II. TURBULENCE. The importance of turbulence forecasting to the flying customer can't be overstated. Forecasting and classifying turbulence, however, is a challenge. The difficulty arises because factors creating turbulence in one instance may not cause turbulence in a similar situation. Complicating matters further is that while one aircraft may report smooth sailing, minutes later, another aircraft flying through the same airspace may report significant turbulence.

Turbulence can rip an aircraft apart in flight, damage the airframe, and cause injury. Therefore, accurate turbulence forecasts are an important part of an aviation brief. If forecasters understand the basics of atmospheric turbulence, they will better analyze and forecast this dangerous phenomenon.

Note: Diagrams presented may show patterns over the United States only. These patterns are applicable, however, to most areas worldwide, given the same synoptic situation.

A. LEVELS OF INTENSITY. The levels of turbulence intensity are based on the impact to aircraft flying through the area of concern.

1. Light Turbulence. The aircraft experiences slight, erratic changes in attitude and/or altitude, caused by a slight variation in airspeed of 5 to 14 knots with a vertical gust velocity of 5 to 19 feet per second. Light turbulence may be found in many areas, such as:

- At low altitudes in rough terrain when winds exceed 15 knots.
- In mountainous areas, even with light winds.
- In and near cumulus clouds.
- Near the tropopause.

2. Moderate Turbulence. The aircraft experiences moderate changes in attitude and/or altitude, but the pilot remains in positive control at all times. The aircraft encounters small variations in airspeed of 15 to 24 knots; vertical gust velocity is 20 to 35 feet per second. Moderate turbulence may be found:

- In towering cumuliform clouds and thunderstorms.
- Within 100 nm of the jet stream on the cold-air side.
- At low altitudes in rough terrain when the surface winds exceed 25 knots.
- In mountain waves (up to 300 miles leeward of ridge), winds perpendicular to the ridge exceed 50 knots.
- In mountain waves as far as 150 miles leeward of the ridge and 5,000 feet above the tropopause when wind perpendicular to the ridge is 25 to 50 knots.

3. Severe Turbulence. The aircraft experiences abrupt changes in attitude and/or altitude and may be out of the pilot's control for short periods. The aircraft encounters large variations in airspeed greater than or equal to 25 knots and the vertical gust velocity is 36 to 49 feet per second. Severe turbulence occurs:

- In and near mature thunderstorms.
- Near jet stream altitude and about 50 to 100 miles on the cold-air side of the jet core.
- In mountain waves (up to 50 miles leeward of ridge), winds perpendicular to ridge are 25 to 50 knots.
- Up to 150 nm leeward of the ridge and within 5,000 feet of the tropopause when a mountain wave exists and winds perpendicular to the ridge exceed 50 knots.

4. Extreme Turbulence. The aircraft is violently tossed about and is practically impossible to control. Structural damage may occur. Rapid fluctuations in airspeed are the same as severe turbulence (greater than or equal to 25 knots) and the vertical gust velocity is greater than or equal to 50 feet per second. Though extreme turbulence is rarely encountered, it is usually found in the strongest forms of convection and wind shear. The two most frequent locations of extreme turbulence are:

- In mountain waves in or near the rotor cloud.

- In severe thunderstorms, especially in organized squall lines.

B. AIRCRAFT TURBULENCE SENSITIVITIES. Different aircraft types have different sensitivities to turbulence. Table 2-7 lists the categories for most military fixed-wing and rotary-wing aircraft at their typical flight configurations. Turbulence forecasts in Aerodrome Forecasts (TAFs) are specified for Category II aircraft. Modify the local turbulence forecast for the type of aircraft supported. Use caution, however; an aircraft's sensitivity varies considerably with its weight (amount of fuel, cargo, munitions, etc.), air density, wing surface area, wing sweep angle, airspeed, and aircraft flight "attitude." Since aircraft sensitivity to turbulence varies considerably, use caution when applying forecast turbulence (Category II) to a specific aircraft type, configuration, and mission profile. Table 2-8 is a guide to convert turbulence intensities for the different categories of aircraft.

Table 2-7. Aircraft category type.

Category	Aircraft Type			
I	OH-58	UH-1	AH-1	
II	C-141	C-9	RAH-66	C-12
	C-21	F-106	C-20	C-5A
	E-4A	F-15	AH-64	B-52
	C-130	C-17	F-117	F-16
	KC-135	C-23	CH-47	U-21
	OV-1	CH-3	UH-60	CH-53
	CH-54	VC-137	T-38	
III	OV-10	KC-10	T-37	A-10
IV	A-7	F-4	B-1B	F-111*

* At 50 degree wing configuration.

Note: turbulence thresholds were developed for aircraft in Category II. Consider the synoptic situation, local terrain effects, pilot reports (PIREPS), and aircraft type and configuration before making turbulence forecasts.

Table 2-8. Turbulence intensities for different categories of aircraft (based on Table 2-7).

	I	II	III	IV
	N	N	N	N
	(L)	N	N	N
	L	(L)	N	N
	L-(M)	L	(L)	N
Turbulence	M	L-(M)	L	(L)
Reported As	M-(S)	M	L-(M)	L
	S	M-(S)	M	L-(M)
	S-(X)	S	M-(S)	M
	X	S-(X)	S	M-(S)
	X	X	S-(X)	S
	X	X	X	S-(X)
	X	X	X	X

N = None ( ) = Occasional (less than 1/3 of the time)
L = Light M = Moderate S = Severe X = Extreme

Note: Use caution when converting extreme turbulence reports between various aircraft types. Extreme turbulence causes a range of effects from a minimum threshold (rapid airspeed fluctuations greater than 25 knots) to a maximum threshold (structural damage). Even though the table considers this, the design is more for the sake of "completeness" rather than observational or scientific evidence.

1. Fixed Wing Aircraft. Generally, the effects of turbulence for fixed-wing aircraft are increased with:

- Non-level flight.
- Increased airspeed.
- Increased wing surface area.
- Decreased weight of the aircraft.
- Decreased air density (increased altitude).
- Decreased wing sweep angle (wings more perpendicular to fuselage).

2. Rotary Wing Aircraft. Generally, the effects of turbulence for rotary-wing aircraft are increased with:

- Increased airspeed.
- Decreased weight of the aircraft.
- Decreased lift velocity (the faster the lift-off, the less the turbulence).
- Increased arc of the rotor blade (the longer the blade, the greater the turbulence).

C. CAUSES OF TURBULENCE. Turbulence is caused by abrupt, irregular movements of air that create sharp, quick updrafts/downdrafts. These updrafts and downdrafts occur in combinations and move aircraft unexpectedly. There are two basic atmospheric conditions that cause turbulence to occur: thermal conditions and mechanical mixing.

1. Thermal Conditions. Surface heating can generate turbulent conditions. As solar radiation heats the surface, the air above it is warmed by contact. Warmer air is less dense, and "bubbles" of warm air rise upward as updrafts. Uneven surface heating, and the cooling of risen air, allows for areas of downdrafts as well. These vertical motions may be restricted to low levels, or may generate cumulus clouds that can grow to great heights as thunderstorms. The following are characteristics of thermal-induced turbulence.

- The maximum occurrence is between late morning and late afternoon.
- Is normally confined to the lower troposphere (surface to 10,000 feet).
- The impact on flight operations is greatest during terminal approach and departure and during low-level flights.
- Moderate turbulence may occur in hot, arid regions, as the result of irregular convective currents from intense surface heating.

The strongest thermal turbulence is found in and around thunderstorms. Moderate or severe turbulence can be found anywhere within the storm, including the clear air along its outer edges. The highest probability of turbulence is found in the storm core, between 10,000 and 15,000 feet.

2. Mechanical Turbulence. Mechanical turbulence is caused by horizontal and vertical wind shear and is the result of pressure gradient differences, terrain obstructions, or frontal zone shear. Three types of mechanical turbulence discussed later in this chapter include the following: Clear Air Turbulence (CAT), Mountain Wave (MV) Turbulence, and Wake Turbulence. The following are some general characteristics of mechanical turbulence:

- Most turbulence results from a combination of horizontal and vertical wind shears.
- Turbulence layers are usually 2,000 feet thick, 10 to 40 miles wide, and several times longer than wide.
- Wind shear turbulence results from strong horizontal pressure gradients alone. It occurs when the pressure gradient causes a horizontal shear in either wind direction or speed.
- Local terrain can magnify gradient winds to cause strong winds and turbulence near the surface. This creates eddy currents that can make low-level flight operations hazardous.

- Most turbulence resulting from upper frontal zone shear occurs between 10,000 and 30,000 feet.

- The jet stream causes most turbulence in the upper troposphere and lower stratosphere, usually occurring in patches and layers, with the stronger turbulence on the low-pressure (cold-air side) of the jet stream.

- Strong turbulence is often associated with irregular and mountainous terrain. The greater the irregularity of the terrain and the sharper the slope of mountains, the greater the intensity and vertical extent of the turbulence.

- Fronts may produce moderate or greater turbulence.

  - Turbulence intensity depends on the strength and speed of the front.

  - Over rough terrain, fronts produce moderate or greater low-level turbulence.

  - Updrafts may reach 1,000 feet per minute in a narrow zone at low levels just ahead of the front.

  - Over flat terrain, fronts moving over 30 knots produce moderate or greater low-level turbulence.

D. CLEAR AIR TURBULENCE (CAT). CAT includes turbulence not associated with visible convective activity. It includes high-level frontal and jet stream turbulence. It may also occur in high-level, non-convective clouds. The following paragraphs describe the classic locations of CAT under specific meteorological conditions. CAT is not limited to these locations; adjustments to the forecast position may be necessary.

1. Surface and Upper-Level Low Patterns.

a. Surface Cyclogenesis. When cyclogenesis occurs, forecast CAT near the jet stream core N-NE of the surface low development (Figure 2-31a). Sometimes the surface low redevelops north of the main jet, with a formation of a secondary jet (Figure 2-31b). Numerical models may not forecast this jet genesis. CAT intensity is directly related to the strength of cyclogenesis, to the proximity of mountains, to the intensity of the jet core, and to the amplification and curvature of the downstream ridge. For cyclogenesis less than 1 mb/hour, expect moderate CAT and for cyclogenesis greater than or equal to 1 mb/hour, expect moderate-to-severe CAT.

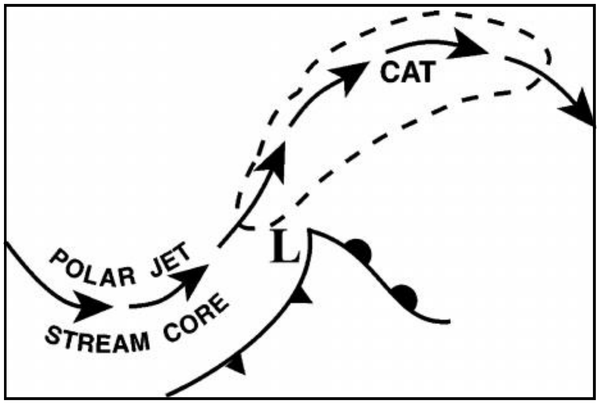


Figure 2-31a. CAT and Surface Cyclogenesis. The figure shows CAT near the jet stream core north to northeast of the surface low development.

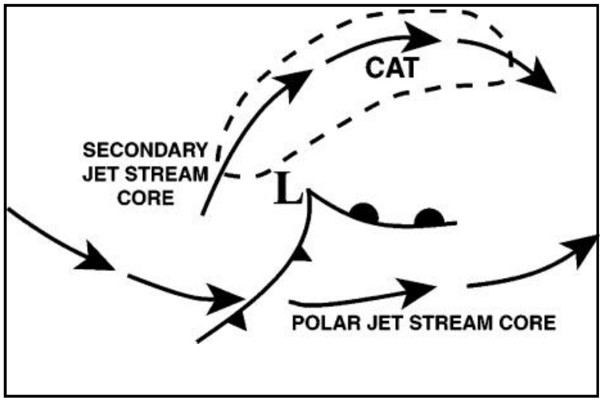


Figure 2-31b. CAT and Surface Cyclogenesis North of the Main Jet. The figure shows CAT near a secondary jet stream core north to northeast of the surface low that developed north of the main jet.

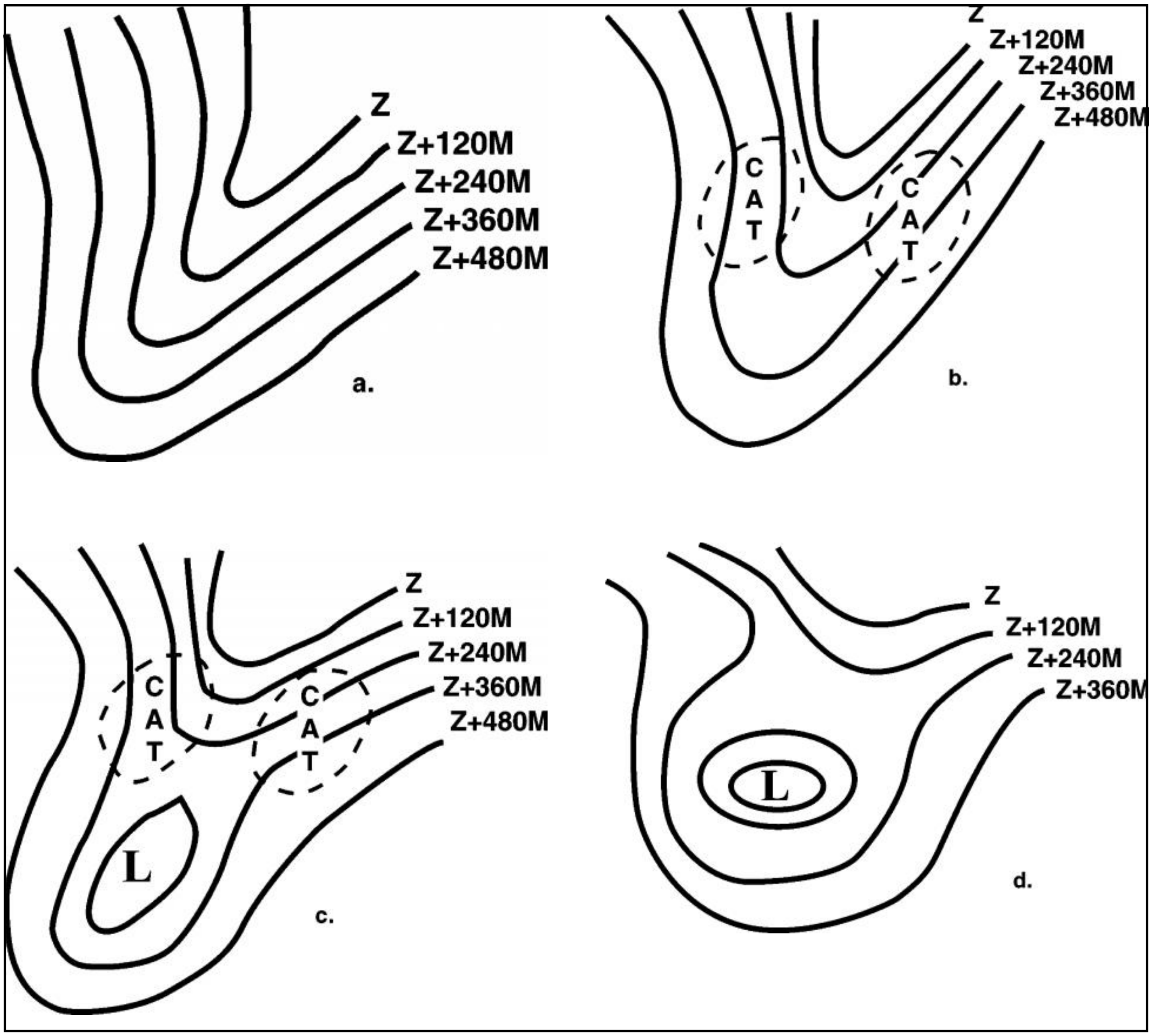


Figure 2-32a-d. CAT and Upper-Level Lows. Figure shows CAT development in various stages during development of a cut-off low.

