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CLEAR AIR TURBULENCE  
FORECASTING TECHNIQUES

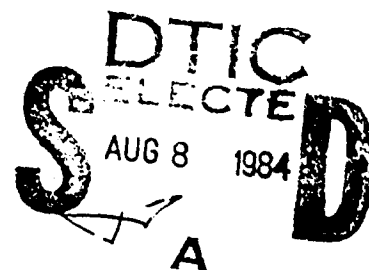
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FEBRUARY 1984  
(REVISED)

UNITED STATES AIR FORCE  
AIR WEATHER SERVICE (MAC)  
AIR FORCE GLOBAL WEATHER CENTRAL  
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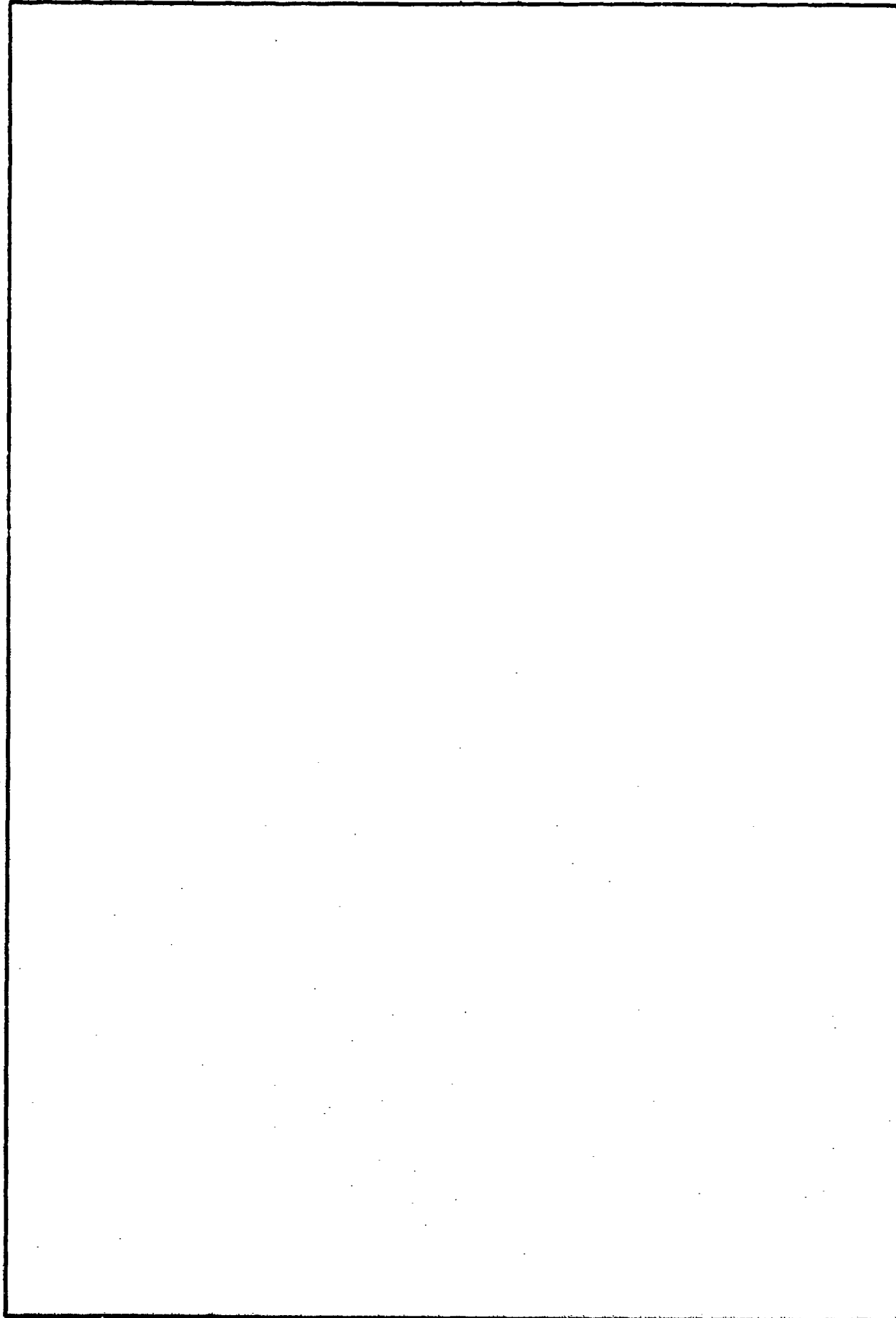


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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br>This technical note is a compilation of the latest clear air turbulence (CAT) forecasting techniques used by AFGWC forecasters. It is a comprehensive treatment of a complex and unique forecasting subject. The methods are relatively easy to follow and are a step-by-step approach to forecasting this weather phenomenon. This document replaces AFGWC Tech Memo 70-7 "Turbulence Forecasting Procedures" by Capt Paul T. Burnett, 15 Dec 70. Over the past 15 years the automated CAT routines have been totally replaced. Also, synoptic rules of thumb and model relationships are now better understood and documented. |                                     |                                                           |

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## PREFACE

This note is a compilation of the latest clear air turbulence (CAT) forecasting techniques used by the Air Force Global Weather Central (AFGWC) forecasters. It is a comprehensive treatment of a complex and unique forecasting subject. The methods are relatively easy to follow and are a step-by-step approach to forecasting this weather phenomenon.

The main references are Sorenson and Beckwith's (1975) CAT classification system and Hopkins' (1976) techniques for forecasting nonconvective turbulence. In addition, Holcomb's (1976) memorandum "Jet Stream Analysis and Turbulence Forecasting" provided much insight into jet stream and turbulence mechanics. Our manual is a further treatment of CAT classifications explained by Holcomb.

David Lee contributed the sections on model relationships of CAT. He collected and verified the information for these sections while serving as a CAT forecaster with the Forecasting Services Division at AFGWC. Roland Stull's primary contributions were the sections dealing with automated aids. He wrote the CATA and MTWVB computer routines while working as a numerical prediction meteorologist in the Technical Services Division of AFGWC. The remaining sections were a joint effort. William Irvine served as technical editor and prepared all charts and figures.

This technical Note replaces AFGWC Tech Memo 70-7 "Turbulence Forecasting Procedures" by Capt Paul T. Burnett, 15 Dec 70. Over the last 15 years the automated CAT routines have been totally replaced. Also, synoptic rules of thumb and model relationships are now better understood and documented.

We gratefully acknowledge Capt James Liberda for his expertise in writing the Northern Hemispheric map display for the CATA output. The suggestions and comments from Capts Thomas Andrew, Dennis Regan, Dennis Newsom, and Norman Carron on the operational performance of the models are also appreciated.

Thanks go to Amn Mark Rankin for the tedious work of verifying the output against pilot reports. Amn Mark Rankin and Sgt Patti Sanders also contributed significantly by calculating the terrain roughness over the Continental United States (CONUS). Many of the figures were drafted by Sgt Ronald Jepson. Portions of the manuscript were typed by Mrs Mary Zimmerman, SSgt Gary Rumery, and SSgt Kathy Tittle.

Appendix A was replaced in this February 1984 revision. This new information, extracted from the Air Force Wright Aeronautical Laboratories (AFWAL) Technical Report (TR)-81-3058, provides an updated guide to determine turbulence intensity for different categories of aircraft.

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## CLEAR AIR TURBULENCE FORECASTING TECHNIQUES

### 1. INTRODUCTION

The Air Force Global Weather Central (AFGWC) provides forecasts of clear air turbulence (CAT) potential in support of all levels of military operations. Although CAT is considered by some as only a nuisance, the National Transportation Safety Board (1971) has reported that structural damage to aircraft, passenger and crew injury, and even fatalities have been attributed to extreme CAT encounters. Also, CAT can adversely affect air-to-air refueling, precision navigation, and low-level bombing missions. As a result, accurate forecasts of CAT are important for Air Force flight planning and aircraft safety.

Problems encountered in forecasting clear-air turbulence include the large temporal and spatial scales of the observation network, the reliability of pilot reports, and the short-lived, random nature of CAT. In other words, CAT is a microscale phenomenon, whereas most existing atmospheric observations are made at the macroscale.

AFGWC turbulence forecasting philosophy is to provide an optimal man-machine mix to produce the best possible forecasts. In this context, computer programs currently check all rawinsonde observations (RAOBs) for microscale phenomena that may indicate turbulence. These computer programs have eliminated the tedious manual searches through stacks of thermodynamic diagrams (skew-T, log P plots). On the other hand, CAT forecasters examine synoptic features that are often associated with CAT. They combine their experience with the automated computer aids to produce comprehensive CAT analyses and forecasts.

Typically, three methods are used at AFGWC to diagnose existing CAT. One method uses the areas encompassing pilot report of CAT as a first guess. The second method uses an automated diagnosis provided by the computer programs at AFGWC. The third method involves synoptic rules-of-thumb compiled by experienced CAT forecasters.

Model relationships of CAT employing time-tested rules-of-thumb have been developed to aid the CAT forecaster in identifying synoptic patterns that frequently cause turbulence. After analyzing a potential CAT situation, the forecaster, using all the available forecast aids, forecasts the progression of the turbulence potential.

Several automated aids exist at AFGWC to assist the CAT forecaster in diagnosing CAT. These routines use the stability and shear data on a scale approaching the microscale and available from rawinsonde observations. Unfortunately, these automated routines are unable to forecast CAT because of the lack of microscale forecasts at AFGWC.

Both the automated and manual techniques used at AFGWC are described in this technical note. Chapters 2 and 3 define CAT and describe its causes and characteristics. Chapter 4 provides an overview of the problems encountered and tools used. Automated aids are detailed in Chapter 5, and rules-of-thumb are listed in Chapter 6. AFGWC TN 76-1, "Jet Stream Analysis and Turbulence Forecasting," complements the information contained in this technical note.

## 2. DEFINITIONS

2.1 Turbulence. Turbulence is the gustiness superimposed on the mean wind. These rapid, turbulent fluctuations in vertical velocity, horizontal velocity, temperature, humidity, and pressure about their mean values are random. Therefore we cannot hope to forecast (specify exact values of these variables in time and space) CAT exactly. Instead, as in molecular physics, we are limited to a statistical description of CAT.

2.2 Mountain Waves. In some cases, the wind flowing over hills and mountains is set into smooth oscillation. These mountain waves are not true turbulence as given by the strict definition in the preceding paragraph because nonstatistical equations can be written to describe their motion. Pilots flying through mountain waves at high speed, however, feel the oscillations as rapid bumps. They, consequently, report this as turbulence or chop. To make matters more difficult, smooth mountain waves can sometimes create conditions favorable to the formation of true turbulence. Mountain waves will be discussed in more detail in Section 6.4 of this technical memo.

2.3 Clear Air Turbulence (CAT). Clear air turbulence is literally that turbulence not associated with convective clouds. This means that turbulence in clear air as well as in clouds is classified as CAT. Although most often associated with turbulence near the jet stream, CAT can also occur near the ground.

2.4 AFGWC CAT Intensity Criteria. At AFGWC, forecasts are made for frequent, (more than one third of the time) moderate, or greater turbulence for category II aircraft. A table for aircraft is found in Chapter 4, AWSP 105-56, "Meteorological Techniques" and the same chart is in Appendix A. The AFGWC specifications for CAT categories are:

**Moderate:** Moderate changes experienced in aircraft attitude or altitude, but the aircraft remains in positive control at all times. Usually, small variations in air speed (15-25 knots) and changes in accelerometer readings of 0.5 g to 1.0 g at the aircraft's center of gravity occur. Occupants feel strain against seat belts or have difficulty walking and loose objects move about. The vertical gust velocity is 20 to 35 feet per second.

**Severe:** Abrupt changes in aircraft attitude or altitude are experienced. Aircraft may be out of control for short periods. Usually, large variations in airspeed (25 knots) and changes in accelerometer readings greater than 1.0 g to 2.0 g at the aircraft's center of gravity occur. Occupants are forced violently against seat belts and loose objects are tossed about. The vertical gust velocity is 35 to 50 feet per second.

**Extreme:** The aircraft is violently tossed about and practically impossible to control. Structural damage may occur. Changes in accelerometer readings greater than 2.0 g and vertical gust velocity greater than 50 feet per second occur. Rapid fluctuations in airspeed are greater than 25 knots.

### 3 CAUSES AND DESCRIPTION OF CAT

CAT is caused by a number of phenomena:

Hot, rising air tends to be turbulent. Static stability is used to determine whether the air breaks down into rising/descending parcels of hot/cold turbulent air, called thermal turbulence.

Even if the air is statically stable, the wind shear may be strong enough to create turbulence. Dynamic stability is the measure of this phenomenon, known as shear turbulence.

Air just above rough terrain tends to be turbulent. This is called mechanical turbulence. Note that mechanical turbulence is slightly different than the mountain-wave turbulence found at higher altitudes.

All three phenomena are discussed in more detail below.

**3.1 Thermal CAT.** Thermal CAT is associated with static instabilities. An excellent measure of the static stability of air is the potential temperature lapse rate,  $L$ :  $L = \Delta\theta/\Delta Z$ , where  $\Delta\theta$  is the change in potential temperature over a layer of thickness  $\Delta Z$ . Dry air is statically stable when  $L$  is positive; that is, when temperature decreases with height more slowly than the dry adiabatic lapse rate of  $9.8^\circ\text{K/km}$  ( $5.4^\circ\text{F/1000 ft}$ ). Statically unstable air occurs with negative  $L$ ; that is, it occurs with superadiabatic lapse rates. Neutral stability occurs when  $L$  is zero, corresponding to an adiabatic lapse rate.

Turbulent convection starts in statically unstable air. This turbulence is usually felt near the earth's surface as the bumpy thermals of hot, rising air on a sunny day. Some of these thermals can rise far enough to cause clouds. Many other thermals are trapped below cloud base by the temperature inversion just below cloud base. Although this thermal turbulence is found most often near the ground, it can occur higher in the atmosphere where radiational cooling or horizontal advection lowers the lapse rate, such as near cirrus clouds.

**3.2 Dynamic CAT.** Turbulence can occur in statically stable air if the wind shear is strong enough. The air is dynamically unstable when this occurs. The Richardson number ( $Ri$ ) is a ratio that compares the relative strength of the static stability versus the wind shear:

$$Ri = \frac{g}{\theta} \left( \frac{\Delta\theta}{\Delta Z} \right) / \left( \frac{\Delta V}{\Delta Z} \right)^2$$

where  $g$  is the acceleration due to gravity and  $\Delta V/\Delta Z$  is the vector wind shear occurring over the vertical distance  $\Delta Z$ .

Basically, wind shears tend to produce turbulent kinetic energy whereas stable lapse rates drain off this energy. Dynamic turbulence can exist only when the wind shear is strong enough to overpower the stability:

$$\left( \frac{\Delta V}{\Delta Z} \right)^2 \geq 4 \left( \frac{g}{\theta} \frac{\Delta\theta}{\Delta Z} \right),$$

where the factor of four is suggested by both theory and experiment. In other words, dynamic turbulence occurs only when  $Ri \leq 4$ . Air which satisfies this criterion is said to be dynamically unstable.

Note that statically unstable air (negative  $L$ ) is also dynamically unstable ( $Ri \leq 1/4$ ) because the Richardson number in that case is negative. Thus, the Richardson number is the only number needed to determine whether turbulence will exist. This relation between turbulence and the Richardson number has been derived theoretically by Miles and Howard (1964) and been experimentally proven in the laboratory by Thorpe (1973) and others. It has been verified in the upper troposphere by Browning (1971) using radar and slow-ascent rawinsondes, and has been verified with turbulence sensors in the boundary layer by Businger et al. (1971). The application of laboratory-derived relations to the free atmosphere case, however, is approximate at best due to many simplifying assumptions.

Dynamically caused CAT often occurs near the jet stream at the tropopause (see Figure 1). These occurrences of CAT peak during winter months and reach a minimum in summer. Mechanisms include strong vertical wind shear (speed or direction) and strong horizontal wind shear. Strong shears can first generate Kelvin-Helmholtz wave, which are unstable. These waves amplify, roll-up, and break similar to ocean waves (see Figure 2). Breakup of Kelvin-Helmholtz waves creates CAT.

3.3 Mechanical CAT. Friction at the ground slows the wind speed at ground level and creates very strong wind shears just above the ground. This leads to dynamic instabilities and turbulence. Hence, the Richardson number can be used to predict some cases of low-level turbulence.

Eddies behind mountains, buildings, trees, and other roughness elements are not so easily definable by an average Richardson number over a layer. No theoretical criteria have been derived for such cases of mechanical turbulence. Hence, empirical relationships that include terrain roughness are used here.

3.4 Mountain Waves. As will be described in Chapter 6, smooth waves can form in the air flowing over mountains. These waves can exist from just above the mountain to above the tropopause. At the crests or troughs of these waves, the wind shear can be enhanced to the point where dynamic instabilities and turbulence can occur (see Figure 3). Strong wind shears also occur where mountain waves hit the earth's surface. In fact, complete overturning under some of the waves can create very turbulent, statically and dynamically unstable rolls and rotor clouds. These mountain-wave phenomena, although sometimes related to dynamic instabilities, are so complex that only the empirical relations described in Section 6 will be used to model them.

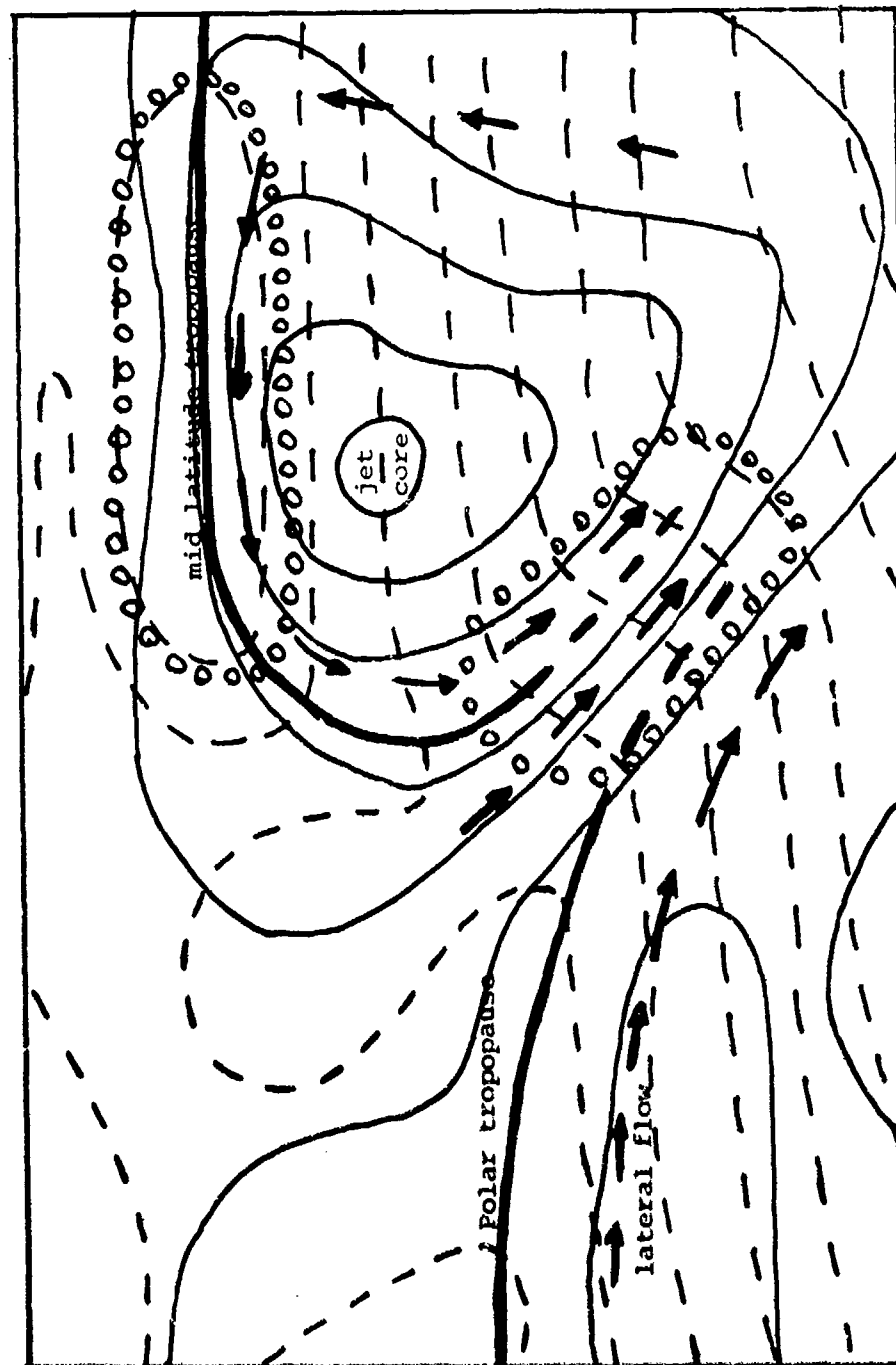


Figure 1. Location of CAT in a typical jet stream. Solid lines are isotherms and dashed lines are isotachs. Open circles indicate regions of possible CAT.

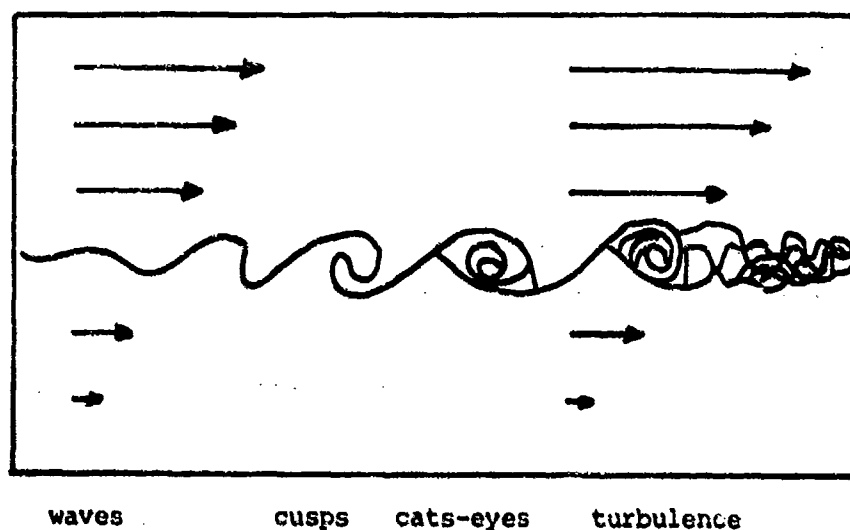


Figure 2. Breakup of Kelvin-Helmholtz waves showing transformation from waves to cusps, cat's-eyes, and finally turbulence in shear flow.

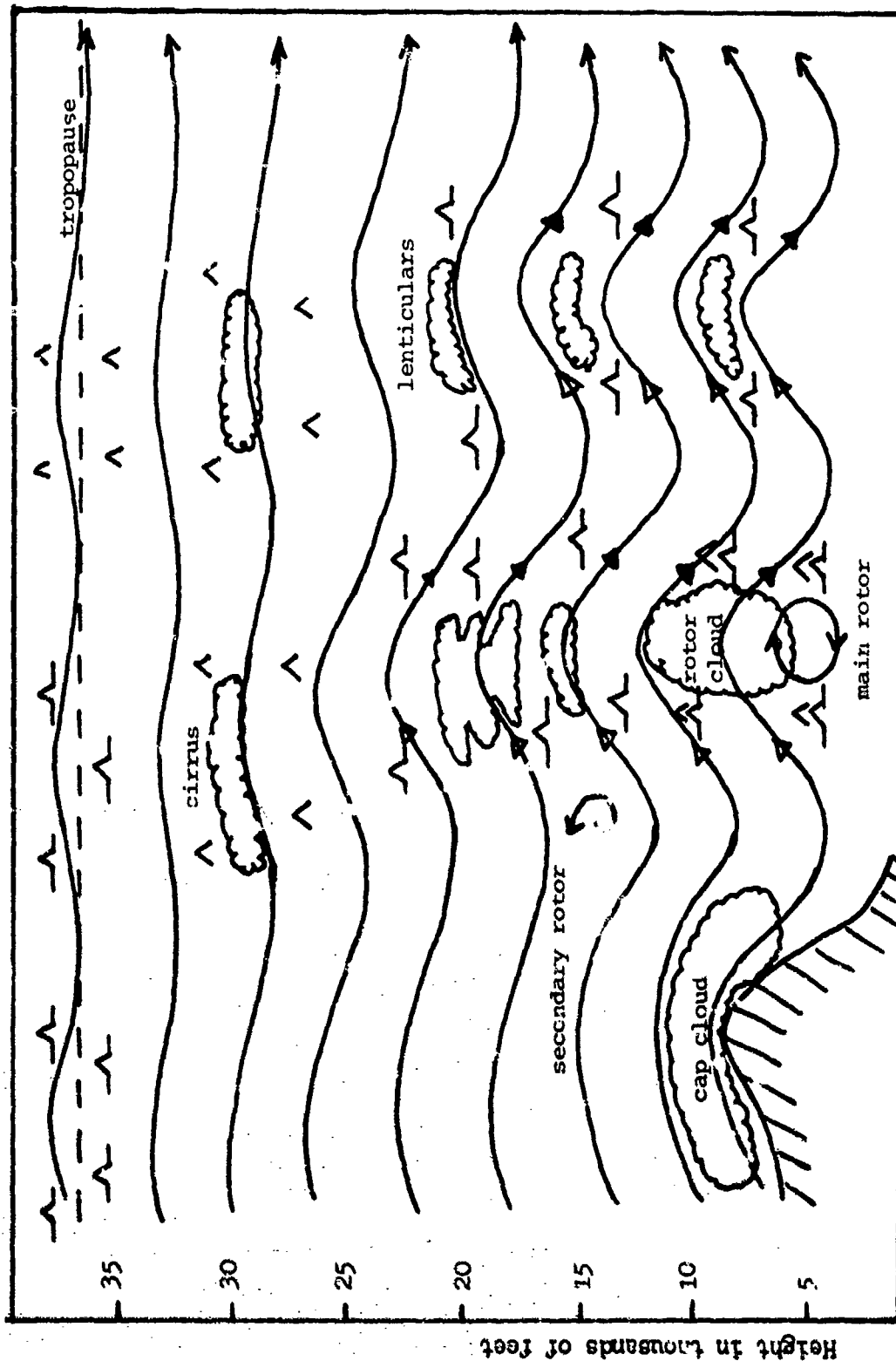


Figure 3. Cross-section of a mountain wave adapted from Ernst (1975).  $\Delta$  indicates light turbulence.  $\Delta$  indicates moderate turbulence,  $\Delta$  indicates severe turbulence,  $\rightarrow$  are updrafts, and  $\rightarrow$  are downdrafts.

#### 4 ANALYSIS AND FORECAST PROBLEM

4.1 Problems. Precise forecasts of CAT are beyond our present capabilities even though the characteristics of turbulent regions are well defined. The problem involves the time and spatial characteristics of the upper-air observation network, the representativeness of pilot reports, and the nature of the turbulence field.

