turbulence and the direction of the temperature change (ref.3). Significant turbulence has been indicated by both an increase or a decrease in temperature at cruising altitude. In a majority

TABLE 2. RELATIONSHIP BETWEEN FLIGHT CONDITIONS AND VERTICAL TEMPERATURE GRADIENTS

VERTICAL TEMPERATURE GRADIENTS

	Average °C Change/1000 ft. ABV. Flt. Alt.		Average °C Total Change at Constant Lapse Rate ABV. Flt. Alt.		Average Thickness Constant Lapse Rate Layer ABV. Flt. Alt.		Average °C Change/1000 ft. BLO Flt. Alt.		Average °C Total Change at Constant Lapse Rate BLO Flt. Alt.		Average Thickness Constant Lapse Rate Layer BLO Flt. Alt.	
CRUISING AIRSPEED	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase
Smooth - Vry. Lt. Chop	-1.7	+0.8	-4.9	+2.3	39 mb	29 mb	-0.7	+1.8	-1.2	+5.2	20 mb	46 mb
Lt. Chop	-1.4	+0.3	-3.9	+1.8	27 mb	24 mb	-0.2	+1.6	-0.3	+6.3	15 mb	47 mb
Lt. - Mdt. Chop	-1.6	0	-3.0	0	17 mb	0 mb	0	+2.0	0	+4.0	0 mb	27 mb
REDUCED AIRSPEED	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase
Lt. Chop	-1.9	+0.3	-4.5	+1.2	34 mb	28 mb	-0.4	+1.8	-0.7	+6.9	13 mb	57 mb
Lt. - Mdt. Chop	-2.0	0	-5.1	0	38 mb	0 mb	0	+2.3	0	+11.8	0 mb	81 mb
Mdt. Chop	-1.8	0	-2.1	0	18 mb	0 mb	0	+1.6	0	+4.1	0 mb	34 mb

of instances, the temperature change began in sufficient time to provide the flight crew with a brief warning period of 1/2 to 4 minutes before the turbulence began. Therefore, the remote sensing of both the rate and total amounts of temperature change by radiometers or other types of instrumentation could provide valuable information for the development of an airborne device to detect clear air turbulence.

During the analysis of the radiosonde charts associated with the temperature and/or turbulence events (ref. 5), several tabulations were made to investigate the possible association of vertical temperature patterns to the turbulence area. These are summarized in Table 2 by comparing the average temperature change and thickness of the layer both above and below flight altitude, with the six classifications of flight conditions. A number of comparisons are possible from the information presented in the table. With regards to the average lapse rate, it may be noted that the decrease in temperature per 1000 feet above flight altitude and the increase in temperature below flight altitude is significantly larger than the converse situation that indicates the presence of inversions or isothermal layers. Also, the average total change in temperature at a constant lapse rate decreases above and increases below the flight altitude a greater amount than the total change in the isothermal or inversion layers.

With the important addition of thickness of the constant lapse rate layer to the temperature information, flight conditions at reduced airspeed show a clearer relationship to the temperature lapse rate rather than to isothermal layers and inversions. However, flight conditions at cruising airspeed are found to be more equally distributed among temperature lapse rates, isothermal layers, and inversions including the tropopause. Therefore, from the analysis of this particular collection of data, it may be deduced that significant turbulence that effects subsonic aircraft occurs primarily below the tropopause.

Table 3 also shows this relationship. Seventy-seven percent of the significant turbulence at reduced airspeed occurred below the tropopause and 23% above. At cruising airspeed, 65% of the smooth or light turbulence occurred below the tropopause and 35% above.

An analysis was made to determine if any relationship existed between tropopause temperatures which were either warmer or colder than standard and flight conditions. Table 3 indicates the preference of tropopause temperatures for colder than standard values. Regarding flight conditions at cruising airspeed, 78% of the tropopause temperatures were colder than standard, 12% warmer than standard, and 10% at standard. For flight conditions at reduced airspeed, 70% of the tropopause temperatures were colder than standard, 23% warmer, and 7% at standard.