b. Upper-Level Lows. There is a potential for moderate CAT in the development of cutoff, upper-level lows. The sequence in Figure 2-32a-d shows CAT development in various stages during development of a cutoff low. CAT usually forms in the areas of confluent and diffluent flow. Once the low is cutoff, CAT will diminish to light in the vicinity of the low.

c. 500-mb CAT Criteria. The 500-mb product is useful for forecasting CAT. However, do not use it exclusively. Consider data at all available levels. The following patterns may signal CAT:

- Shortwave troughs near one another (double troughs).

- Well-defined thermal trough.

- A narrow band of strong winds with strong horizontal wind shears.

- Closed isotherm cold pocket moving through an open flow pattern (i.e., height field with no closed contours).

- 500-mb winds greater than 75 knots in areas with wind shifts greater than or equal to 20°, and tight thermal gradients.

- Troughs associated with a surface frontal wave (often indicated by sharply curved isotherms around the northern edge of a warm tongue).

Note: Unless otherwise indicated, Figures 2-32 through 2-46 show 500-mb level data, though text will also associate turbulence observed at other levels.

d. Shear Lines in Upper-Level Lows. Forecast moderate CAT when the jet stream is greater than or equal to 50 knots around a closed upper-level low, and a very narrow neck occurs with a shear line separating the prevailing flow around the low. Forecast moderate to severe CAT if the jet reaches 115 knots. The potential for CAT is greatest between the two anticyclonically curved portions of the jet (see Figure 2-33).

2. Wind.

a. Jet Stream Turbulence Model. In the early 1960s, the meteorology department at United Airlines developed a basic jet stream turbulence model (Figure 2-34). The following applies to CAT occurrence in the model:

- Associated with converging polar and subtropical jets, mountain waves, and strong upper-level frontal zones.

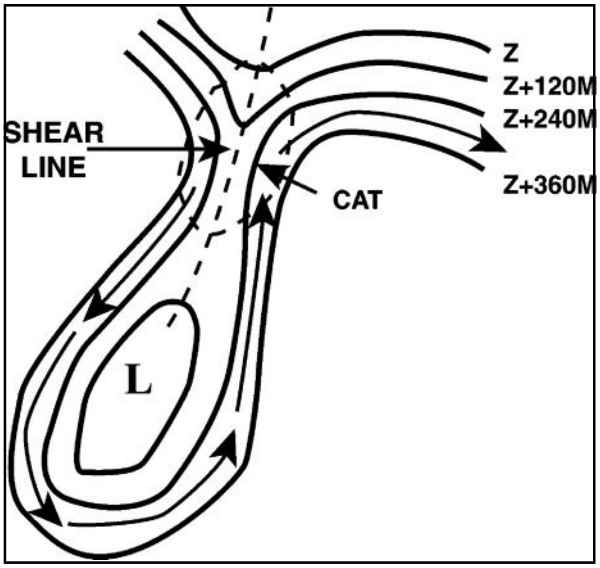


Figure 2-33. CAT and the Shear Line in the Throat of an Upper-Level Low. Forecast moderate or greater turbulence when a shear line separates the prevailing winds around a low.

- Horizontal wind shear should be greater than 40 knots/150 nm and/or vertical wind shear should be greater than 6 knots/1,000 feet.

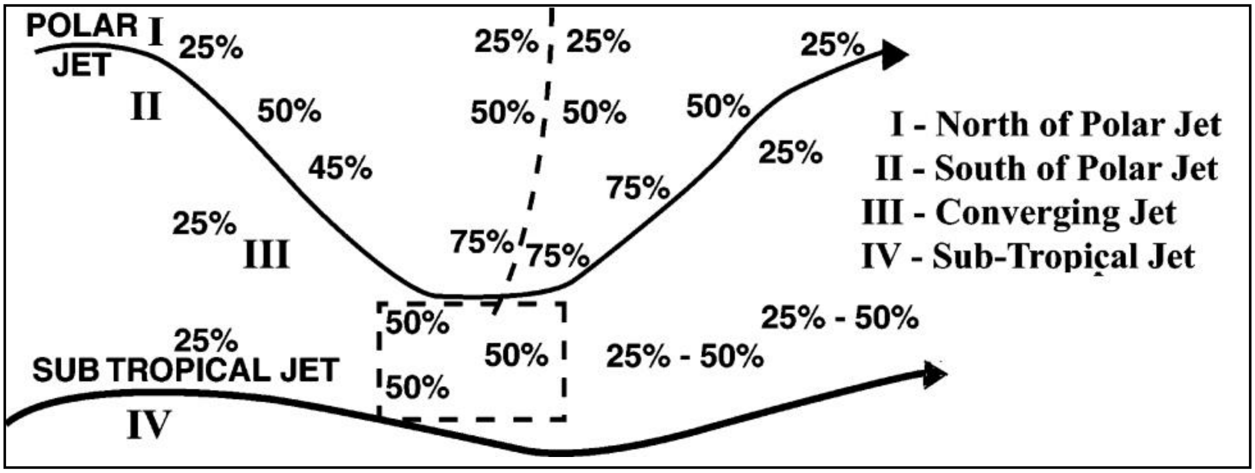


Figure 2-34. United Airlines Jet Stream Turbulence Model. A flight through the box would have a 50 percent chance of encountering CAT. Probabilities are not cumulative and are estimated.

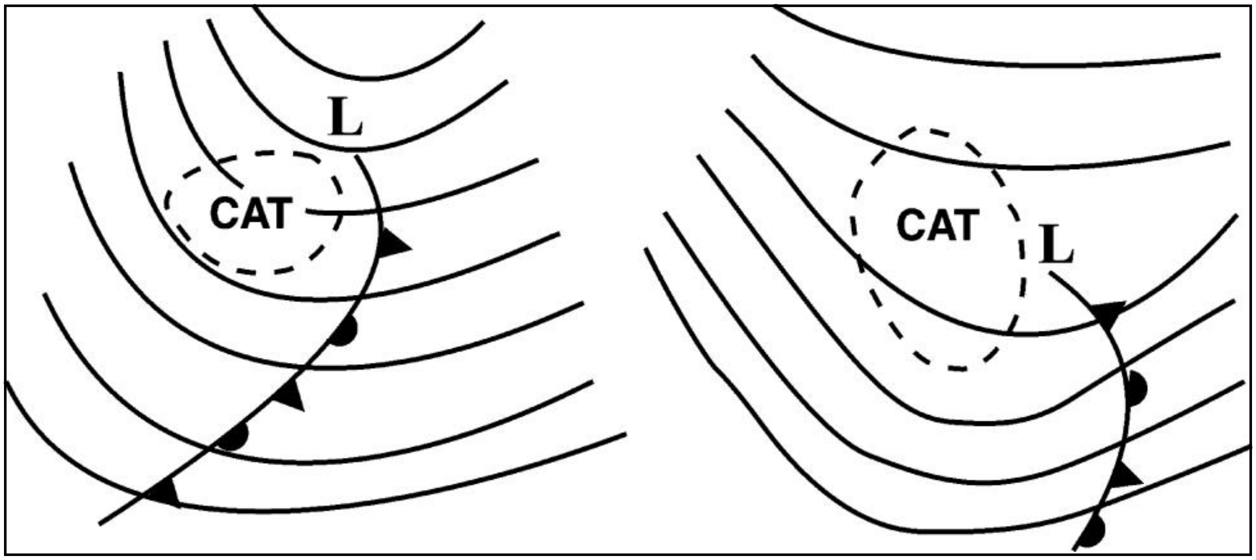


Figure 2-35. CAT and Diffluent Wind Patterns. The potential for CAT increases in the areas of diffluent flow near the surface system.

b. Diffluent Wind Patterns. Most CAT is observed during formation of diffluent upper-level wind patterns. After the diffluent pattern establishes, CAT may weaken in the diffluent zone. However, when a surface front is present (or forming), the potential for CAT increases in the areas of diffluent flow near the surface system (see Figure 2-35)

c. Strong Winds. CAT can exist in areas of strong winds when isotherms and contours are nearly parallel and only minor variations exist in wind direction (about 20° per 4 degrees of latitude) with exceptionally tight thermal gradients. Figure 2-36 illustrates a situation in which 500-mb winds exceeded 100 knots in the vicinity of a very high thermal gradient. CAT was observed between flight level of 18,000 feet (FL180) and FL330. Additionally, CAT often occurs along and above a narrow band of strong 500-mb winds when horizontal wind shears are strong on either side of the band, especially if the winds have an ageostrophic tendency.

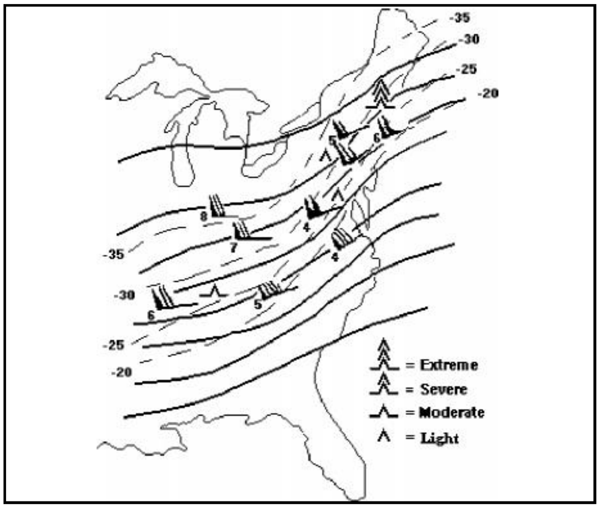


Figure 2-36. CAT and Strong Winds. Isotherms, 500-mb contours, and winds shown. Turbulence between FL180 and FL330.

d. Confluent Jets. When two jet stream cores converge to within 250 nm, the potential for CAT increases. Figure 2-37 shows the potential CAT area where two jets come within a distance of 5° latitude. Since the poleward jet is usually associated with colder temperatures and is lower than the second

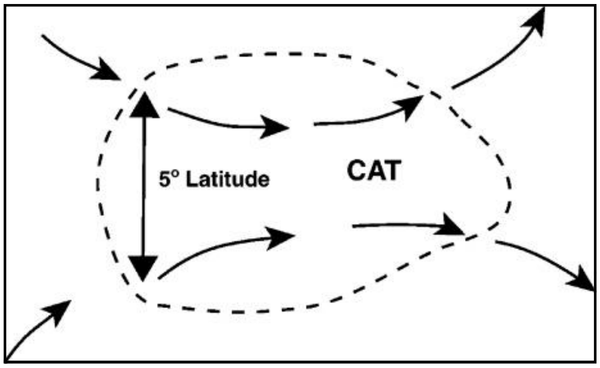


Figure 2-37. Turbulence with Confluent Jets. The CAT area occurs where two jets come within a distance of 5° latitude.

jet, the poleward jet will often undercut the other. This increases the static stability and produces strong vertical wind shears. The potential for CAT ends where the jets diverge to a distance of greater than 5° latitude.

3. Thermal Patterns. Analyze both the thermal and wind patterns to assess the potential for CAT. Appreciable cold-air advection is one significant clue to CAT potential.

a. Temperature Gradients at/above 300-mb. Expect CAT when a temperature gradient of greater than or equal to 5°C/120 nm exists or is forecast to occur and at least one of the following is observed:

- Trough movement greater than or equal to 20 knots.

- Wind shift greater than or equal to 75° in the region of cold advection.

- Horizontal wind shear greater than or equal to 35 knots/110 nm (~200 km).

- Wind component normal to the cold advection is greater than or equal to 55 knots.

b. Open-Isotherm Troughs. This situation encompasses the majority of the CAT patterns. The noticeable bulging of a cold-air tongue in a relatively tight thermal gradient may occur at or near the bottom of the trough. In either case, the isotherms curve more sharply than the contours (see Figures 2-38a-b and 2-39). In both cases, moderate turbulence was reported between FL250 and FL350.

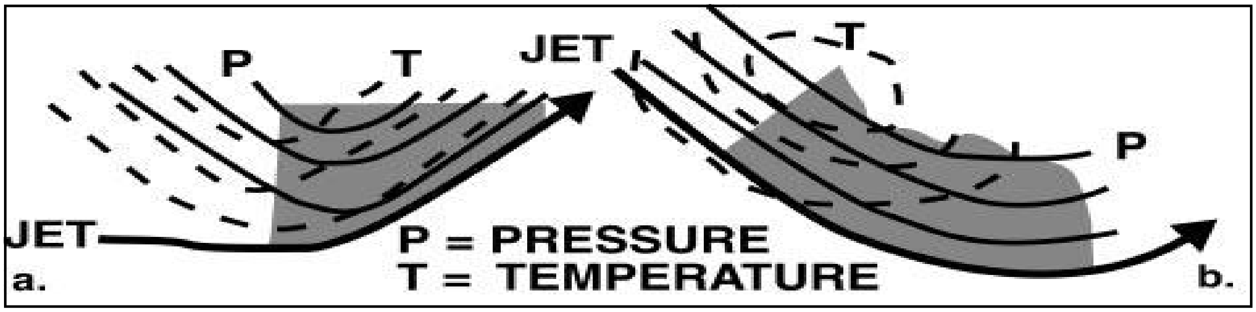


Figure 2-38. Two Basic Cold-Air Advection Patterns Conducive to CAT. Shaded areas highlight thermal patterns conducive to generation of CAT.