4.1.1 The density, frequency, and resolution capability of the present upper-air observation network is incompatible with the micro-scale nature of CAT. Observations are taken at 12-hour intervals at stations averaging several hundred miles separation with a vertical resolution of about 2,000 feet. Over oceanic areas, virtually no stations exist. Therefore, with the current system, it is practically impossible to clearly define existing areas of CAT. Also, if computer forecast models are utilized, the problem is again complicated by the vertical and horizontal smoothing performed in the computer program.

4.1.2 The arguments against the representativeness of pilot reports of turbulence include (from Holcomb, 1976):

4.1.2.1 Poor data coverage. Many areas around the globe are not included in regular commercial airliner routes. Therefore, where aircraft do not fly routinely, pilot reports are not available routinely. This does not help the forecaster accurately evaluate all potential turbulence areas.

4.1.2.2 Aircraft type and mission. Light aircraft (Cessnas, Pipers, etc.) report greater intensities of CAT than heavier aircraft (Boeing-707, DC-9, etc.). Also, commercial aircraft pilots are very concerned with passenger comfort and tend to report CAT intensities based on passenger reactions. See Appendix A for more details.

4.1.2.3 Subjectivity. Individual pilot's interpretations of CAT encounters as well as the responses of different aircraft vary. In general, inexperienced civilian pilots tend to report greater CAT intensities than experienced military pilots. Also, when flying in extremely smooth air, turbulence encounters may surprise the pilot and lead him to report a higher intensity. The opposite applies when flying in rough air; CAT encounters may be downgraded somewhat due to the pilot's adjustment to existing turbulent conditions.

4.1.2.4 Avoidance. If CAT has been forecast, pilots may totally avoid turbulent areas or use avoidance procedures designed to lessen the impact of existing turbulence. Certain cloud formations (for example, altocumulus standing lenticular, and wave clouds) associated with turbulence are well-known and avoided. In mountainous regions, specific turbulence avoidance routes are flown when mountain waves are forecast. The result is a decrease in total turbulence reports and a reduction in CAT intensities.

4.1.3 Nature of turbulence field. CAT is a short-lived, micro-scale, random phenomenon. For example, an aircraft reports severe CAT at a certain altitude and location. Ten minutes later, an aircraft flying through the same area at the same altitude may report no turbulence or light chop. Obviously, the turbulence has either moved out of

the area, decreased in intensity, or completely dissipated.

Through experience and a sound method of equating turbulence reports, a forecaster can reckon with the problem of the unreliability of pilot reports. To overcome the problem of a crude observational network, the CAT forecasters must apply proven model relationships of CAT, a micro-scale phenomenon, to macroscale features to produce rather short-range (up to 36 hour) forecasts. The forecast reliability depends upon the accuracy of the model relationships and the precision of the upper-air forecasts.

4.2 Tools. Many operational analysis and forecast tools are used in identifying and forecasting ideal CAT relationships.

4.2.1 In the analysis, the forecaster attempts to delineate areas of potential CAT, as well as define areas where the phenomenon has been recently reported.

4.2.1.1 The first step in the analysis is a detailed examination of the 250 mb pressure level. This level is studied to determine the current position of the jet stream core and to locate other features associated with CAT.

4.2.1.2 Infrared and visual satellite photographs from the Defense Meteorological Satellite Program (DMSP) and Geostationary Operational Environmental Satellite (GOES) are reviewed and related to 300 mb synoptic systems and scrutinized for certain macroscale and mesoscale cloud features known to be associated with areas of probable CAT. Jet streams and short-wave features can be readily identified from the cloud configuration. Short transverse bands or a general herring-bone appearance and standing mountain-wave clouds are normally associated with moderate or greater CAT. Also, satellite data are highly useful in filling in data-void areas and making short-range turbulence forecasts.

4.2.1.3 Next, the 200 mb analyzed height and temperature fields are inspected for regions of strong isotherm packing in association with strong wind flow. The 200 mb isotherms closely align themselves with the 500 mb vorticity pattern and clearly depict short waves and developing systems.

4.2.1.4 The 500 mb analyses of heights, temperature, and vorticity are used to identify areas of thermal advection, short-wave troughs, and wind components normal to mountain ridges.

4.2.1.5 The 700 mb and 850 mb height and isotherm fields are used to identify regions of thermal advection and wind components normal to mountain ridges.

4.2.1.6 The analyzed surface fronts and pressure centers are checked against the analyzed jet-stream core to determine the stack (tilt) of the system. Dynamic systems must tilt toward the cold air because of hydrostatic considerations and tilt from southwest to northeast to provide for momentum equilibrium. This tilt is important because CAT normally occurs in a dynamic atmosphere.

4.2.1.7 After examining these products and reviewing the latest pilot reports (PIREPs - see appendix A) of occurrence and non-occurrence of CAT, the forecaster reviews the AFGWC CATA automated rawinsonde analysis of turbulence potential. CATA locates areas of strong vertical wind shears (the most effective producer of CAT) and stable layers.

4.2.1.8 In the final analysis, the CAT forecaster checks the AFGWC 250 mb maximum wind analysis to refine and recheck the analysis. Using computer displayed wind fields and aircraft reports, upper-air and CAT forecasters analyze the flow between 200 mb and 300 mb. Shear lines, maximum wind cores, jet diffluence and confluence, and subtropical and polar jet interaction are vividly depicted.

4.2.1.9 To identify areas of possible mechanical or mountain-wave activity, MTWVB, an automated mountain-wave analysis product, is checked and compared with the synoptic situation. MTWVB considers pressure gradient, mountain-top winds, pressure tendencies, surface wind reports, and thermal gradients to determine mountain-wave and mechanical turbulence using the criteria suggested by Sorenson and Beckwith (1975).

4.2.2 After a careful turbulence analysis, the forecaster turns to forecast guidance tools to prepare the turbulence forecast.

4.2.2.1 The 250 mb forecast is the primary tool for determining future jet stream positions. In addition, other 250 mb synoptic features associated with turbulence can be forecast.

4.2.2.2 The 500 mb height and isotach forecast can be used to approximate future jet stream positions and wind components normal to mountain ranges, as well as the general synoptic pattern.

4.2.2.3 The Limited-area Fine-mesh Model (LFM) 500 mb height and vorticity package, which is available from the National Meteorological Center (NMC), is extremely useful in determining regions of possible cyclogenesis and in noting the movement of short waves across North America. For other areas in the Northern Hemisphere, global-scale 500 mb hemisphere height and vorticity fields are used.

4.2.2.4 The forecast surface fronts and pressure centers are inspected for signs of cyclogenesis and checked against the forecast jet stream positions.

4.2.2.5 MTWVB also contains 12- and 24-hour forecasts of mechanical and mountain-wave turbulence.

4.2.2.6 Again, the LFM 700 mb height forecast and other 700 mb and 850 mb wind forecasts are particularly useful in verifying MTWVB forecasts and synoptic pattern changes.

4.2.2.7 Significant Meteorological Information reports (SIGMETs) are helpful in identifying existing and potential turbulence areas. This information tends to be pessimistic because it applies to all types of aircraft.

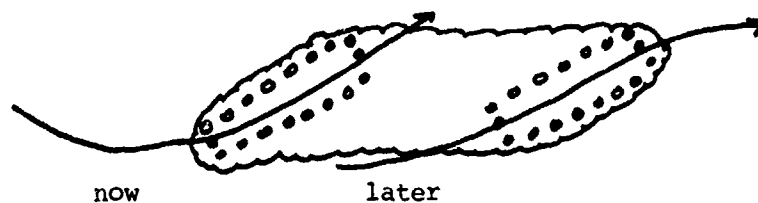
4.2.2.8 The NMC Significant Weather (SIG WX) forecasts (400-150 mb) are consulted for an additional opinion of where turbulence might exist.

4.2.2.9 At AFGWC, continuity is an important forecasting tool. Under no circumstances will a forecast area be added, dropped, or modified unless sufficient data and sound meteorological logic warrant a change.

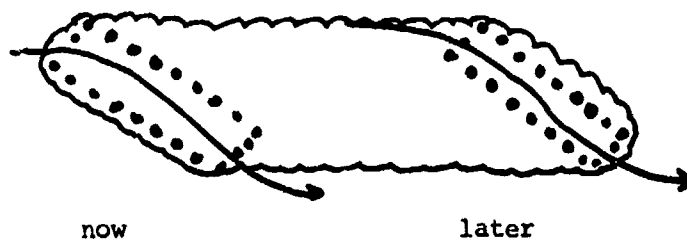
4.2.3 While reviewing all of these tools, the forecaster must note the progression of turbulence areas. Their movement, growth, intensification, and dissipation are important factors to consider in moving the systems. Once a region of CAT is located, it is possible to move it in time, maintaining association with the same synoptic features. The resulting AFGWC CAT forecast must include the total area swept-out by the moving patch of CAT. However, this approach to CAT forecasting sometimes results in forecast turbulence areas that are too large to be useful. (See Figure 4 for examples).

4.3 Microscale versus macroscale. At first glance, the Richardson number approach for analyzing CAT and the synoptic rules-of-thumb may appear to be completely different. This is not true. The rules-of-thumb compiled by experienced forecasters focus on those synoptic features that also produce low Richardson numbers. The low Richardson numbers are, in turn, always associated with CAT. Hence, we see that both the rules-of-thumb approach and the Richardson number approach should indicate turbulence in the same regions around the globe.

The computer can easily be programmed to look at microscale phenomena. It can calculate Richardson numbers from the upper-air soundings at each RAOB site. From these Richardson numbers, it can then diagnose regions where CAT is likely to occur. However, it is very difficult to program the computer to recognize macroscale patterns such as converging jets; hence, synoptic pattern recognition is left to the CAT forecaster. Lists of synoptic patterns often associated with CAT complete the rules-of-thumb models. Both the rules-of-thumb and the computerized forecast methods are discussed in detail in this tech note.



Cold air advection in short-wave trough at middle levels.



Warm air advection in short-wave ridge at middle levels.

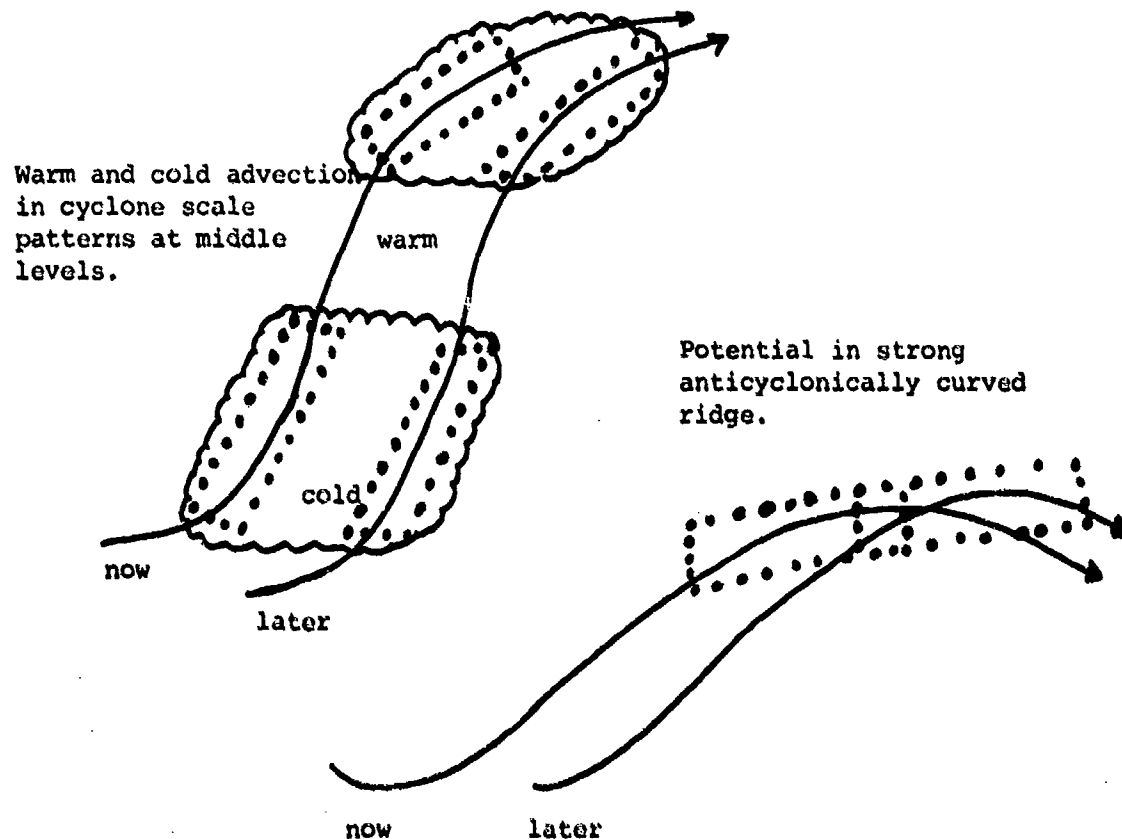


Figure 4. Examples of forecasting CAT potential over an extended period of time, after Holcomb (1976). Potential at start of forecast period is "now", while "later" refers to the end of period. Scallop show the entire forecast area of turbulence potential.

## 5 AUTOMATED AIDS

AFGWC has two major automated CAT forecasting computer programs, CATA and MTWVB. CATA consists of a system of programs that diagnose CAT based on RAOB data. One portion of CATA uses the Richardson number to diagnose dynamic instabilities between the surface and 80,000 feet. Another portion diagnoses thermal turbulence within the lowest few thousand feet of the atmosphere. The third portion diagnoses mechanical turbulence over rough terrain. MTWVB diagnoses and forecasts mountain-wave turbulence near a specified number of locations over the globe.

CATA is run twice daily on the computer from the 00Z and 12Z RAOB data, whereas MTWVB is run 8 times per day.

Before CATA became operational, CAT forecasters were required to search manually through hundreds of skew-T graphs to find regions of strong wind shear with proper stability. The CATA program now does this search automatically. Using this aid, CAT forecasters save about 1½ hours each day.

### 5.1 CATA program.

5.1.1 Dynamic CAT. CATA calculates Richardson numbers from rawinsonde wind and temperature observations. It has relatively good vertical resolution because it considers both the mandatory and significant levels. It is a diagnostic model that uses only observed data and cannot make CAT forecasts.

CATA accesses the Northern Hemisphere RAOB data that have been validated and stored in the AFGWC data base. Each RAOB is examined individually and the following calculations are made.

First, CATA splits the winds at each reported level into the U and V components. Next, a five-point filter is used on each of the wind components to smooth unrealistically sharp kinks from the vertical wind profile. These kinks occur when slightly different wind speeds or directions are reported at adjacent mandatory and significant levels. Experience has shown that often these kinks are caused by restrictions imposed on the resolution of reported RAOB data ( $\pm 1$  m/s speed and  $5^\circ$  direction change), rather than by true wind shears. The problem of profile kinks is particularly acute when the two levels in question are less than 100 m apart. Hence, this filter is designed to smooth closely spaced levels more strongly than distant levels.

In general terms, five weighting values are calculated and applied to five wind values to calculate a filtered wind value,  $V_i$ . If we denote each weight  $\omega_{ij}$ , then

$$\omega_{ij} = \left( |h_i - h_j| + B \right)^{-1}$$

where the index  $j$  refers to the  $j$ th weight,  $h_i$  and  $h_j$  are the heights (in meters) above the surface, and  $B$  is the filter bandwidth ( $B = 100$  m).

When  $j$  is allowed to vary from  $i-2$  to  $i+2$  the resulting five weights will be inversely proportional to the vertical separation between reported levels. The filtered value,  $V_i$ , can be written

$$V_i = \sum_{j=-2}^2 V_j \omega_{ij} / \sum_{j=-2}^2 \omega_{ij}$$

An example of the use of these weights follows. If  $i=3$  and we assume that  $h_{i+1} > h_i$ , then

$$\omega_{31} = (h_3 - h_1 + B)^{-1}$$

$$\omega_{32} = (h_3 - h_2 + B)^{-1}$$

$$\omega_{33} = B^{-1}$$

$$\omega_{34} = (h_4 - h_3 + B)^{-1}$$

$$\omega_{35} = (h_5 - h_3 + B)^{-1}$$

If the wind values depicted by the solid line in Figure 5 are to be filtered, then the filtered V-component wind at  $h_3$  is:

$$V_3 \Big|_{\text{filtered}} = \frac{\omega_{31}V_1 + \omega_{32}V_2 + \omega_{33}V_3 + \omega_{34}V_4 + \omega_{35}V_5}{\omega_{31} + \omega_{32} + \omega_{33} + \omega_{34} + \omega_{35}}$$

This filter is similarly used on both components of the wind in the RAOB report. Figure 6 shows the highly peaked variation of weights with distance from the center point,  $h_i$ .

After filtering, the vector wind shears (that is, speed and direction changes) and potential temperature lapse rates are calculated between each pair of adjacent reported levels. Note, that if temperatures or winds are missing at one of the levels, then a substitute value is interpolated from the two closest levels with data. CATA then calculates a Richardson number for each layer.

Unfortunately, the significant and mandatory levels from RAOB data do not offer sufficient vertical resolution to apply the Richardson number criterion of  $Ri = \frac{1}{4}$  directly. Even if occasionally there are closely spaced levels, the filter previously described smooths the winds because it cannot distinguish between good and erroneous wind shear data. Consequently, the calculated Richardson numbers will rarely be less than  $\frac{1}{4}$ .

Hence, we assume that within any reported layer there is a chance that a thinner layer exists having a Richardson number small enough to be turbulent. This chance increases as the Richardson number (over the thicker layer) becomes smaller. The computer thus calculates a probability of CAT occurrence based on the information in Figure 7. There is a high probability of CAT if the whole RAOB layer has a Richardson number less than  $\frac{1}{4}$ .

Although the Richardson number is an indicator of CAT occurrence, there is no proven method in the available literature to estimate CAT

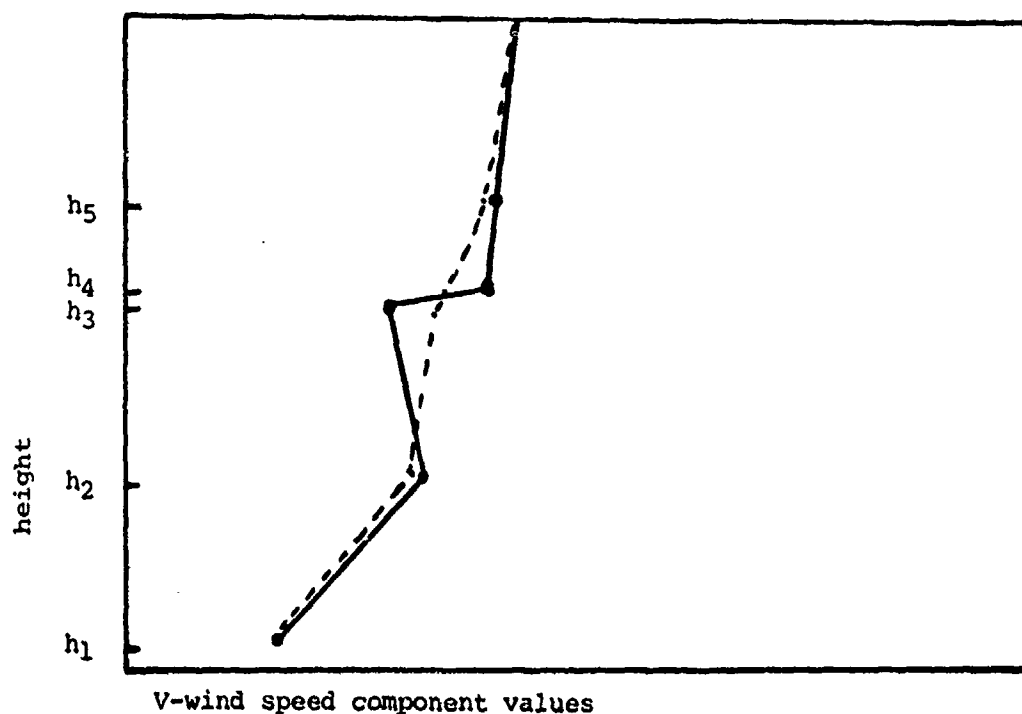


Figure 5. An example of the effects of a five-point filter on raw vertical wind data. Solid line indicates raw wind data and dashed lines the resulting smoothed wind values.

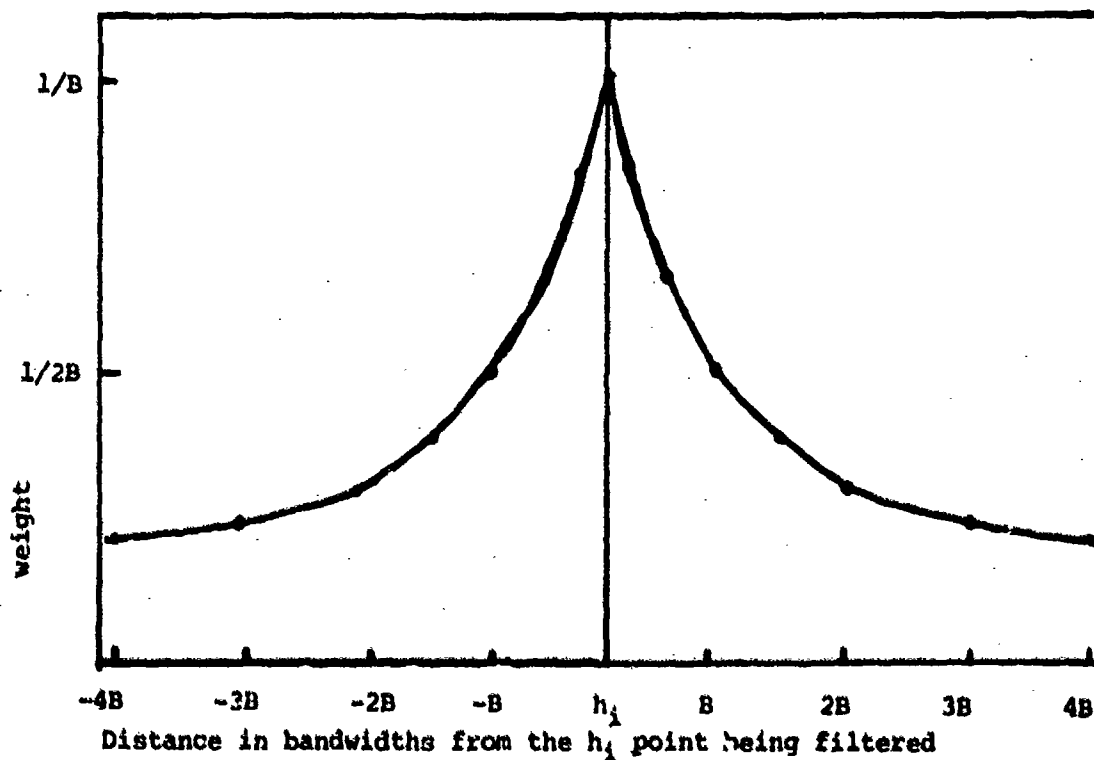


Figure 6. Five-point filter weighted values as a function of distance from the central point,  $h_1$ .

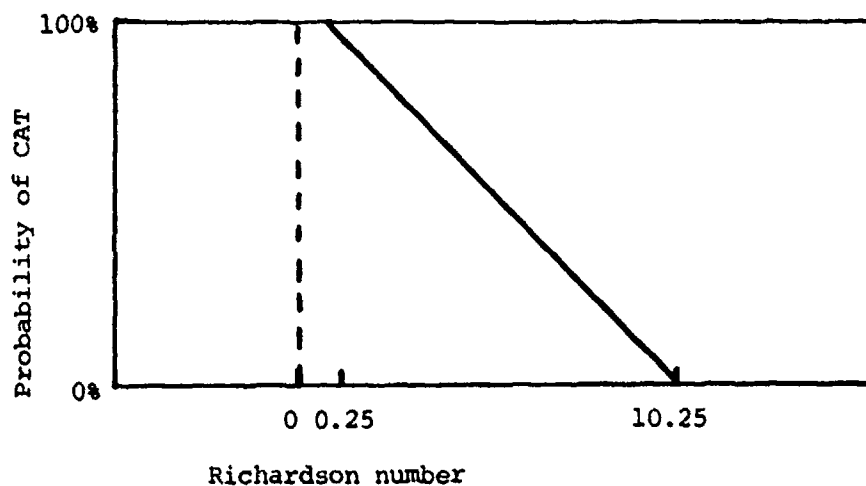


Figure 7. Relationship between the bulk Richardson number,  $Ri$ , over a layer and the probability of turbulence within that layer. This curve was developed empirically at AFGWC.

| Wind Speed<br>m/s<br>(kt) | Vector wind shear $S^{-1}$ (kt/1000 feet) |                       |                        |                        |                        |                   |
|---------------------------|-------------------------------------------|-----------------------|------------------------|------------------------|------------------------|-------------------|
|                           | .0084-.0118<br>(5-7)                      | .0118-.0169<br>(7-10) | .0169-.0338<br>(10-20) | .0338-.0506<br>(20-30) | .0506-.0844<br>(30-50) | .0844---<br>(50+) |
| 20-30<br>(40-60)          | N                                         | L                     | L-M                    | M                      | M-S                    | S                 |
| 30-60<br>(60-120)         | L                                         | L-M                   | M                      | M-S                    | S                      | S-X               |
| 60+<br>(120+)             | L                                         | L-M                   | M                      | M-S                    | S                      | X                 |

Figure 8. Empirically derived relationship between turbulence intensity and the wind speed and shear. "N" indicates none, "L" is light, "M" is moderate, "S" is severe, and "X" is extreme turbulence.

intensity. CATA, therefore, employs the empirical procedures summarized in Figure 8. That is, CAT intensity increases with wind speed and particularly with wind shear. The exact values in Figure 8 are based on recommendations from experienced CAT forecasters at AFGWC.

Such a relation between intensity and winds is seen to be reasonable. The product of wind speed times wind shear can be related to the change in mean kinetic energy per unit mass (KE) with height. Using basic calculus concepts where U is total wind speed, one can write:

$$U \frac{dU}{dz} = \frac{d}{dz} \left[ \frac{1}{2} U^2 \right] = \frac{d}{dz} \left[ KE \right]$$

After turbulence occurs, wind shears and kinetic energy gradients become much smaller. Thus, the change in mean wind kinetic energy with height is a measure of the energy available to produce turbulence.

Present policy at AFGWC requires a yes-no forecast of moderate or greater turbulence. Hence, CATA is designed to output a turbulence forecast only if both the probability is greater than or equal to 50% and the intensity is light-moderate or greater. This is equivalent to assuming a modified critical Richardson number of 5.25.

In summary, CATA produces values of CAT probability and intensity for every layer in every RAOB sounding. This information is then converted into a yes-no diagnosis of CAT.

5.1.2 Thermal CAT. Turbulent thermals are assumed to rise from the surface whenever the surface potential temperature is warmer than the boundary layer air just above it. CATA obtains the surface temperature from the RAOB data. CATA assumes that the boundary layer temperature is represented by the temperature at the second reported height above the surface. All thermal CAT is assumed to be of light intensity only. Thermal CAT is diagnosed to exist between the surface and the height where the environmental potential temperature equals the surface potential temperature (see Figure 9).