Continuing the investigation of the behavior of the tropopause, an analysis was conducted to determine if significant turbulence could be related to 12 hour tropopause height and temperature changes. A number of comparisons were made including height increases with resulting colder or warmer temperatures, height decreases with colder or warmer temperatures, and these combinations of height and temperature both 12 hours before or 12 hours after the radiosonde which corresponded to the actual flight time.

As seen in Table 4, there is no readily apparent association between the tropopause height and temperature changes and smooth or light chop flight conditions. Although some of

TABLE 3. RELATIONSHIP OF TROPOPAUSE HEIGHT AND TEMPERATURE TO FLIGHT CONDITIONS

	TROP. ABOVE FLIGHT ALTITUDE	TROP. BELOW FLIGHT ALTITUDE	TROP. TEMPERATURE COLDER than STANDARD	TROP. TEMPERATURE WARMER than STANDARD	TROP. TEMPERATURE STANDARD
CRUISING AIRSPEED					
Smooth - Vry. Lt. Chop	56	35	70	11	10
Lt. Chop	24	8	25	5	2
Lt. - Mdt. Chop	2	0	2	0	0
REDUCED AIRSPEED					
Lt. Chop	12	5	13	4	0
Lt. - Mdt. Chop	10	2	7	3	2
Mdt. Chop	2	0	2	0	0

TABLE 4. RELATIONSHIP BETWEEN TROPOPAUSE HEIGHT AND TEMPERATURE CHANGE TO FLIGHT CONDITIONS

CRUISING AIRSPEED

	AVERAGE TROPOPAUSE HEIGHT AND TEMPERATURE CHANGE — 12 Hours Earlier than Flight Radiosonde				AVERAGE TROPOPAUSE HEIGHT AND TEMPERATURE CHANGE — 12 Hours Later than Flight Radiosonde			
	Higher/Colder Ft./°C	Higher/Warmer Ft./°C	Lower/Colder Ft./°C	Lower/Warmer Ft./°C	Higher/Colder Ft./°C	Higher/Warmer Ft./°C	Lower/Colder Ft./°C	Lower/Warmer Ft./°C
Smooth - Vry. Lt. Chop	+4500'/-6.1°	+1400'/+3.4°	-2600'/-3.5°	-2200'/+6.6°	+4200'/-4.5°	+2700'/+2.5°	-800'/-1.9°	-3700'/+3.8°
Lt. Chop	+3200'/-2.3°	+100'/+5.2°	-1800'/-1.7°	-2500'/+2/0°	+2700'/-5.6°	+5500'/+4.2°	-1400'/-6.1°	-4100'/+5.2°
Lt. - Mdt. Chop	--/--	--/--	--/--	--/--	--/--	--/--	--/--	-3400'/+3.9°
Total Radiosondes	19	5	7	19	17	5	10	20

REDUCED AIRSPEED

	Higher/Colder Ft./°C	Higher/Warmer Ft./°C	Lower/Colder Ft./°C	Lower/Warmer Ft./°C	Higher/Colder Ft./°C	Higher/Warmer Ft./°C	Lower/Colder Ft./°C	Lower/Warmer Ft./°C
Lt. Chop	+8200'/-9.6°	--/--	--/--	-1900'/+5.6°	+4400'/-4.3°	--/--	--/--	-5000'/+7.2°
Lt. - Mdt. Chop	+10,300'/-6.3°	--/--	--/--	-6900'/+5.3°	+2900'/-9.0°	--/--	--/--	-2500'/+8.0°
Mdt. Chop	--/--	--/--	--/--	--/--	+3100'/-2.3°	--/--	--/--	-400'/+1.4°
Total Radiosondes	9	0	0	8	9	0	0	3

the height changes associated with turbulence at reduced airspeed were somewhat larger in magnitude, the amount of data is smaller for this category. The larger average temperature change follows the height change pattern in general. It may be noted that significant turbulence was associated with 100% of the radiosondes that exhibited either an increase in tropopause height with a decrease in temperature or a decrease in height with an increase in temperature. Smooth or light to moderate chop at cruising airspeed was associated with the same height and temperature relationship in 76% of the radiosondes 12 hours earlier than the flight radiosonde. This amount was reduced slightly to 71% for the same height and temperature relationship at cruising airspeed 12 hours after the flight radiosonde.

