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WIND SHEAR

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FOREWORD

During the period 1964-1983*, low-level wind shear was cited in at least 28 large transport aircraft accidents/incidents which together resulted in over 500 fatalities and 200 injuries. The increased awareness within the aviation community of the hazardous and insidious nature of low-level wind shear is reflected in the fact that it is considered by the ICAO Council to be one of the major technical problems facing aviation.

Lack of adequate operational remote-sensing equipment, the complexity of the subject, the wide range of scale of wind shear and its inherent capriciousness have all conspired to hinder a complete solution of the problem which, in turn, has limited so far the development of the necessary international Standards and Recommended Practices for the observing, reporting and forecasting of wind shear.

In 1975 there were five jet transport aircraft accidents/incidents in which wind shear was cited, one of which resulted in major loss of life[1]. This latter accident, which occurred at John F. Kennedy International Airport, New York on 24 June 1975, and an accident at Denver some six weeks later on 7 August 1975, which fortunately resulted in no loss of life and happened to occur in an area where detailed monitoring of the wind field was possible, will likely be viewed in the future as marking a turning point in the history of wind shear. The detailed and exhaustive analysis of the role played by wind shear in these particular accidents served to remove any lingering doubt which may have still remained regarding the reality of the danger of wind shear. The accelerated research effort which followed, culminating in the massive Joint Airport Weather Studies (JAWS) project at Stapleton Airport, Denver, Colorado in 1982, considerably improved and continues to improve our understanding of the problem, particularly regarding wind shear associated with thunderstorms.

The ICAO Eighth Air Navigation Conference (Montreal, 1974)[2] recommended the preparation and publication of guidance material to assist all concerned to make the best possible use of such information on wind shear as was available. In order to assist in the preparation of this guidance material, the culmination of which is the publication of this circular, the Low-level Wind Shear and Turbulence (WIST) Study Group was formed. With the assistance of the group a statement of operational requirements for observing and reporting wind shear and turbulence was developed. This statement, together with an initial list of recommended terms and their explanations and a progress report on wind shear largely based upon circulars issued by some States, was sent as guidance to States in State letter AN 10/4.6-79/142 dated 31 August 1979.

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* 1983 is the latest complete year, at the time this circular was published, for which reports are available in the ICAO Accident/Incident Reporting Data Bank.

Following the increased research effort referred to above, it proved possible to develop Amendment 64 to Annex 3 - Meteorological Service for International Air Navigation which became applicable in November 1983 and included, among other things, new provisions and a revision of existing provisions for the observing and reporting of low level wind shear. At the same time, the statement of operational requirements was modified slightly, the revised version of which is given in Appendix A to this circular.

In 1982, the United States Subcommittees on Investigations and Oversight and, on Transportation, Aviation and Materials of the House of Representatives' Committee on Science and Technology held joint hearings on weather problems affecting aviation, including wind shear. Following these hearings, the Federal Aviation Administration (FAA) contracted with the National Academy of Sciences "to study the state of knowledge, alternative approaches and the consequences of wind shear alert and severe weather conditions relating to take-off and landing clearances for commercial and general aviation aircraft". In order to accomplish this task, an ad hoc Committee for the Study of Low-Altitude* Wind Shear and its Hazard to Aviation was formed. The Committee produced an extremely comprehensive report and a series of conclusions and recommendations.[1] This report has been of considerable assistance in the preparation of this circular, and the set of recommendations made by the Committee are reproduced in Appendix C.

Since 1967 the FAA has had a detailed programme directed towards reducing the hazard to aviation of low-level wind shear. Under this over-all programme, action has been or is being taken on the recommendations made by the Committee referred to in the previous paragraph and also on recommendations made from time to time by the National Transportation Safety Board following accident investigations. In this regard, the FAA is developing an "Integrated Wind Shear Programme" which involves close co-operation with a number of government agencies (e.g. the National Aeronautical and Space Administration) the aerospace industry in its widest sense, pilot associations and ICAO. The objective of the programme is to further develop and refine over the next five to ten years the education/training and operational procedures, surface-based and airborne wind shear detection technology and on-board flight guidance systems. At the same time, further elucidation of the wind shear hazard will be provided by continued scientific research. The individual sub-programmes are discussed in more detail in the relevant chapters of this circular.