5.1.3 Mechanical CAT. Mechanical CAT intensity is calculated from the nomogram in Figure 10. This nomogram is defined by the following equation:

$$INTENSITY = a \times U \times R + b$$

where: U is the average mountain-top wind speed (m/s)  
 R is the upwind terrain roughness (m)  
 a is an empirical factor ( $3.0 \times 10^{-4}$ ) s/m<sup>2</sup>  
 b is an empirically derived, dimensionless constant (2.7).

This nomogram states that faster winds blowing over rougher terrain produce turbulence of greater intensity.

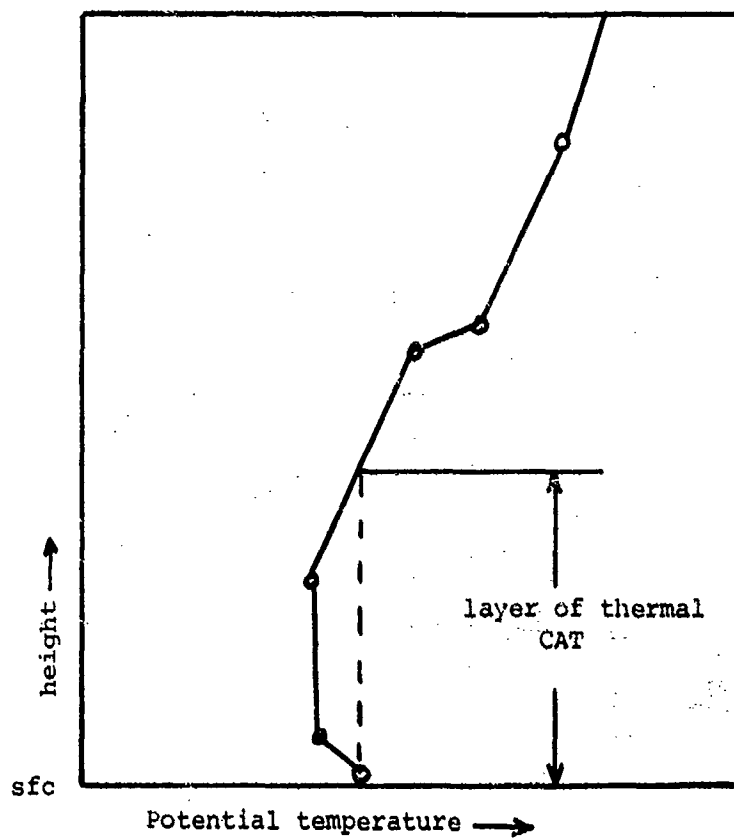


Figure 9. A method used to calculate the thickness of a thermal CAT layer. Reported RAOB temperatures indicated by open circles.

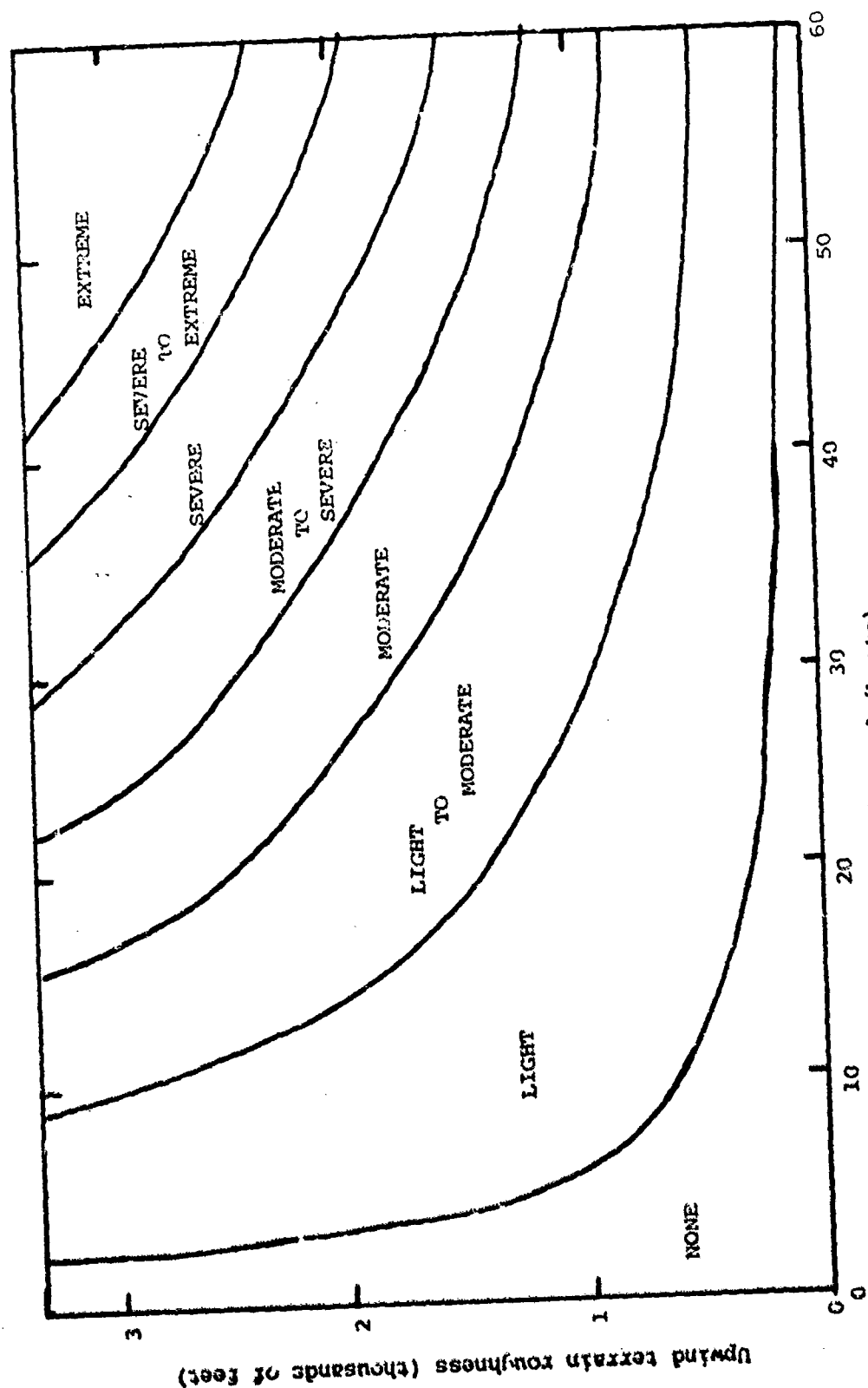


Figure 10. Nomogram used to estimate mechanical turbulence intensity.

Roughness values for the CONUS are displayed in Figure 11. This roughness is the standard deviation of terrain height (in ft). It was derived from WAC aviation charts by picking-off the terrain height every 5 miles along 150-mile long legs. A leg extends from each RAOB station in each of the eight primary compass directions. The standard deviation for each leg was then calculated from these heights. (Actually, the roughness values stored in the computer are slightly different than that displayed in Figure 11. The standard deviations in the computer were found by weighting the terrain heights inversely as the distance from the RAOB station. Thus, mountains far away from the RAOB station would produce less CAT at the station than that produced by closer mountains.)

The CATA routine selects the highest terrain feature within 150 miles upwind of the RAOB station. The RAOB winds from the surface up to 1000 ft above this maximum height are then averaged together. This average wind speed is assumed to be the average mountain-top wind used in Figure 10. The average wind direction is also used to select the proper upwind roughness. Mechanical CAT is assumed to occur throughout the layer from the surface to 1000 feet above the maximum height.

#### 5.1.4 Output products.

5.1.4.1 CATA makes horizontal analyses of CAT from the surface to 80,000 ft. Four Northern Hemispheric charts are printed, each with a different range of heights. Runstreams CATONE and CATRE cause the following charts to be printed by CATA:

CATONE: Surface to 16,000 ft  
16,000 to 40,000 ft

CATRE: 40,000 to 56,000 ft  
56,000 to 80,000 ft

Each Chart is printed on a 1:15 million scale polar-stereographic map of the Northern Hemisphere. Included on each chart are latitude and longitude lines. These runstreams are executed at the following times every day:

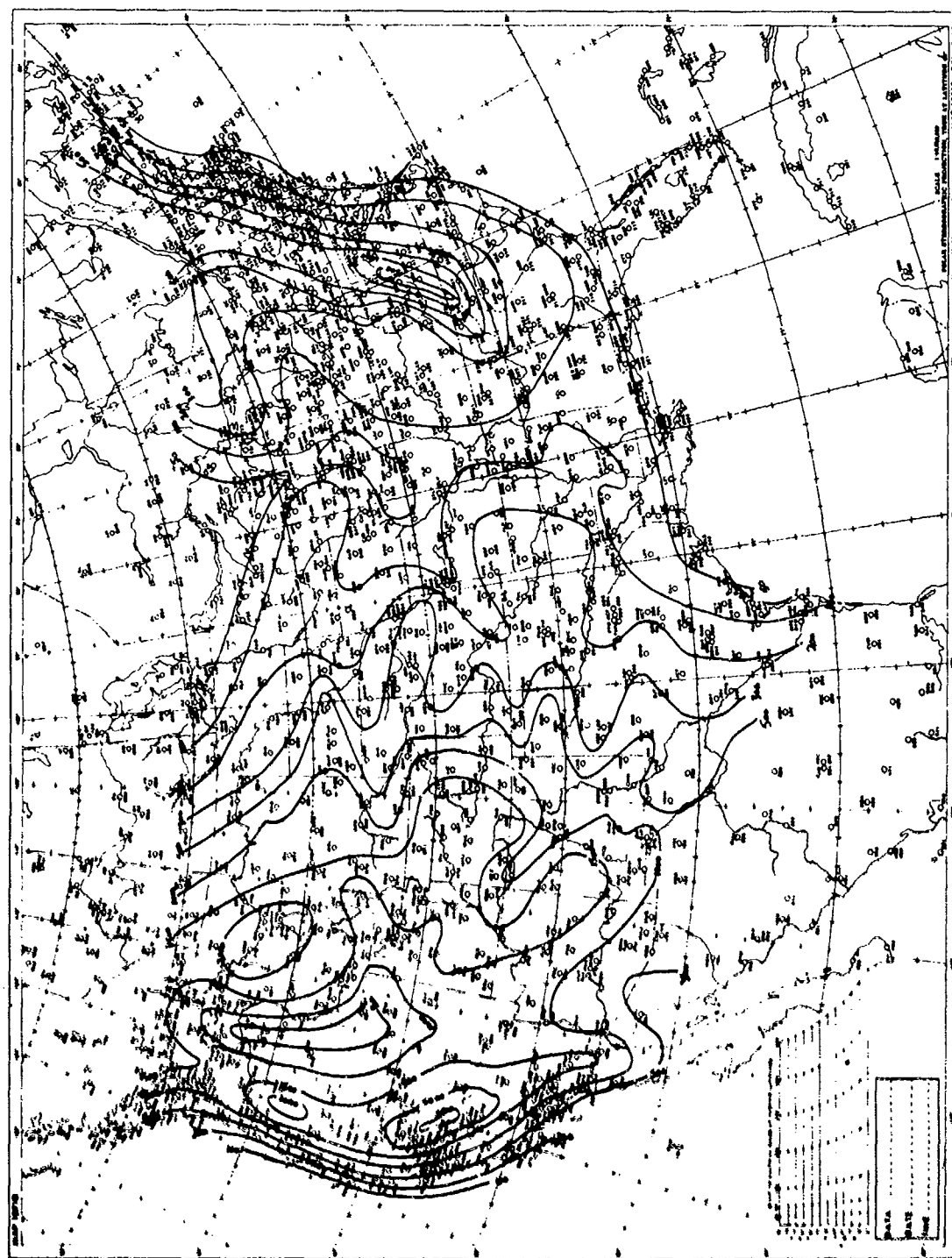
CATONE: 3Z, 15Z and 4Z, 16Z

CATRE: 5Z, 17Z

A sample of the CATA output is included in Appendix B-1.

Note that the Richardson number approach is used to analyze CAT in all layers reported by the RAOB. In addition, thermal and mechanical CAT are analyzed and printed on only the lowest chart (surface to 16,000 feet).

5.1.4.2 CAT values for every RAOB layer are sorted into specified height intervals (see Figure 12). If any one RAOB sounding has more than one layer in a height interval, then only the most intense CAT value is associated with that interval. For example, if the RAOB data show two layers of light CAT, one layer of moderate CAT, and two layers without CAT all between 37,000 and 40,000 feet, then CATA output



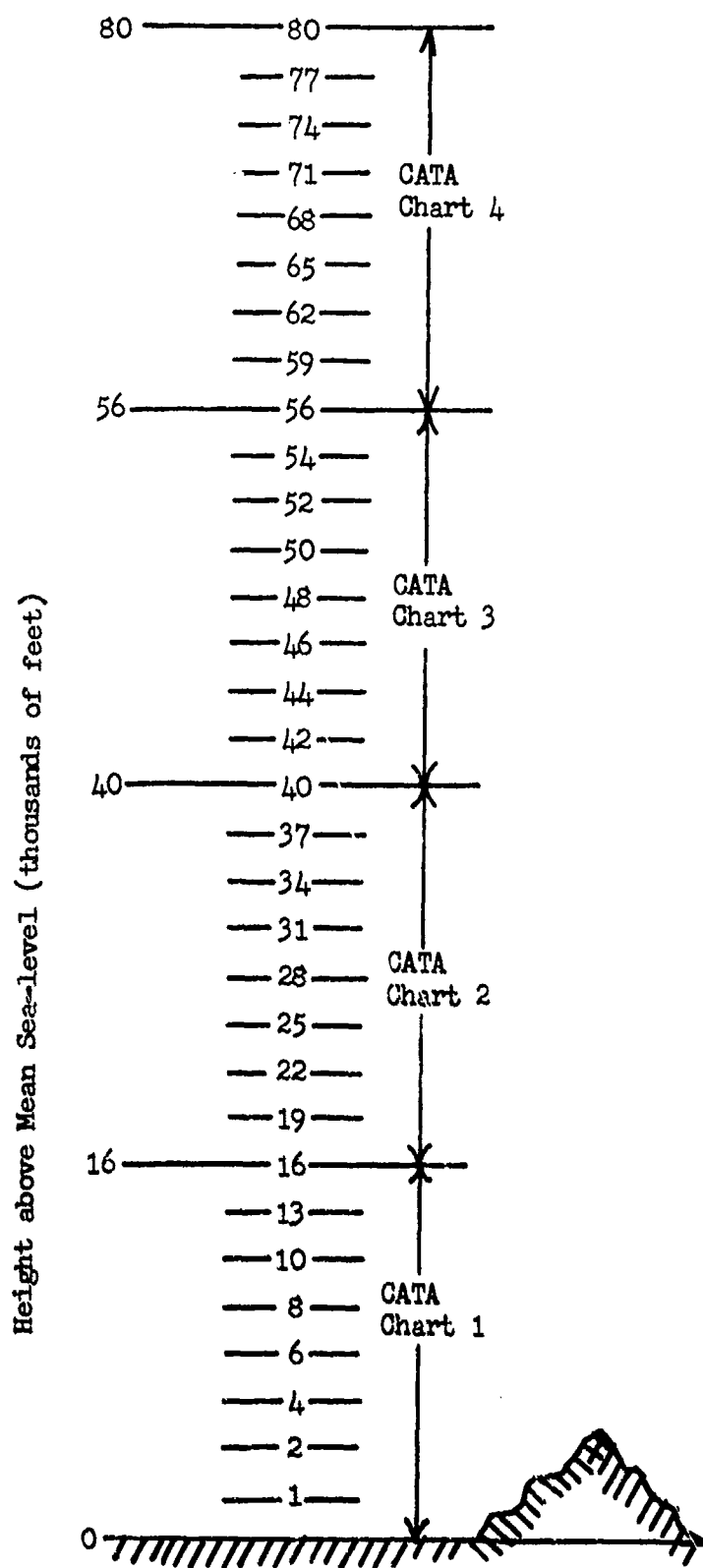


Figure 12. Height intervals for CATA display.

indicates that there is moderate CAT in the 37,000-40,000 foot height interval at that one RAOB station.

5.1.4.3 Tropical and southern hemispheric RAOBs are also analyzed by CATA. CAT diagnoses for these stations are listed in tabular format (see Appendix B-2) rather than being plotted on a map. CAT diagnoses are listed for 16 layers between the surface and 40,000 feet.

5.2 MTWVB program. MTWVB is a computer program that provides analyses and 12- and 24-hour forecasts of mountain-wave turbulence. It does not use the equations of motion to forecast exact air flow over mountains. Such a computer program would take too long to run operationally. Instead, MTWVB uses the rules-of-thumb presented by Sorenson and Beckwith (1975). A sample of MTWVB output is included in Appendix C.

Sacrifices in physics within MTWVB were necessary to enable timely execution of the program. Both the atmospheric stability and the exact mountain shape are neglected. Basically, MTWVB assumes that mountain waves occur when strong winds blow over high mountains. Additionally, turbulence is correlated with other parameters such as surface pressure difference, 850 mb and 200 mb temperature gradients, maximum winds at mountain top and below 500 mb, surface gusts, and tropopause heights and temperatures.

The rules-of-thumb programmed into MTWVB are summarized in Tables 1-3 and Figures 13 and 14. The criteria in these tables are modifications of Sorenson and Beckwith's (1975) proposals. The following paragraphs describe the usage of these parameters in more detail.

5.2.1 Low-level mountain-wave turbulence. Figure 15 shows how data are selected for each mountain-wave region. Certain regions downwind of mountain ranges are known from experience to have more mountain-wave turbulence than other parts of the world. These regions have been selected by hand and delineated by boxes. At present, 49 mountain-wave boxes are being used by the computer (see Figure 16).

For each box, a primary and alternate pair of surface observation stations have been selected. Each pair has an upwind and a downwind station. Surface pressure differences across the mountain range are obtained from these station pairs. Surface gust data are also obtained from the two downwind stations.

Also superimposed on this picture, as is sketched in Figure 15, are four coarse-mesh grid points. The entire array of these points (see the AFGWC Grids Tech Note 79-003) covers much of the Northern and Southern Hemispheres. Analyzed and computer forecast fields of meteorological variables (such as winds, temperatures, humidities) are stored (remembered) at each of those grid point positions for each of the mandatory pressure levels. For each box, the four closest grid points (numbered 1, 2, 3, and 4 in this sketch) have been selected by hand.

These grid points can be used in place of missing surface stations to get surface pressure differences across the mountain range. Grid-point data are also used by the computer to get 850 mb temperature differences and gradients, 200 mb temperature gradients, mountain-top winds, 500 mb winds, and tropopause heights and temperatures. Also,

| Low-level feature                                                                                                                                                                                                                                                                                                          | Turbulence intensity                                                       | Low-level mountain-wave turbulence (surface to 10,000 feet maximum above ridge)            |                               |                             |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|-------------------------------|-----------------------------|
|                                                                                                                                                                                                                                                                                                                            |                                                                            | LIGHT                                                                                      | MODERATE                      | SEVERE                      |
| Wind component normal to mountain range at mountain top $\geq 25$ knots<br>-and-<br>AP across mountain at surface<br>$\Delta T$ across mountain at 850 mb<br>$\left  \frac{\Delta T}{\Delta x} \right $ across mountain range at 850 mb<br>Lee side surface gust (analysis only)<br>Winds below 500 mb greater than 50 kts | AP across mountain at surface                                              | See Figure 13                                                                              | See Figure 13                 | See Figure 13               |
|                                                                                                                                                                                                                                                                                                                            | $\Delta T$ across mountain at 850 mb                                       | $< 6^{\circ}\text{C}$                                                                      | 6 - $9^{\circ}\text{C}$       | $> 9^{\circ}\text{C}$       |
|                                                                                                                                                                                                                                                                                                                            | $\left  \frac{\Delta T}{\Delta x} \right $ across mountain range at 850 mb | $< 4^{\circ}\text{C}/60$                                                                   | 4 - $6^{\circ}\text{C}/60$ mm | $> 6^{\circ}\text{C}/60$ mm |
|                                                                                                                                                                                                                                                                                                                            | Lee side surface gust (analysis only)                                      | $< 25$ knots                                                                               | 25 - 50 knots                 | $> 50$ knots                |
|                                                                                                                                                                                                                                                                                                                            | Winds below 500 mb greater than 50 kts                                     | Increase turbulence intensity (found from the other parameters) by one degree of intensity |                               |                             |

Table 1. Criteria for low-level mountain-wave turbulence.

| Low-level turb \ High-level turb | MODERATE | SEVERE   |
|----------------------------------|----------|----------|
| LIGHT                            | ---      | ---      |
| MODERATE                         | LIGHT    | MODERATE |
| SEVERE                           | MODERATE | SEVERE   |
| Mid-level turbulence value       |          |          |

Table 2. Mid-level mountain-wave turbulence values based on low-level considerations. Relationship was established empirically at AFGWC for heavy aircraft.

| Feature \ Turbulence intensity                    |                                   | High-level clear air turbulence<br>+/- 5000 feet of tropopause |                       |
|---------------------------------------------------|-----------------------------------|----------------------------------------------------------------|-----------------------|
|                                                   |                                   | MODERATE                                                       | SEVERE                |
| MODERATE or SEVERE low-level turbulence -- and -- | Tropopause height and temperature | MODERATE from Figure 14                                        | SEVERE From Figure 14 |
|                                                   | Temperature gradient at 200 mb    | < 5°C/120 nm                                                   | ≥ 5°C/120 nm          |

Table 3. Criteria for high-level mountain-wave turbulence. Values were determined empirically at AFGWC for heavy aircraft.

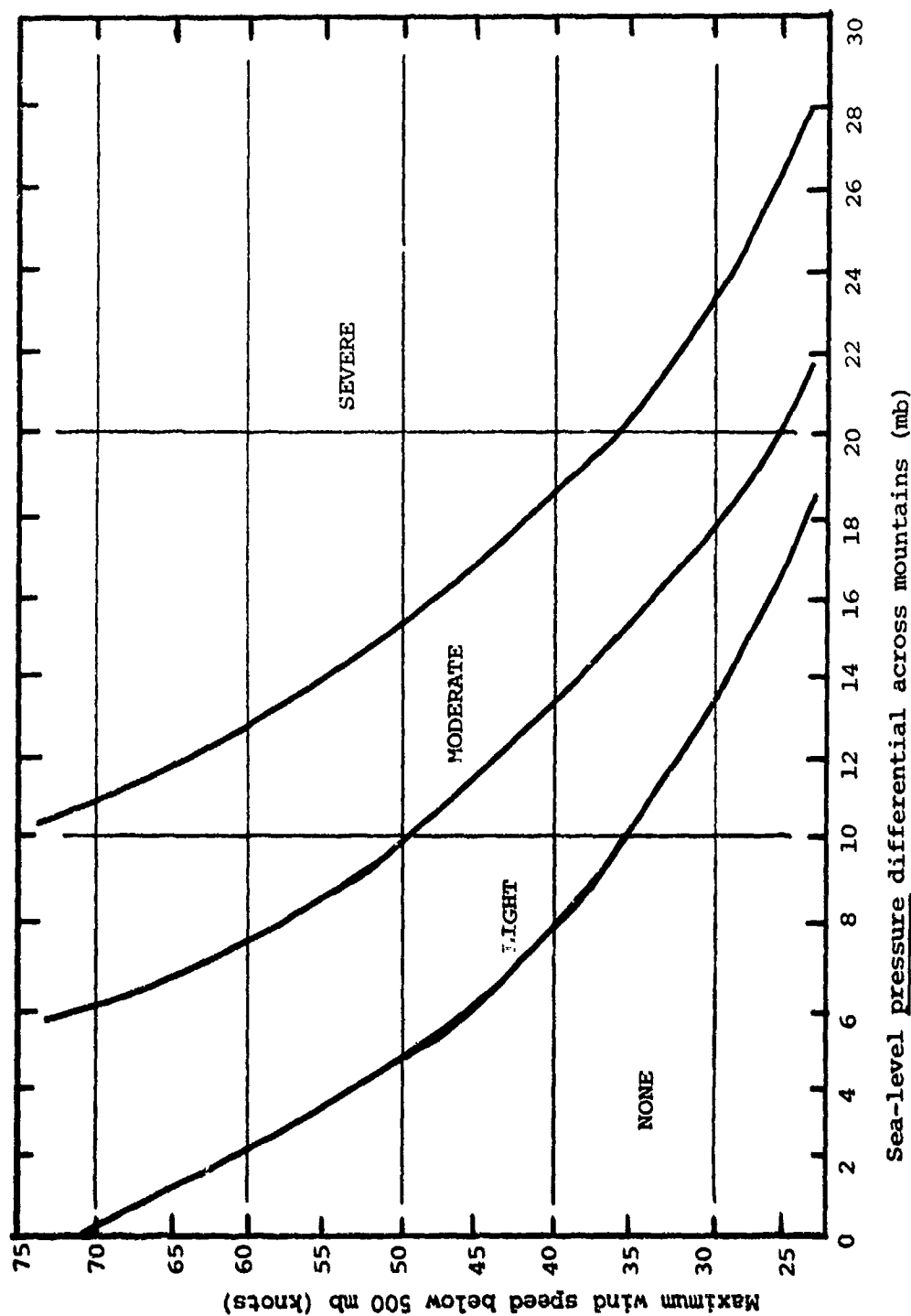


Figure 13. Turbulence intensity as a function of maximum wind speed and sea-level pressure differential, after Harrison (1965).

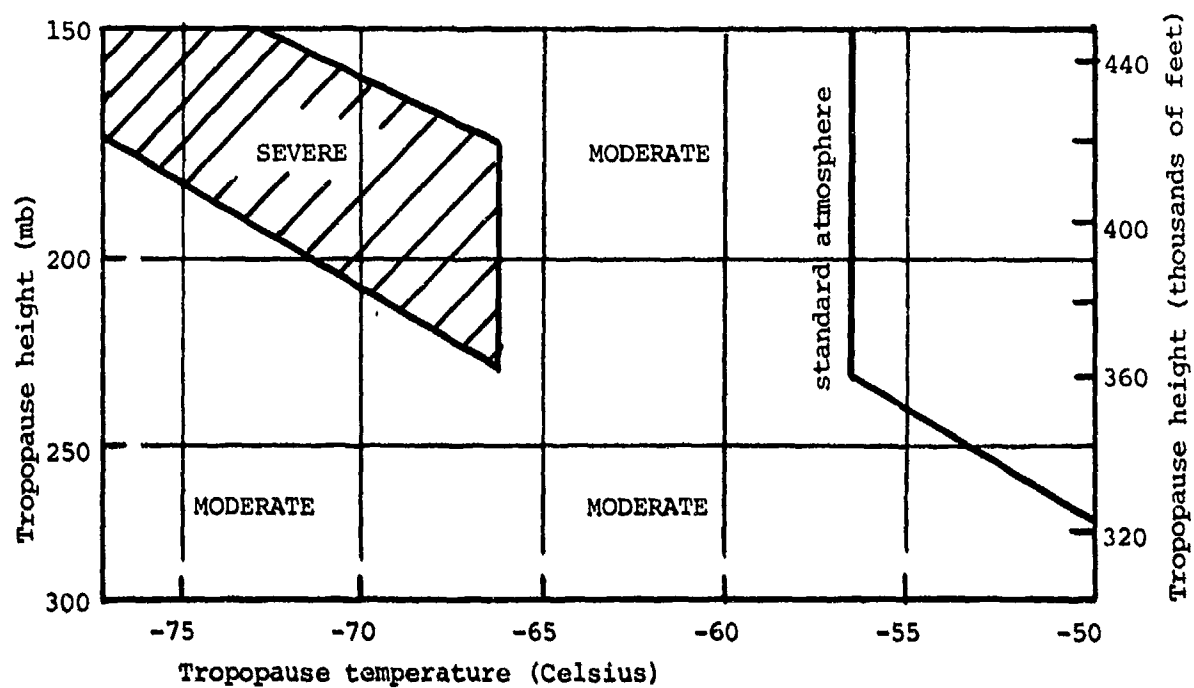


Figure 14. High-level turbulence intensity as a function of tropopause height and temperature. Data from Sorenson and Beckwith (1975).