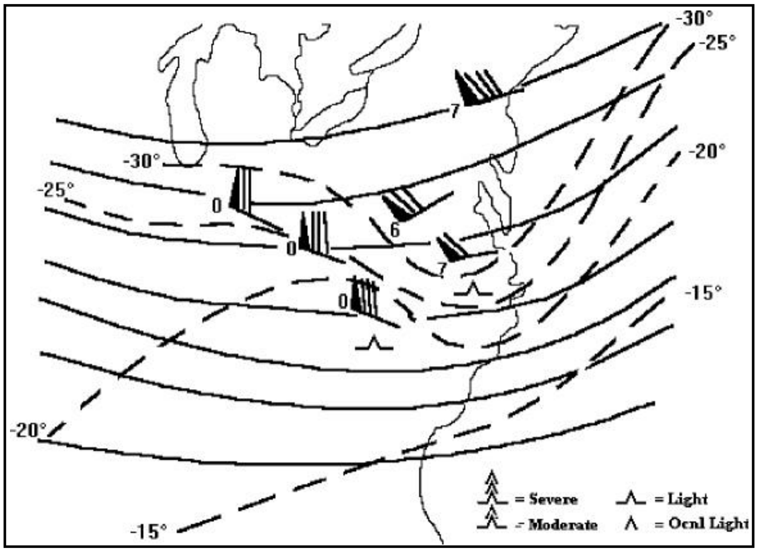


Figure 2-39. Common Open-Isotherm CAT. This situation encompasses the majority of the CAT patterns.

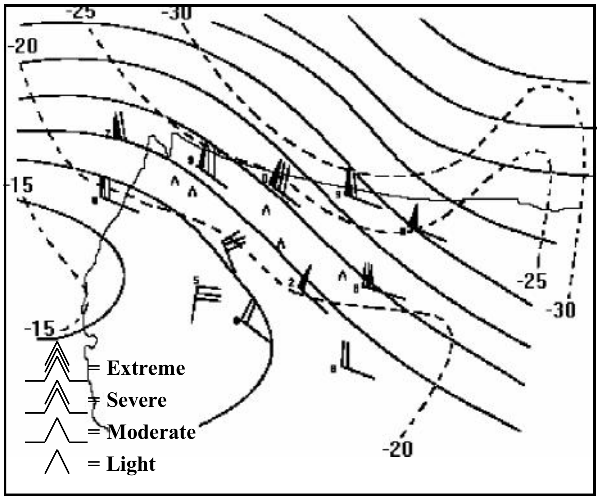


Figure 2-40a. CAT in Thermal Troughs. CAT was reported from FL 280 to FL 370.

Cold tongues commonly develop and move in from the northwest behind a pressure trough. Wind direction changes only gradually in this area. These troughs often move into the western states from the Pacific (see Figures 2-40a-b). Once the thermal configuration shown becomes apparent, check for development at higher levels. In Figure 2-40a, a trough and tongue of cold air at 300 mb extended across the indicated turbulence zone on a northwest-southeast line and was instrumental in creating the turbulence. The lack of turbulence indication in the strong CAA area in south central Canada probably is due to no PIREPS.

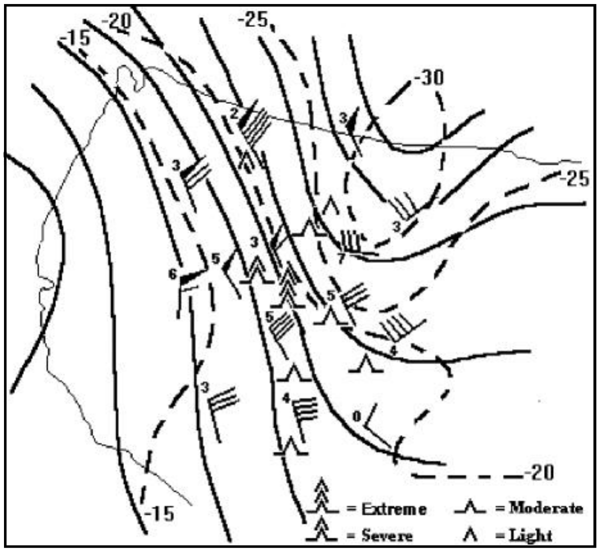


Figure 2-41. Closed Isotherm CAT. CAT was reported between FL240 and FL370.

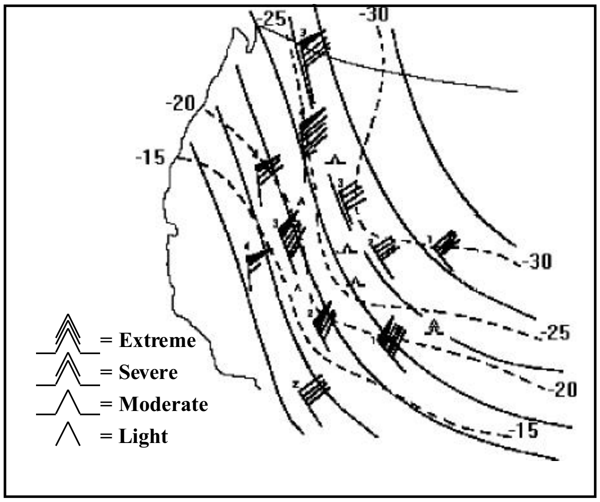


Figure 2-40b. CAT in Thermal Troughs. CAT was reported from FL 250 to FL 320 except over Utah where the report was at FL390.

Figure 2-40b shows a thermal gradient in combination with a smooth, strong wind flow pattern and a high isotherm amplitude. This pattern indicates a strong probability of CAT. The tight thermal gradient produced an average of 8 knots/ 1,000 feet of wind shear between 24,000 and 26,000 feet in Northern Utah. CAT began with a tightening thermal gradient. Strong winds, an abnormally tight thermal gradient, and higher amplitude isotherms than contours at 500 mb were strong indicators.

c. Closed Isothermal Patterns. CAT is often found in a moving, closed cold-air isotherm pattern at 500 mb when the height contours are not closed (see Figure 2-38b). CAT incidents between FL240 and FL370 were numerous (see Figure 2-41) in this rapidly moving pattern. The shear zone in the east region of the jet streak over the northern U.S. Rockies contributes to the CAT.

4. Troughs and Ridges.

a. Shearing Troughs. Rapidly moving troughs north of a jet may produce CAT in the confluent flow at the base of the trough (see Figure 2-42). The main area of CAT is north of the jet core.

b. Strong Wind Maximum to the Rear of the Upper Trough. CAT potential is high when a strong North-South jet is located along the backside of an upper trough. CAT usually occurs in the area of decreasing winds between the base of the trough and the maximum wind upstream. The change of

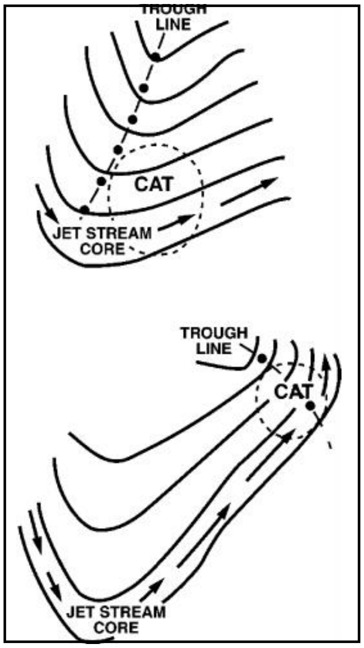


Figure 2-42. CAT and Shearing Troughs. The area of CAT is concentrated north of the jet stream core.

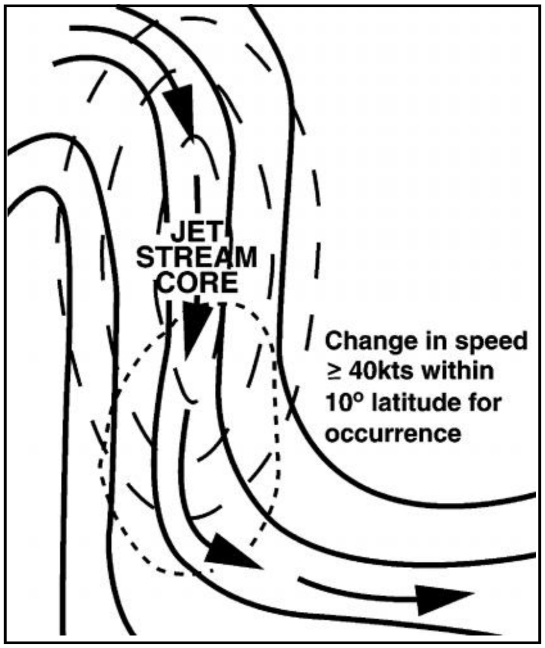


Figure 2-43. CAT Associated with Strong Wind Maximum to Rear of the Upper Trough. The potential is high when a strong North-South jet is located along the back-side of an upper trough.

wind speed should be greater than or equal to 40 knots within 10° of latitude for CAT to occur. If the difference between the jet core and the minimum wind speed is greater than or equal to 60 knots, CAT is most likely to occur between the jet core and the base of the trough, centered on the warm-air side of the jet (Figure 2-43).

c. 500-mb Deep Pressure Trough. A common configuration is a relatively deep pressure trough at 500 mb. CAT is often found in a sharply anticyclonic, persistent isotherm pattern downwind of the trough. In the example shown in Figure 2-44, the isotherms are sharply curved anticyclonically through eastern Mississippi and

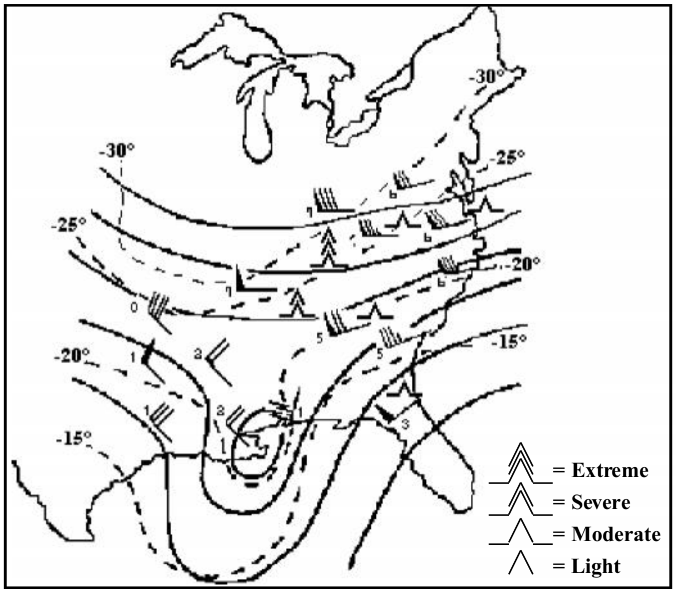


Figure 2-44. CAT in a Deep 500-mb Pressure Trough. CAT was reported between FL180 and FL 260.

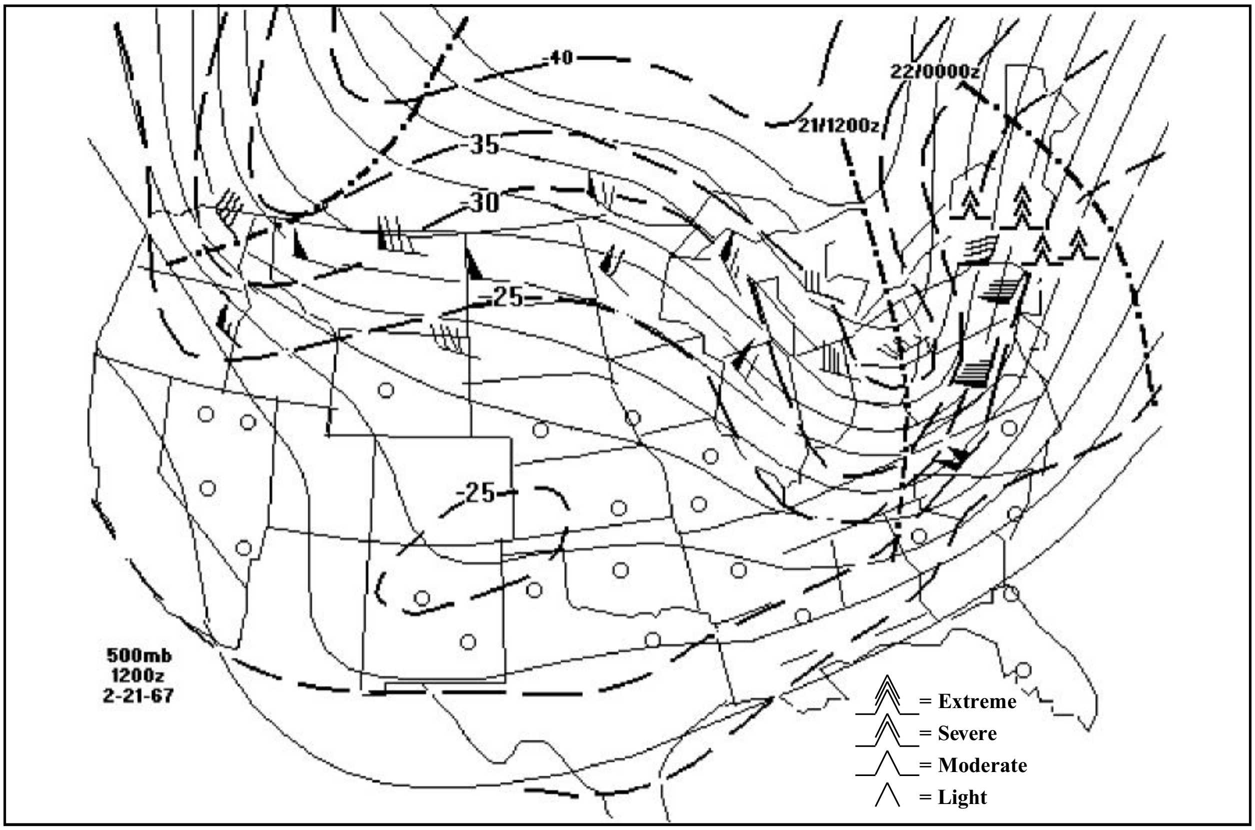


Figure 2-45. Double Trough Configuration. Moderate to extreme CAT was reported between 18,000 and 30,000 Feet (MSL)

Alabama, and the amplitude of the isotherms exceeds that of the contours. CAT was found downwind from the sharp curvature in the isotherms lee of the trough between FL180 and FL260.

d. Double Trough Configuration. Strong CAT is often associated with two troughs when they are close enough together that the trailing trough influences the airflow into the leading trough. This common pattern is often associated with a flat or flattening intervening ridge, which advects warm air into the bottom of the lead trough. Although the double trough can be detected at a number of levels, the 500-mb product is the best to use. Figure 2-45 depicts two troughs that are quite far apart. Nevertheless, the trailing trough exerts a definite influence on the airflow into the leading trough. Moderate to extreme CAT was reported between FL180 and FL300.

e. Upper-Level Ridges. Expect at least moderate CAT on both sides of the jet near the area where the jet undergoes maximum latitudinal displacement in an amplifying ridge (see Figure 2-46). Maximum CAT is located in the area of greatest anticyclonic curvature (usually within 250 nm of the ridge axis and elongated in the direction of the flow). Expect moderate or greater CAT with the following conditions (cyclogenesis may also occur downstream of these upper-level features):

- Strong vertical wind shear greater than or equal to 10 knots/1,000 feet.
- Winds greater than 135 knots in an area of large anticyclonic curvature.
- Large latitudinal displacement of the jet with winds greater than 115 knots.