Many aspects of the wind shear subject are in a highly fluid state with comprehensive research continuing and, for the most part, accelerating along a broad front. This circular encompasses most relevant aspects of the subject and, as well, covers all the main trends. Due to the dynamic nature of the subject, however, it only presents a "snapshot", albeit a fairly detailed one, indicating how things stand in 1986. Readers should be aware, therefore, that this is not expected to be the last word on wind shear; rather, it is somewhat in the nature of a situation report. It is intended to promote a wider understanding of the subject and to offer pointers, some in the form of extensive references, to assist those who wish to delve more deeply into the subject.

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* In this circular the qualifying term "low-level" has been retained due to the fact that "altitude" is a defined ICAO term meaning "the vertical distance of a level, a point or an object considered as a point measured from mean sea level". The critical issue with respect to wind shear is the effect on aircraft performance when in relatively close proximity to the ground. It is not felt that "low-level" in this context could be misconstrued as meaning low-level "in intensity".

Finally, it should be emphasized that the provisions concerning wind shear now contained in ICAO regulatory documents are only the minimum which it was possible to develop given the current state of knowledge and the continued lack of operational remote-sensing equipment. The bulk of the information available on wind shear, particularly the operational aspects, is still not sufficiently mature to be translated into regulatory provisions. The purpose of this circular is to gather together such information and present it in a consolidated form, in order to assist all those connected with the operational side of aviation to gain a better understanding of the danger that wind shear poses to aircraft.

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Chapter 1

INTRODUCTION

1.1 Low-level wind shear, in the broadest sense, encompasses a family of air motions in the lower levels of the atmosphere ranging from small-scale eddies and gustiness which may affect aircraft as turbulence, to the large-scale flow of one air mass layer past an adjacent layer. Included among the wide variety of phenomena which produce such air motions are thunderstorms, land/sea breezes, low-level jet streams, mountain waves and frontal systems. In order to understand, in this particular context, the common denominator linking such varied phenomena, it is necessary to explain the meaning of the term "wind shear" itself. The most generalized explanation of wind shear is: "a change in wind speed and/or direction in space, including updrafts and downdrafts". From this explanation it follows that any atmospheric phenomenon, or indeed any physical obstacle to the prevailing windflow, which produces a change in wind speed and/or direction is, in effect, causing wind shear.

1.2 Wind shear is always present in the atmosphere and its presence is often visible to an observer. Examples of this would be cloud layers at different levels moving in different directions; smoke plumes sheared and moving in different directions at different heights; rotating suspended debris and/or water droplets in the relatively innocuous dust-devils and in the extremely dangerous water spouts and tornadoes; the "wall-like" leading edge of dust/sand storms; and trees bending in all directions in response to sudden gusts from a squall line. All of these visual effects testify to the universal presence of wind shear and wind shear-causing phenomena in the atmosphere.

1.3 The significance of wind shear to aviation lies in its effect on aircraft performance and hence its potentially adverse effect on flight safety. Although wind shear may be present at all levels of the atmosphere, its occurrence in the lowest 500 m (1 600 ft) is of particular importance to aircraft landing and taking off. During the climb-out and approach phases of flight, aircraft airspeed and height are near critical values, thus rendering the aircraft especially susceptible to the adverse effects of wind shear. As will become clear in subsequent chapters of this circular, the response of aircraft to wind shear is extremely complex and depends on many factors including the type of aircraft, the phase of flight, the scale on which the wind shear operates relative to the size of the aircraft and the intensity and duration of the wind shear encountered.