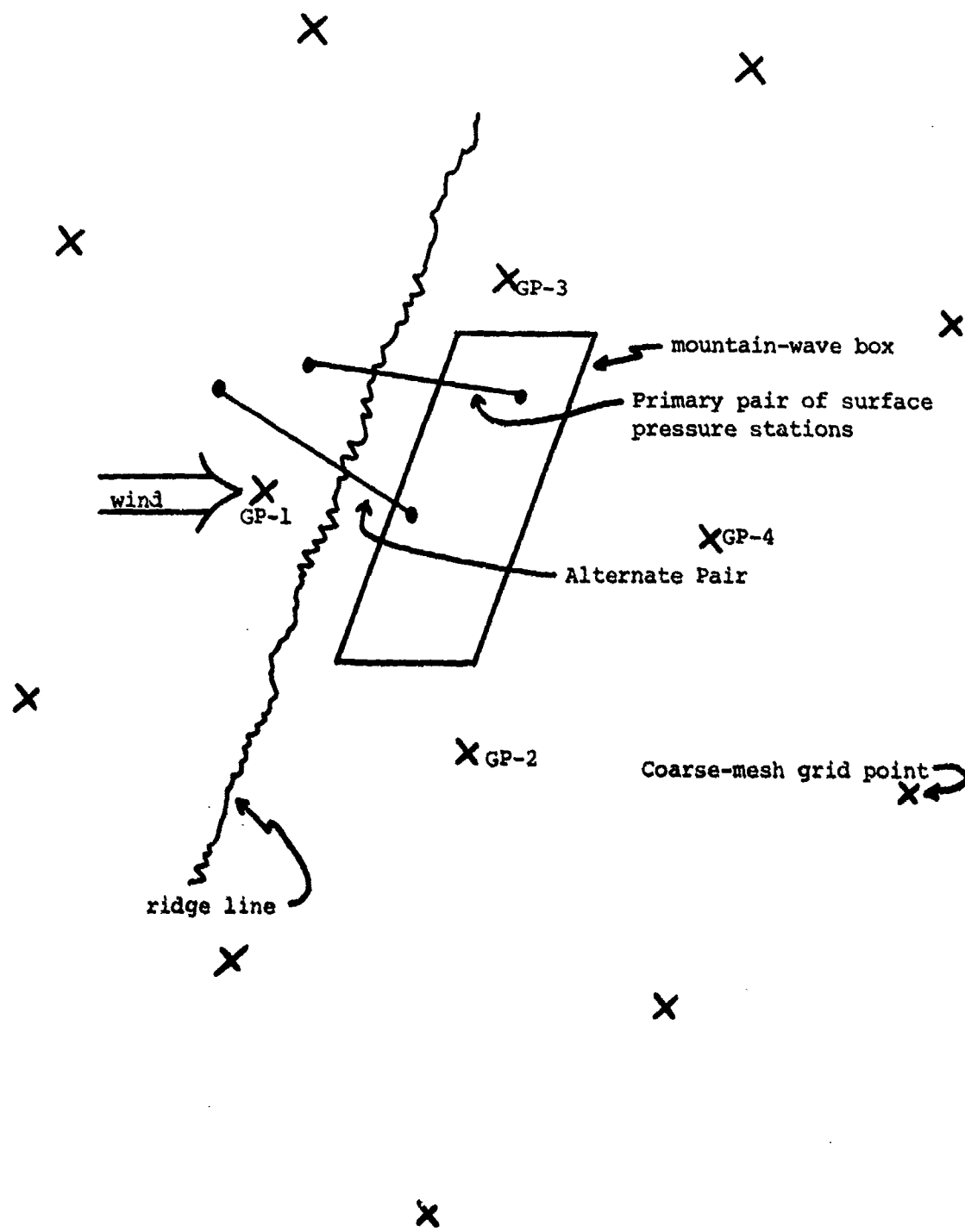


Figure 15. A schematic of data points used to evaluate mountain-wave turbulence potential.

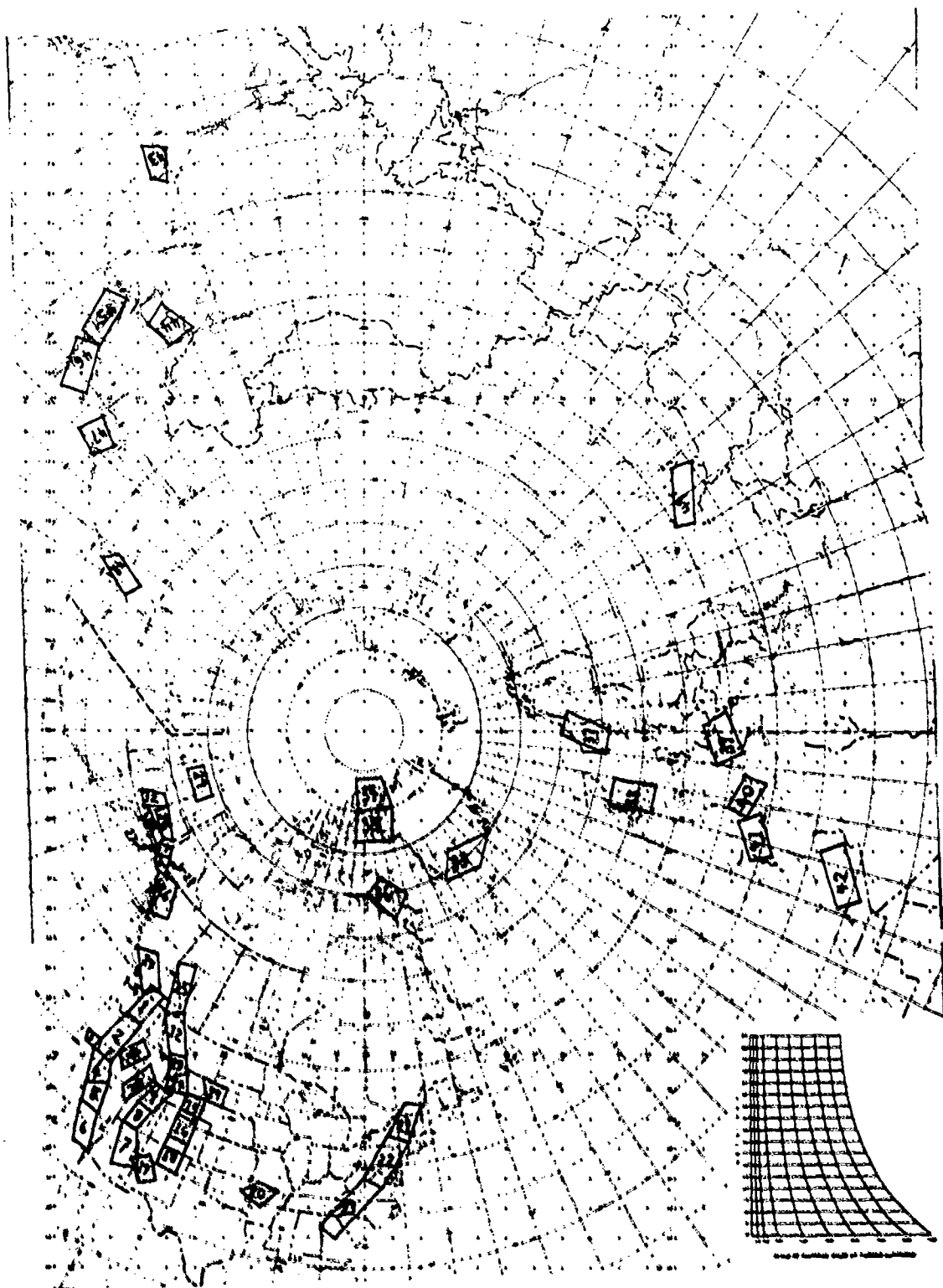


Figure 16. Northern hemisphere mountain-wave boxes.

when available, half-mesh grid points are used instead of coarse-mesh grid points.

Unfortunately, the grid points are not always aligned parallel or perpendicular to the ridge line, and sometimes no one grid point lies within the box. The best grid points to use for each box have been subjectively selected. Refer to the sketch again as an example: grid point one (GP1) may be selected to represent the best conditions inside of the box, GP1 with GP2 may be used for along-the-ridge conditions, while GP1 with GP3 (or GP1 with GP4) may be used for across-the-ridge conditions.

The mandatory pressure level that best represents conditions at mountain top is an arbitrary choice. At present, the lowest mandatory level above the mountain top<sup>1</sup> is used, this choice is partially subjective. The levels used for each box are summarized in Table 4, along with the average ridge heights.

Now, back to the computer routine. First, the computer checks whether the component of the mountain top wind that crosses the ridge within a small range of angles (see Table 4 for list of wind directions) is greater than or equal to 25 knots. If this condition is not satisfied then no turbulence is predicted at any level for that box.

If this condition is satisfied, the computer goes on to consider the other parameters in Table 1. The maximum wind speed below 500 mb and the positive sea-level pressure difference across the mountain range (see Figure 13) are considered<sup>2</sup>. A positive pressure difference means that the upwind pressure is greater than the downwind pressure. This pressure difference can be obtained from either the surface station observations or from grid-point fields. Empirical correction factors (see Table 4) are added to the surface station pressure differences before Figure 13 is used.

MTWVB also considers the absolute values of the 850 mb temperature differences across and along the mountain range. Finally, it looks at gust data at the surface stations on the lee side of the range.

The four parameters ( $\Delta P$ ,  $\Delta T$ ,  $\Delta T/\Delta X$ , gusts) may predict different values of turbulence intensity for any one box. The maximum value is used. Next, this maximum value is increased one turbulence degree (for example from moderate to severe) if the maximum winds below 500 mb are greater than 50 knots. The resulting intensity is assumed to apply to a region over the mountain-wave box from the surface to 5000 ft above the surface (AGL).

5.2.2 High-level mountain-wave turbulence. Next, the computer finds the turbulence intensity in the high-level part of the mountain-

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1. The terms "mountain top" and "average ridge height" have the same meaning in this note.

2. Note that a few boxes accept all wind directions (see Table 4). For these boxes, both positive and negative  $\Delta P$  are used; that is, the absolute value of  $\Delta P$  is used in Figure 13.

| BOX<br>NUM | ACCEPTABLE WIND<br>DIRECTIONS<br>(DEGREES FROM<br>THE NORTH) | LOWEST<br>MANDATORY<br>PRESSURE<br>LEVEL (MB) | AVERAGE<br>HEIGHT OF<br>RIDGE (FT) | PRESSURE<br>DIFFERENTIAL<br>ADJUSTMENT<br>FACTOR |
|------------|--------------------------------------------------------------|-----------------------------------------------|------------------------------------|--------------------------------------------------|
| 1          | 250 - 270 - 290                                              | 700                                           | 7,000                              | +4                                               |
| 2          | 250 - 270 - 290                                              | 700                                           | 6,500                              | +4                                               |
| 3          | ALL                                                          | 700                                           | 7,000                              | +4                                               |
| 4          | 240 - 250 - 290                                              | 700                                           | 10,000                             | +4                                               |
| 5          | 240 - 250 - 270                                              | 700                                           | 11,000                             | +2                                               |
| 6          | All                                                          | 700                                           | 7,000                              | +1                                               |
| 7          | 220 - 250 - 290                                              | 700                                           | 8,000                              | -3                                               |
| 8          | 250 - 280 - 330                                              | 700                                           | 10,000                             | +3                                               |
| 9          | 250 - 270 - 290                                              | 700                                           | 11,000                             | -1                                               |
| 10         | ALL                                                          | 700                                           | 8,000                              | 0                                                |
| 11         | 220 - 270 - 290                                              | 700                                           | 7,000                              | -1                                               |
| 12         | 270                                                          | 700                                           | 8,000                              | +4                                               |
| 13         | 270                                                          | 700                                           | 10,000                             | 0                                                |
| 14         | 270                                                          | 700                                           | 10,500                             | -4                                               |
| 15         | 260 - 280 - 310                                              | 700                                           | 10,000                             | -4                                               |
| 16         | ALL                                                          | 700                                           | 11,000                             | 0                                                |
| 17         | 250 - 270 - 290                                              | 700                                           | 8,500                              | +3                                               |
| 18         | 250 - 270 - 290                                              | 700                                           | 11,000                             | 0                                                |
| 19         | 220                                                          | 700                                           | 7,000                              | +1                                               |
| 20         | 220                                                          | 850                                           | 2,000                              | +1                                               |
| 21         | 240 - 280 - 290                                              | 850                                           | 3,000                              | -4                                               |
| 22         | 260 - 290                                                    | 850                                           | 2,000                              | -1                                               |
| 23         | 320                                                          | 850                                           | 4,000                              | 0                                                |
| 24         | 220                                                          | 700                                           | 8,000                              | 0                                                |
| 25         | 210 - 220 - 230                                              | 700                                           | 10,000                             | -4                                               |
| 26         | 220                                                          | 700                                           | 8,000                              | -4                                               |
| 27         | 220                                                          | 500                                           | 12,000                             | +1                                               |
| 28         | 220 - 230 - 240                                              | 500                                           | 13,500                             | -4                                               |
| 29         | 340                                                          | 700                                           | 6,500                              | -4                                               |
| 30         | 330 - 350 - 010                                              | 700                                           | 8,000                              | 0                                                |
| 31         | 360                                                          | 700                                           | 8,000                              | +4                                               |
| 32         | 310 - 330                                                    | 700                                           | 10,000                             | +3                                               |
| 33         | 250 - 270 - 290                                              | 700                                           | 10,000                             | -8                                               |
| 34         | 340                                                          | 700                                           | 6,000                              | 0                                                |
| 35         | 330                                                          | 850                                           | 5,000                              | -4                                               |
| 36         | 230                                                          | 850                                           | 5,000                              | 0                                                |
| 37         | 290                                                          | 700                                           | 6,000                              | -1                                               |
| 38         | 270                                                          | 850                                           | 2,000                              | +2                                               |
| 39         | 340                                                          | 700                                           | 8,500                              | 0                                                |
| 40         | 200                                                          | 700                                           | 8,000                              | 0                                                |
| 41         | 320 - 330                                                    | 700                                           | 6,000                              | -4                                               |
| 42         | 330 - 340 - 350                                              | 700                                           | 9,000                              | -1                                               |
| 43         | 300                                                          | 700                                           | 10,000                             | +5                                               |
| 44         | 240 - 250                                                    | 850                                           | 3,000                              | +3                                               |
| 45         | 330 - 340                                                    | 850                                           | 5,000                              | +1                                               |
| 46         | 320                                                          | 700                                           | 6,000                              | +1                                               |
| 47         | 280                                                          | 850                                           | 5,500                              | +2                                               |
| 48         | 290                                                          | 850                                           | 5,000                              | 0                                                |
| 49         | 100 - 200 - 300                                              | 700                                           | 10,000                             | 0                                                |

Table 4. Mountain-top data associated with 49 specific mountain-wave turbulence regions. See Figure 16 for the location of each numbered box.

wave box. High-level turbulence is assumed to exist within 5000 feet above and below the tropopause. If moderate or severe low-level turbulence is expected, then moderate high-level turbulence is automatically assumed to exist (see Table 3). In addition, if either the maximum temperature gradient at 200 mb is greater than  $2.5^{\circ}\text{C}/60\text{ nm}$  or if the tropopause height and temperature for any one of the four grid points associated with a box lies within the shaded area of Figure 14, then severe upper-level turbulence is expected.

5.2.3 Mid-level mountain-wave turbulence. Finally, the mid-level turbulence intensity is found using Table 2. Once the low-level turbulence intensity (leftmost column) and the high-level turbulence intensity (top row) are determined, a mid-level turbulence intensity is assigned to this region between the low and high levels.

It is interesting to note that the following predictions will always occur based on the logic just presented:

If the low-level turbulence is MDT,  
then the high-level will always be at least MDT,  
and the mid-level will always be LGT.

If the low-level turbulence is SVR,  
then the high-level will always be at least MDT,  
and the mid-level will always be MDT.

Also, note that some mountain ranges are so high that the mountain-top winds are taken from the 500 mb pressure level (see Table 4). For these cases, the mountain top winds that are printed out by the computer are equal to the maximum winds below 500 mb, which are also printed.

The average tropopause height is calculated from the tropopause heights at the four grid points nearest the box. Hence, this average value may differ from the one tropopause height selected that is closest to the shaded area on Figure 14.

5.3 CATB program. Before leaving the subject of CAT forecasting aids, the CATB computer program should be mentioned briefly. This program was unsuccessful, and thus never implemented at AFGWC. Its purpose was to forecast, rather than analyze, CAT.

Basically, CATB was to diagnose CAT from the macroscale forecast fields of wind and temperature. Theoretically, the same physics should hold whether one diagnoses CAT from forecast fields or from observed (RAOB) fields. However, the forecast fields at AFGWC have a resolution too coarse to study microscale phenomena such as CAT. Also, the forecast fields appear increasingly smoother as the forecast progresses. Thus, the CAT forecasts provided by CATB are of insufficient quality to justify operational use.

## 6 OPERATIONAL CAT FORECASTING BASED ON MODEL OUTPUT AND OTHER INFORMATION

CAT may occur in any of the following situations:

- Areas of Thermal Advection
  - Cold-air Advection
  - Warm-air Advection
  - Rapid Surface Cyclogenesis
  - Outflow Area of Cold Digging Jet
- Areas of Considerable Vertical Directional Shear
  - Tilted Trough
  - Tilted Ridge
  - Confluent Jet Streams
  - Sharp Ridge
- Areas of Considerable Horizontal Directional and/or Speed Shear
  - Sharp Anticyclonic Curvature
  - Development of Cutoff Low
  - Diffluent Upper Flow
- Areas near Mountains
- Areas in the Stratosphere

### 6.1 Thermal advection.

6.1.1 Cold-air advection. CAT frequently occurs in regions of increasing thermal gradients, as best illustrated by cold-air advection in long- and short-wave troughs. Figure 17 shows examples of CAT forecasts associated with cold advection in an upper-air trough. The horizontal temperature gradients associated with the jet front in the middle troposphere are clearly depicted. At 300 mb, there is normally an absence of cold-air advection so a careful analysis of the 200 mb height and temperature fields is necessary. To forecast CAT associated with cold-air advection, Sorenson and Beckwith (1975) suggest that a strong temperature gradient of  $5^{\circ}\text{C}/120\text{ nm}$  at 200 mb should exist with one of the following features:

Speed of trough movement of at least 25 knots.

A strong horizontal wind shear of at least 40 knots/120 nm in the region of closely packed isotherms.

A wind component greater than 65 knots normal to the region of closely packed isotherms.

A sharp wind shift of at least  $75^{\circ}$  in a region of closely packed isotherms.

The 500 mb analysis of observed data may clearly depict the cold-air advection. According to Sorenson and Beckwith (1975), CAT is expected when the amplitude of the 500 mb temperature field exceeds the amplitude of the 500 mb height field by a factor of two, (thus each 500 mb isotherm must cross at least two 500 mb height contours with a trough speed greater than 25 knots.)

The 500 mb height and vorticity fields can be used to identify short waves that are indirectly related to this advection. CAT is forecast in the area of strongest isotherm packing just ahead of the temperature trough. Areas of considerable positive vorticity advection are indic-

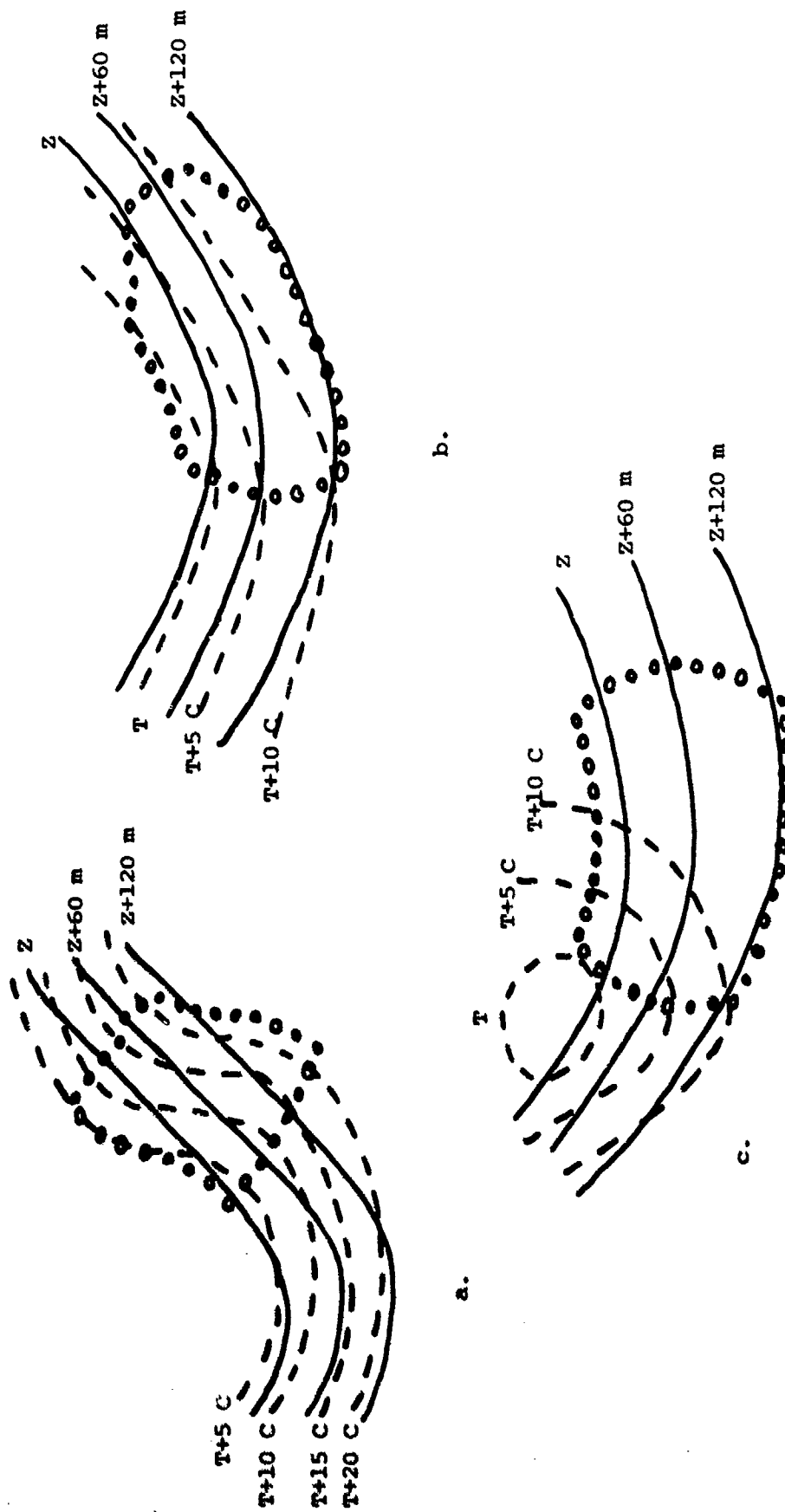


Figure 17. CAT forecast areas associated with 500 mb cold-air advection, after Sorenson and Beckwith (1975).

ative of development and can be used to approximate the future region of cold-air advection (see Figure 18). The vertical placement of CAT varies with the wind speed, the height of the tropopause, and the synoptic situation. Normally, moderate turbulence should be forecast from the height where sufficient vertical shear associated with the cold advection is found to 2,000 feet above the tropopause in cyclone-scale waves. Figure 19 is an example of a CAT forecast in long-wave cold-air advection.

Severe CAT may be forecast for cases of very strong cold-advection ( $5^{\circ}\text{C}/120\text{ nm}$ ) in mountainous regions where large values of vertical shear exist with other turbulence producing mechanisms. CAT will normally continue as long as significant cold-air advection exists.

Sorenson and Beckwith (1975) pointed out that low-level cold advection under a ridge tends to increase the vertical shear and probability of CAT. Figure 20 shows an example of CAT near the jet stream core in an upper-level ridge with low-level cold advection at the 850 mb and 700 mb levels.

6.1.1.1 Short-wave troughs. CAT is also probable when a short-wave trough accompanied by a sharp thermal trough moves out rapidly ahead of a deepening trough. Figure 21 shows where CAT can be expected when a short-wave trough moves through the long-wave pattern. Hopkins (1976) suggests that the major axis of the CAT forecast areas should be approximately 150 nm in length, centered north of the jet stream core and east of the trough line.

One should forecast moderate CAT from 2,000 feet above the tropopause to 6,000 feet below the tropopause. Short-wave troughs may be found anywhere in the flow and CAT can occur as low as 18,000 to 27,000 feet. Forecasts of 500 mb height and vorticity predict positions and intensities well.

6.1.1.2 Sharp troughs. The axis of a sharp, rapidly moving trough in the contour pattern (see Figure 22) denotes another area of potential turbulence. Burnett (1970) noted that the large horizontal wind shears found near the base of the trough, where the direction of flow changes most rapidly, are indicative of large gradients of vertical motion. Tightly packed isotherms are frequently found in these areas. The vertical wind shear is, according to the thermal wind equation, proportional to the horizontal thermal gradient. These conditions are conducive to the formation of the shallow stable layers and coincident layers of wind shear associated with CAT. The trailing edge of the turbulent area is often found to be at the axis of a thermal trough somewhat to the rear of the advancing contour trough. One should forecast moderate turbulence when the wind speeds are between 60 and 120 knots with a wind shift of greater than 120 degrees. (Note: this turning should occur within a 200 nm area.) Forecast severe turbulence when the winds exceed 120 knots with a wind shift of between 90 and 120 degrees or when the winds are greater than 60 knots with a wind shift of greater than 120 degrees.

CAT associated with sharp, rapidly moving troughs is rather short-lived (on the order of 3 to 6 hours), but quite intense. Normally, these systems either weaken and become broad or develop into cutoff lows.

