Federal Aviation Agency

ADVISORY CIRCULAR

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GENERAL

EFFECTIVE: 12/16/65

SUBJECT: TURBULENCE IN CLEAR AIR

1. PURPOSE. This circular provides information on the subject of atmospheric turbulence and its corollary, wind shear. It emphasizes important points pertaining to the common causes of turbulence, the hazards associated with it, and the conditions under which it is most likely to be encountered. Although occasional reference is made to visible signs of turbulence, such as cumuliform and lenticular clouds, this advisory deals primarily with the problem as it relates to comparatively dry or clear air. It does not deal with turbulence associated with thunderstorms or visible frontal weather except incidentally.

2. REFERENCES. Federal Aviation Agency, Flight Standards Service, and the Department of Commerce Weather Bureau publication, "Aviation Weather," (AC-00-6) of 1965; the United States Air Force publication, "Aerospace Safety," April 1965; Trans World Airlines, Inc. Meteorology Department, Technical Bulletin No. 61-3, "Wind Shear Effects on Airspeed," 1961; Time/Life Books, Life Science Library's "Weather," 1965; and Arizona State Department of Aeronautic's "Arizona Aviation," May-June 1965.

3. BACKGROUND. Certain cloud types, because of the weather conditions associated with them, serve as warning signals for the existence of turbulence to the informed pilot. Such forewarning permits the pilot to change speed or course, to land, or to take such other course of action as may be appropriate to cope with the situation. Unfortunately, turbulence may exist with little or no warning of its presence. With the growing utility of light aircraft, more and more pilots are discovering that moderate, severe, and even extreme turbulence can be encountered in a cloudless sky. In order to permit the pilot to better understand the relationship between his aircraft and its operational environment, we will discuss here some of the factors pertinent to turbulence and wind shear. Knowledge of the principal causes and effects of such conditions as well as where they are most likely to be encountered will be helpful in flight planning and in anticipating steps to take in order to avoid the hazards they present.

4. WHAT IS TURBULENCE? Turbulence is caused by the irregular motion of air. The motion of turbulent air is characterized by gusts. A gust is a sudden and comparatively momentary surge of fast-moving air. It can and does come from any and all directions of the compass, or from above or below, or at any angle. Gusts vary in intensity and frequency. Some have very sharp boundaries in space and the pilot will encounter them with no warning whatever. Others are less sharply bounded and may gradually increase in frequency or intensity.

5. WHAT CAUSES ATMOSPHERIC TURBULENCE? Turbulence can occur when: (1) temperature conditions cause atmospheric instability (thermal turbulence), (2) air moves over obstructions, such as mountains, irregular terrain, buildings, etc. (mechanical turbulence), (3) warm unstable air is lifted by a frontal surface and/or because of friction between warm and cold air masses (frontal turbulence), and (4) when, for any reason, abrupt changes in wind speed or direction take place over a short distance, either in a vertical or horizontal plane (wind shear). It is not unusual for more than one of these factors to be present at the same time.

6. WHAT IS THERMAL OR CONVECTIVE TURBULENCE? Thermal turbulence is simply atmospheric instability caused by surface heating. It is the main cause of the familiar bumpiness at low altitudes in warm weather. Cumulus type clouds and "dust devils" are visible evidence of the existence of such convective currents. Frequently, convective activity will be present when a cold mass of air moves over a warm surface or when cooling aloft produces instability. This type of turbulence may occur at anytime of the year and may be marked by alto-cumulus clouds. Often, however, a pilot cannot anticipate its presence without the help of a trained meteorologist.