1.4 Having drawn attention to the prevalence of wind shear in the atmosphere and its potential danger to aircraft, in order to keep things in perspective it would be as well to remember that, considering the high number of aircraft landings and take-offs which take place around the world, only a very small number of aircraft ever encounter difficulties which result in accidents and, of these accidents, in only a fraction is wind shear a factor. Nevertheless, the mere fact that wind shear has contributed at all to aircraft accidents in the past is sufficient reason for everyone engaged in aviation operations to gain a sound understanding of the dramatic effect that wind shear can have on aircraft performance, particularly during the landing and take-off phases.

Chapter 2

CHARACTERISTICS OF LOW-LEVEL WIND SHEAR

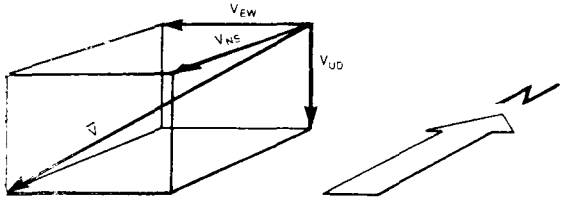
2.1 WIND IN THE ATMOSPHERE

2.1.1 The simplest definition of "wind" is: "air motion relative to the earth's surface". The wind so defined can, and of course does, blow freely in three-dimensional space and, having both speed and direction, must be considered as a vector which can be resolved into three orthogonal components. Relative to the earth, this means components in the north/south, east/west and upwards/downwards directions. Relative to an aircraft's flight path it means headwind/tailwind (longitudinal) components, left/right crosswind (lateral) components and updraft/downdraft (vertical) components (see Figure 2-1). Except in special cases, the vertical component of the wind in the atmosphere is usually small compared with one or both of the horizontal components. This is especially true near the ground where the wind is constrained to move in the horizontal plane. As the horizontal components generally predominate, when speaking about wind we tend to assume a horizontal wind blowing parallel to the earth's surface, thus neglecting the vertical component. The special cases referred to earlier where the vertical component of the wind predominates are produced by, among other things, convective cloud (thunderstorms particularly), mountain waves and thermals; being of particular relevance to wind shear, the first two phenomena are discussed in detail in Chapter 3.

2.1.2 Because the aircraft, by suitable choice of runway, generally lands or takes off into wind, the head/tailwind or longitudinal component automatically tends to predominate over the crosswind or lateral component. This explains why, in the wind shear discussions which follow, emphasis is normally placed on changes in the head/tailwind (longitudinal) component, except in those special cases already mentioned where the vertical component (updraft/downdraft) predominates.

2.2 WIND CHANGING IN SPACE -- WIND SHEAR

2.2.1 In the explanation of wind shear given in the introduction, the changes referred to concern changes in the mean (or prevailing) wind from one reference point in space to another. Short-term fluctuations of the wind about a mean direction and/or speed are normally referred to as "variations" from the prevailing wind. Such variations of the wind, individually at least, are temporary, somewhat in the nature of eddies; whilst the eddies clearly involve wind shear, as they are on a much smaller



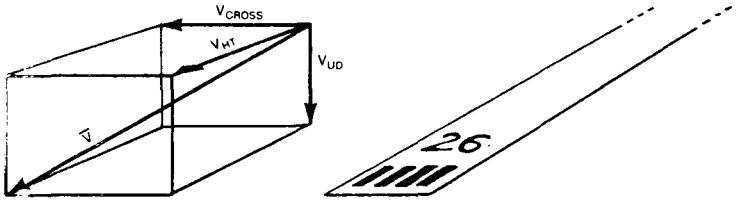
a) Components in terrestrial reference frame