5. Uses of Upper-Air Data to Forecast CAT. Here are some hints for using upper-air products to pick out synoptic conditions favorable for CAT, as described elsewhere.

a. 700- and 850-mb Height and Temperature Fields. These tools are useful in identifying regions of thermal advection, wind components normal to

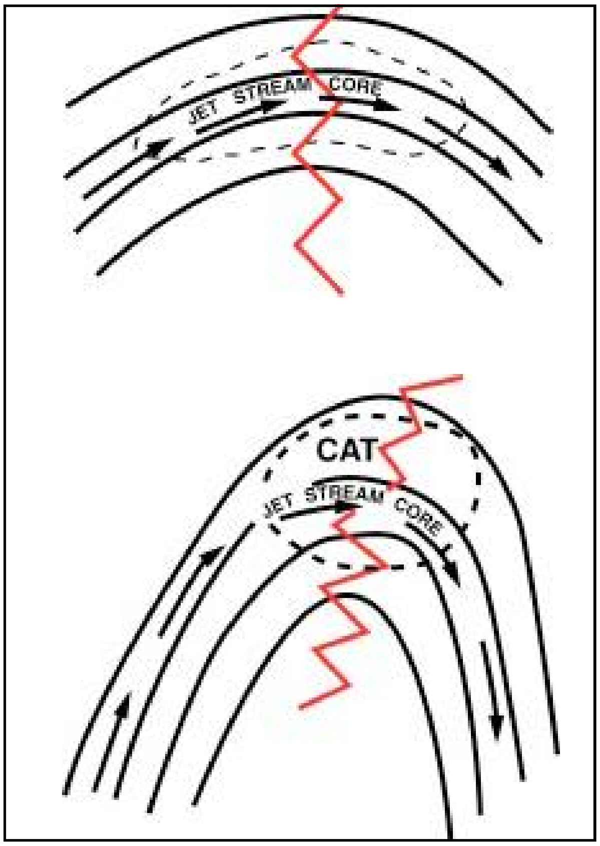


Figure 2-46. CAT and Upper-Air Ridges. Maximum CAT is located in the area of greatest anticyclonic curvature.

mountain ridges, mid- or low-level turbulence, and upper-level frontal boundaries.

b. 500-mb Analysis of Heights, Temperature, and Vorticity. Key on areas of thermal advection, shortwave troughs, and wind components perpendicular to mountain ridges. A 500-mb chart can also be used to approximate jet stream positions and the general upper-air synoptic pattern. For example, place jets near the following isotherms:

- Subtropical jet –11°C
- Polar front jet –17°C
- Arctic jet –30°C

c. 250-mb Jet Steam. Analyze closely to determine the current and future jet stream core position.

d. 200-mb Analyzed Height and Temperature Fields. Look for regions of strong isotherm packing in association with strong wind flow. The 200-mb isotherms correspond closely with the 500-mb vorticity pattern and clearly depict short waves and developing systems.

E. MOUNTAIN WAVE (MW) TURBULENCE. The most severe type of terrain-induced turbulence is mountain wave turbulence. It often occurs in clear air and in a stationary wave downwind of a prominent mountain range. It is caused by the mechanical disturbance of the wind by the mountain range.

The sketch in Figure 2-47a shows a foehn gap, indicating turbulent lee waves are present. The gap is located between the cirrus clouds and mountain range on the leeward side of the range. Wave intensity depends on several factors:

- Wind speed.

- Height and slope of the mountain (high mountains with steep slopes produce the most intense turbulence).

- Stability of the lower troposphere above and to the lee of the mountain (the most intense turbulence is associated with stable air above and to the lee of the mountain barrier).

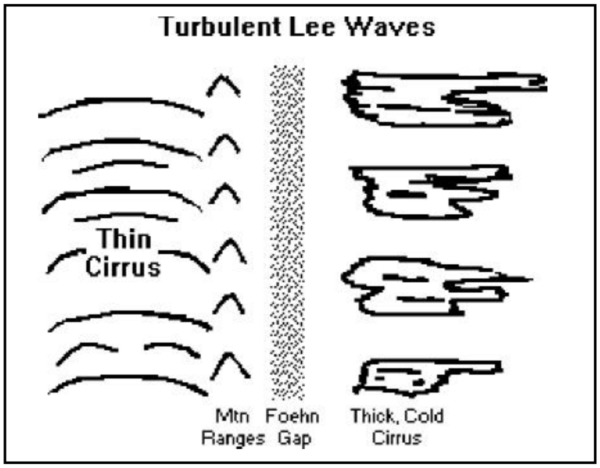


Figure 2-47a. Mountain-Wave Clouds. A foehn gap, indicates turbulent lee waves are present.

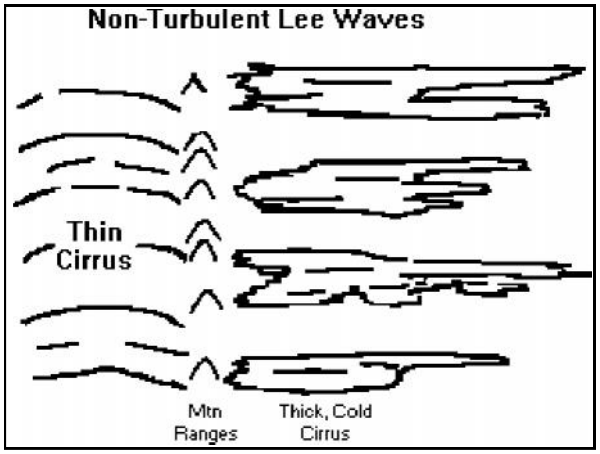


Figure 2-47b. Mountain-Wave Clouds. The lack of a foehn gap indicates the absence of turbulent lee waves.

The most dangerous turbulence is found in the rotor and cap clouds. Downdrafts in these clouds can force a plane into a mountain. The sketch in Figure 2-47b has no foehn gap; the clouds nestle against the mountain range on the leeward side. This indicates an absence of turbulent waves.

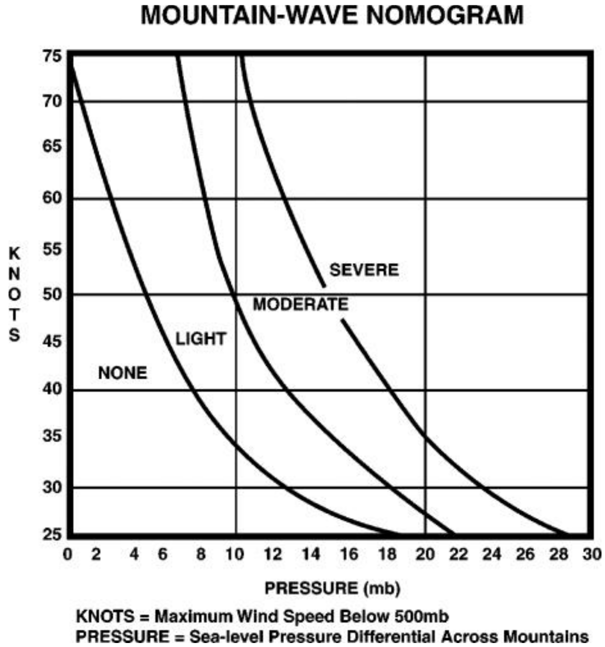


Figure 2-48. Mountain-Wave Nomogram. Use this nomogram to predict mountain wave intensity.

A necessary ingredient for severe mountain wave development is a minimum wind component of 25 knots perpendicular to the mountain ridge at the height of the ridge. Also, the wind profile should include little change of wind direction with height and increasing wind speeds with altitude high into the troposphere. Table 2-9 and Figure 2-48 (used together), provide guidance in forecasting mountain-wave turbulence.

Table 2-9. Low-level mountain wave turbulence.

Low-Level Mountain-Wave Turbulence (Surface To 5,000 Ft Above Ridge Line)			
Low-Level Feature Wind Component Normal to Mountain Range at Mountain Top and > 24 kt **and**	**Turbulence Intensity** **Light**	 **Moderate**	 **Severe**
dP Across Mountain at Surface is	See Figure 2-48	See Figure 2-48	See Figure 2-48
|dT| Across Mountain at 850 mb is	< 6°C	6°C - 9°C	> 9°C
|dT/dX| Along Mountain Range at 850 mb is	<4°C/60 NM	4-6°C/60 NM	>6°C/60 NM
Lee-Side Surface Gusts	< 25 kt	25 - 50 kt	> 50 kt
Winds Below 500 mb > 50 kt	Increase the Turbulence found by one degree of intensity (i.e., Moderate to Severe)		

Notes: (1) dP is the change in surface pressure across the range.
(2) |dT| is the absolute value of the 850-mb temperature difference across the range.
(3) |dT/dX| is the absolute value of the 850-mb temperature gradient along mountain range.
(4) Turbulence category forecast is the worst category obtained from each of the four parameters.

1. ***Associated Clouds.*** There are specific clouds associated with mountain wave turbulence. These are cap (foehn wall), roll (rotor), lenticular, and "mother-of-pearl" clouds. Figure 2-49 illustrates the structure of a strong mountain wave and associated cloud patterns. The lines and arrows depict windflow.

a. Cap Cloud. The cap cloud hugs the tops of mountains and flows down the leeward side with the appearance of a waterfall. This cloud is dangerous because it hides the mountain and has strong downdrafts associated with it. The downdrafts can be as strong as 5,000 to 8,000 feet per minute.

b. Roll Cloud. The roll cloud, also called a rotor cloud, looks like a line of cumulus clouds parallel to the ridge line. It forms on the lee side and has its base near the height of the mountain peak and top near twice the height of the peak. The roll cloud often merges with the lenticular clouds above, forming a solid cloud mass to the tropopause. The roll cloud is dangerously turbulent with strong updrafts (5,000 feet per minute) on the windward side and dangerous downdrafts (5,000 feet per minute) on its leeward edge. This cloud may form immediately on the lee of the mountain or it may be a distance of 10 miles downwind – depending on wind speed.

c. Lenticular Clouds. Lenticular clouds are relatively thin, lens-shaped clouds with bases above the roll cloud. Their tops extend to the tropopause. These clouds have a tiered or stacked look due to atmosphere stability above the mountain ridge. All lenticular clouds are associated with turbulence. In polar regions, lenticular clouds can appear in the stratosphere as high as 80,000 feet. These clouds are called "mother-of-pearl" (nacreous) clouds.

2. ***Occurrence Indicators.***

- Rapidly falling pressure to the lee side of mountains.

- Broken or ragged-edged ACSL reported to the lee of the mountains.

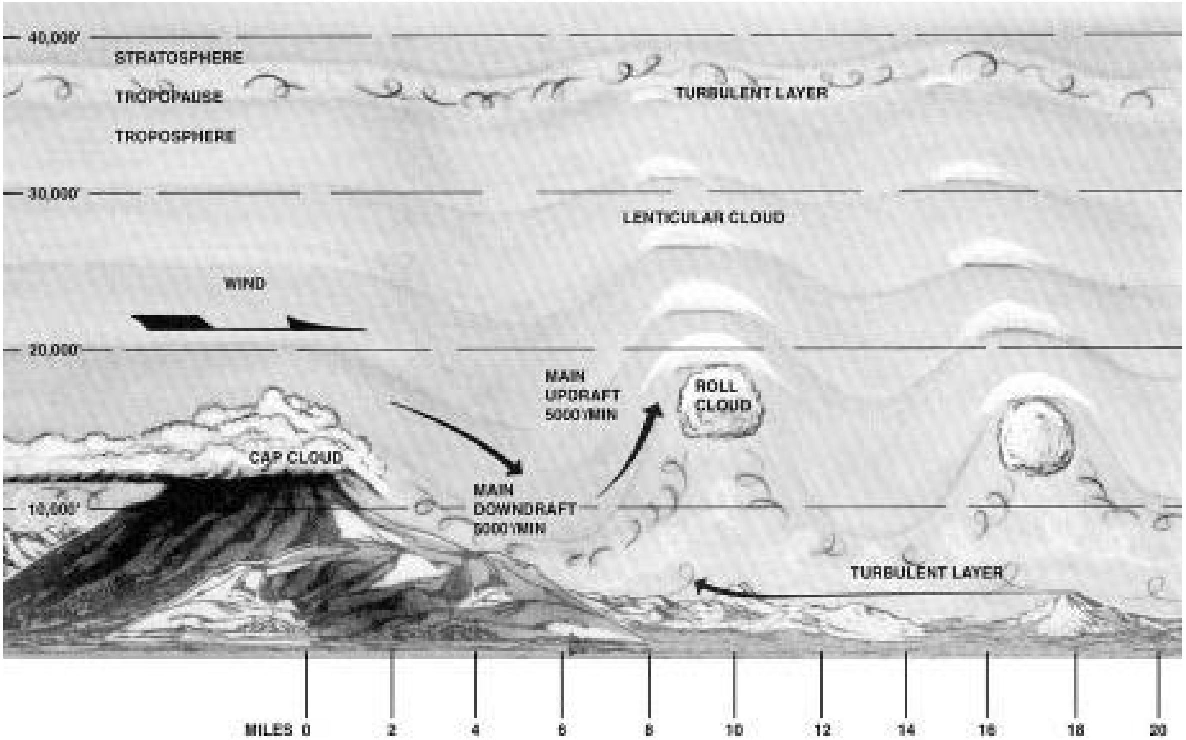


Figure 2-49. Mountain-Wave Cloud Structure. The figure illustrates the structure of a strong mountain wave and associated cloud patterns. The lines and arrows depict windflow.