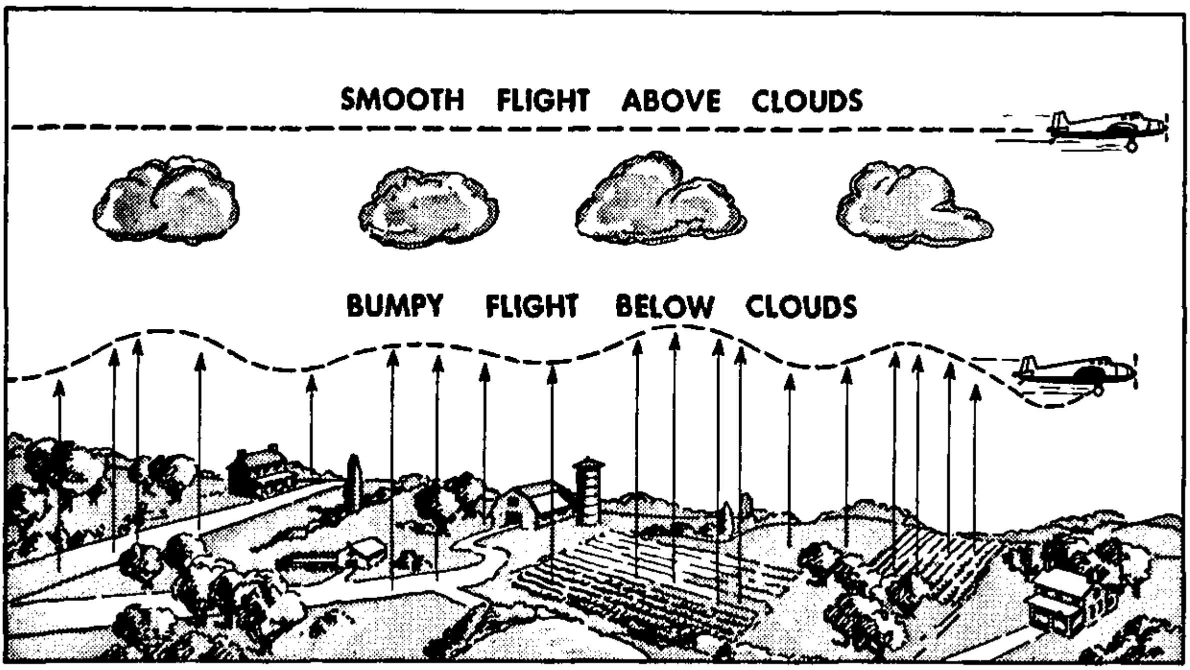

FIG. 1 CONVECTIVE TURBULENCE

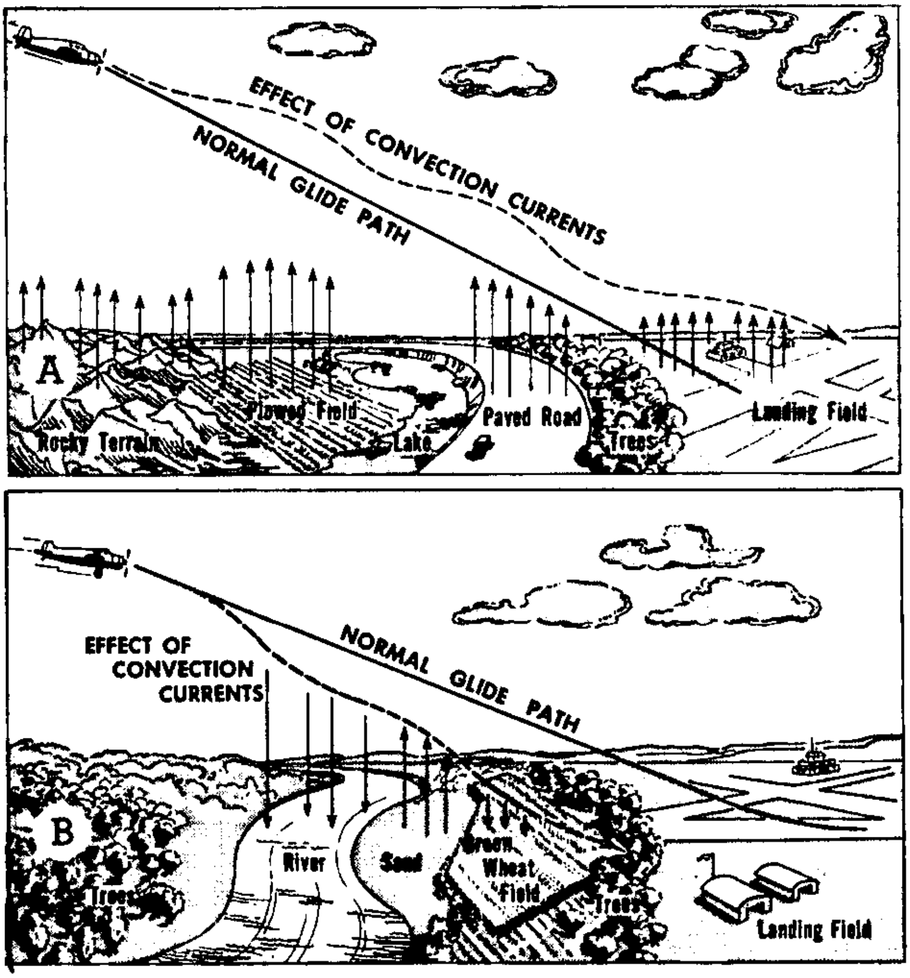

FIG. 2 THE EFFECTS OF CONVECTIVE TURBULENCE ON FINAL APPROACH. (A) OVERSHOOTING (B) UNDERSHOOTING

7. <u>DOES THERMAL TURBULENCE CONSTITUTE A HAZARD FOR LIGHT AIRCRAFT?</u> In clear air conditions, it normally does not. Turbulence of this type is created by the convective currents associated with uneven heating of the earth's surface. It can be uncomfortable and create problems (note the variations in glide slope and point of touchdown in Figure 2) but it is seldom hazardous <u>in</u> <u>itself</u>. The hazards associated with a highly turbulent upsetting of the atmosphere due to thermal activity also requires considerable moisture and thus gives visible warning of its existence in the form of towering cumulus or cumulonimbus clouds. This, of course, can be a truly hazardous condition.

8. WHAT IS MECHANICAL TURBULENCE? The turbulence which occurs when air flows over an irregular surface is produced by a mechanical process, and may exist in conjunction with or independently of thermal activity. At or near the earth's surface where trees, buildings, hills, mountains, valleys, etc., interfere, the normal horizontal flow of air is scrambled into a vastly complicated snarl of eddies and air currents, roughly analogous to the flow of water in a swift mountain stream.