V_{EW} = east/west component

V_{NS} = north/south component

V_{UD} = updraft/downdraft (vertical) component

$\bar{V}$ = actual three-dimensional wind vector



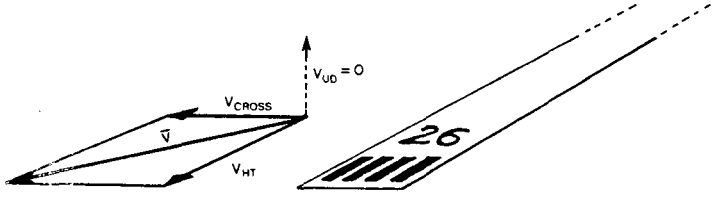
b) Components in relation to orientation of runway

V_{CROSS} = crosswind (lateral) component

V_{HT} = head/tailwind (longitudinal) component

V_{UD} = updraft/donwndraft (vertical) component

$\bar{V}$ = actual three-dimensional wind vector



c) Components in relation to orientation of runway when vertical component neglected or equal to zero

V_{CROSS} = crosswind (lateral) component

V_{HT} = head/tailwind (longitudinal) component

V_{UD} = updraft/downdraft (vertical) component

$\bar{V}$ = two-dimensional wind vector

Figure 2-1. Components of the wind in various coordinate systems

scale than an aircraft they tend to affect the aircraft as bumpiness or turbulence. The scale on which the wind shear operates, in relation to the over-all size of the aircraft concerned, is thus of fundamental importance.

2.2.2 From the foregoing it may also be seen that, whilst all turbulence involves wind shear, albeit on a very small scale, wind shear, especially large-scale, does not necessarily involve turbulence. This point has been mentioned because some people still have the erroneous impression that wind shear is simply some form of clear-air turbulence. It is important to understand at the outset that wind shear on a scale which affects aircraft performance does not necessarily imply turbulence[1].

2.3 CALCULATION OF WIND SHEAR

2.3.1 Wind shear, being the change of wind vector from one point in space to another, is given by the vector difference between the winds at the two points, which itself is a vector (having both speed and direction). The intensity of the shear is calculated by dividing the magnitude of the vector difference between the two points by the distance between them, using consistent units. The calculation of the shear may be done graphically using the triangle of velocities or by subtraction of the components of the two wind vectors either manually or by computer or by trigonometry. By way of example consider a wind $\mathbf{V}_1$* of 240° 30 kt at point A 1 000 ft above ground level (AGL) changing to a wind $\mathbf{V}_2$ of 220° 10 kt at point B 500 ft AGL. In Figure 2-2 I, the wind shear vector is calculated graphically by subtraction of the two wind vectors $(\mathbf{V}_2 - \mathbf{V}_1)$ or $(\mathbf{V}_1 - \mathbf{V}_2)$; its relationship to the "resultant wind" vector which is obtained by the addition of the two wind vectors $(\mathbf{V}_1 + \mathbf{V}_2)$ is also shown. The resultant can act in only one direction because $(\mathbf{V}_1 + \mathbf{V}_2) = (\mathbf{V}_2 + \mathbf{V}_1)$, but the vector difference can act in one of two reciprocal directions (with the same speed) depending upon which of the winds is being subtracted (in other words, which way the observer is moving, from point A to point B or from point B to point A). This is because $(\mathbf{V}_2 - \mathbf{V}_1) \neq (\mathbf{V}_1 - \mathbf{V}_2)$ except in the trivial case $\mathbf{V}_1 = \mathbf{V}_2$, i.e. where there is no shear.

2.3.2 The action of the vector difference or the wind shear vector in two reciprocal directions, depending on the sense of the wind change is of considerable importance with respect to its effect on aircraft. This matter is considered in detail in Chapter 4, but even at this stage it is easy to see that, in the foregoing example, the wind shear vector for landing going from point A to point B would be $(\mathbf{V}_2 - \mathbf{V}_1)$, whereas for take-off going from B to A, it would be $(\mathbf{V}_1 - \mathbf{V}_2)$, i.e. both the same speed but each the reciprocal direction of the other. In Figure 2-2 II a) and b) the vector difference is calculated using components and by standard formulae respectively. In practice, tables are normally pre-calculated giving wind shear magnitude by insertion of the two wind speeds and the angle between them (see Figure 2-2 II b)).