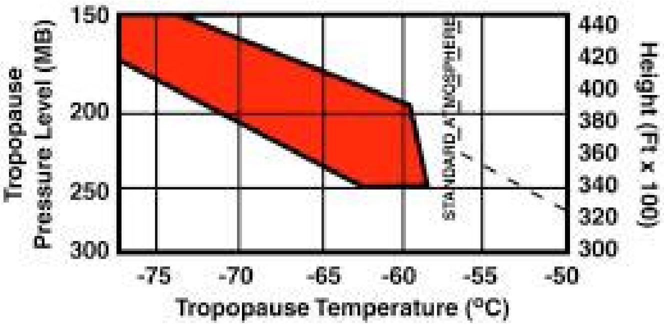


Figure 2-50. Graph of Mountain-Wave Potential. When tropopause temperature and height readings fall within the shaded area, the potential for mountain-wave turbulence exists when the wind speed and direction criteria are met.

- Lee side gusty surface winds at nearly right angles to the mountains.

- Blowing dust picked up and carried aloft to 20,000 feet MSL or higher.

- Temperature of -60°C or less in the upper atmosphere near the mountain-wave zone (see Figure 2-50).

F. WAKE TURBULENCE. Although neither forecasted nor recorded in a TAF, wake turbulence is a problem with the increased use of heavy aircraft. You should be aware of how wake turbulence forms and be aware of its effects.

1. Characteristics. Every aircraft generates two counter-rotating wingtip vortices. Wake turbulence results when an aircraft encounters vortices from another aircraft. Vortex generation begins when the nose wheel lifts off the ground and ends when the nose touches back down again during landings. A vortex forms at each wingtip as air circulates outward, upward, and around the wingtip. The diameter of the vortex core varies with the size and weight of the aircraft.

These vortices can be 25 to 50 feet in diameter with a much larger area of turbulence. They usually stay fairly close together (about 3/4 of the wing span) until dissipation. They sink at a rate of 400 to 500 feet per minute and stabilize about 900 feet below the flight path, where they begin to dissipate. Vortex size is reduced by the use of winglets, smaller “wings” that curve upward from aircraft wing tips.

2. Dissipation. Atmospheric turbulence increases the dissipation of wake turbulence while ground effect and surface winds alter the low-level vortex characteristics only slightly. As the vortex sinks into the boundary layer, it begins to move laterally at about 5 knots. A crosswind will decrease the lateral movement of a vortex moving toward the wind and increase the movement of a vortex moving with the wind. This could hold one of the vortices over the runway for an extended period or allow one to drift onto a parallel runway. Vortices persist longer during inversions.

Listed below are some rules for avoiding wake turbulence (Federal Aviation Administration (FAA) Aeronautical Information Manual):

- Stable conditions combined with a crosswind of about 5 knots may keep the upwind vortex over the runway for periods of up to 15 minutes.

- Vortex generation begins with lift-off and lasts until touchdown. Therefore, aircraft should avoid flying below the flight path of a recent arrival or departure.

- If two aircraft fly in the same direction within 15 minutes of each other, the second should maintain an altitude equal to or higher than the first. If required to fly slightly below the first, the second aircraft should fly upwind of the first.

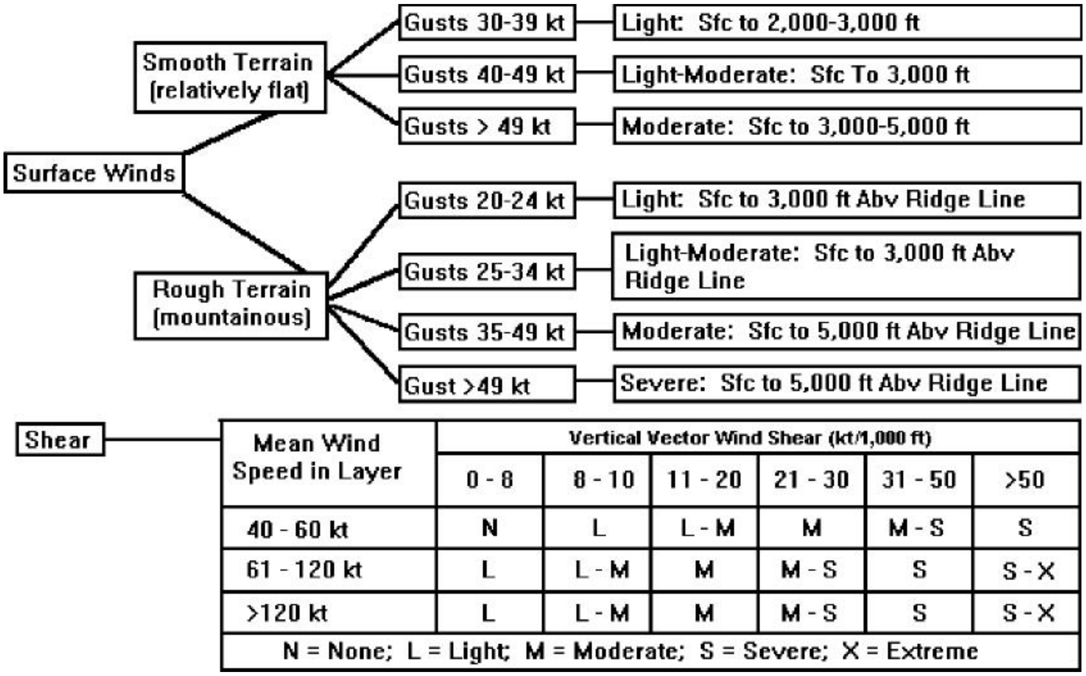
G. FORECASTING AIDS. Use the following list of checklists, figures, standard system tools, and tables provided to aid you in providing accurate turbulence forecasts.

1. Location of Turbulence Conditions. The general location of turbulence should be anticipated in the following areas:

- Thunderstorms
- Areas of strong thermal advection, such as:
  - Cold-air advection.
  - Warm-air advection.
  - Strong upper-level fronts.
  - Rapid surface cyclogenesis.
  - Outflow area of cold digging jet.
- Areas of considerable horizontal directional and/or speed shear, such as in:
  - Mountain areas.
  - Diffluent upper flow.
  - Developing cutoff lows.
  - Sharp anticyclonic curvature.
- Areas of considerable vertical shear, particularly below strong stable layers in:
  - Tilted ridges.
  - Sharp ridges.
  - Tilted troughs.
  - Confluent jet streams.

2. Basic Forecasting Checklist for Low-Level (Surface to 10,000Feet) Turbulence. Low-level turbulence can dramatically impact flight operations. Aircrews operating in high speed, low altitude training routes must be prepared to make quick corrections to avoid catastrophic accidents (see Figure 2-51).

Note: Checklist is based on Category II aircraft. Adjust turbulence values for supported aircraft using Tables 2-7 and 2-8.



Mean Wind Speed in Layer	Vertical Vector Wind Shear (kt/1,000 ft)					
	0 - 8	8 - 10	11 - 20	21 - 30	31 - 50	>50
40 - 60 kt	N	L	L - M	M	M - S	S
61 - 120 kt	L	L - M	M	M - S	S	S - X
>120 kt	L	L - M	M	M - S	S	S - X

N = None; L = Light; M = Moderate; S = Severe; X = Extreme

Figure 2-51. Forecasting Checklist for Low-Level Turbulence. This checklist is designed for Category II aircraft.

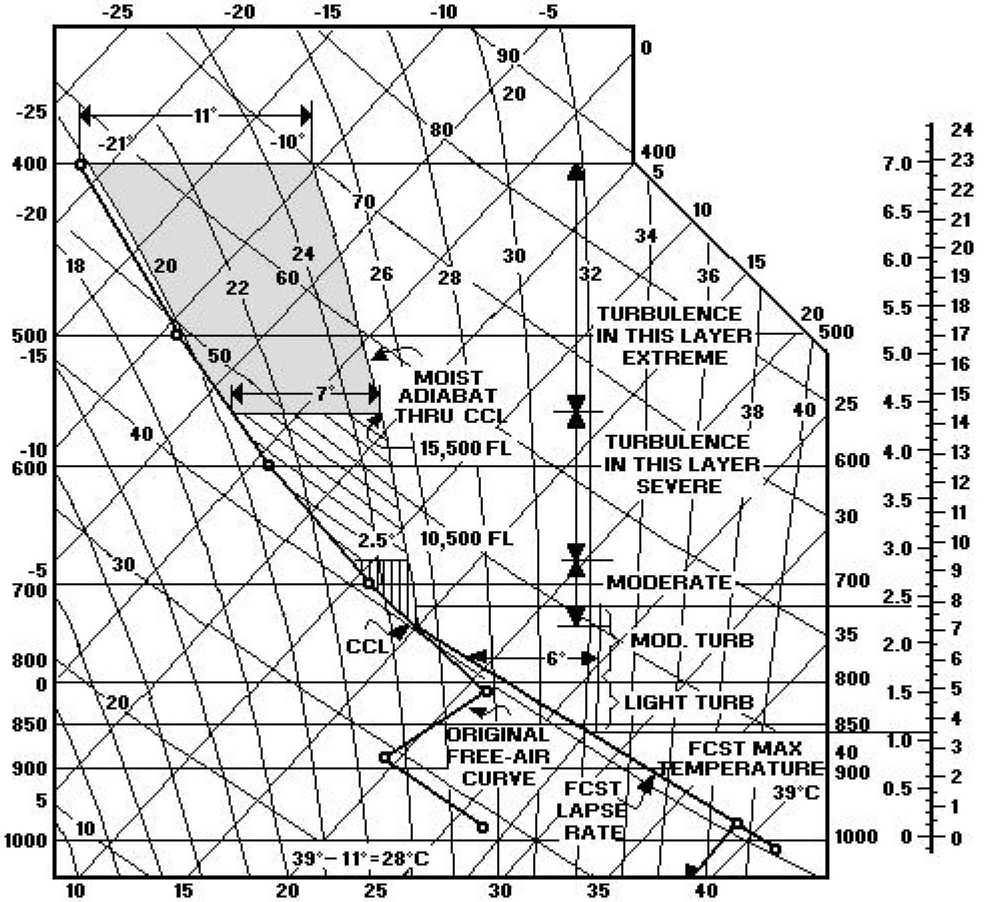


Figure 2-52. **Turbulence Forecasting from Skew-T.** The figure depicts a method for forecasting turbulence in convective clouds using a Skew-T.

3. ***Forecasting Turbulence in Convective Clouds.*** This section describes a method for forecasting turbulence in convective clouds using a Skew-T. The method considers two layers of the atmosphere: surface to 9,000 feet MSL and above 9,000 feet MSL (see Figure 2-52). The forecast is designed for Category II aircraft and must be modified for other types of aircraft.

a. Layers from Surface to 9,000 feet. Use the steps below to estimate the buoyant potential in the lower atmosphere. Use the results obtained from this method to estimate turbulence in thunderstorms.

- Use the convective temperature to forecast the maximum surface temperature. Project a dry adiabat from the CCL to the surface. This gives the convective temperature. Adjust this temperature using temperature curves for local effects.

- Subtract 11°C from the final forecast maximum temperature. Follow this isotherm to its intersection with the dry adiabat projected upward from the forecast maximum temperature.

If the intersection is above 9,000 feet MSL, forecast no turbulence below 9,000 feet MSL. If the intersection is below 9,000 feet, draw a moist adiabat from the intersection of the isotherm and the dry adiabat upward to the 9,000-foot level. The temperature difference between this moist adiabat and the free-air temperature curve determines the severity of the turbulence as well as the limits of the layers of each degree of turbulence. Apply the temperature differences to Table 2-10.

b. Layers Above 9,000 Feet. Follow the moist adiabat that passes through the CCL upward to the 400-mb level. The maximum temperature difference between this moist adiabat and the forecast free-air temperature curve is the central

Table 2-10. Layers below 9,000 feet using temperature differences.

Layers Where Temperature Difference is	**Turbulence is Forecast as**
0° to 6°C	Light
6° to 11°C	Moderate
11°C or More	Severe

Table 2-11. Layers above 9,000 feet using temperature differences.

Layers Where Temperature Difference is	**Turbulence is Forecast as**
0° to 2.5°C	Moderate
2.5° to 7°C	Severe
7°C or More	Extreme

portion of the most turbulent area. The intensity of the turbulence is found in Table 2-11.

4. ***Low-Level Turbulence Nomogram.*** The graph in Figure 2-53 can be used to predict turbulence using forecast or observed winds and the temperature differences across a surface front.