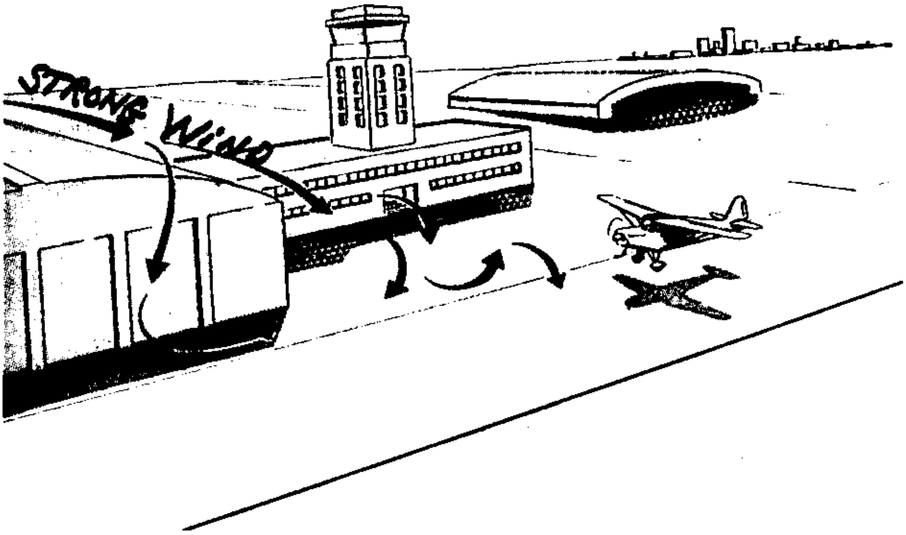

FIG. 3 TURBULENCE CAUSED BY OBSTRUCTIONS

9. CAN MECHANICAL TURBULENCE BE A HAZARD TO LIGHT AIRCRAFT? Indeed it can! A study of recent accident reports reveals that in a one-year period over 500 accidents were attributed to unfavorable wind conditions for taxiing, takeoff, or landing. Strong or gusty wind conditions may trap an unwary pilot in dangerous situations. Low wind speeds create stationary eddies or rotating pockets of air of mild intensity which remain close to the windward and leeward side of obstructions. But strong winds or sudden increases in wind speed will not only increase the intensity of these irregular eddies, but will carry them some distance "downstream" from the obstruction. Thus, the uninformed or inexperienced pilot may, as they say, be caught "fat, dumb, and happy," if a landing area or runway is located in the proximity of such obstructions (see Figure 3). When the wind blows over a rough surface at speeds in excess of 20 knots, the eddy currents and turbulence are likely to have considerable effect on the flying characteristics of an airplane taking off or landing. Since such turbulence is invisible, it can be a very real hazard if care is not exercised.