2.3.3 The previous example illustrates wind shear in the vertical as would be measured by an anemometer at 1 000 ft and one at 500 ft above ground level. The same calculation could be made for wind shear in the horizontal, i.e. if the same two anemometers were spaced (500 ft) apart at ground level. Given the same wind values (240/30 and 220/10), exactly the same wind shear vector would result and its direction would again depend on whether the observer was going from A to B or B to A, as in the previous example.

---

* Vector indicated by bold printed V.

2.3.4 It would be difficult to over-emphasize the fact that wind shear is a vector and hence the speed and the direction of the two winds concerned must be taken into account. Wind shear cannot be calculated by simple scalar subtraction of the wind speeds, except in the specific case where the directions of the two winds concerned are exactly the same or are exact reciprocals. Finally, it should be mentioned that the scalar shear (i.e. direct subtraction of wind speeds taking no account of their directions) is always less than or equal to the vector shear and thus for most cases underestimates the actual shear magnitude.

2.4 UNITS OF MEASUREMENT FOR WIND SHEAR

2.4.1 In the example given in Figure 2-2 the wind shear between points A and B is 070°/21 kt and the shear between points B and A is 250°/21 kt. The intensity of the shear in both cases is 21/5 = 4.2 kt per 100 ft. It is common practice to give the wind shear intensity in kilometres per hour per 30 m, or metres per second per 30 m, or in knots per 100 ft, as these units are convenient and well understood by aviation personnel. In the particular case of aircraft landing or taking off where the glide path or take-off path is a known fixed angle, e.g. 3° glide path, and the ground speed of the aircraft is known and relatively constant, the wind shear can be converted from kt/100 ft or m/s/30 m into kt/s or m/s/s which gives the intensity of the wind shear in units of acceleration (i.e. change in speed in time) which are particularly useful to pilots (see Figure 4-5)[2].

2.4.2 Alternative wind shear units, which are often used by researchers and therefore encountered in research papers and scientific publications, may be derived by dimensional analysis as follows:

Wind shear = (e.g.) kt per 100 ft which is: $$\frac{\text{speed units}}{\text{distance units}} = \frac{L/T}{L} = \frac{1}{T} = T^{-1}$$

where: L = length; and
T = time,

hence the units may be given as s^{-1}. While, scientifically speaking, s^{-1} must be considered the proper units for wind shear, physically the unit is difficult to interpret and in practice it is not particularly useful in respect of aircraft operations.

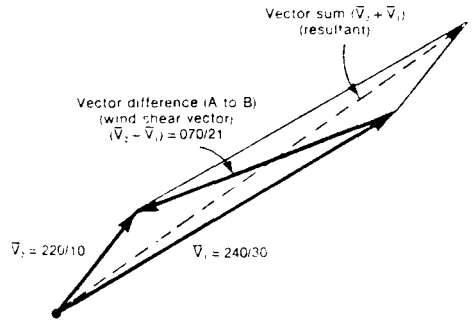
2.4.3 Summarizing the three ways of expressing wind shear intensity discussed above in terms of the example given in Figure 2-2, in the case of a wind changing from V_1 at point A to V_2 at point B (e.g. an aircraft landing), the wind shear vector between points A and B is 070° 21 kt over 500 ft, therefore:

a) the intensity in kt/100 ft = 4.2 kt/100 ft;

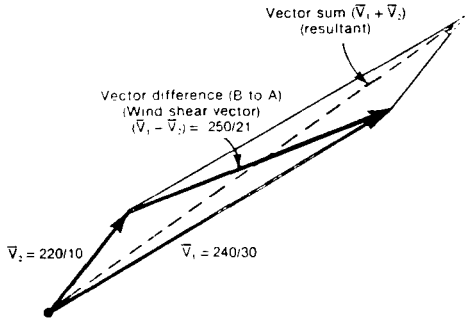
b) the same intensity in scientific units = 0.07 s^{-1}; and

c) the intensity as it might affect a landing aircraft in kt/s for a 3° glide slope and 150 kt ground speed (i.e. rate of descent 13 ft/s) = 0.546 kt/s.