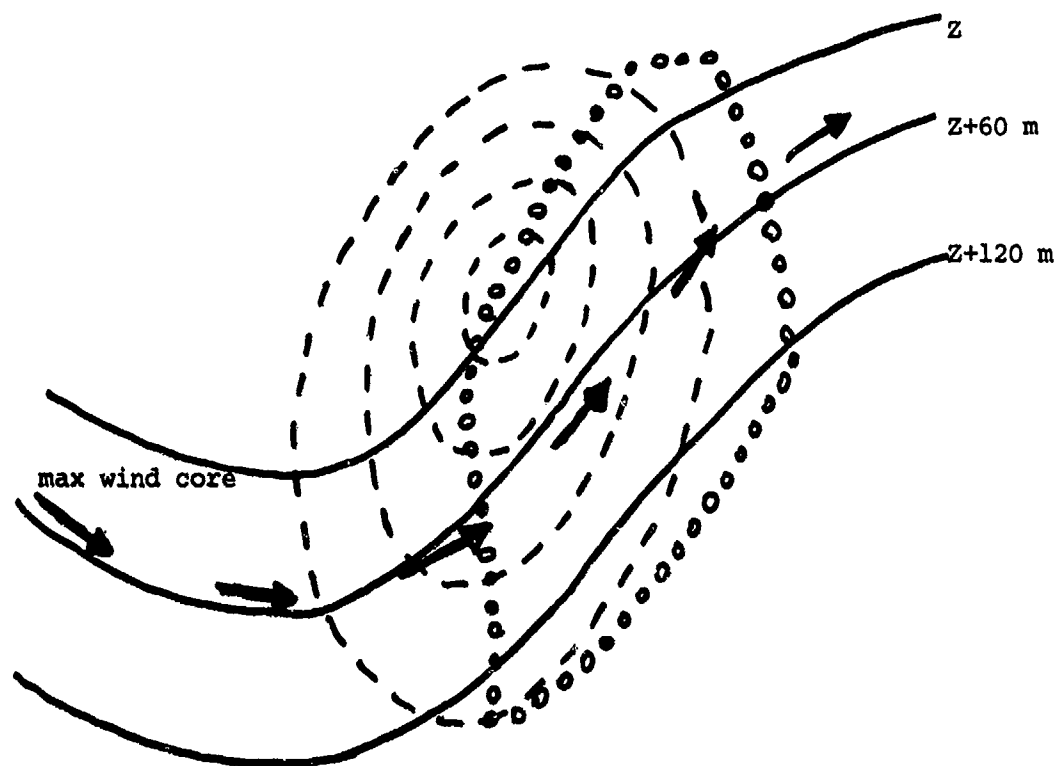
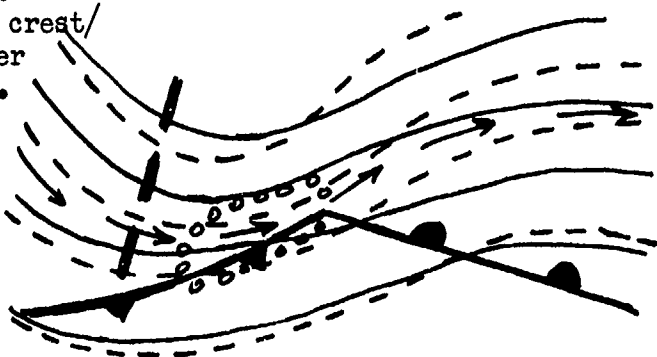


Figure 18. A possible CAT forecast associated with considerable positive vorticity advection (PVA) at 500 mb. Open circles indicate area of possible CAT and dashed lines a vorticity maximum.

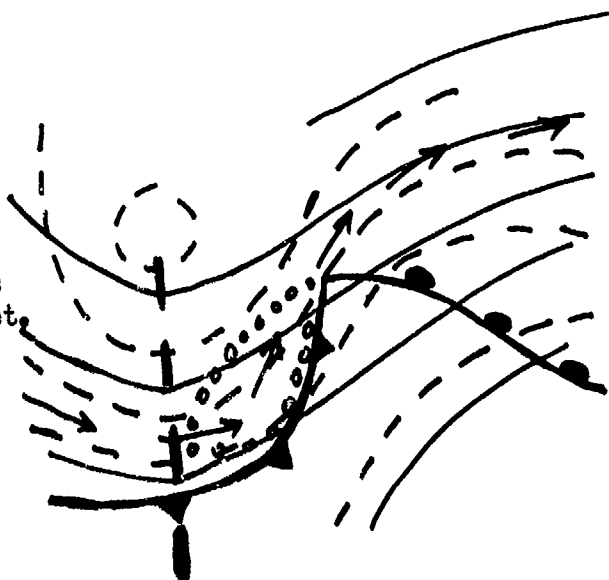
a. Early stage.

Potential is greatest between surface wave crest/triple point and upper level thermal trough. This holds for all stages. Vertical extent of maximum potential is middle troposphere (20,000 to 27,000 feet).



b. Mature stage.

Vertical extent of maximum potential is 15,000 to 30,000 feet. Area is in cold air behind cold front.



c. Occluded stage.

Potential weakens with upper-air trough, however, watch for reinforcement.

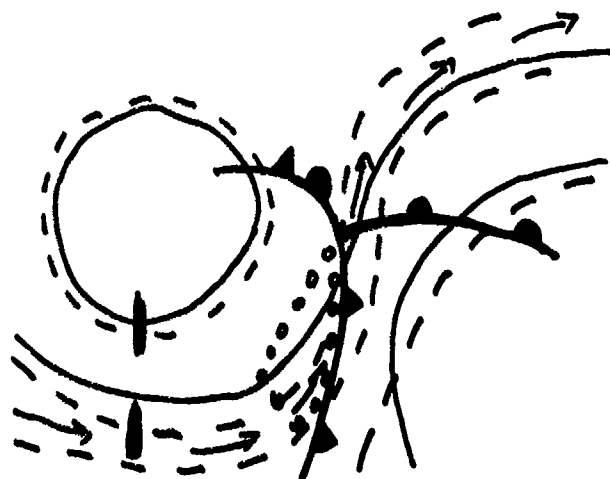


Figure 19. Turbulence potential associated with cyclone-scale advection, after Sorenson (1964). Solid lines are height contours, dashed lines are isotherms, arrows indicate the jet stream core, and open circles potential turbulence.

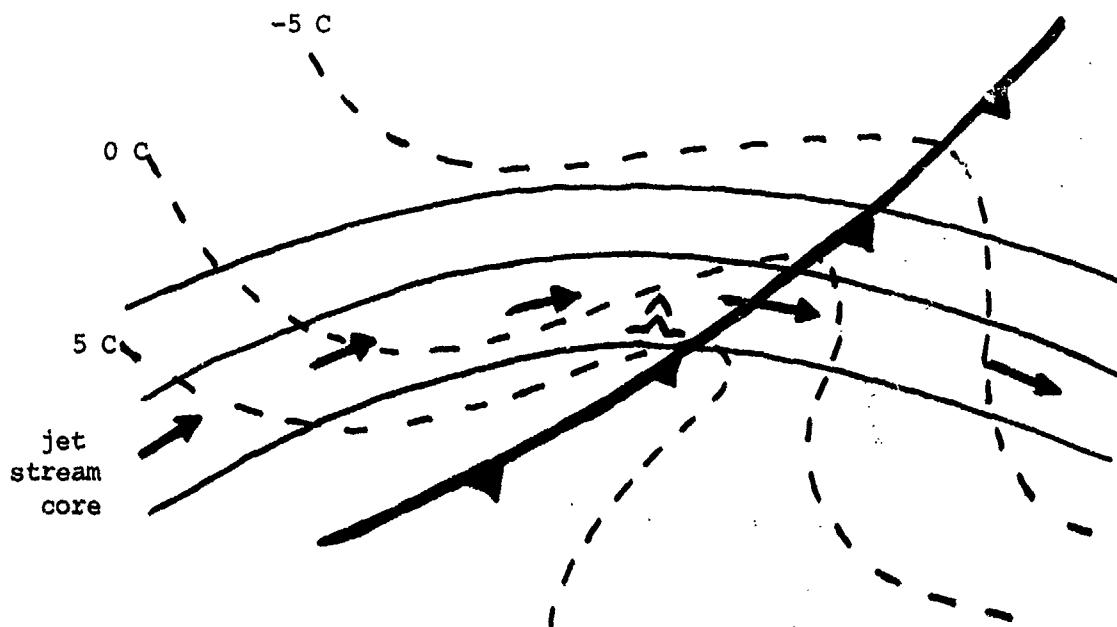
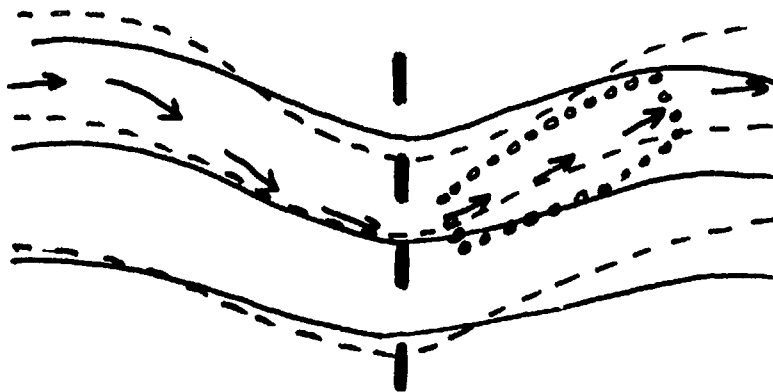
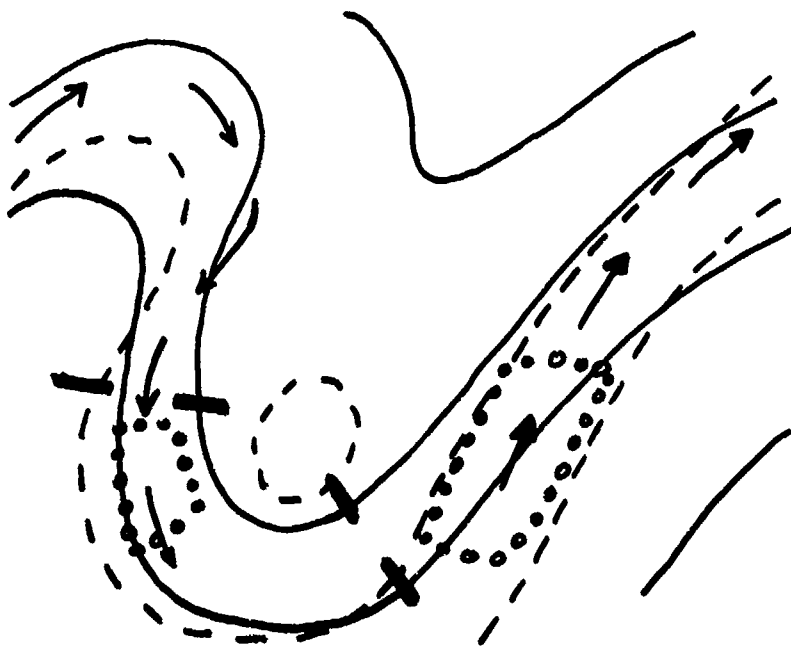


Figure 20. Severe CAT associated with low-level cold advection at 700 mb under a ridge. Example taken from Sorenson and Bockwith (1975).



Potential is greatest ahead of and near the thermal trough. Turbulence areas move with short waves and change intensities as waves do. Vorticity forecasts predict intensities well. Vertical extent of maximum potential is middle troposphere (18,000 to 27,000 feet).



Short wave troughs may be found anywhere in the flow. One area of interest is the rear of cutoff lows. Area merges with preceding area as thermal troughs combine.

Figure 21. Turbulence potential (open circles) of short-wave cold-air advection, from Sorenson (1964).

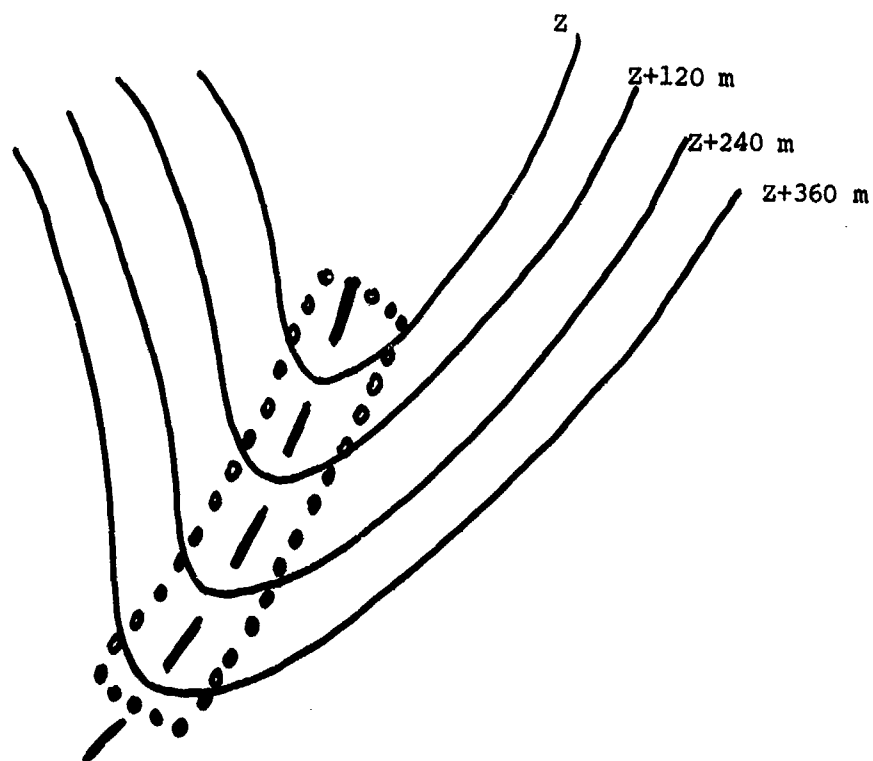


Figure 22. Turbulence potential (open circles) in a sharp trough at 300 mb. Example from Burnett (1970).

6.1.2 Warm-air advection. Warm-air advection can also increase horizontal temperature gradients, though this mechanism is weaker in short waves and may be overlooked when cold-air advection is nearby. Adjacent to the tropopause, however, the association of warm-air advection with anticyclonic accelerations and the resulting horizontal speed shear make an effective combination for turbulence potential (see Figure 23).

Sorenson and Beckwith (1975) showed that CAT is expected near an anti-cyclonically curved jet stream core in the vicinity of a warm front when the wind speed at the jet stream core is greater than 75 knots, the 850 mb temperature gradient is greater than  $5^{\circ}\text{C}/120\text{ nm}$ , and there are low-level convergent winds across the front (see Figure 24).

Hopkins (1976) generalized that the CAT forecast area associated with warm-air advection into an upper-level ridge is nearly symmetric about the ridge axis and the jet stream core, shifted slightly north of the jet stream core, located on and downstream of the ridge axis. The CAT forecast area should extend vertically for 4,000 feet both above and below the maximum wind level and/or 2,000 feet above the tropopause to 6,000 feet below the tropopause.

Moderate and severe CAT can also occur on both sides of the jet stream core and where the jet stream core experiences the greatest latitudinal displacement in an amplifying ridge. The region of maximum CAT is found in the area of greatest anticyclonic curvature, which is usually within 300 nm upstream and downstream of the ridge axis. Hopkins (1976) suggested that severe CAT should be forecast in a ridge when one of the following conditions is met:

Strong vertical shear (20 knots/1000 feet or greater);

Wind speeds in excess of 140 kts in a region of strong anti-cyclonic curvature; or

A large latitudinal displacement of a jet stream core with wind speeds in excess of 120 kts.

6.1.3 Rapid surface cyclogenesis. During the early stages of surface cyclogenesis, the main jet stream core is usually  $5^{\circ}$  to  $10^{\circ}$  latitude north of the surface low. However, some low centers move or redevelop north of the main jet stream core while still in the early stages of cyclogenesis. This results in a second jet stream core forming  $5^{\circ}$  to  $10^{\circ}$  latitude to the left of, and parallel to, the main jet stream core. Because upper-air (300 mb) forecasts indicate little evidence of the new jet stream formation, CAT forecasters often miss these situations entirely.

Rammer (1973) shows the most probable area for CAT to occur with respect to a developing surface low and the main jet stream core (Figure 25). When surface cyclogenesis is forecast, CAT should be forecast to occur near the jet stream core north and east of the surface cyclogenetic area within 300 nm upstream and downstream of the upper-level ridge axis. Figure 26 shows an overlay used to locate a first-guess area of CAT from the forecast position of surface cyclogenesis.

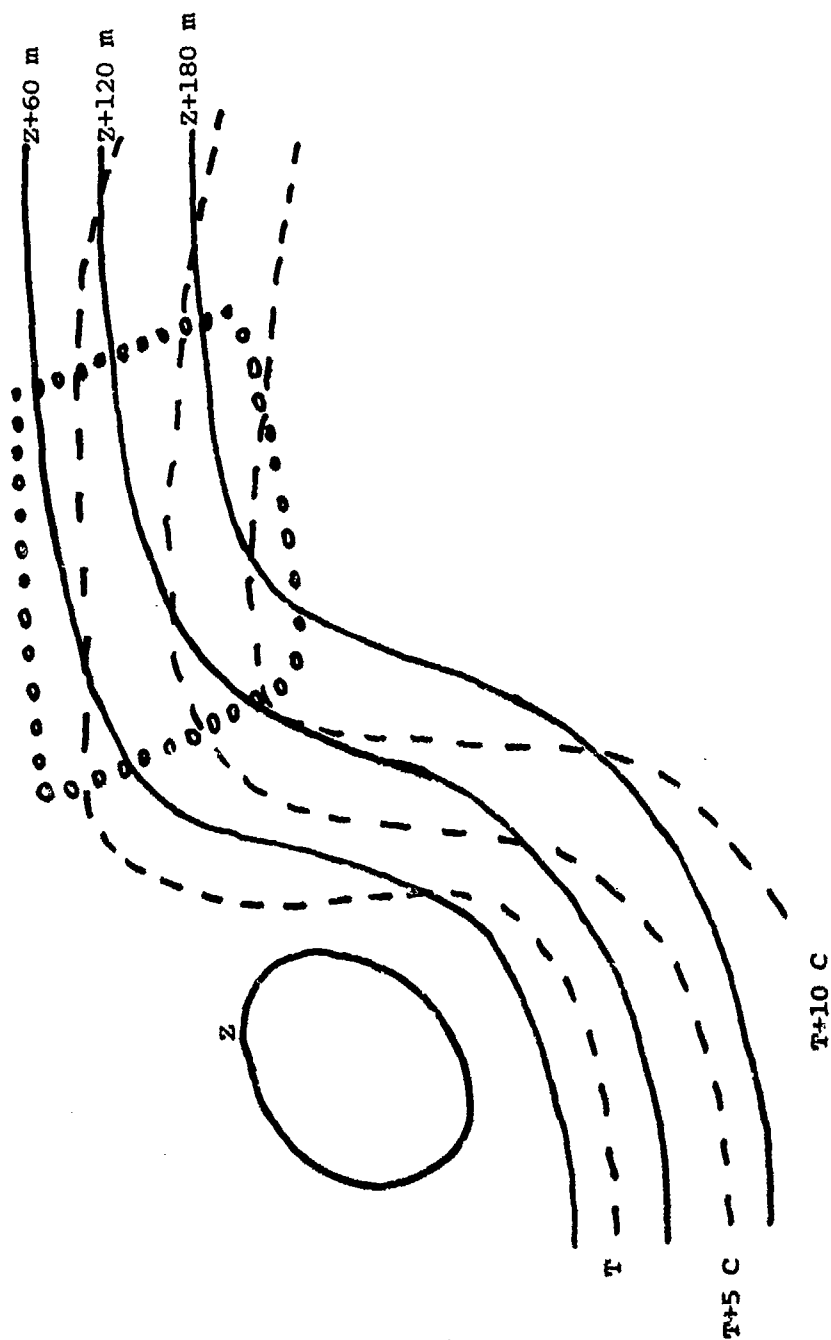
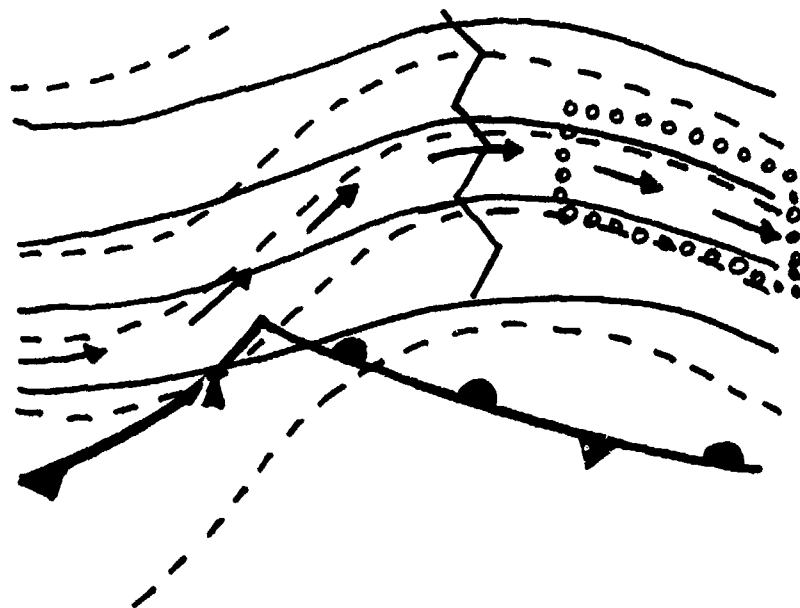
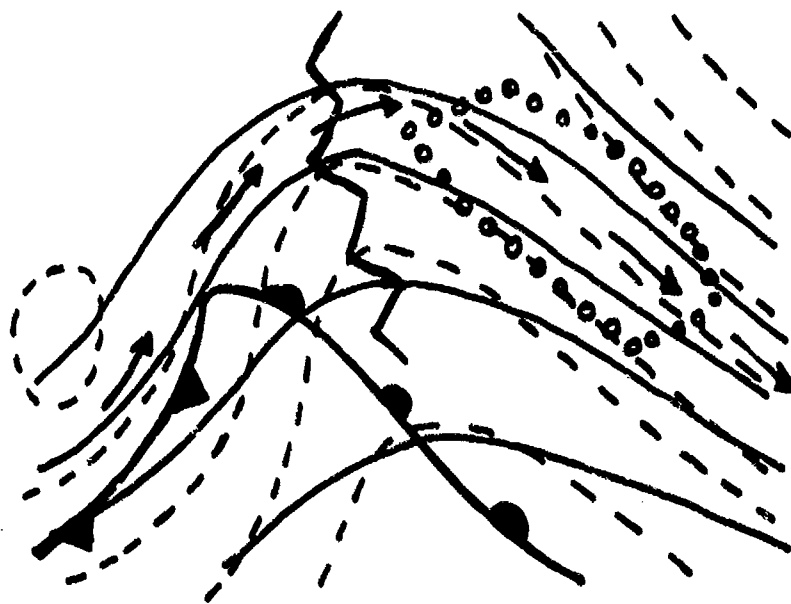


Figure 23. CAT forecast associated with strong warm-air advection at 500 mb, from Sorenson (1964). CAT forecast indicated by open circles.

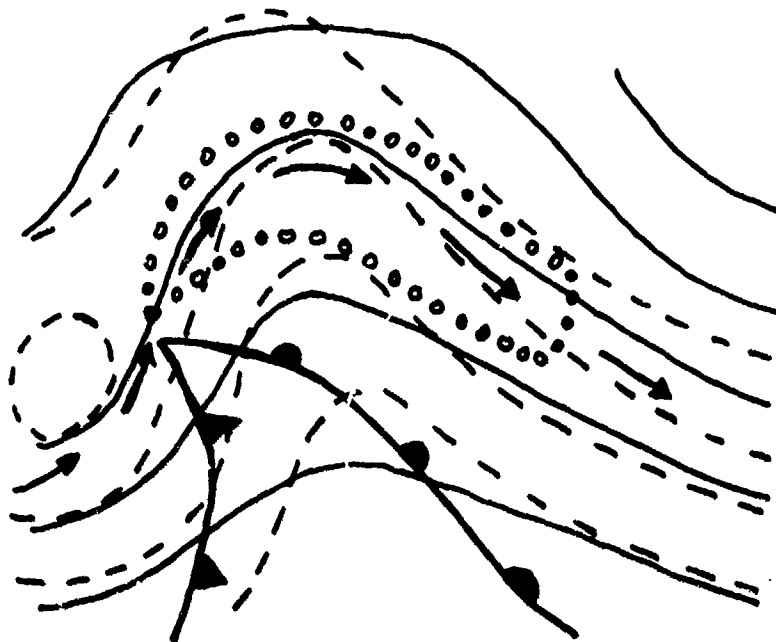


a. Early stage. Potential is greatest ahead of thermal ridge, this holds for all stages. Vertical extent of maximum potential is 25,000 to 33,000 feet, the upper troposphere. Turbulence potential may be slight at this stage.

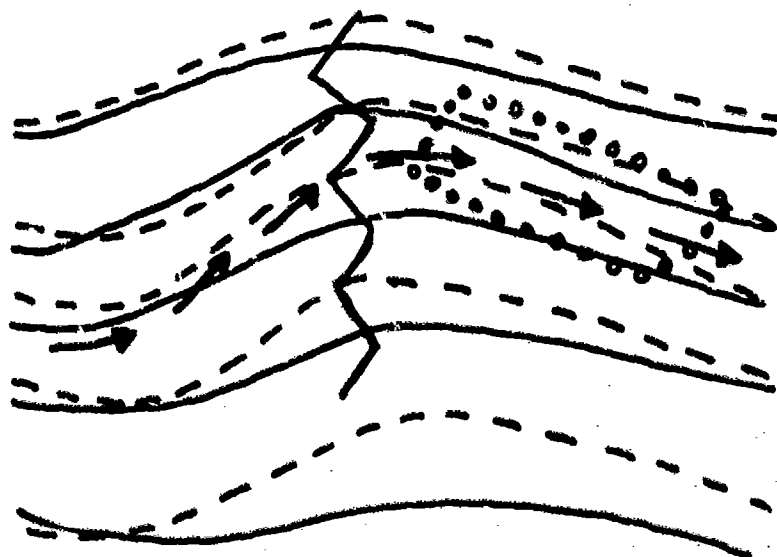


b. Mature stage (1). Vertical extent of maximum potential is 25,000 to 40,000 feet. It may merge with the next case, but is most intense in sharp dynamic ridges. Note that the thermal ridge may lie just ahead of the occlusion so that the potential area is closer to the fronts. Potential decreases as this system occludes.

Figure 24. Turbulence potential (open circles) of cyclone-scale warm-air advection. Example from Sorenson (1964).



c. Mature stage (2). Strong jet flow with horizontal speed shears over 25 knots per degree latitude generates potential near tropopause in broad ridges. Potential is with and ahead of jet maximum in contour ridge from 35,000 to 45,000 feet.



d. Potential is greatest ahead of and near the ridge. Turbulence areas move with short waves and change intensities as waves do. Vorticity forecasts predict future intensities well. Vertical extent of maximum potential is upper troposphere (25,000 to 33,000 feet). Potential is generally limited and insufficient.

Figure 24. Turbulence potential (open circles) of cyclone-scale warm-advection. Example from Sorenson (1964). (Continued.)