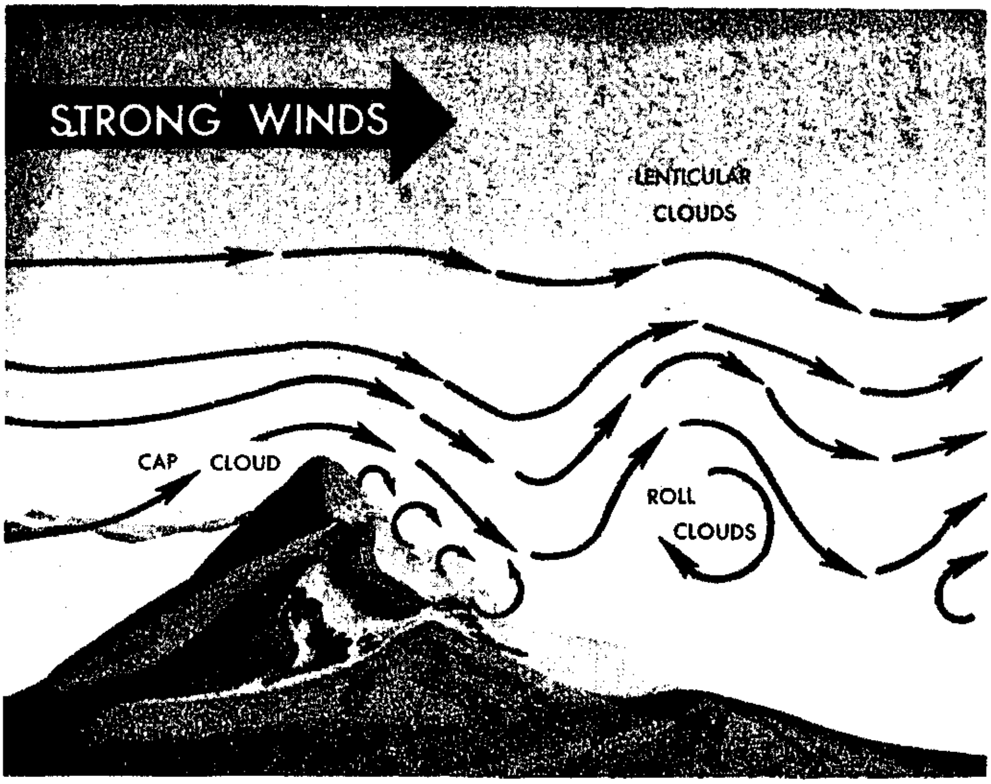

FIG. 4 THE MOUNTAIN WAVE

A similar but potentially much more severe and dangerous type of mechanical turbulence is probable over mountainous terrain when (1) wind speeds approach or exceed 35 knots, (2) wind direction is approximately 90° to the mountain range, (3) there are abrupt changes in terrain elevations, and (4) the air is stable. If the amplitude of the atmospheric waves varies considerably with height, an especially vicious form of such turbulence is exemplified by the "mountain wave" phenomenon found in mountainous areas such as the Rockies or Alleghenies (see Figure 4). The crest of these waves may be marked by elongated or lens-shaped clouds (standing lenticular) which seem to hang stationary over a mountain ridge or at a fixed point some distance downwind from the range. These waves may extend as much as 150 miles "downstream." The roll cloud is generally about the height of the mountain ridge and may be as much as 10 miles "downstream." The standing lenticular clouds may exist in several layers to above 20,000 feet.

If the air is unstable and conditions (1), (2), and (3), on page 6 are present, severity of turbulence near and immediately to the lee of the mountains may be intensified. This unstable condition may be indicated by convective clouds to the windward side and over the mountains. However, the most severe turbulence may be in the clear air to the lee of the mountains. The steady flow of air is broken up by the convective currents, and the mountain wave, depicted in Figure 4, will not develop downstream.

Clouds as indicated in Figure 4, of course, are visible signs of much turbulence and are illustrated and discussed here to permit location of areas of greatest turbulence. These are the areas where turbulence will get you if you don't watch out! Remember, however, that the same turbulence can exist without clouds. Turbulence is often like a ghost; only at times can you see signs of its presence.

This hazard can be magnified by altimeter errors occurring in the areas of turbulence. Actual altitude may be as much as 1,000 feet lower than indicated altitude!

This type of turbulence can cause structural damage to the aircraft or even loss of control. The existence of winds and gusts strong enough to lift a P-38 15,000 feet with both propellers feathered, or to tear the vertical stabilizer and rudder from a B-52 have been recorded. It is apparent, therefore, that certain types of mechanical turbulence must be classified as one of the most hazardous conditions of the atmosphere.

10. WHAT IS WIND SHEAR? When wind changes direction and/or speed abruptly in a short distance, it results in a tearing or shearing effect, creating a turbulent area. The intensity of turbulence increases as the amount of wind shear increases.