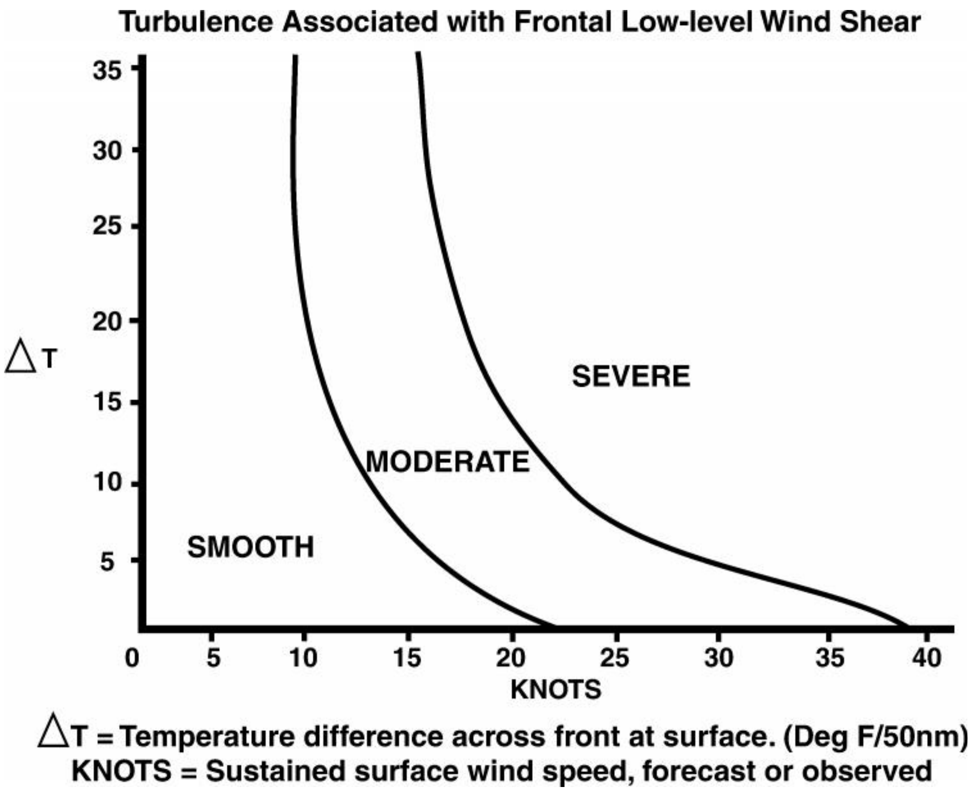


Figure 2-53. Turbulence Nomogram—Temperature Gradient and Surface Winds. Use this figure to predict turbulence using forecast or observed winds and temperature differences across a surface front.

Table 2-12. Wind shear critical values.

	Turbulence Intensity			
	Light	**Moderate**	**Severe**	**Extreme**
Horizontal Shear		25-49 kt/90 NM	50-89 kt/90 NM	≥ 90 kt/90 NM
Vertical Shear	3-5 kt/1,000 ft	6-9 kt/1,000 ft	10-15 kt/1,000 ft	> 15 kt/1,000 ft

5. ***Wind Shear Critical Values.*** Use Table 2-12 if receiving PIREPs with turbulence for a particular area and you want to quickly confirm if the turbulence will likely continue in the area. When two of the criteria are present in the same region, forecast the higher turbulence intensity (e.g., if moderate horizontal criteria and severe vertical criteria are present in the same region, forecast severe turbulence in this region).

6. ***Significant Parameter Checklist.*** This checklist (see completed checklist in Table 2-13) lists significant turbulence-producing parameters arranged in three situations. Use situations Ia or b, II, and III over land. For over water use, only Ib applies.

- Situation I: high-level wind and temperature field.
- Situation II: terrain parameters.
- Situation III: gravity wave atmospheric parameters.

Note: If a parameter is only marginally suitable for turbulence, enter an "X" in the suitability column; enter two "X's" if a parameter is strongly

Table 2-13. Significant Parameter Checklist.

Situation		**Parameter**	**Suitability**	**Remarks**
High-level wind and Temperature Fields	Ia	Vertical shear (jet stream vicinity)	XX	Strong double jet stream
		Cyclonic shear (cyclonic side of jet)	X	Approximately under jet stream; difficult specify shear
		Vicinity of tropopause		Well below tropopause
		Low static stability (destabilizing differential advection)	XX	Moderate cold-air advection at 300 mb but not at 500 mb
		Cyclonic curvature and diffluence (troughs and exit regions)	X	Trough to west; difficult to determine diffluence pattern
	Ib	Vertical shear (jet stream vicinity)		
		Anticyclonic shear		
		Anticyclonic curvature		
		Low static stability (destabilizing differential advection)		
		Exit region of isotach maximum		
Terrain Parameters		Height of ridge (presence of ridge)	X	Not high
	II	Ridge well-defined sharp	XX	
		Series of well-spaced ridges	XX	
Gravity wave parameters	III	Strong low-level winds	XX	About 25 kt
		Low-level winds normal to ridge	XX	Winds 290° - ridge 200-020
		Increasing wind with height (strong winds aloft)	XX	
		Little change of direction with height	XX	Only about 20-30 degrees
		Low-level unstable layer (cold-air advection)	XX	Surface to 850 mb
		Intermediate stable layer and less stable above	XX	

suitable for turbulence. The more "X's" in the suitability column, the greater the turbulence occurrence and severity. Stations should determine their own thresholds for what number of "X's" are significant to their operations. In the example above, several aircraft experienced severe turbulence; one aircraft crashed.

*7. **NESDIS CAT Tool.*** The National Environmental Satellite, Data, and Information (NESDIS) decision tree in Figures 2-55 through 2-61 helps produce a turbulence forecast from hourly satellite infrared images, daytime visible and water vapor channel images, and rawinsonde wind and temperature observations (or 6- to 12-hour forecasts), at standard levels. In order to correctly use the decision tree, first understand both the dynamics that cause turbulence and satellite imagery analysis techniques. Be familiar with and recognize the following features:

a. Deformation Zone. A region where the atmosphere is undergoing contraction in one direction and elongation or stretching in the perpendicular direction, relative to the motion of the air stream (see Figure 2-54). A cloud border is often located near and parallel to the stretching axis. Situations where moderate to severe turbulence is most likely are as follows:

- Low and associated comma-cloud system is dissipating.

- A flattening of the cloud border on the upstream side of the comma.

- Cyclogenesis is in progress, accompanied by a building or rapidly moving upper ridge to the east of the storm.

- The cloud system is encountering confluent (opposing) flow caused by a blocking upper-level system (a closed low or anticyclone) downstream.

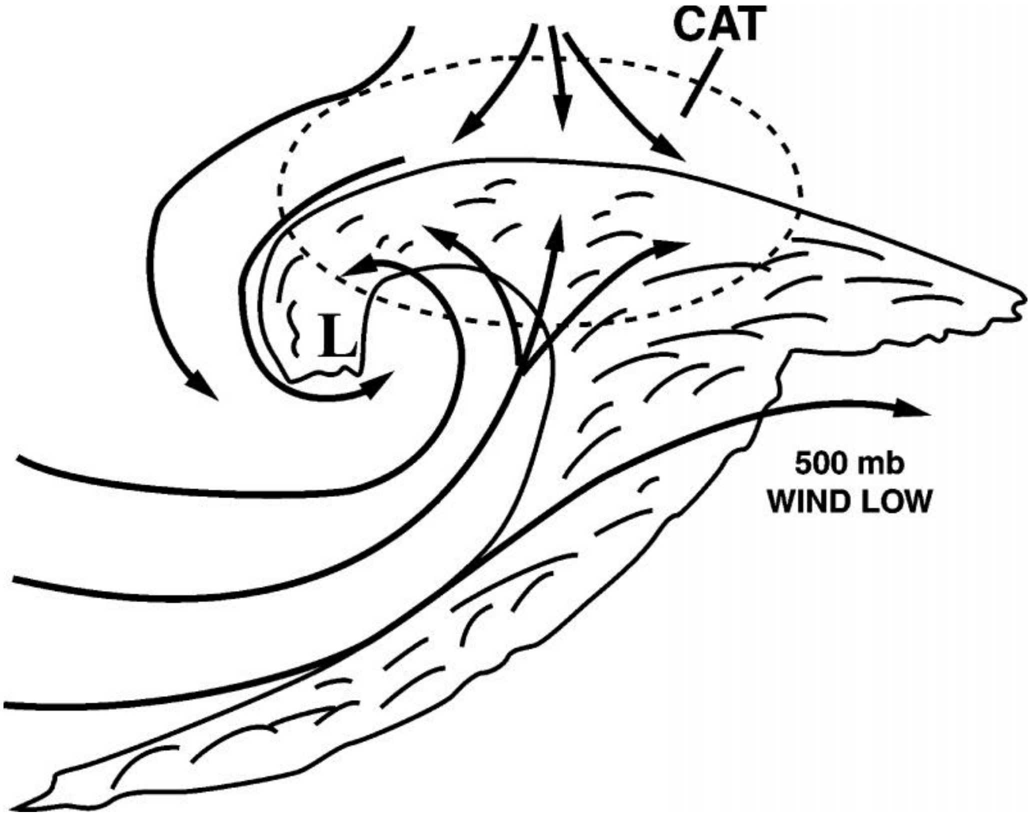


Figure 2-54. CAT in a Deformation Zone. Moderate to severe turbulence can occur in the dotted area.

b. Wave Cloud Signatures.

(1) Transverse Bands. Defined as irregular, wavelike cirrus cloud patterns that form nearly perpendicular to the upper flow. They are usually associated with the low latitude subtropical jet stream and indicate large vertical and possibly horizontal wind shears. Generally, the wider, thicker transverse bands are more likely to contain severe turbulence, possibly due to the added presence of thermal instability. In these situations, the bands often have a carrot-shaped appearance, similar to cumulonimbus anvils. Cloud bands, in general, tend to be aligned with the cloud layer shear vector. For this reason, the presence of cirrus bands which differ in orientation from the prevailing wind direction (transverse to the flow) indicate directional shear with height.

(2) *Billows.* Defined as wave cloud patterns in cirrus, or middle-level clouds which are regularly spaced, narrow, and oriented to the upper flow. They are most often seen when a strong jet intersects either a frontal cloud system or a line of cumulonimbus clouds at a large crossing angle. The anvil debris of convective clouds in these situations extends well downstream from its source. Although individual waves dissipate quickly (less than 30 minutes), new waves can reform nearby under favorable conditions. The longer the wavelength of the billows, the better the chance for significant turbulence. Kelvin-Helmholtz instability is often made visible in billow clouds.

(3) Water Vapor Image Darkening. This refers to elongated bands, or in some cases, large oval-shaped gray regions that become darker in successive images. The darkening is usually accompanied by cold advection and convergence in the mid- and upper-levels of the troposphere resulting in compensating sinking through a deep layer. Cross sections of such features reveal sloping baroclinic zones (tropopause leaves or folds). This indicates stratospheric air is descending into the upper troposphere. Moderate or stronger turbulence occur 80 percent of the time when image darkening occurs, especially if it persists for at least 3 hours.

(4) Mountain Waves. Defined as stationary waves situated downwind of a prominent mountain range and caused by the disturbance of the wind by the mountain range. Usually the wave appears as a stationary, narrow clearing zone parallel to steep mountain ranges. It may also occur in foehn wind synoptic situations, near or just east of the upper ridge and south of the jet stream.

(5) CAT Decision Tree. The decision tree summarizes subjective and objective techniques developed by NESDIS (see Figures 2-55 through 2-59). The decision tree starts with an assessment of the upper-level synoptic flow pattern over the area of interest and then asks questions about features observed in satellite imagery. Sketches are included to help visualize the image features or flow patterns being described. The decision tree has built-in redundancy. If a mistake is made in the analysis of the synoptic flow pattern, it is still possible to arrive at the correct solution. Sketches are included to help visualize the image features or flow patterns being described.

Confidence levels are stated when a solution level is reached. The estimates are based on a study completed by NESDIS. In most cases confidence levels range from 50 to 80 percent. Confidence level is usually lowest in mountainous regions where turbulence may occur without any conspicuous satellite image features.

Turbulence intensities are Light (L), Moderate (M), and Severe (S). The intensities have been determined from numerous large commercial and military aircraft pilot reports. A solution of Moderate Or Greater (MOGR) means that moderate turbulence is likely and severe turbulence is possible. A solution of “M-S” means that moderate to occasional severe turbulence is likely.

Turbulence Decision Tree

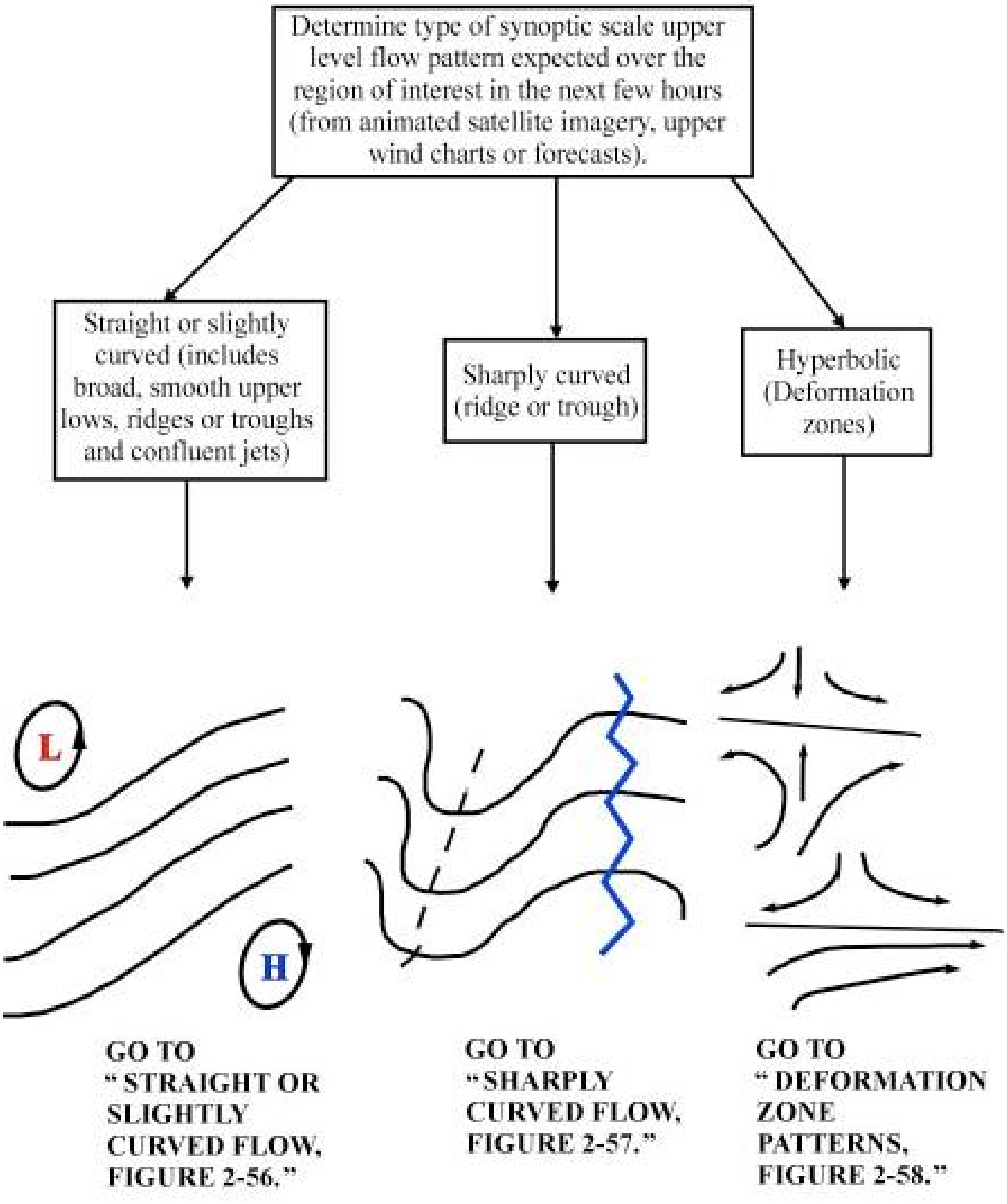


Figure 2-55. Clear-Air Turbulence Decision Tree.