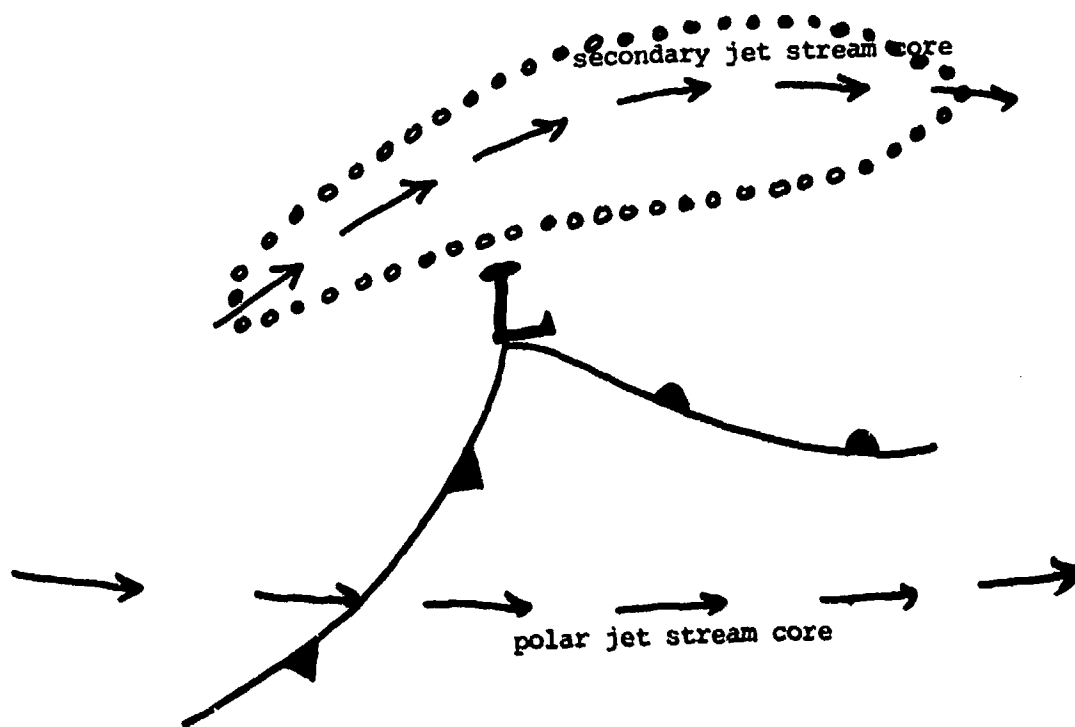


Figure 25. CAT forecast area associated with rapid surface cyclogenesis. Example from Rammer (1973).

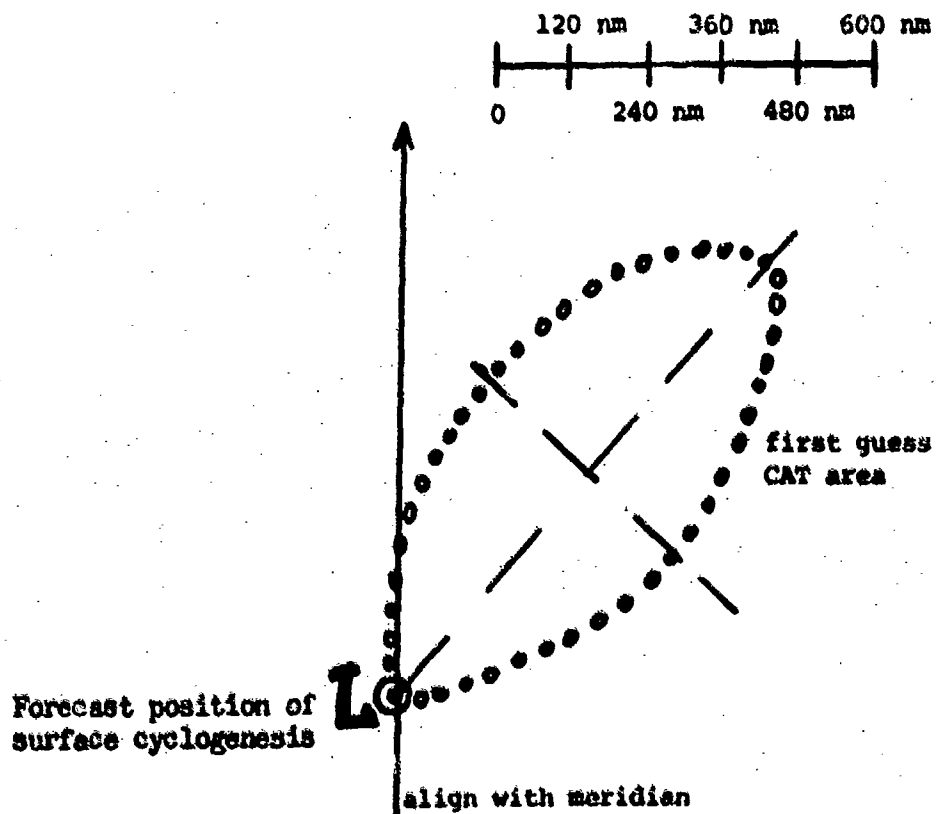


Figure 26. Overlay used to locate first-guess CAT area associated with surface cyclogenesis, from Rammer (1973).

The extent and intensity of CAT associated with surface cyclogenesis is directly related to the rate of cyclogenesis. Moderate CAT is usually forecast with systems that are expected to deepen at a rate of 1 mb/hr and moderate to occasional severe CAT is usually forecast with systems that are expected to deepen at a rate of greater than 1 mb/hr with wind speeds greater than 140 knots. The intensity of this CAT also depends on the proximity of mountains, the strength of the jet stream core, and the degree of amplification and curvature of the downstream ridge. In most cases, the CAT forecast area should extend vertically from about 2,000 feet above to 6,000 feet below the tropopause in the area shown in Figures 25 and 26. Greater thicknesses (surface to 2,000 feet above the tropopause) have been observed in the lee of the Rocky Mountains.

6.1.4 Outflow area of a cold digging jet. CAT will occur with a very high probability in the outflow area of a cold digging jet stream core to the rear of an upper trough. The outflow area on the back side of a trough is the area between the wind maximum and the trough line where the instantaneous wind on a horizontal plane decreases. Figure 27 shows where CAT occurs with respect to the wind field in the outflow area. Cold-air advection over the warm ridge decreases the vertical lapse rate making the atmosphere statically unstable. Pronounced deceleration (large amounts of kinetic energy rapidly transformed to other forms of energy with decreasing stability in the outflow area) causes widespread turbulence.

The decrease in wind speed along the jet stream core is directly proportional to the extent and intensity of the turbulence. Generally, at least a 40 knot decrease of wind speed within  $10^{\circ}$  latitude of the wind maximum must be forecast to justify the issuance of a CAT advisory. A study by Kuessner (1975) shows that if there exists a difference in wind speed of at least 60 knots between the jet stream core minimum in the trough and a point in the jet stream core  $10^{\circ}$  latitude upstream, there is an 82% probability of moderate or greater CAT in the outflow area. The probability of CAT is also directly proportional to the strength of the jet stream core and is greatly increased in mountainous regions. The CAT forecast area should extend from the isotach maximum to the base of the trough and should be centered on the warm-air side of the jet stream core as shown in Figure 27. The vertical extent of the CAT forecast area should extend from 2,000 feet above the tropopause to 6,000 feet below the tropopause. Significant CAT has been observed in thicker layers (from 20,000 feet to just above the tropopause) in mountainous areas. Forecast moderate CAT for most outflow stations. Hopkins (1976) suggests that moderate with occasionally severe CAT may be forecast with wind speeds greater than 130 knots in mountainous regions.

6.2 Areas of considerable vertical shear. The importance of vertical directional shear is best understood by observing certain highly turbulent synoptic situations.

According to Sorenson (1964), tilted ridges and troughs move faster in certain levels than in others so that a station could lie underneath an upper-air ridge or trough line and report winds from different directions at different levels. Figure 28 shows examples of both. The ridge is folding over the low; other analyses have shown that turbulence was reported in vertical directional shear north of the trough line, which

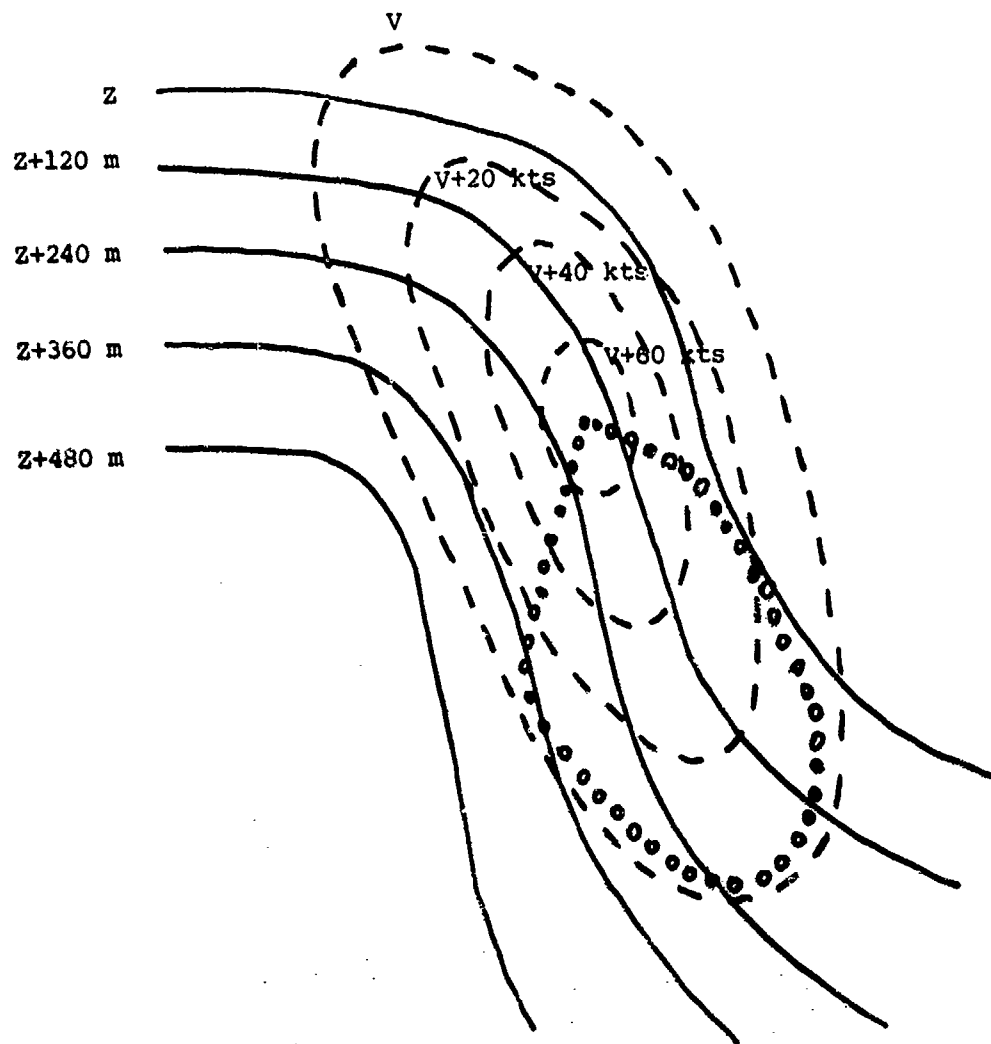


Figure 27. CAT forecast (open circles) in outflow area of cold digging jet at 300 mb, after Kuessner (1975).

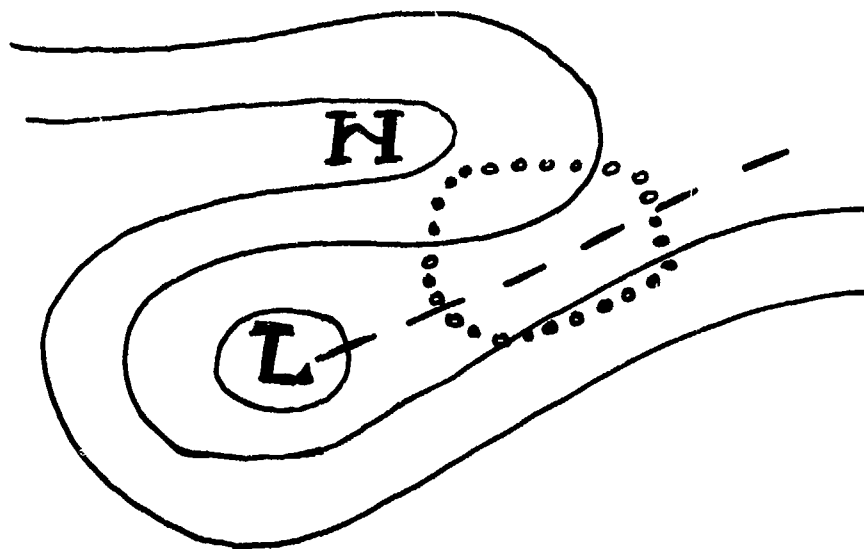


Figure 28. CAT (open circles) in tilted ridge and trough pattern at 300 mb, after Sorenson (1964).

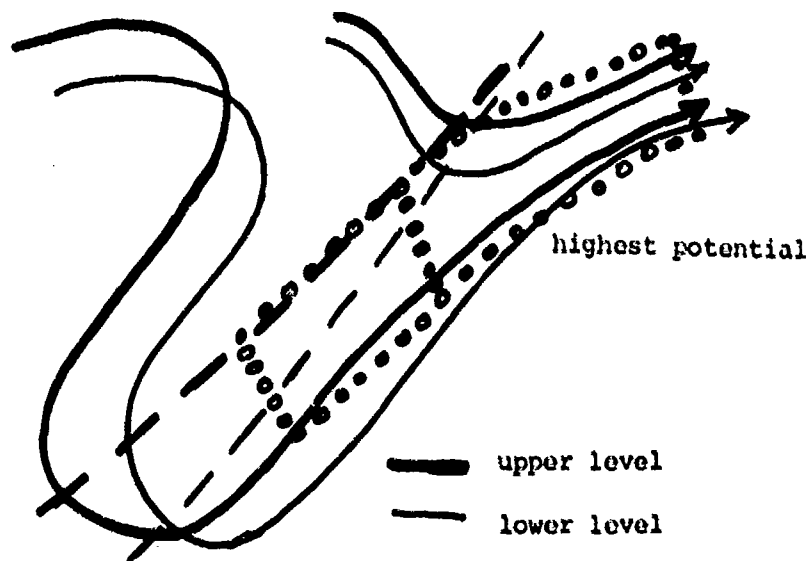


Figure 29. Turbulence potential (open circles) in tilted troughs associated with vertical directional shear. Cutoff troughs may move east faster at lower levels so that there is vertical directional shear ahead of trough and in interacting jets near col. This situation coincides closely with warm-air advection case. Potential is highest from 22,000 to 35,000 feet.

is tilted toward the south with increasing altitude. Occurrence of jet stream winds 75 knots or greater may be used to define an area of potential moderate turbulence. Though not a frequent pattern, it usually produces turbulence for a day or two.

6.2.1 Tilted troughs. Tilted troughs usually occur when the cut-off low is pulling out, moving northeastward. Often, the trough moves out faster at lower levels causing this tilt. This feature often occurs with warm-air advection in the ridge near the col (south jet branch). Turbulence occurs near the col in both cases so the predominant cause may be hard to pinpoint. If turbulence is at middle or high levels in the southerly jet stream, warm-air advection is the likely cause. Tilted trough turbulence usually occurs at middle levels (from 22,000 to 35,000 feet) in the nearby col area (see Figure 29). This may be the most common cause of col turbulence. Turbulence intensity is directly proportional to wind speed and vertical directional shear and can reach moderate/occasional severe intensities.

6.2.2 Tilted ridge. Dynamic folding ridges lag at higher levels (such as near the tropopause), so that the low-level jet flow lies under the trough line. The highest potential for turbulence is north of the trough from 27,000 to 40,000 feet (see Figure 30). Moderate CAT is normally forecast for this situation, which occurs rarely.

6.2.3 Confluent jet streams. When two confluent jet stream cores are within 300 nm of each other, there is a high probability of CAT in the confluent zone between the two jet stream cores.

Because the northern jet stream core is associated with colder temperature and thus a lower altitude than the southern jet stream core, it will often cut underneath the southern jet stream. The result is an increase in static stability and strong vertical directional and speed shears in the confluent zone. Also, in the confluence zone a rapid backing of the wind with height is observed between the levels of the two jet stream cores.

In Figure 31, Sorenson (1964) shows that CAT is most likely to occur in the confluent zone between the two jet stream cores from a point where the jet stream cores approach within  $5^{\circ}$  latitude of each other to where the jet stream cores begin to diverge. Vertically, CAT is forecast to occur between the heights of the two jet stream cores, normally from 25,000 feet to 37,000 feet.

CAT associated with subtropical jet stream interaction normally occurs above 30,000 feet and is fairly difficult to forecast. Because subtropical jet streams are gradient induced, one should look for the deepening of a 300 mb trough at low latitudes (equatorward of  $30^{\circ}$ ). Moderate CAT is forecast for most confluent jet stream cases. However, when jet stream cores of approximately 120 knots or greater approach at an angle greater than  $45^{\circ}$ , forecast moderate with occasionally severe turbulence for the period when the 90 knot isotach of the northern jet stream core passes under the southern jet stream core. Normally, this situation will persist for approximately six hours.

6.2.4 Sharp ridge. Holcomb (1975) concluded that turbulence in

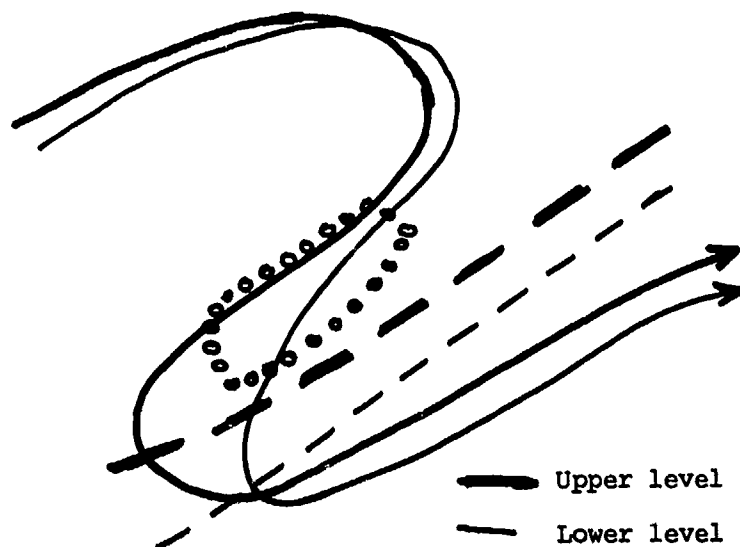


Figure 30. Turbulence potential (open circles) in tilted ridges. Dynamic folding ridges lag at higher levels (tropopause), so that low-level jet flow lies under trough line. Highest potential is north of trough and 27,000 to 40,000 feet. Potential may be slight. Example from Sorenson (1964).

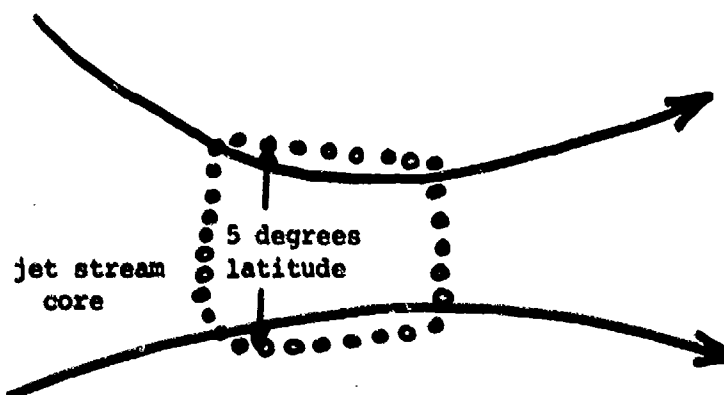


Figure 31. CAT (open circles) associated with confluent jet streams, after Sorenson (1964).

sharp ridges is neither widespread nor often long lasting. Winds here cannot be geostrophic due to the strong positive effect of the Coriolis force. The feature may be tilted with thermal ridging displaced from the contours and the ridge axis may vary greatly in the vertical (see Figure 32). All these factors may combine to produce turbulence. Winds are relatively light (50 kts or greater for moderate CAT); however, reports do occur but are rather uncommon. Generally, forecast moderate CAT from 25,000 to 33,000 feet.

### 6.3 Areas of considerable horizontal shear.

6.3.1 Sharp anticyclonic curvature. A study by Binding (1965) of CAT observations over the North Atlantic shows that 61% of the moderate or greater CAT reports were associated with anticyclonically curved jet stream cores compared with 27% associated with sharp troughs.

Studies by Endlich (1964) and Sorenson and Beckwith (1975) show that CAT is more likely to occur to the north of the jet stream core in the region of strong cyclonic horizontal shear. If a change in wind direction of at least  $15^{\circ}$ /120 nm occurs near the jet stream core (Sorenson and Beckwith, 1975) or horizontal speed shearing over 25 knots per degree latitude exists in a large-amplitude ridge, CAT should be forecast in the region of sharpest anticyclonic curvature.

These areas of strong horizontal directional or speed shear can be easily detected using satellite imagery and upper-level isotach analyses and forecasts. It can be shown, based on dynamics, that horizontal wind shear greater than 25 knots per degree latitude at middle latitudes is sufficient to generate large transverse waves that are best observed when transverse banding (herringbone cloud pattern) is noted on satellite imagery. This concept is best applied south of the jet axis where strong anticyclonic horizontal shear exists and slightly north of the jet stream core where strong cyclonic horizontal shear exists. These large waves alternately expand and compress the shear zone at the tropopause, and in the process amplify existing turbulence.

Hopkins (1976) states that the CAT forecast area associated with a sharp upper-level ridge is shifted slightly to the north of the jet stream core and to the downstream side of the ridge axis (see Figure 33). Normally, forecast moderate CAT 2,000 feet above the tropopause to 6,000 feet below the tropopause when 100 to 140 knot winds with horizontal shear of 25 to 50 knots per degree latitude are expected in a sharp anticyclonic ridge. Forecast moderate with occasionally severe turbulence when strong winds in excess of 140 knots and horizontal shears greater than 50 knots per degree latitude exist in a sharply turning ridge. In any case, look for strong wind maxima entering sharp ridges.

CAT can also occur in strong troughs where there is considerable anticyclonic horizontal shear (see Figure 34). CAT can be rather intense but is fairly short lived (around six hours duration) and uncommon. Look for jet stream maxima climbing into strong ridge patterns and the resulting strong anticyclonic turning and transverse banding.

Sharp anticyclonic subtropical jet streams are a well-known producer of CAT. These jets are fairly easy to analyze but practically impossible to forecast. Using satellite imagery, look for anticyclonically curved

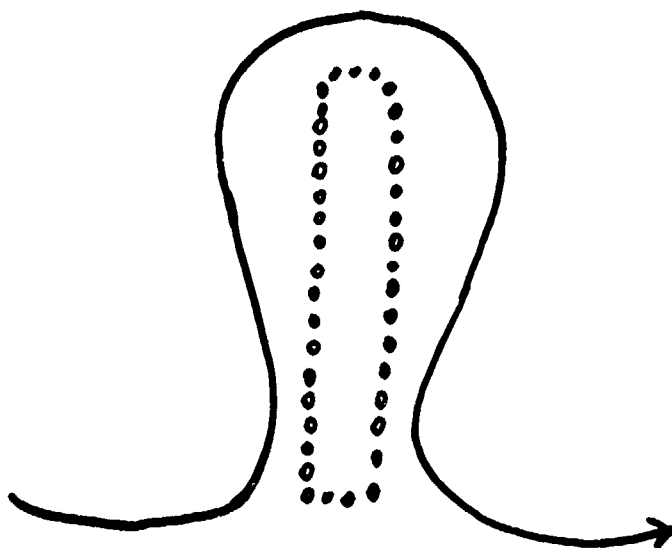


Figure 32. Turbulence potential (open circles) in sharp ridges at 300 mb. Unstable ridge axis may vary greatly in the vertical. Reports are uncommon but do occur, especially at neck or ridge near 25,000 to 33,000 feet. Example after Sorenson (1964).

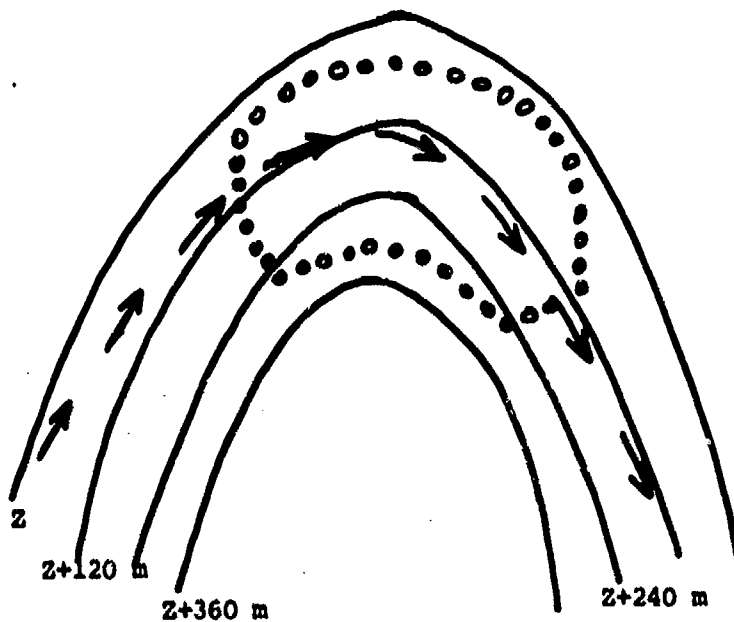


Figure 33. CAT (open circles) associated with sharp anticyclonic curvature at 300 mb. after Hopkins (1976).