11. WHERE IS WIND SHEAR FOUND? Many pilots associate wind shear and related turbulence only with high-level jet streams. While it is true, of course, that jet streams supply dramatic evidence of the turbulence caused by wind shear, it is only one example of where it may be found. By definition, wind shear will be present any time there is marked change in wind speed and direction over a short distance. Therefore, it is not limited to the vicinity of a jet stream. It can be present at any level with or without visual clues of its existence, and can exist in either horizontal or vertical directions--sometimes in both directions simultaneously.

12. WHAT CONDITIONS ARE CAPABLE OF PRODUCING WIND SHEAR IN CLEAR AIR? In addition to those factors previously discussed which produce turbulence and therefore in a broad sense relate to wind shear of one intensity or another, the following conditions are particularly associated with wind shear. (As previously noted, its existence is not necessarily marked by visible clues.)

a. A narrow zone along a "dry" cold front.
b. Conditions of pronounced gustiness.
c. A steep temperature inversion near the surface.
d. Jet streams.
e. A sharp decrease in wind speed with decrease of altitude near the ground (vertical wind gradient).
f. Aircraft wake turbulence (see FAA Advisory Circular 90-23A, "Wake Turbulence").

13. UNDER WHAT CONDITIONS ARE THE VARIOUS INTENSITIES OF TURBULENCE MOST LIKELY TO BE ENCOUNTERED? The following rough guide should be helpful in flight planning and operations:

a. LIGHT TURBULENCE.

(1) In hilly and mountainous areas even with light winds.
(2) In and near small cumulus clouds.
(3) In clear-air convective currents over heated surfaces.
(4) With weak wind shears in the vicinity of:
  (a) troughs aloft.
  (b) lows aloft.
  (c) jet streams.
  (d) the tropopause (the boundary between the troposphere and the stratosphere).
(5) Within the layer from the surface to around 5,000 feet
  (a) when surface wind speeds are 15 to 25 knots.
  (b) where the air is colder than the underlying surfaces.

b. MODERATE TURBULENCE.

(1) In mountainous areas with a wind component of 25 to 50 knots approximately perpendicular to and near the level of the ridge:
  (a) at all levels from the surface to 5,000 feet above the tropopause with preference for altitudes:
    1 within 5,000 feet of the ridge level.
    2 at the base of relatively stable layers below the base of the tropopause.
    3 within the tropopause layer.
  (b) Extending outward on the lee of the ridge for 150 to 300 miles.

(2) In and near thunderstorms in the dissipating stage.
(3) In and near other towering cumuliform clouds.
(4) In the lower 5,000 feet of the troposphere:
    (a) when surface winds exceed 25 knots.
    (b) where heating of the underlying surface is unusually strong.
    (c) where there is an invasion of very cold air.
(5) In fronts aloft.
(6) Where:
    (a) vertical wind shears exceed 6 knots per 1,000 feet, and/or
    (b) horizontal wind shears exceed 18 knots per 150 miles.

c. SEVERE TURBULENCE.

(1) In mountainous areas with a wind component exceeding 50 knots when approximately perpendicular to and near the level of the ridge:
    (a) In layers generally about 5,000 feet thick.
        1 at and below the ridge level in rotor clouds or rotor action.
        2 at the tropopause.
        3 sometimes at the base of other stable layers below the tropopause.
    (b) Extending outward on the lee of the ridge for 50 to 150 miles.
(2) In and near growing and mature thunderstorms.
(3) Occasionally in other towering cumuliform clouds.
(4) 50 to 100 miles on the cold side of the center of the jet stream, in troughs aloft, and in lows aloft where:
    (a) vertical wind shears exceed 6 knots for 1,000 feet, and
    (b) horizontal wind shears exceed 40 knots per 150 miles.

d. EXTREME TURBULENCE.

(1) In mountain wave situations, in and below the level of well-developed rotor clouds. Sometimes it extends to the ground.
(2) In growing severe thunderstorms (most frequently in organized squall lines) indicated by:
    (a) large hailstones (3/4 inch or more in diameter),
    (b) strong radar echo and echo gradients, or
    (c) almost continuous lightning.

14. HOW ARE TURBULENCE INTENSITIES CLASSIFIED? Though much time and effort has been spent in attempts to develop a common language and consistent measurement criteria, objective classification of turbulence intensities remains a difficult problem. Usually, neither pilots nor weathermen have any routinely available method of directly measuring turbulence intensity. The most exact method devised so far uses accelerometers to measure gust velocities. Though such derived gust velocities may have little meaning for the typical VFR pilot, they are included in the table below to show how they relate to the descriptive criteria.