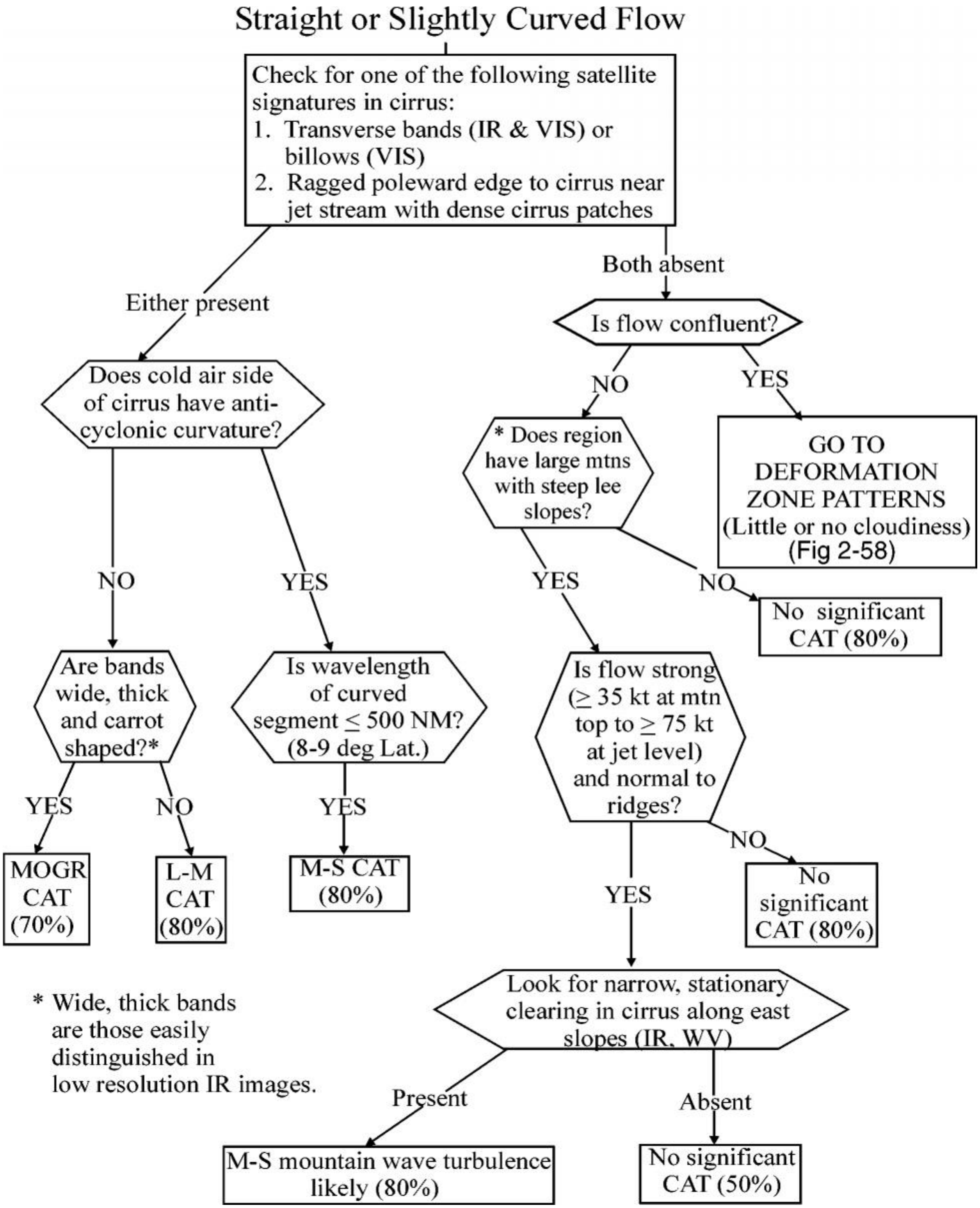
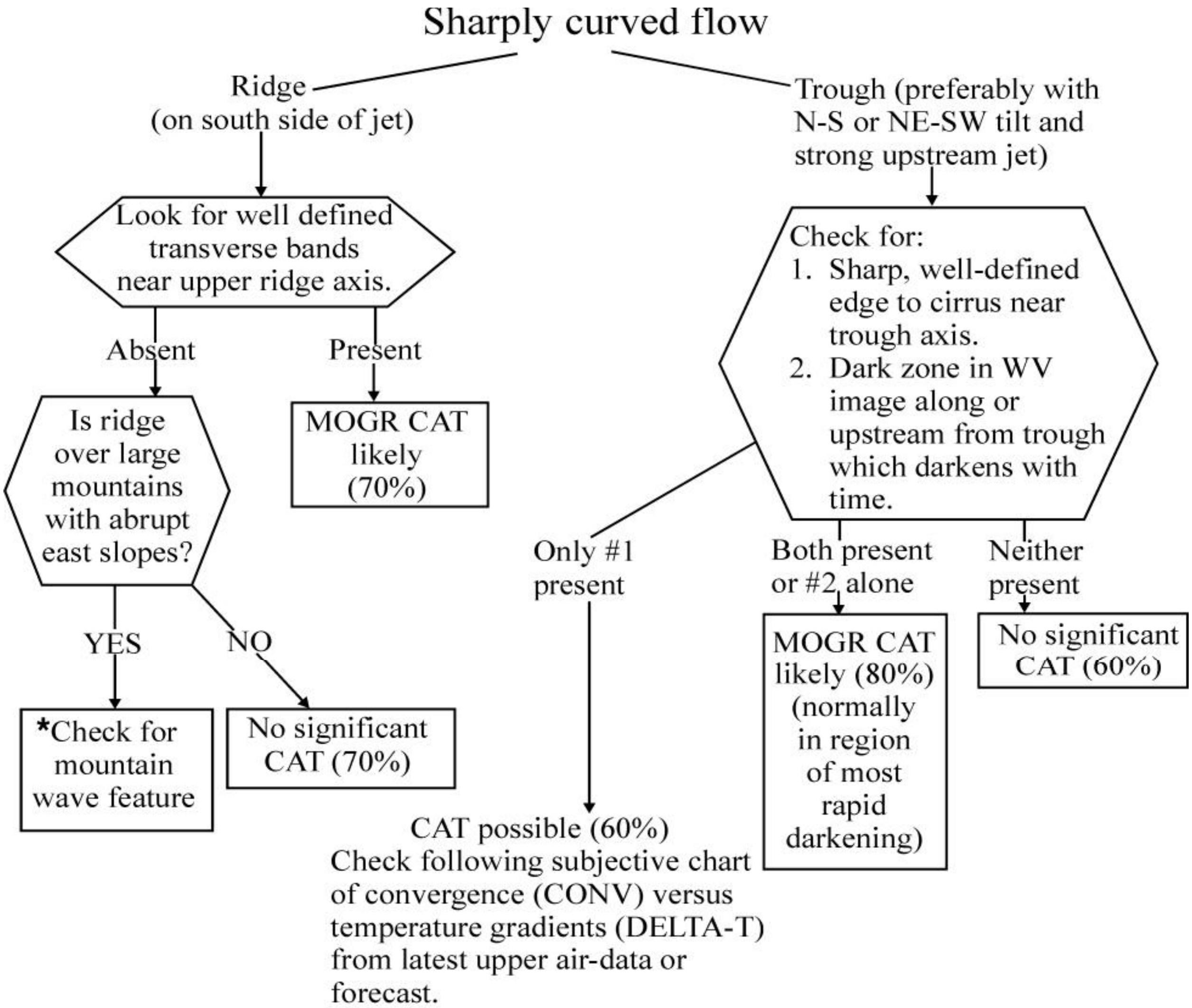


Figure 2-56. CAT Forecasting—Straight or Slightly Curved Flow.



CONV[1]	DELTA-T[2]	CAT
Strong	Large	M-S
Strong	Small	M
Moderate	Large	M
Moderate	Small	L-M
Weak	Large	L-M
Weak	Small	None

[1] **Strong CONV is defined as a deceleration of about 50 knots (25 m/sec) in 4 degrees latitude. Moderate CONV would occur with about a 35 knot deceleration.**

*** (Go to * in Figure 2-56)**

[2] **Large DELTA-T is >4°C/180 NM (3 degrees latitude).**

Figure 2-57. CAT Forecasting—Sharply Curved Flow.

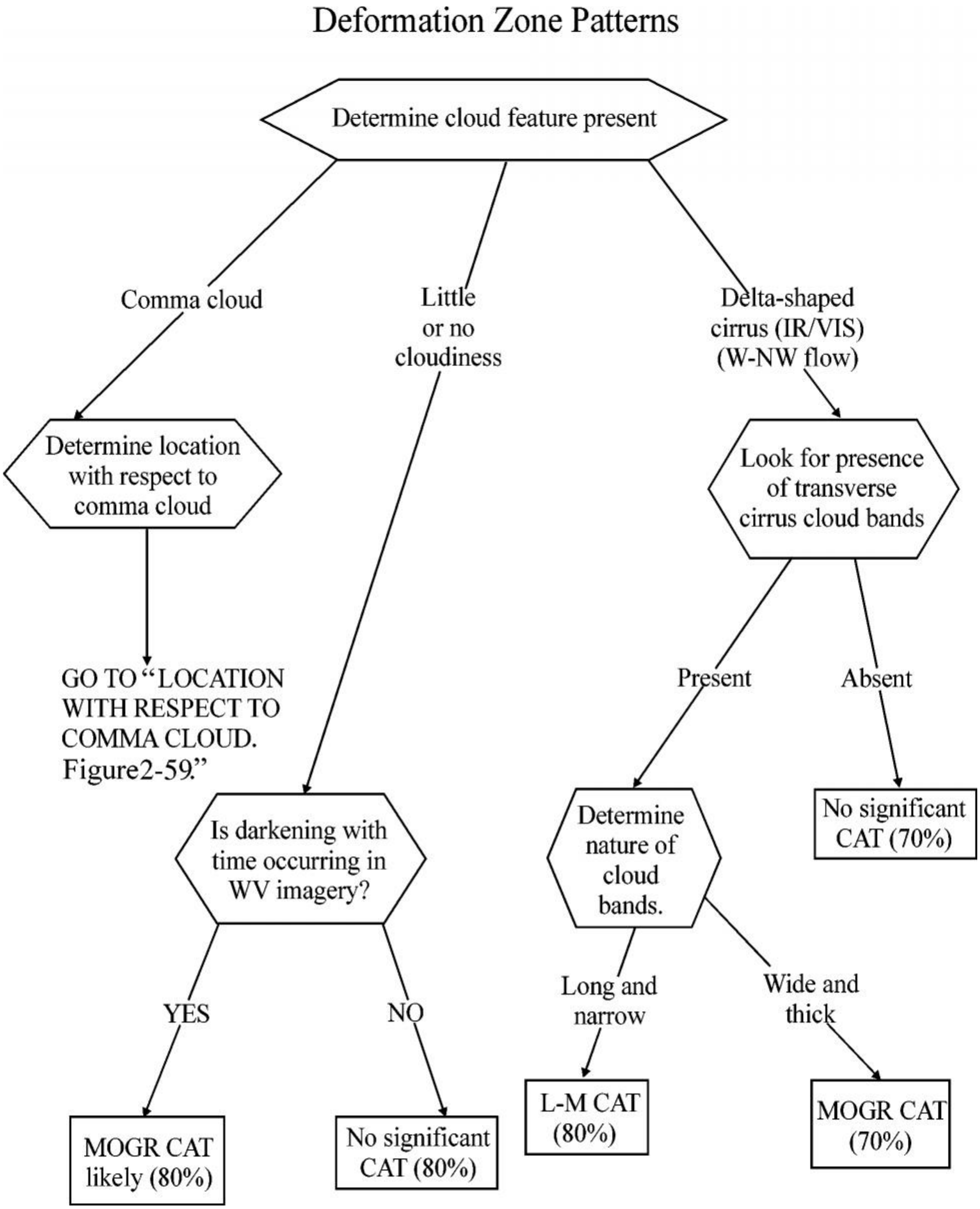


Figure 2-58. CAT Forecasting—Deformation Zone Patterns.