A data analysis was made utilizing vertical wind shear information obtained from the Layer of Maximum Wind and Shear Analysis Chart prepared by the National Meteorological Center. Average shear values of 3.2 and 4.3 knots shear per 1000 feet were found to be associated with smooth and light to moderate chop flight conditions respectively at cruising airspeed. For light and moderate turbulence at reduced airspeed, these values increased slightly to 3.9 and 5.5 knots shear respectively per 1000 feet above and/or below the maximum wind level.

Features of upper air patterns associated with turbulence cases were also identified. Although the 98 cases of temperature change and/or turbulence that were investigated occurred over the United States, Canada, western Atlantic Ocean, and Gulf of Mexico, the majority occurred east of the Rocky Mountains. Therefore, mountain wave experience was limited. In those cases where significant turbulence at reduced airspeed was encountered, the jet stream was observed to be in the immediate area or within 100 nautical miles, 38% of the time. Jet streams farther distant than 100 nautical miles, closed lows, upper troughs, converging flow patterns and ridges comprised the balance of influencing upper air features that were associated with significant clear air turbulence.

The temperature patterns on the radiosonde charts above 100 mb were also investigated. However, no pilot reports of flight conditions above 41,000 feet, associated with this data source, were available for verification. Three categories of vertical temperature profiles were established:

Inversions	— Temperature Change >1.0°C/1000 feet
Gradual Temperature Changes	— 0.3°C to 1.0°C/1000 feet
Isothermal Layers	— Temperature Change ⩽0.2°C/1000 feet

Inversions and secondary tropopause layers were found to occur in the majority of cases analyzed. Two separate inversions, each with vertical temperature gradients greater than 1.0°C per 1000 feet with warming trends between 100 and 10 mb, were rather prevalent. Significant variations in temperature at these levels were rather common with observed gradual temperature rises ranging from -70°C to -45°C. Temperatures 15 degrees colder than standard and 20 degrees warmer than standard were also observed. Large isothermal layers in the stratosphere, greater in depth than 30 mb, occurred less than 25% of the time.

Table 5 summarizes the occurrence of the three most common temperature profiles above 100 mb that were observed on the radiosonde charts. Temperature and tropopause inversions were

TABLE 5. TEMPERATURE PROFILES ABOVE 100 MB (53,000 FEET) RELATED TO FLIGHT CONDITIONS BELOW 180 MB (41,000 FEET)

	ISOTHERMAL	GRADUAL TEMPERATURE RISE	TROPOPAUSE OR TEMPERATURE INVERSION
		CRUISING AIRSPEED	
Smooth - Vry. Lt. Chop	15%	33%	52%
Lt. Chop	21%	21%	58%
Lt. - Mdt. Chop	0%	0%	100%
		REDUCED AIRSPEED	
Lt. Chop	10%	32%	58%
Lt. - Mdt. Chop	8%	33%	59%
Mdt. Chop	0%	0%	100%

associated with flight conditions of all intensities a majority of the time. From this small sample of data, an average increase in temperature in the inversion of 1.5°C or more per 1000 feet above 100 mb was found to be associated with significant turbulence below 41,000 feet. Also a gradual temperature increase with altitude of approximately 1.0°C per 1000 feet above 100 mb or above the highest inversion, appeared to provide a similar correlation to significant turbulence at the lower altitudes. Since this information was obtained from temperature and/or turbulence cases, a similar analysis is needed for smooth air and smooth temperature gradient events to properly evaluate the significance of these results.