The descriptive terms in the table, however, are meaningful to most everyone. The pilot must appreciate that the turbulence intensity described is based upon its effect on transport aircraft. This is his starting point. He must then relate this to his operational equipment and personal experience and limitations. By so doing, the individual pilot has based his evaluation on the same starting point used by weathermen in forecasting intensity and in evaluating pilot reports on turbulence. In connection with the latter, emphasis is placed upon the fact that at the present time the forecaster is more dependent upon pilot reports in predicting turbulence than in predicting almost any other atmospheric condition.

Adjective Class	Transport Aircraft Operational Criteria	Derived Gust Velocity Criteria
Light	A turbulent condition during which occupants may be required to use seat belts, but objects in the aircraft remain at rest.	5 to 20 feet per second.
Moderate	A turbulent condition in which occupants require seat belts and occasionally are thrown against the belt. Unsecured objects in the aircraft move about.	20 to 35 feet per second.
Severe	A turbulent condition in which the aircraft momentarily may be out of control. Occupants are thrown violently against the belt and back into the seat. Objects not secured in the aircraft are tossed about.	35 to 50 feet per second.
Extreme	A rarely encountered turbulent condition in which the aircraft is violently tossed about, and is practically impossible to control. May cause structural damage.	More than 50 feet per second.

FIG. 5 TURBULENCE CRITERIA TABLE

15. COGENT COMMENTS. The observations and comments which follow relative to the problem of mechanical turbulence were made by various airline and military pilots and are based on personal experience under conditions of little visible evidence of turbulence.

"Although we got slammed around quite a bit in the thunderstorms, the turbulence was never as rough as clear air turbulence."

"We searched, found, and measured turbulence powerful enough to destroy aircraft!!"

"No one anticipated . . . gusts that would yield a rap of a 7 G differential."

"Positive control of the body was sometimes extremely marginal . . . . We had to position the throttle, brace ourselves as well as possible, hang onto the stick, and ride it out like a bucking bronc."

"We found it difficult and sometimes impossible to talk coherently when riding out the severe turbulence."

"Personally, I most fear and respect turbulence over all other weather phenomena, and I think this is true of many pilots."

16. SUMMARY.

a. Wind shear created by convective or mechanical turbulence, contrary to popular opinion, is a common occurrence in flight operations.

b. Generally, wind shear due to convective turbulence or strong wind gradient (change of wind velocity with altitude) is primarily a nuisance.

c. Unusually strong convective turbulence or strong wind gradients, alone or in combination with strong mechanical turbulence, can be very real hazards on takeoffs and landings.

d. Mechanical turbulence under favorable conditions of terrain and wind speed can create conditions which exceed not only the ability of the pilot to cope with the situation, but the structural design load limits of the aircraft.

e. Light to extreme thermal and/or mechanical turbulence can exist with little or no visible evidence of its presence.

17. SUGGESTED PILOT ACTIONS.

a. Carefully consider the different courses of action possible when operating in the vicinity of large, multi-engine aircraft. (See Advisory Circular 90-23A, "Wake Turbulence").

b. Carefully evaluate wind direction and speed in relation to any obstructions in the immediate proximity of the takeoff or landing area.

c. Either avoid or exercise great care in taxiing, takeoffs, and landing where the following conditions leave little margin for error in terms of pilot ability or equipment limitations:

(1) strong wind gradients.
(2) high winds and crosswinds.
(3) strong gusts.
(4) pronounced wind shifts associated with active "dry" fronts.

d. Plan route and altitude of flight carefully over rough mountainous terrain when winds aloft at 35 knots or more are approximately 90° to the ridges or mountain range.

e. If not familiar with the area, consult with local pilots, Flight Service Station and Weather Bureau personnel on recommended procedures and current conditions.

f. Allow for the funneling or venturi effect which increases wind speed through passes and valleys.

g. Expect mountain waves in mountainous terrain where winds exceed 40 knots and direction is approximately 90° to the mountains.

h. Fly at an altitude 50% greater than height of range where the possibility of mountain waves exist.

i. Observe the maximum design maneuvering speed of your aircraft, or if available, observe the manufacturer's recommended turbulent air penetration speeds relative to gust velocity and aircraft configuration criteria.

j. Consider the performance capabilities of your equipment and your personal competence and experience.

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