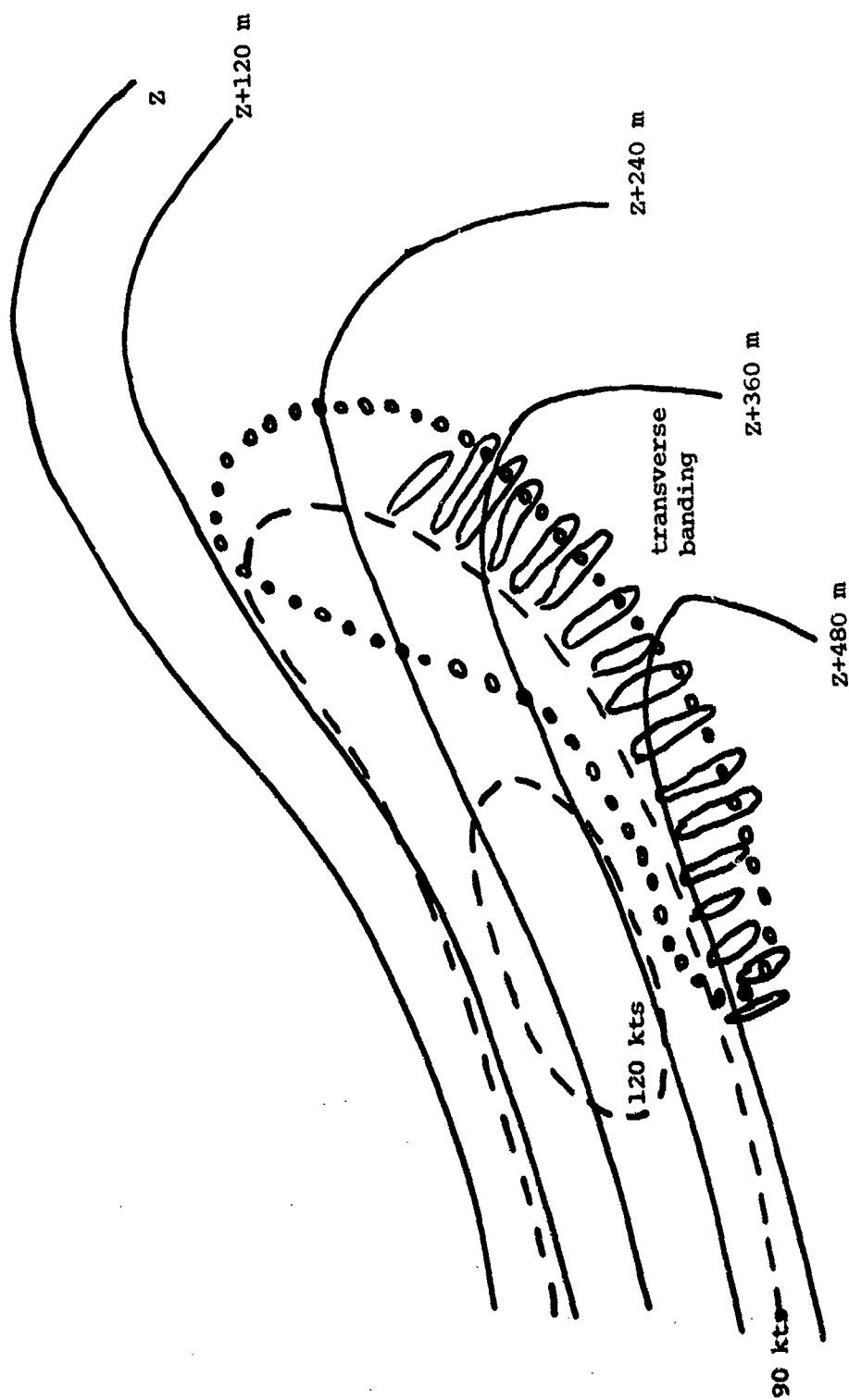


Figure 34. CAT (open circles) forecast in anticyclonic horizontal shear and speed convergence at 300 mb.

jet stream's cirrus shields. At times, transverse banding will be apparent and depict exactly where the CAT exists. Using the 300 mb analyses, look for deep troughs that reach equatorward of  $30^{\circ}$ . The AFGWC 250 mb maximum wind analysis will pinpoint these jet streams and vividly depict their curvature (see Figure 35). There is presently no accurate upper-air forecast tool for latitudes equatorward of  $25^{\circ}$ , so a forecaster must maintain forecast continuity until sufficient PIREPs and new 250 mb isotach analyses signal the end of turbulence potential. Normally, it will take approximately 90 knots of wind and sufficient anticyclonic curvature (greater than  $15^{\circ}/120$  nm) to produce moderate or greater turbulence in subtropical jet streams. Severe turbulence associated with sharp anticyclonic subtropical jet streams is rare.

6.3.2 Development of cutoff low. With the development of an upper-level cutoff low (Figure 36), CAT often occurs in the zones of confluent and diffluent flow with converging axes of maximum wind and large wind shear. The flow is subjected to rapid deceleration in the diffluent flow and rapid acceleration in the confluent flow. Hopkins (1976) theorizes that after the cutoff low forms only light CAT can be expected in the region just north of the low center. The 300 mb analyses and forecasts handle this situation well. The AFGWC 250 mb isotach analysis can be used to refine the analysis. Forecast moderate turbulence (severe CAT is rare) from 2,000 feet above the tropopause to 6,000 feet below the tropopause.

CAT may also occur in the throat and base of high-level cutoff lows. CAT can be expected to occur along the horizontal wind shear line separating the two opposing anticyclonically curved flows. If the jet stream at the base of the trough exceeds 90 kts, moderate CAT associated with strong cyclonic horizontal shear may exist (see Figure 37). If the strength of the two opposing jet stream cores is at least 50 knots, forecast moderate turbulence from 2,000 feet above the tropopause to 6,000 feet below the tropopause. When the forecast wind speeds for both the opposing jet stream cores exceeds 120 knots near the potential CAT area, upgrade the forecast to moderate with occasional severe turbulence. In the tropics, even with weak winds (at least 50 knots) horizontal wind shear lines are often associated with the occurrence of moderate CAT.

6.3.3 Diffluent upper flow. CAT can occur in the formation of a diffluent upper flow pattern. Hopkins (1976) reports that once the diffluent flow pattern becomes established, the probability of CAT in the region is low. The probability of CAT is increased if a surface frontal system is nearby. Figure 38 shows where CAT is likely during the formation of a diffluent upper flow pattern. At 300 mb, look for a wind maximum of greater than 90 knots approaching an area of diffluent flow. Upper-air forecasts normally depict future diffluent zones fairly well. Forecast moderate CAT from 2,000 feet above the tropopause to 6,000 feet below the tropopause in the zone of diffluence between the northern and southern wind maxima. If wind maxima of greater than 120 knots and considerable cyclonic and anticyclonic horizontal shears exist in the zone of diffluence, consider forecasting moderate with occasionally severe turbulence.

6.4 Mountain-wave turbulence. Most of the rules-of-thumb for fore-

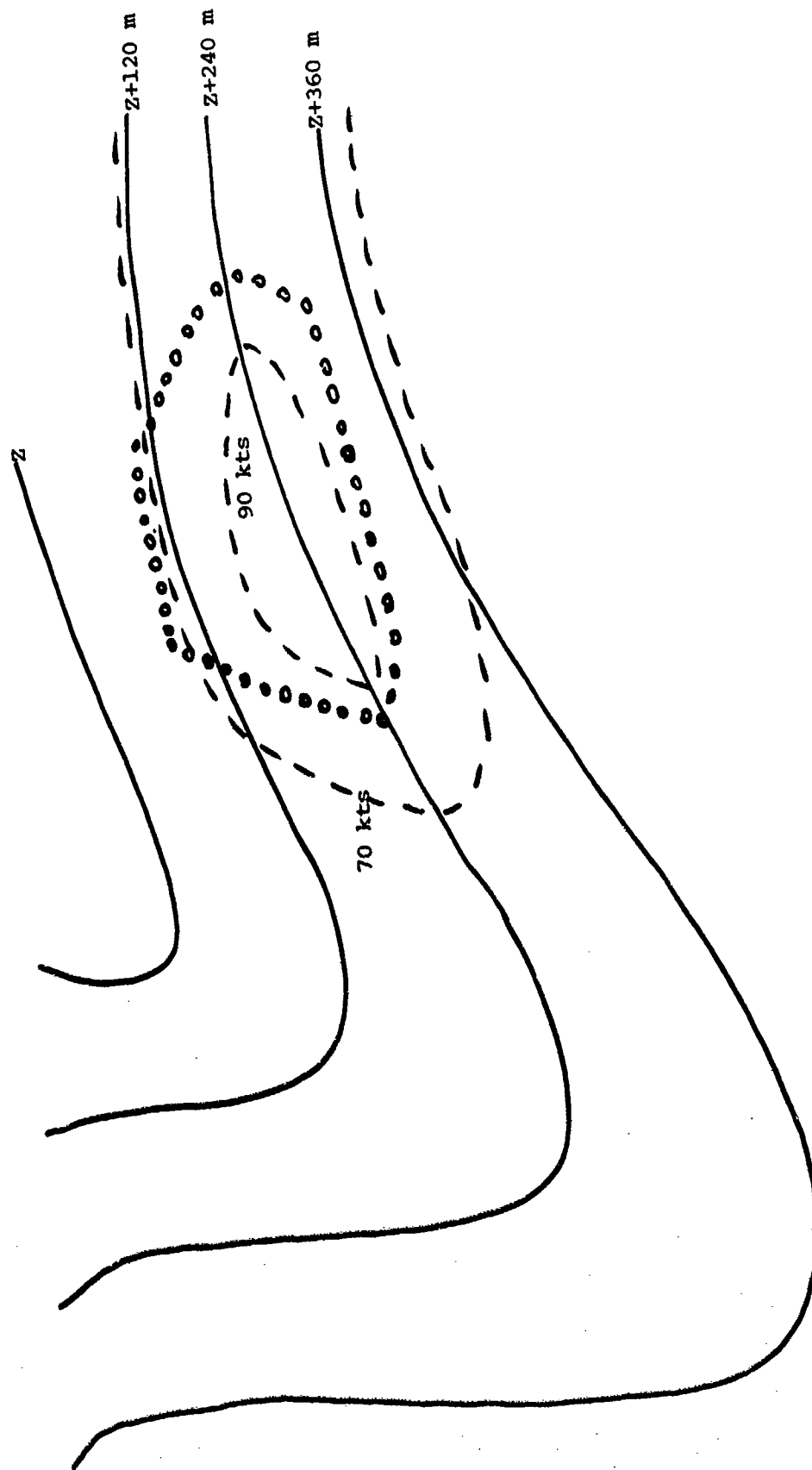


Figure 35. CAR (open circles) associated with anticyclonic turning of a subtropical jet stream at 300 mb.

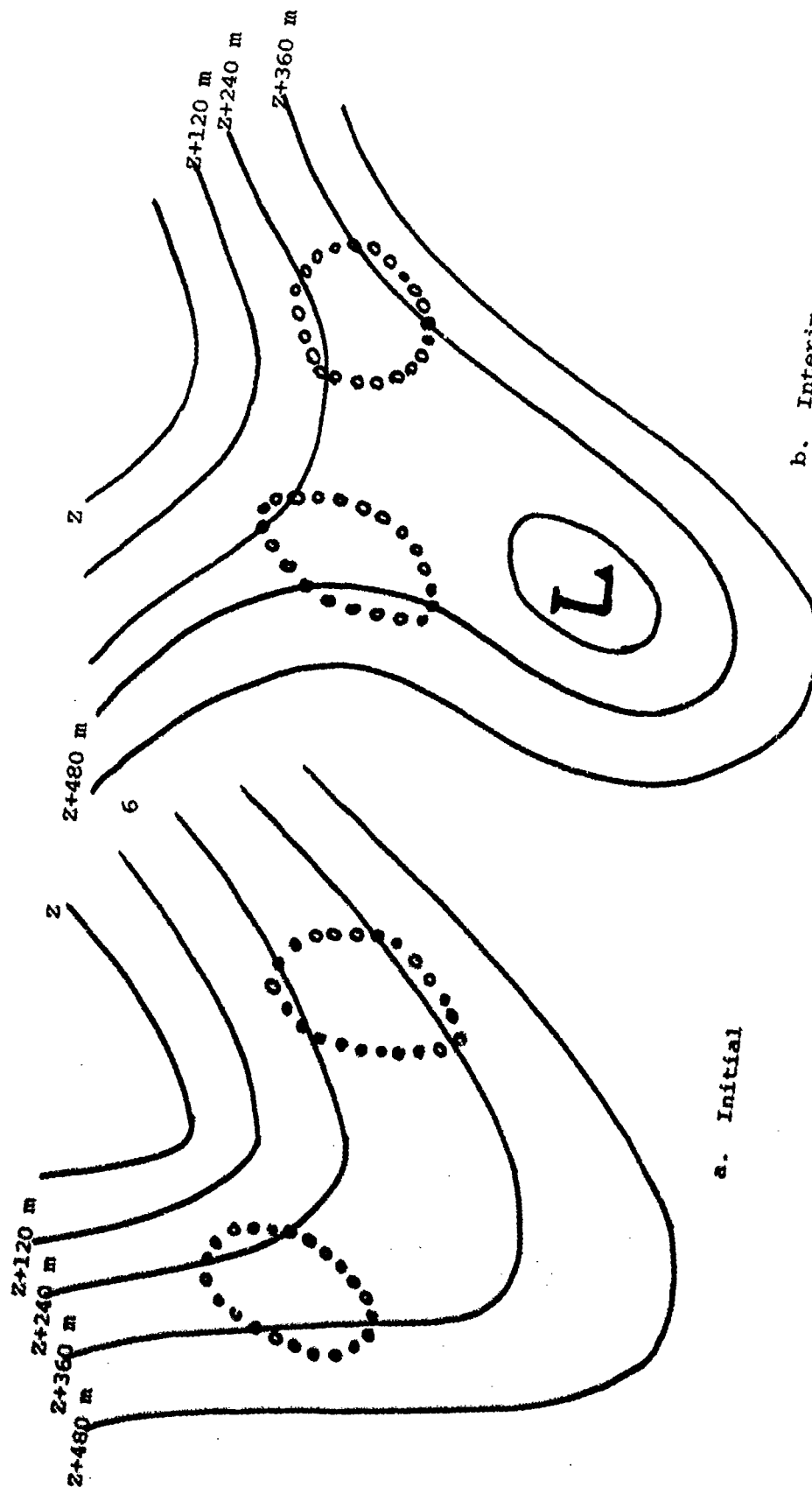


Figure 36. CAT associated with three stages in the development of a cutoff low at 300 mb, from Hopkins (1976).

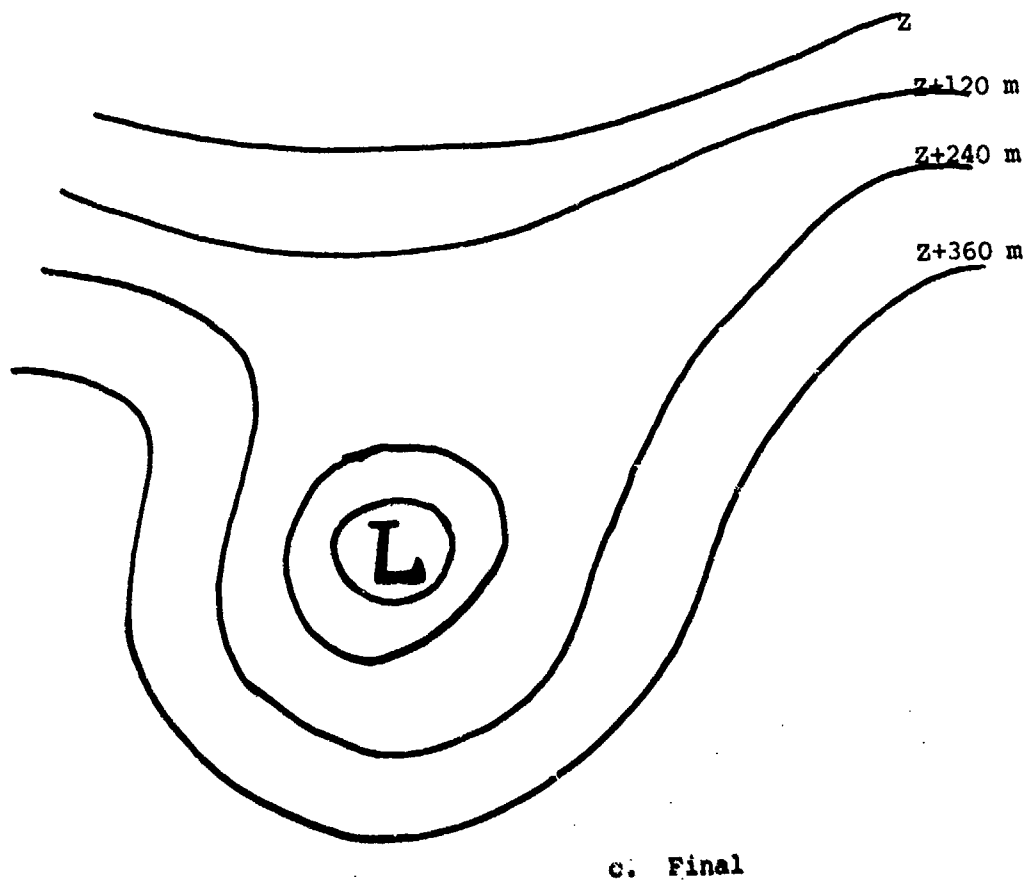


Figure 36. (continued).

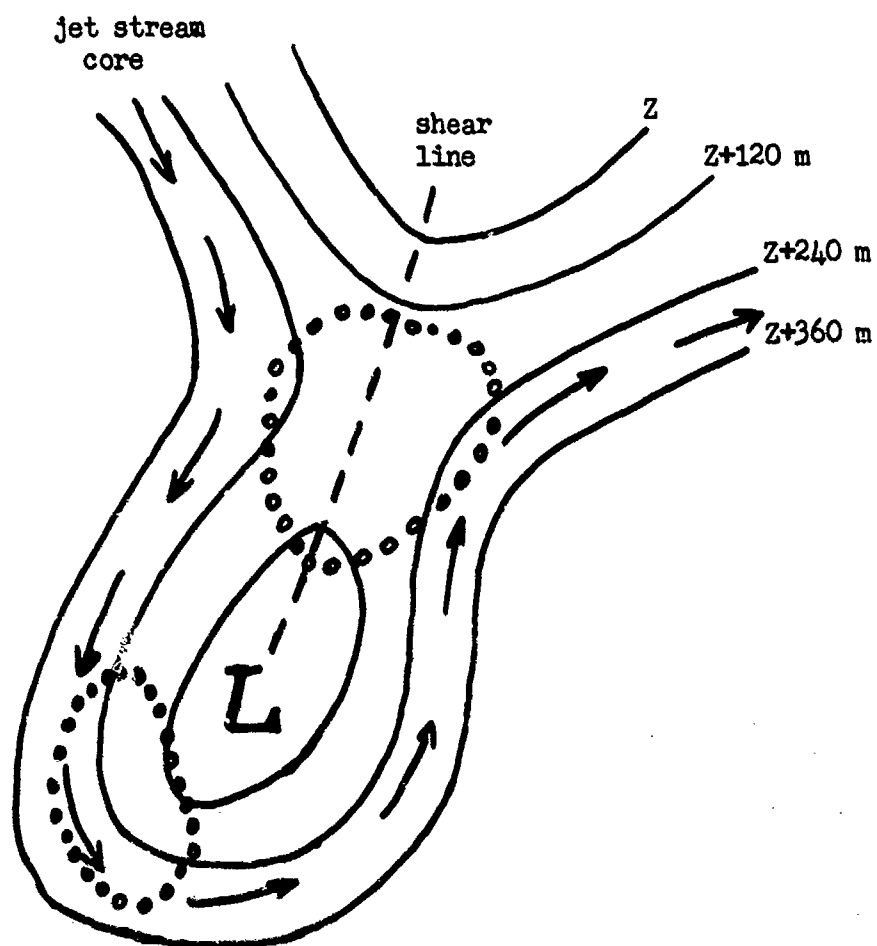


Figure 37. CAT forecast in the throat and base of a 300 mb cutoff low, adapted from Hopkins (1976).

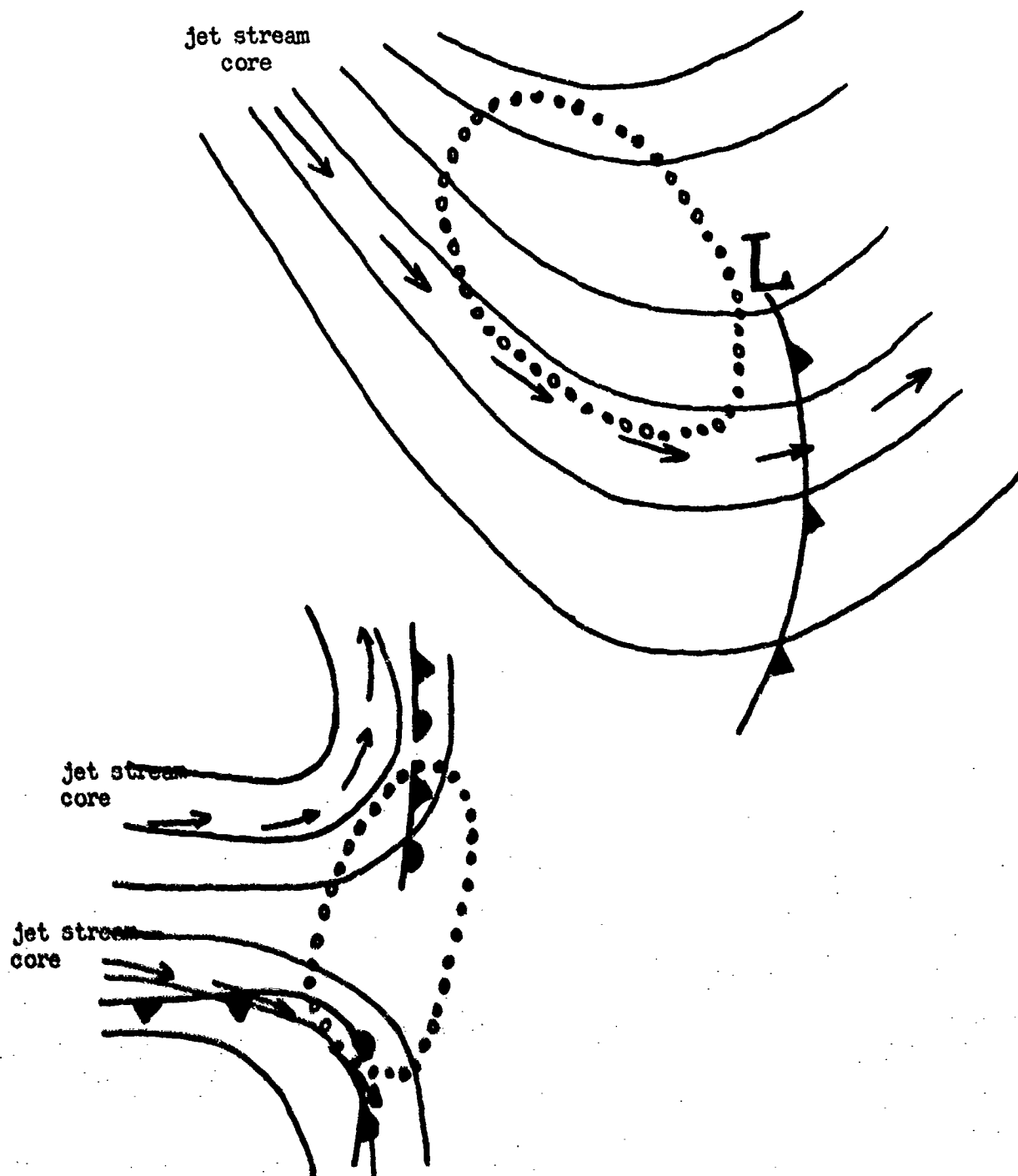


Figure 38. CAT (open circles) in diffluent, upper-flow pattern at 300 mb. Adapted from Hopkins (1976).

casting mountain-wave turbulence have been incorporated into the MTWVB computer program. The CAT forecaster can trust MTWVB products. If the MTWVB products are missing, the CAT forecaster can manually produce similar forecasts using the same tables and figures as in Section 5.2 of this memo. Some additional pointers are described below.

Mountain-wave turbulence is often associated with a sufficiently strong wind component normal to a ridge line at the mountain top level. Exact wind conditions sufficient to cause CAT vary with respect to the topography. Generally, winds of 35 knots or more crossing the ridge line within  $30^{\circ}$  of normal are necessary for most mountain ranges except the Denver area where only 25 knots are needed. In Japan and the eastern U.S. (Appalachian ranges) 40 knots or more are required at mountain-top. Sorenson (1976) states that the severity and extent of mountain-wave activity are greater in the lee of ridges than in the lee of isolated peaks. The shape of the ridge top and the existence of mountain passes are thought to influence the wave production capacity of a mountain barrier.

According to Sorenson (1976), gusty surface winds greater than 25 knots and reports of pressure falling rapidly in the lee of the mountain range are good indicators of the existence of standing mountain waves. Also, surface observations such as AcSL, CcSL, rotor clouds, etc., and pilot reports are other useful indicators of standing mountain waves. Satellite images depicting wave clouds in mountainous areas are another important aid. Horizontal temperature gradients are indicators of vertical wind shears, as implied by the thermal wind equation. At 850 mb look for temperature gradients greater than  $6^{\circ}\text{C}$  across the mountain range and greater than  $4^{\circ}\text{C}/60\text{ nm}$  along the mountain range.

The issuance of a mountain-wave forecast is a highly significant event. The Strategic Air Command's low-level routes and many high-level flights are diverted from forecast mountain-wave areas because treacherous turbulence is often found there (mountain-wave downdrafts can reach 80 feet per second or 3 to 4 g loading). Therefore, forecasting mountain waves at AFGWC follows a time-consuming and painstaking process.

If MTWVB suggests mountain-wave potential, then forecast turbulence when one of the following seven statements is true:

The area meets the mountain top wind criteria.

There is an approaching short-wave trough as seen on 500 or 300 mb analyses.

There is a cold front approaching or stationary to the north.

Rawinsonde ascents indicate a stable atmosphere at and above mountain tops. Stability is a critical factor in forecasting mountain-wave formation.

The jet stream is located near the mountain range. The actual CAT area will be centered on the jet stream core, immediately downstream from the mountain ridge line as illustrated in Figure 39. It usually extends about 120 nm on both sides of the jet stream core and is from 50 to 120 nm long.

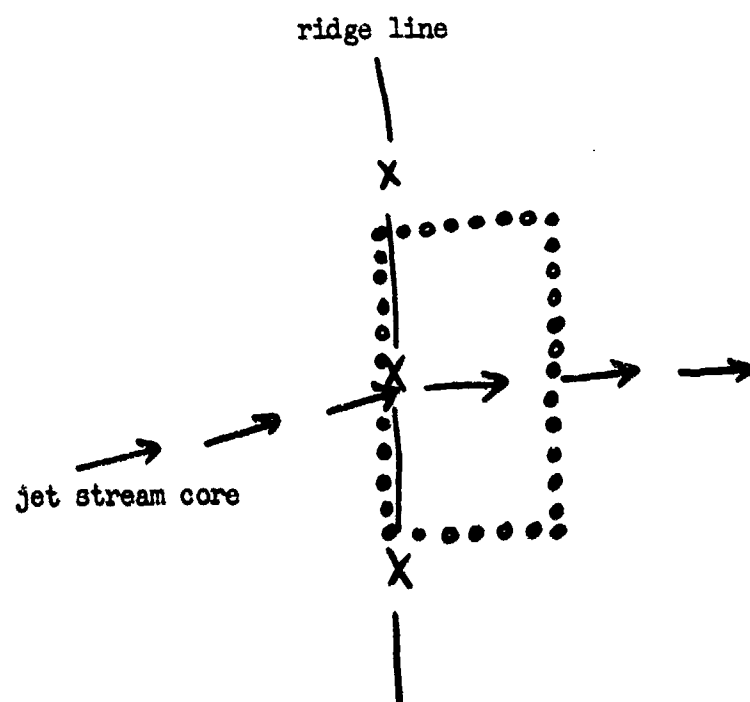


Figure 39. Normal forecast area associated with mountain wave. Example from Hopkins (1976). Open circles indicate CAT area.