I. By construction (draw to scale and measure magnitude (speed) and direction using ruler or scale, and protractor)



a) Point A to point B



b) Point B to point A

The easiest graphical method is to plot the winds on a polar diagram, i.e. as a "hodograph" (for an example see Figure 3-2).

II. By calculation

a) from components		East/West components	North/South components
1 000'AGL	Point A, $\mathbf{V_1}$ = 240/30	+26	+15
500'AGL	Point B, $\mathbf{V_2}$ = 220/10	+6.4	+7.7

Note.- Signs of components are reciprocals of usual trigonometric sign convention as wind direction is the direction from which the wind is blowing.

Vector difference from point A to point B (e.g. in direction of aircraft landing) = $\mathbf{V_2} - \mathbf{V_1}$

East/west component of vector difference = (6.4-26) = -19.6
North/south component of vector difference = (7.7-15) = -7.3

magnitude (speed) of vector difference $\mathbf{V_2} - \mathbf{V_1} = \sqrt{(-19.6)^2 + (-7.3)^2}$
$= 20.9$
$= 21$ kt

direction of vector difference $\mathbf{V_2} - \mathbf{V_1} = \tan^{-1}\left(\frac{-7.3}{-19.6}\right) = 20°$

As both components of the vector difference (shear) are negative, direction of wind shear vector is from the north-east quandrant and as east/west component > north/south component direction = (090-020)
= 070°

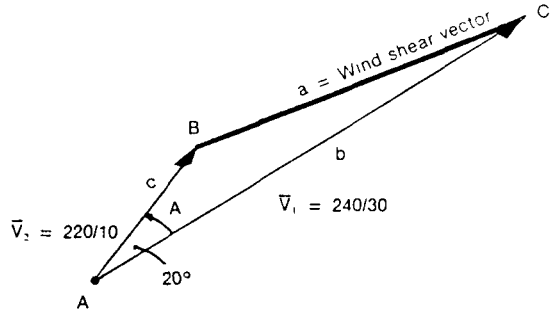
Wind shear vector from point A to point B (landing) = 070/21

Wind shear vector from point B to point A (take-off) = 250/21

Figure 2-2. Calculation of wind shear

II.

b) By calculation using trigonometry



This is a case where two sides of a triangle are known and the included angle, side "b" = 30, side "c" = 10 and the angle between winds $\mathbf{V}_1$ and $\mathbf{V}_2$ = 240° - 220°

A = 20°

From basic trigonometry, in such a triangle

$a^2 = b^2 + c^2 - 2bc \cos A$

(where "a" is the magnitude of the vector difference (shear)),

$\therefore$ speed of shear = "a" which = $\sqrt{b^2 + c^2 - 2bc \cos A}$

$= \sqrt{900 + 100 - 600 \cdot (0.9397)}$

$= \sqrt{436.2} = 20.9$

= 21 kt

Now all the three sides of the triangle are known (a = 21, b = 30 and c = 10). The direction of the shear vector may be found as follows:

$b^2 = a^2 + c^2 - 2ac \cos B$

$$B = \cos^{-1}\left[\frac{a^2 + c^2 - b^2}{2ac}\right] = \frac{-363}{418} = -0.8684 = 150°$$

Direction of shear vector from geometry of diagram = (180° - 150° + 40°) = 070° (or reciprocal 250° depending on order of subtraction of wind vectors)

Figure 2-2 (cont.)