The analysis of the five simultaneous XB-70 — commercial flights included the important addition of pilot reports from several altitudes to determine flight conditions over comparable routes.

The initial commercial/XB-70 flights of the series, on June 2, 1967, did not encounter any turbulence greater than light chop at cruising airspeed between 32,000 and 41,000 feet.

A gradual temperature rise of less than 1.0°C per 1000 feet characterized the temperature soundings above 100 mb in the vicinity of the flight tracks. No significant horizontal temperature changes were encountered by the commercial flight.

Similar flight conditions were encountered by the XB-70 during the second test flight on June 22, 1967. However, one radiosonde station 6 hours before the flight, reported an inversion at 56,000 feet with a temperature rise of 5.0°C in 1000 feet while the aircraft encountered light chop 6000 feet below the inversion. Six hours later there were no inversions above 50,000 feet at this station. Within 30 minutes of the XB-70 encounter of light chop, the commercial flight, approximately 275 nautical miles to the northwest, encountered light to moderate turbulence at reduced airspeed at 35,000 feet.

A horizontal temperature change of 1.0°C in one minute was encountered coincidental to the beginning of the turbulence. An immediate descent was begun to avoid the turbulence as well as prepare for the landing at Seattle. Therefore, it was impossible to record the total amount of horizontal temperature change in the turbulence area. Turbulence of the same intensity was experienced by the commercial flight two hours later and 150 nautical miles south of the first encounter. A horizontal temperature change of 3.0°C in 3 minutes was experienced upon encountering the turbulence.

This turbulence was associated with a tropopause height change that increased 9,400 feet in height in 12 hours, with a corresponding 15.0°C decrease in temperature. A 300 mb (30,000 feet) closed low with a polar jet stream approximately 100 nautical miles south of the area of turbulence dominated the upper air pattern over the Pacific Northwest.

The third and fourth comparative flights on August 24 and September 8, 1967, respectively, encountered smooth to light chop flight conditions at cruising airspeed between 30,000 and 59,000 feet. No significant horizontal temperature changes or turbulence were experienced by the commercial flight. The vertical temperature profiles above the tropopause were generally characterized by gradual temperature rises with no significant inversions.

On the fifth comparative flight on October 11, 1967, moderate turbulence was encountered by the XB-70 for the first time during this data collection period. Five areas of light chop at or below 55,000 feet were encountered over Nevada. Over south-central Idaho, moderate turbulence was experienced at Mach 2.4 for 10 to 15 seconds at 56,000 feet.

An analysis of the Boise radiosonde at 1200Z revealed a gradual temperature rise of 1.0°C per 1000 feet with no inversions above 50,000 feet. This same profile characterized the vertical temperature soundings at Winnemucca, Nevada, Salt Lake City, Utah, and Ely, Nevada at 1200Z or about five hours before the turbulence encounter. However, at 0000Z or seven hours after the turbulence incident, Winnemucca displayed a pronounced inversion between 55,500 and 57,200 feet with a 10.0°C temperature rise in this layer. The Boise 0000Z sounding ended at 39,500 feet while Salt Lake City at the same time, displayed an inversion between 53,100 and 57,500 feet with a 7.0°C temperature rise.

The commercial flight at 35,000 feet and approximately 200 nautical miles west of the turbulence area, had smooth flight conditions with a 2.0°C temperature change in 4 minutes.

In conjunction with the post flight analysis, it was noted that scattered convective activity was present at the time of the XB-70 flight, from northern to south-central Idaho with radar tops reported at 26,000 feet near Boise. Furthermore, on the second portion of the commercial flight, and approximately 3 hours after the turbulence incident, well-defined mountain wave lenticular clouds were observed east of the Cascade and Sierra-Nevada ranges. The upper air pattern displayed a broad trough off the California coast with west-southwesterly flow over the Pacific Northwest. A polar jet stream was located over central Washington with a velocity of 135 knots at 33,000 feet.