The tropopause height is above 250 mb.

Pilot reports of at least light to moderate intensity are received from heavy aircraft.

Mountain-wave intensity is computed by the MTWVB output and/or by manual means. Normally, forecast severe turbulence when the wind component perpendicular to the mountain ridge exceeds 50 knots and a strong thermal gradient exists at low levels. Forecast areas are included in the MTWVB listing for most areas in the Northern Hemisphere.

The vertical extent of the forecast areas is automatically provided by MTWVB. Manually, the vertical extent is determined according to the mountain-wave intensity. For a moderate mountain wave, forecast moderate CAT up to 5,000 feet above the maximum mountain tops and 5,000 feet above and below the tropopause. For a strong mountain wave, forecast moderate with occasionally severe turbulence up to 10,000 feet above the maximum mountain tops, 5,000 feet above and below the tropopause, and moderate CAT in between. For a very strong mountain wave, forecast severe CAT for all levels up to 5,000 feet above the tropopause.

Sorenson (1976) states that the start of mountain-wave activity is indicated by:

The occurrence of the first low-level temperature falls over the mountain range or sharply increasing 500 mb windspeeds in the mountain-wave zone.

The end of such activity occurs when one of the following happens:

The low-level wind is no longer normal to the mountain range.

The isotherm packing at the 200 mb weakens.

The tropopause height drops below 250 mb.

Surface frontal passage occurs in the area.

Lee-wave turbulence (low-level oscillating flow) is similar to mountain-wave turbulence except that it does not extend into higher levels (the vicinity of the tropopause). If the atmosphere directly over the mountain tops is unstable, lee waves may form but will dissipate rapidly as they propagate upward. AcSL clouds can form and turbulence may be reported at relatively low levels; however, the important dynamic effects of waves affecting the tropopause do not occur. Forecast moderate turbulence from 5,000 to 10,000 feet above the maximum mountain tops when the mountain top wind (within 50° of a line normal to the ridge line) exceeds 35 knots (25 knots for Denver and 40 knots for Japan and eastern U.S.). If the winds exceed 50 knots, consider forecasting moderate with occasionally severe turbulence.

**6.5 Stratospheric CAT.** The present knowledge of stratospheric CAT is incomplete because of limited high-altitude data; however, there is a consensus that CAT decreases with height upward from the tropopause.

Stratospheric turbulence is thought to be caused by vertically propagating waves interacting with pre-existing vertical wind shears. These gravity waves can be caused by dynamic perturbation motions in a stable atmosphere, similar to generation of CAT at the tropopause. Stratospheric CAT occurs in thin homogeneous stable layers with thickness of 500 to 4,000 feet. Thicknesses less than 500 feet are considered trivial, while those much over 4,000 feet are probably multiple layers. Stratospheric CAT is usually less severe than tropospheric CAT. However, many pilots of supersonic stratospheric aircraft (U-2, YF12A, XB-70) have reported severe CAT while their aircraft accelerometers record only 0.6 to 1.0 g peak-to-peak accelerations. Amplification of turbulent vibrations from the aircraft center of gravity to the cockpit may be the reason that pilots report greater turbulence than meteorological conditions seem to warrant.

The current knowledge of stratospheric CAT is confined to the middle latitudes where significant vertical shears are known to exist. In the lower stratosphere, a mean vertical wind shear exists as the westerlies decrease with height. Above the winter hemispheric region of decreasing westerlies, the wind speed increases with height up to the level of the mesospheric jet stream core, which is at about 90,000 feet between 55°N and 70°N. Strong vertical wind shears associated with this jet stream core often extend down to 60,000 feet and below. The vertical wind shears can be as strong as the shears encountered near tropospheric jet stream cores.

Large horizontal temperature gradients at high levels with the associated vertical shears are indicative of stratospheric CAT:

2°C/100 nm at 100 mb (53,000 feet)

1°C/100 nm at 50 mb (68,000 feet)

1°C/100 nm at 30 mb (78,000 feet)

Radiosonde ascents yielding vertical temperature and wind profiles can be studied for vertical shears occurring in stable layers. CATA, the AFGWC automated rawinsonde CAT analysis tool, computes layers with low Richardson numbers and determines an intensity using vertical shear and mean-height wind data. Wind shears of greater than 10 knots per 1000 feet and mean winds greater than 50 knots are generally necessary to produce moderate or greater CAT.

Circulation features generally associated with stratospheric CAT include ridges and cutoff highs. The turbulence aligns itself with anticyclonic curvature from inflection point to inflection point (see Figure 40). Lower stratospheric CAT can also be related to and forecast with underlying tropospheric systems.

Forecast turbulence of the intensity and height computed by CATA when two or more stations report similar layers associated with the same upper-air feature. Turbulence tends to occur 1,000 feet below the reported stable layers so the forecast should be extended downward to include it.

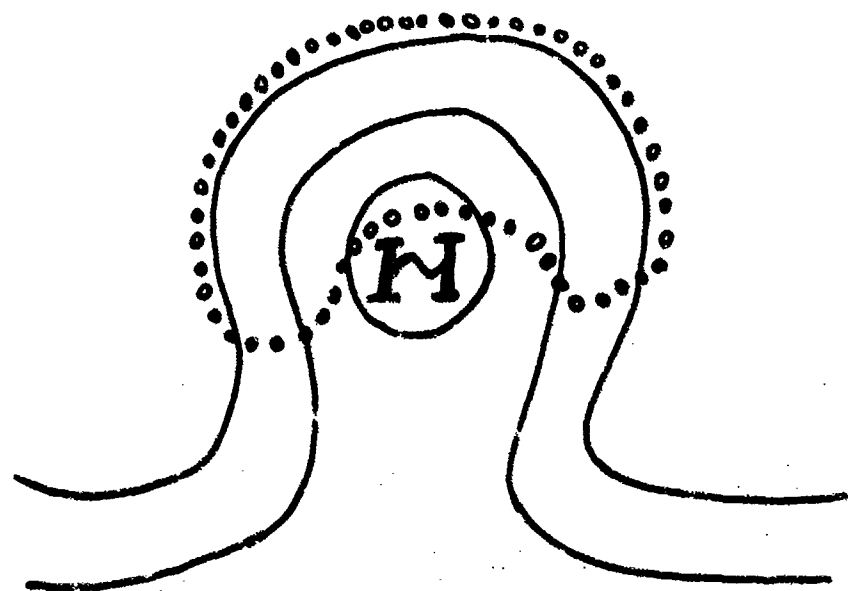
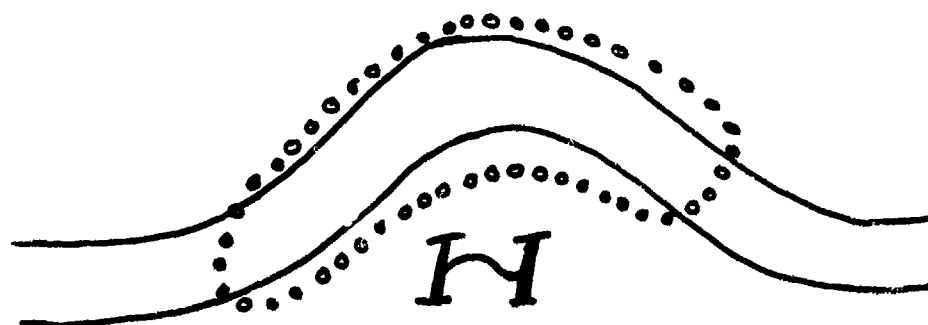


Figure 40. Stratospheric CAT (open circles) forecast area at 100 mb.

Stratospheric mountain-wave CAT can also be caused by the propagation of mountain waves upward into the stratosphere from the lower tropopause. If mountain-wave turbulence is forecast or observed near the tropopause, it should also be forecast in regions approximately over the mountain-wave area according to Table 5.

| If CAT due to mountain wave +/- 5000 feet of tropopause is: | Then forecast stratospheric CAT tropopause to 60,000 feet: |
|-------------------------------------------------------------|------------------------------------------------------------|
| MODERATE                                                    | LIGHT                                                      |
| SEVERE                                                      | MODERATE                                                   |

Table 5. Empirically derived stratospheric CAT intensities associated with mountain-wave turbulence.

## 7 CONCLUDING REMARKS

Many of these models relating CAT to atmospheric flow are simplifications of the highly complex real atmosphere. At times, many of the turbulence mechanisms (thermal advection, horizontal shear, etc.) may be acting in unison. In those cases, the probability of encounter, the horizontal and vertical extents, and the intensity of turbulence is much greater.

Overforecasting in size and intensity is a common failure of CAT forecasters. At times, CAT forecasters "chase" pilot reports and issue large area CAT advisories just to cover the reports and protect themselves from any repercussions should an aircraft file a hazard report. To avoid "crying wolf" all of the time, forecasters will have to, at times, suffer a few isolated missed occurrences of CAT. If a CAT report cannot be associated with a specific synoptic feature, then ignore it unless other reports are received in the same area. In any case, the area forecasts must be made as small as possible.

As can be seen in this tech note, CAT forecasting is still more of an art than a science. The automated products that are produced at AFGWC are very limited in capability. This reflects the infancy of the science. The art of successful CAT forecasting can only be gained by experience. A CAT forecaster must combine personal skills with the automated aids to produce the final CAT forecast. This man-machine mix results in the best possible forecast within the limitations of the present state of the art.

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## Appendix A

### The Use of Pilot Reports in CAT Forecasting

Different types of aircraft have different sensitivities to turbulence. The Air Force Wright Aeronautical Laboratories (AFWAL), in their Technical Report (TR)-81-3058, used computer simulation to investigate these sensitivities. Table A-1, which was constructed from data in this TR, lists the sensitivities for most USAF fixed-wing aircraft at their typical flight conditions. Table A-1 also incorporates rotary-wing aircraft. The categories for rotary-wing aircraft in Table A-1 were based on observational data at 7WS units and 30WS units. (Reference 2WW Technical Bulletin, Nov 77, and 30WSR 105-8, 10 Aug 82.) Combining sensitivities for rotary and fixed-wing aircraft into one table facilitates use by forecasters. CAUTION: An aircraft's sensitivity varies considerably with its weight (amount of fuel, cargo, or munitions), the density of air, wing surface area, wing sweep angle, and airspeed. Generally the following conditions increase the effects of turbulence:

- a. Decreased weight of aircraft.
- b. Decreased air density (increased altitude).
- c. Increased wing surface area.
- d. Decreased wing sweep angle (wings more perpendicular to fuselage).
- e. Increased airspeed.

Therefore great caution must be exercised when applying forecast turbulence conditions to a specific aircraft and its flight conditions. For take-offs and landings (altitude less than 10,000 feet and reduced airspeed), the AFWAL TR showed that an aircraft's sensitivity was reduced by about one-half of a category. For example, a category II aircraft's sensitivity became intermediate between a II and a III. Rather than developing a 1/2-category system, forecasters should assume that an aircraft's category at its typical flight condition will also be the same category below 10,000 feet and reduced airspeeds. Table A-2 is a guide to convert turbulence intensities for the different categories of aircraft in Table A-1. The following situation is an example how Tables A-1 and A-2 could be used at a weather unit.

"AWSR 105-27, Terminal Aerodrome Forecast (TAF), requires that turbulence forecast in TAFs be specified for category II aircraft. The TAF for Scott AFB indicates moderate turbulence from the surface to 5,000 feet. A weather forecaster at Little Rock AFB is briefing a C-130 to Scott AFB. What intensity of turbulence does he/she brief? The Little Rock AFB forecaster uses Table A-1 to convert the TAF forecast for category II aircraft (MODERATE) to a forecast for category III aircraft (LIGHT OCNL MODERATE)."

In all cases, Table A-1 is used to determine an aircraft's turbulence category, and Table A-2 is used to modify observations or forecasts or turbulence intensity between different types of aircraft. AFGWC routinely forecasts for category II aircraft.

TABLE A-1. TURBULENCE SENSITIVITY FOR VARIOUS AIRCRAFT AT TYPICAL FLIGHT CONDITONS

| CATEGORY | TYPE<br>AIRCRAFT   | SENSITIVITY<br>g's/ft/sec | ALTITUDE<br>1000<br>ft | GROSS WT<br>1000<br>lb | CALIBRATED<br>AIRSPEED<br>Knots | TRUE<br>AIRSPEED<br>Knots |
|----------|--------------------|---------------------------|------------------------|------------------------|---------------------------------|---------------------------|
| I        | FALCON 20          | .046                      | 35                     | 16                     | 291                             | 490                       |
|          | FALCON 50          | .046                      | 35                     | 33.2                   | 291                             | 490                       |
|          | FJF 20, C, D, E    | .044                      | 30                     | 26                     | 304                             | 471                       |
|          | T-39               | .043                      | 35                     | 16                     | 258                             | 440                       |
|          | OH-58 <sup>1</sup> |                           |                        |                        |                                 |                           |
|          | UH-1 <sup>1</sup>  |                           |                        |                        |                                 |                           |
|          | AH-1 <sup>1</sup>  |                           |                        |                        |                                 |                           |
|          | C-12 <sup>1</sup>  |                           |                        |                        |                                 |                           |
|          | C-21A              |                           |                        |                        |                                 |                           |
| II       | VC-140             | .039                      | 35                     | 32                     | 271                             | 460                       |
|          | C-141              | .037                      | 33                     | 260                    | 261                             | 430                       |
|          | C-9                | .037                      | 31                     | 90                     | 298                             | 470                       |
|          | F-106              | .035                      | 37                     | 38                     | 305                             | 530                       |
|          | C-5A               | .034                      | 31                     | 590                    | 270                             | 430                       |
|          | B-747              | .034                      | 33                     | 550                    | 301                             | 490                       |
|          | F-15               | .033                      | 36                     | 42                     | 306                             | 520                       |
|          | BOEING 707-300     | .032                      | 30                     | 300                    | 303                             | 470                       |
|          | T-38               | .032                      | 33                     | 13                     | 322                             | 520                       |
|          | DC-8-50, 61        | .032                      | 36                     | 280                    | 266                             | 460                       |
|          | DC-8-50, 63        | .032                      | 36                     | 300                    | 266                             | 460                       |
|          | B-52               | .032                      | 31                     | 325                    | 257                             | 410                       |
|          | DC-9-10            | .031                      | 32                     | 86                     | 279                             | 450                       |
|          | F-16               | .031                      | 25                     | 25                     | 383                             | 540                       |
|          | BOEING 727         | .031                      | 30                     | 170                    | 303                             | 470                       |
|          | KC-135             | .030                      | 33                     | 220                    | 274                             | 450                       |
|          | CH-47 <sup>1</sup> |                           |                        |                        |                                 |                           |
|          | U-21 <sup>1</sup>  |                           |                        |                        |                                 |                           |
|          | RV-1 <sup>1</sup>  |                           |                        |                        |                                 |                           |
|          | CONVAIR 440, 330   | .029                      | 23                     | 48                     | 183                             | 260                       |
|          | DC-9-30, 40, 50    | .029                      | 32                     | 100                    | 279                             | 450                       |
|          | BOEING 737         | .027                      | 30                     | 100                    | 282                             | 440                       |
|          | BOEING 747SP       | .027                      | 39                     | 660                    | 267                             | 490                       |
|          | DC-10-10           | .027                      | 36                     | 400                    | 276                             | 475                       |
| III      | C-130              | .027                      | 27                     | 120                    | 198                             | 300                       |
|          | O-2                | .027                      | 8                      | 4.2                    | 103                             | 120                       |
|          | OV-10              | .026                      | 10                     | 10                     | 155                             | 180                       |
|          | DC-10-20           | .026                      | 36                     | 480                    | 276                             | 475                       |
|          | T-37               | .025                      | 15                     | 11                     | 241                             | 300                       |
|          | A-10               | .025                      | 15                     | 34                     | 192                             | 240                       |
|          | CH-53 <sup>1</sup> |                           |                        |                        |                                 |                           |
|          | CH-54 <sup>1</sup> |                           |                        |                        |                                 |                           |

TABLE A-1 (CONTINUED)

## TURBULENCE SENSITIVITY FOR VARIOUS AIRCRAFT AT TYPICAL FLIGHT CONDITIONS

| CATEGORY | TYPE<br>AIRCRAFT    | SENSITIVITY | ALTITUDE   | GROSS WT   | CALIBRATED       | TRUE             |
|----------|---------------------|-------------|------------|------------|------------------|------------------|
|          |                     | g's/ft/sec  | 1000<br>ft | 1000<br>lb | AIRSPED<br>Knots | AIRSPED<br>Knots |
| IV       | BAC 1-11-200        | .019        | 30         | 75         | 181              | 290              |
|          | BAC 1-11-400        | .018        | 33         | 82         | 178              | 300              |
|          | A-7                 | .020        | 35         | 35         | 265              | 450              |
|          | F-4                 | .020        | 31         | 50         | 305              | 480              |
|          | F-111 <sup>2</sup>  | .016        | 25         | 70         | 336              | 480              |
|          | FB-111 <sup>2</sup> | .015        | 38         | 70         | 267              | 480              |

NOTE 1: Sensitivities for these aircraft were derived from observational data in Europe or Korea. UH-1 Operator's Manual prohibits flight into areas of moderate turbulence that is reported by transport aircraft (Cat II). OH-58 may be the most sensitive aircraft in its category, but current evidence does not indicate a higher category.

NOTE 2: At 50° Wing Sweep Angle

TABLE A-2. CONVERSION OF TURBULENCE INTENSITIES FOR CATEGORIES OF AIRCRAFT

|            | I              | II             | III            | IV             |
|------------|----------------|----------------|----------------|----------------|
|            | N              | N              | N              | N              |
|            | (L)            | N              | N              | N              |
|            | L              | (L)            | N              | N              |
|            | L-(M)          | L              | (L)            | N              |
|            | M              | L-(M)          | L              | (L)            |
| Turbulence | M-(S)          | M              | L-(M)          | L              |
| Reported   | S              | M-(S)          | M              | L-(M)          |
| As         | S-(X)          | S              | M-(S)          | M              |
|            | X <sup>1</sup> | S-(X)          | S              | M-(S)          |
|            | X              | X <sup>1</sup> | S-(X)          | S              |
|            | X              | X              | X <sup>1</sup> | S-(X)          |
|            | X              | X              | X              | X <sup>1</sup> |

N = None  
 ( ) = occasional (less than 1/3 of the time)  
 L = light  
 M = moderate  
 S = severe  
 X = extreme

NOTE 1: Caution must be used when converting extreme turbulence reports between various types of aircraft. Extreme turbulence causes a range of effects from a minimum threshold (e.g., rapid airspeed fluctuations greater than 25 knots) to a maximum threshold (e.g., structural damage). Even though Table 2 considers this range, the design is more for the sake of "completeness" rather than observational or scientific evidence.

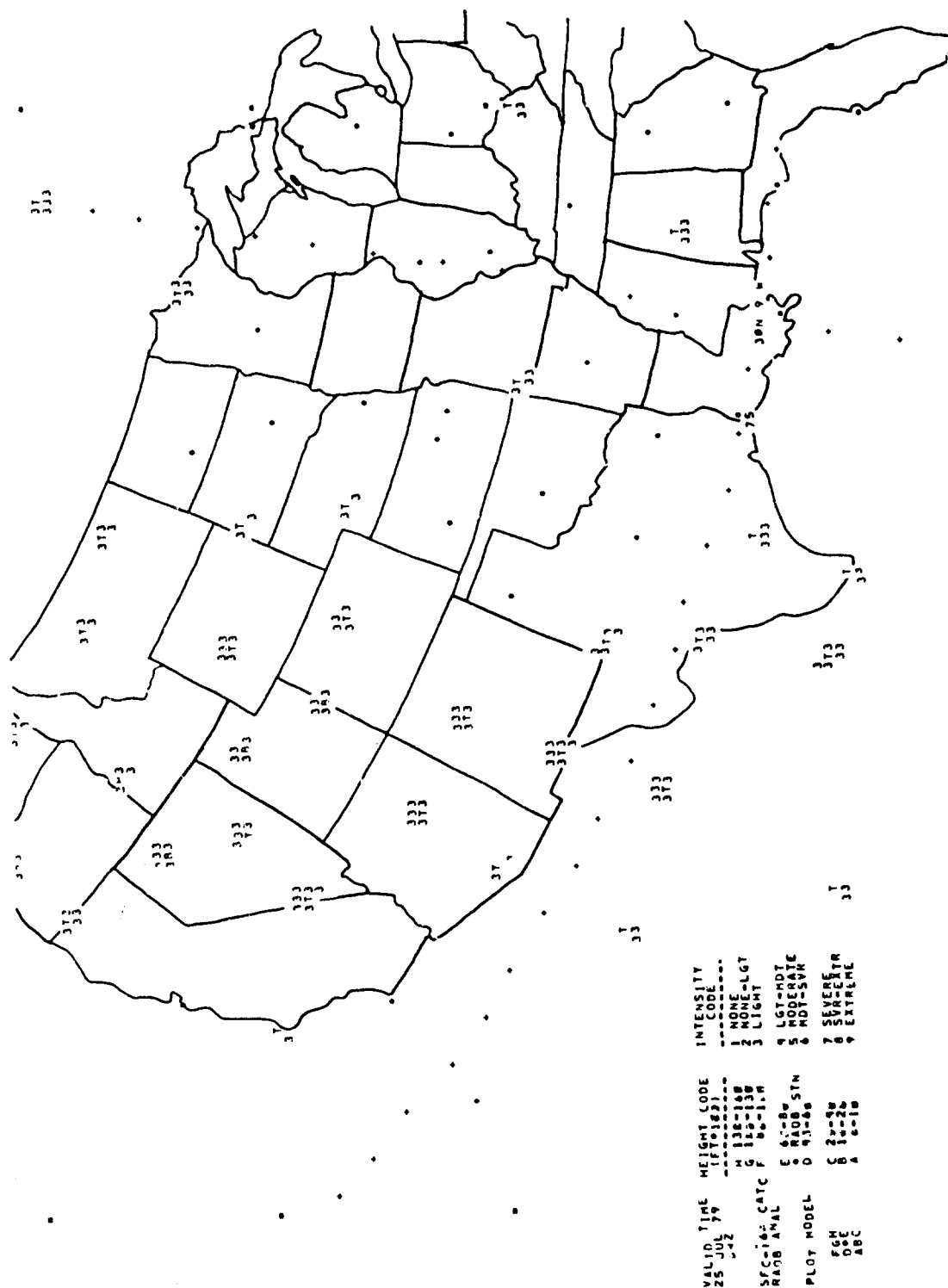


Figure B-1. Northern Hemispheric map of CAT values.

[illegible]

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| DATA<br>LOCATION<br>LAT/LONG | PRG  | TURBULENCE<br>FORECAST<br>REMARKS OF FILE | 050 MB TEMP<br>DIFFICULTY<br>SFC PKG<br>JIFF (MB) | MAX MIN<br>WIND 500MB<br>MIN TOP<br>WIND | TAXIUM<br>TURNING<br>TUT A<br>TURNING | TEMP GRAD<br>AT 200 MB<br>AT 850 MB<br>(C/5,MB) | SEC<br>GUSTS<br>(KTS) | TRUP<br>MTFT,<br>TRUP<br>TEMP (P) | AVG TRUP MT<br>MTN PEAK MT<br>AVG RIDGE MT<br>(F1100) |
|------------------------------|------|-------------------------------------------|---------------------------------------------------|------------------------------------------|---------------------------------------|-------------------------------------------------|-----------------------|-----------------------------------|-------------------------------------------------------|
| 33<br>COORE LAKE             | ANAL | NOT CAT 223-243<br>NOT CAT 182-163        | 15 P                                              | 280/ 23                                  | 31                                    | A                                               | MSNG                  | 273                               | 273<br>180                                            |
| 720/ 030                     | 12NR | NOT CAT 233-233<br>NOT CAT 182-233        | -3                                                | 270/ 37                                  | 91                                    | -1                                              |                       | 284                               | 283<br>134                                            |
| 030/ 030                     | 24NR | NOT CAT 182-150                           | 15 P                                              | 270/ 37                                  | 91                                    | -2                                              |                       | -03                               | 100<br>100                                            |
| 040/ 700                     | 24NR | -                                         | 15 P                                              | 280/ 28                                  | 143                                   | -1                                              |                       | 284                               | 288<br>134                                            |
|                              |      | NOT CAT 182-150                           |                                                   |                                          |                                       |                                                 |                       | -01                               | 100<br>100                                            |
| 34<br>INULE MECH             | ANAL | -                                         | 3                                                 | 330/ 13                                  | 52                                    | 2                                               | MSNG                  | 343                               | 392<br>75                                             |
| 030/ 050                     | 12NR | -                                         | MSNG                                              | 330/ 10                                  | 72                                    | 2                                               |                       | -05                               | 68<br>68                                              |
| 030/ 050                     | 24NR | -                                         | MSNG                                              | 330/ 21                                  | 13                                    | 2                                               |                       | 317                               | 313<br>75                                             |
| 040/ 050                     | 24NR | -                                         | -1                                                | 310/ 14                                  | 41                                    | 1                                               |                       | 327                               | 314<br>75                                             |
|                              |      | -                                         | MSNG                                              | 330/ 7                                   | 1                                     | 0                                               |                       | -06                               | 68<br>68                                              |
| 35<br>INULE MECH             | ANAL | -                                         | MSNG                                              | 210/ 17                                  | 21                                    | 1                                               | MSNG                  | 299                               | 302<br>79                                             |
| 030/ 050                     | 12NR | -                                         | MSNG                                              | 190/ 12                                  | 22                                    | 0                                               |                       | -06                               | 50<br>50                                              |
| 030/ 050                     | 24NR | -                                         | 2                                                 | 180/ 21                                  | 13                                    | 1                                               |                       | 316                               | 106<br>79                                             |
| 770/ 060                     | 24NR | -                                         | MSNG                                              | 180/ 12                                  | 13                                    | 2                                               |                       | -06                               | 50<br>50                                              |
|                              |      | -                                         | 2                                                 | 170/ 18                                  | 3                                     | 1                                               |                       | 322                               | 300<br>79                                             |
|                              |      | -                                         | MSNG                                              | 170/ 12                                  | 3                                     | 1                                               |                       | -06                               | 53<br>53                                              |
| 36<br>JAFFLA ISL             | ANAL | -                                         | 1 P                                               | 280/ 12                                  | 51                                    | 1                                               | 5                     | 305                               | 295<br>79                                             |
| 720/ 030                     | 12NR | -                                         | 3 P                                               | 270/ 8                                   | 42                                    | 1                                               | 30                    | 312                               | 304<br>79                                             |
| 030/ 050                     | 24NR | -                                         | 6 P                                               | 260/ 8                                   | 73                                    | 2                                               |                       | -01                               | 50<br>50                                              |
| 020/ 700                     | 24NR | -                                         | 1 P                                               | 280/ 8                                   | 33                                    | -1                                              |                       | 299                               | 296<br>79                                             |
|                              |      | -                                         | 6 P                                               | 250/ 4                                   | 33                                    |                                                 |                       | -57                               | 50<br>50                                              |

Appendix C. MTWVB output.

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