At this point it should be noted that the wind shear discussed so far is acting in the free atmosphere and exists whether an aircraft is there or not. In fact such wind shears are being used by meteorologists when they plot hodographs or when the thermal wind is being calculated. In these cases the shear between winds at two levels in the atmosphere is calculated by subtracting the lower-level wind vector from the upper-level wind vector, i.e. $\mathbf{V}_1 - \mathbf{V}_2$ in the example given in 2.3.1. In Chapter 4, where the effect of the wind shear on an aircraft's performance is considered, the direction of the wind shear vector in relation to the aircraft's flight path becomes important.

2.5 LIMITATIONS ON PRACTICAL APPLICATION OF METHODS FOR CALCULATING WIND SHEAR

2.5.1 The methods for calculating wind shear described in 2.3 can, of course, only be used where information on the wind at two points in space is available, e.g. from an aircraft report on descent, from a rawinsonde report, or from two anemometers spaced at different levels on a mast or along a runway. This places a considerable restriction on the practical usefulness of these methods because information on the winds at particular points of interest is not usually available. There are two other limitations from an operational standpoint, which must also be borne in mind. Calculation of the wind shear from two winds at points separated by a given distance simply gives the over-all shear between the two points. No indication is forthcoming on whether the rate of shear is in fact linear or, if not linear, at least gradual between