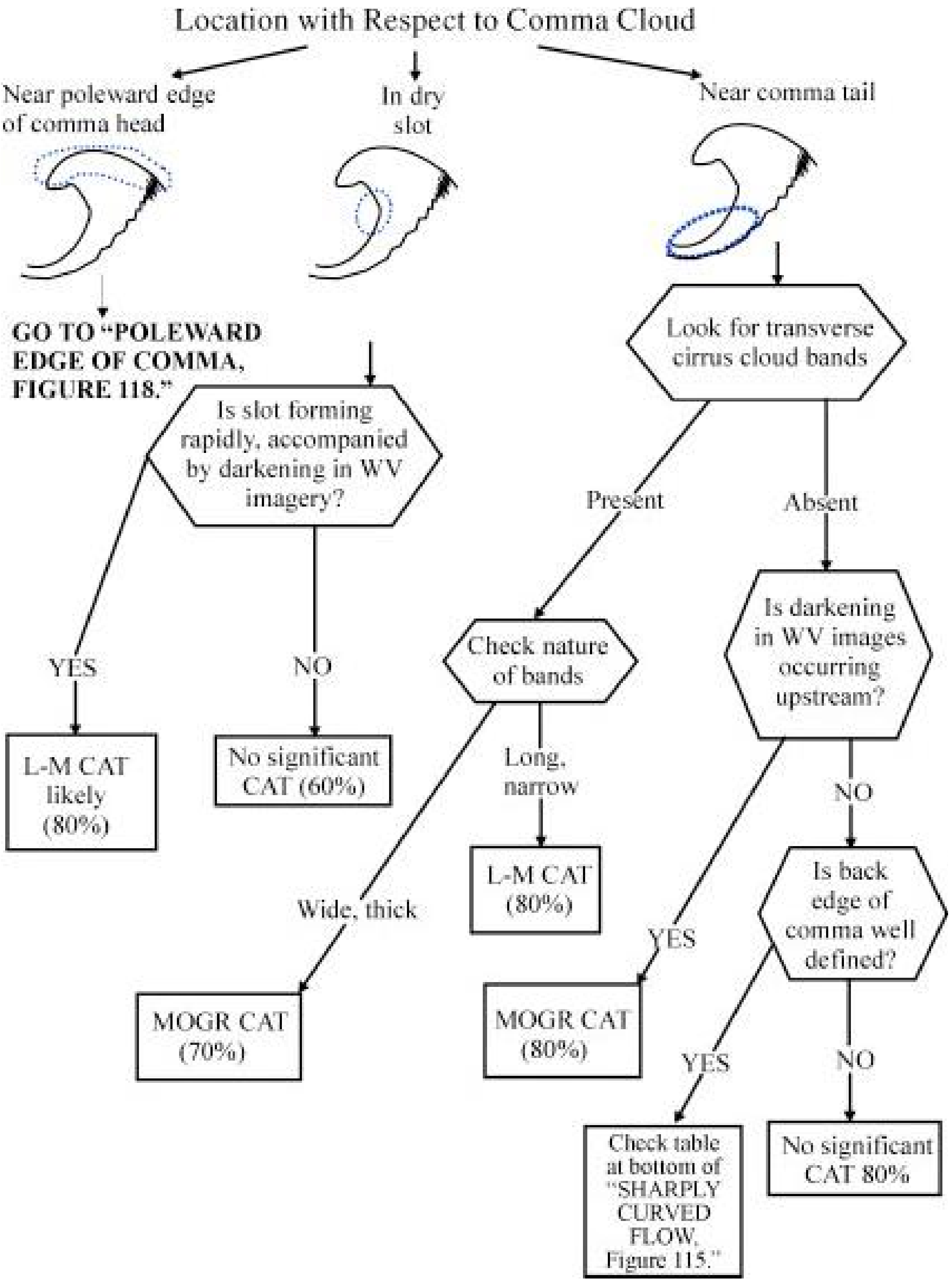


Figure 2-59. CAT Forecasting—with Respect to Comma Cloud.

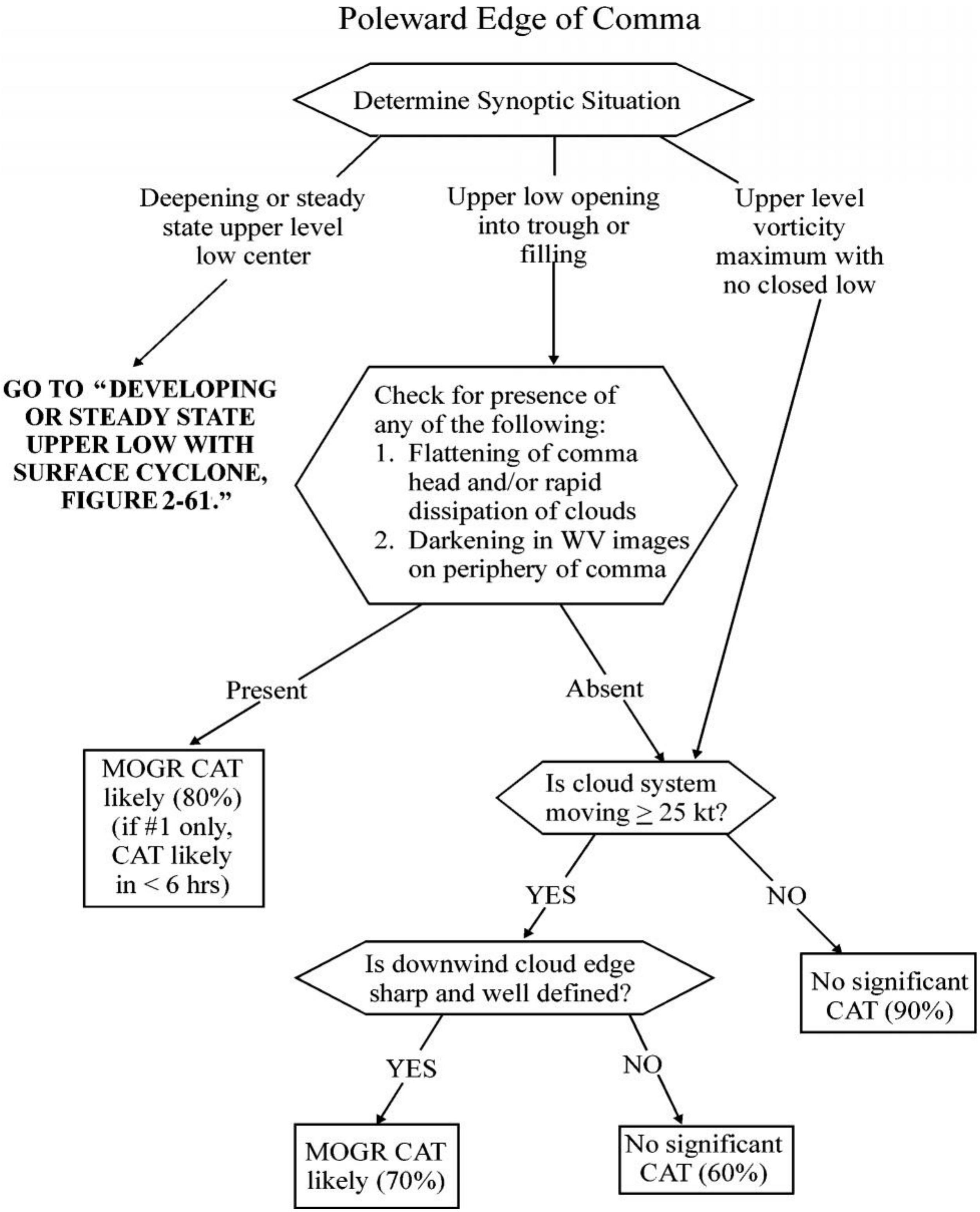
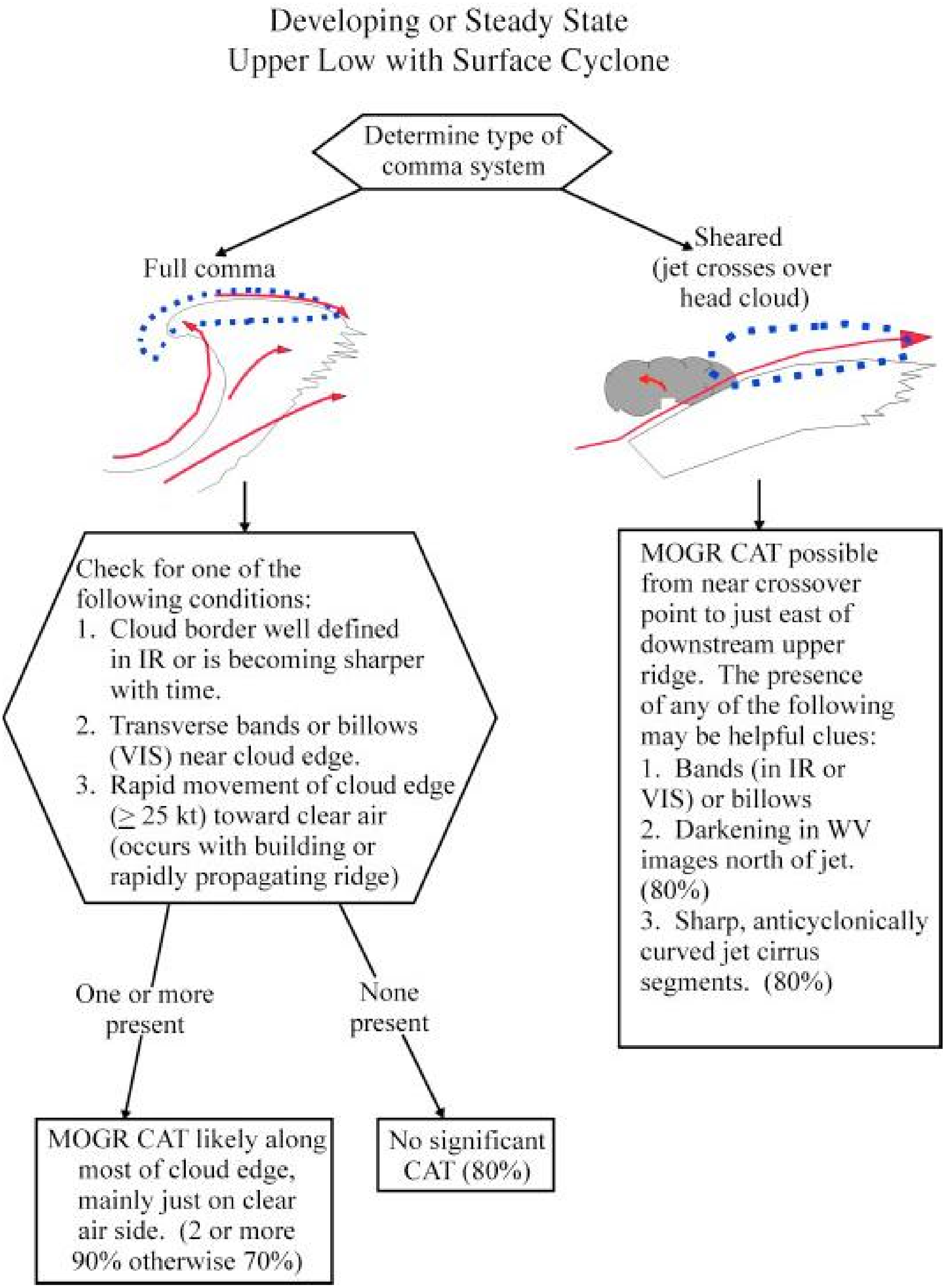


Figure 2-60. CAT Forecasting—Poleward Edge of the Comma Cloud.



Check for one of the following conditions:

1. Cloud border well defined in IR or is becoming sharper with time.
2. Transverse bands or billows (VIS) near cloud edge.
3. Rapid movement of cloud edge (≥ 25 kt) toward clear air (occurs with building or rapidly propagating ridge)

MOGR CAT likely along most of cloud edge, mainly just on clear air side. (2 or more 90% otherwise 70%)

No significant CAT (80%)

MOGR CAT possible from near crossover point to just east of downstream upper ridge. The presence of any of the following may be helpful clues:

1. Bands (in IR or VIS) or billows
2. Darkening in WV images north of jet. (80%)
3. Sharp, anticyclonically curved jet cirrus segments. (80%)

Figure 2-61. CAT Forecasting—Developing or Steady State Upper-Low with Surface Cyclones.

8. Vertical Cross Sections. Vertical cross-sections of the atmosphere (e.g., Distance-log p diagrams) can greatly increase the understanding of atmospheric structures that contribute to turbulence development. Standard computer software packages can quickly generate and analyze Skew-T data or use gridded fields to generate vertical cross-sections needed for this technique. Isoplething wind speeds (10 knot intervals) and temperature (at 5°C intervals) will reveal jet cores and strong vertical temperature gradients associated with atmospheric turbulence. Frontal boundaries and areas of wind shear that contribute to turbulence can also be found.

9. Doppler Weather Radar. This radar provides unique, near real-time capabilities to detect and display turbulence indicators such as frontal boundaries, low-level jets, gust fronts, and upper-level wind shear.

a. Spectrum Width. Though not conclusive, spectrum width values of 8-11 knots are often associated with moderate turbulence (CAT II aircraft). Values 12 knots or higher may indicate severe turbulence. Use the spectrum width product to confirm suspected turbulence areas found using other products such as base velocity

b. Velocity Azimuth Display (VAD) Wind Profile (VWP). The VWP is a graphic display of winds. This product allows you to examine the current and past vertical wind structure to help identify meteorological conditions associated with atmospheric turbulence evolving over time (e.g., inversions, wind shears, and development of jet streams). Look for areas of sharp turning in the winds with high wind speeds to identify strong local vertical wind shear.

c. Base Velocity. This product displays horizontal wind velocities. Areas of sudden speed or directional shifts are associated with wind shear and atmospheric turbulence. Intense shear regions, such as the top of the thunderstorm associated with storm top divergence, can also be located using base velocity.

d. Vertically Integrated Liquid (VIL). VIL values indicate thunderstorms that may have stronger potential for severe convective weather and associated wind shear and atmospheric turbulence.

III. AIRCRAFT ICING. Structural icing interferes with aircraft control by increasing drag and weight while decreasing lift. Engine-system icing reduces the effective power of aircraft engines. The accuracy of the icing forecast begins with an accurate prediction of precipitation, clouds, and temperature.

Aircraft icing generally occurs between the freezing level and –40°C. However, icing can occur at –42°C in the upper parts of cumulonimbus clouds. The frequency of icing decreases rapidly with decreasing temperatures, becoming rare at temperatures below –30°C. The normal atmospheric vertical temperature profile usually restricts icing to the lower 30,000 feet of the atmosphere.

Icing may occur during any season of the year. In the middle latitudes (such as in most of the United States, Northern Europe, and the Far East), icing is most frequent in winter. Frontal activity is also more frequent in winter, and the resulting cloud systems are more extensive, creating favorable icing conditions. In winter, however, polar regions are normally too cold to contain the concentration of moisture necessary for icing. Generally locations found at higher latitudes (such as Canada and Alaska) have the most severe icing conditions in spring and fall.

A. ICING FORMATION PROCESSES AND CLASSIFICATION.

1. Processes. The initial formation of ice on an aircraft requires the existence of supercooled water droplets in the atmosphere. Aircraft icing then forms by sublimation or by conduction and evaporation after the droplets strike the aircraft. Each of these processes depend on other variables being in place.

a. Supercooled Water Droplets. The supercooled temperature at which droplets start to freeze is known as the spontaneous freezing temperature. The spontaneous freezing temperature of a water droplet can vary from –10° to –42°C. This temperature also varies with droplet size and with the amount and type of foreign particles (freezing nuclei) in suspension. The spontaneous freezing temperature usually decreases with droplet