This turbulence encounter is an example of how upper air data may be more efficiently analyzed with the valuable addition of pilots reports from various levels of the atmosphere. The occurrence and dimensions of turbulence layers associated with recognizable features of atmospheric behavior can, at the present time, be verified only by the passage of the aircraft through the area.

CONCLUSIONS

Horizontal and vertical temperature gradients have been found to be associated with clear air turbulence that occurs in the upper troposphere and lower stratosphere. Horizontal temperature gradients recorded by subsonic aircraft in clear skies have revealed that a temperature change of at least 3.0°C occurring at an average rate of 0.9°C per minute is associated with significant turbulence.

Analyses of vertical temperature profiles in conjunction with subsonic flights indicate that 77% of the significant turbulence occurred below the tropopause and 23% above. Tropopause temperatures colder than standard were associated with significant turbulence at reduced airspeed in 70% of the temperature profiles that were analyzed.

No clearly defined relationship was established between 12 hour height changes of the tropopause and flight conditions. Although some of the height changes associated with turbulence at reduced airspeed were somewhat larger in magnitude, the data sample was too small to establish a definite pattern.

Since the vertical wind shear analysis was extracted from the Layer of Maximum Wind and Shear Analysis Chart prepared by the National Meteorological Center, the average shear values were rather low when compared to narrow shear layers near the turbulence area. Turbulence at reduced airspeed varying from light to moderate chop was associated with layer of maximum wind average shear values of 3.9 to 5.5 knots per 1000 feet respectively.

Investigation of temperature profiles above 100 mb revealed significant variations in temperature. Gradual temperature rises ranging from -70°C to -45°C were rather common. From this small sample of data, an average temperature increase in the inversions above 100 mb of 1.5°C or greater per 1000 feet was found to be associated with significant turbulence below

41,000 feet. In addition, a gradual temperature increase with altitude of approximately 1.0°C per 1000 feet above 100 mb or above the highest inversion, also appeared to be correlated to significant turbulence. A similar analysis is needed for smooth air cases with no temperature gradients to properly evaluate the full significance of these results.

The jet stream was found to be present in the area of clear air turbulence in 38% of the cases, which was more than any other single upper air feature. Jet streams also influenced changes in height of the tropopause, which on some occasions amounted to more than 10,000 feet in 12 hours. These height changes in turn, produced changes in stability in the lower stratosphere. Further investigation of jet stream, mountain wave, and tropopause relationships to stratospheric turbulence is encouraged. However, multi-level pilot reports must accompany research of this nature to verify the presence of significant turbulence that often occurs in selective layers.

Temperature information obtained by aircraft in flight has provided at least one method of detecting impending turbulence. The remote measurement of specific rates and total amounts of temperature change for both subsonic and supersonic aircraft by radiometers or other types of instrumentation could provide valuable information in the development of an airborne device for detecting clear air turbulence.

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REFERENCES

1. Endlich, Roy M., and McLean, George S.: Analyzing and Forecasting Meteorological Conditions in the Upper Troposphere and Lower Stratosphere. AFCRL-TN-60-262. U. S. Air Force, April 1960.

2. Reiter, Elmar R.: Nature and Observation of High-Level Turbulence Especially in Clear Air. (Contract No. N 189(188)55120A), U. S. Weather Research Facility, December 1962.

3. Kadlec, Paul W.: Flight Observations of Atmospheric Turbulence. (Contract No. FA66WA-1449), Federal Aviation Agency, June 1966.

4. Ehernberger, L. J.: Meteorological Aspects of High Altitude Turbulence Encountered by the XB-70 Airplane. Proceedings of the 3rd National Conference on Aerospace Meteorology, New Orleans, La., May 6 - 9, 1968.

5. Air Weather Service: Tropopause Analysis and Forecasting. AWSTR 105-86, U. S. Air Force, March 1952.