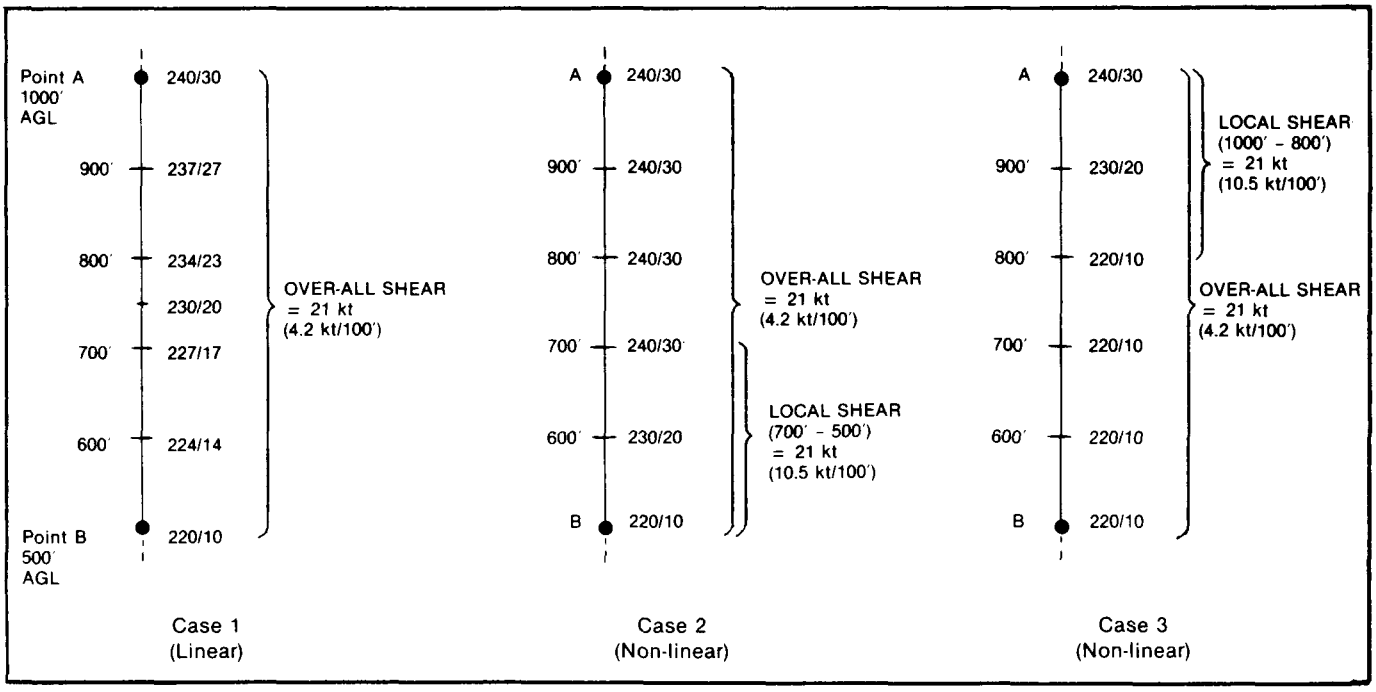


Figure 2-3. Linear and non-linear wind shear

the points, or whether most of the shear occurs over a short distance somewhere between the points. Hence, it does not necessarily give the maximum shear in the layer, which is what the pilot needs to know. This problem is illustrated in Figure 2-3, using the wind shear previously calculated in the example given in Figure 2-2.

2.5.2 In Case 1 of Figure 2-3 the shear between 1 000 ft and 500 ft is approximately linear and the over-all shear of 21 kt at a rate of 4.2 kt/100 ft given by calculation (from the only two winds available, at points A and B), reflects the actual conditions very well. This is not true in Cases 2 and 3 where, although the over-all shear is still calculated as 21 kt or 4.2 kt/100 ft, in fact the true situation is that this shear is concentrated in 200 ft in an unsuspected local wind shear far in excess of 4.2 kt/100 ft, in the examples given reaching a maximum of 10.5 kt/100 ft. In practice, however, it should be noted that linear or at least gradual wind shear at low levels represents the more typical case with non-linear shear being the exception under certain conditions (see 3.1.2.3).

2.5.3 The second limitation concerns the calculation of wind shear using rawinsonde or pilot balloon winds[3]. In this regard it should be noted that these winds already represent mean winds for successive layers of the atmosphere with winds for specific levels being obtained by interpolation[4] and, as such, may not indicate the actual wind shear between two particular levels.

Chapter 3

METEOROLOGICAL CONDITIONS AND PHENOMENA WHICH CAUSE LOW-LEVEL WIND SHEAR

3.1 WIND PROFILE IN THE LOWER LEVELS OF THE ATMOSPHERE

3.1.1 General

3.1.1.1 It is a well known fact that, even outside the influence of specific wind shear-causing meteorological phenomena, wind shear is always present in the atmosphere, although under normal circumstances such wind shear does not cause difficulty for a pilot. It is especially noticeable below 600 m (2 000 ft) where frictional drag on the air closest to the earth's surface causes changes in both wind speed and direction with height. This layer is generally referred to as the "friction layer" which can be further sub-divided as follows into:

a) the "surface boundary layer" from the earth's surface up to about 100 m (330 ft) in which air motion is controlled predominantly by friction with the earth's surface; and

b) the "Ekman layer" from about 100 m (330 ft) up to at least 600 m (2 000 ft) in which the effect of friction, whilst still significant, diminishes progressively with increasing height, and other controlling factors, such as the coriolis force and horizontal pressure gradient force, become increasingly important.

3.1.1.2 In the friction layer the wind speed tends to increase with height throughout, with the largest change occurring immediately above the earth's surface in the surface boundary layer. The wind direction tends to remain constant with height in the surface boundary layer, but to veer (back) with height in the northern (southern) hemisphere throughout the Ekman layer.

3.1.2 The surface boundary layer

3.1.2.1 In the lowest layer of the atmosphere, below about 100 m (330 ft), the wind direction is approximately constant with height whilst the wind speed is observed to increase with height, the change being most rapid immediately above the surface[1]. The derivation, from physical principles, of a theoretical relationship between wind speed and height in the surface boundary layer under all possible stability conditions

presents some difficulties[2]. It is, however, a relatively straightforward matter to derive such a relationship for the special condition of neutral stability (i.e. neither stable nor unstable), in which the actual lapse rate is assumed to be equal to the dry adiabatic lapse rate in unsaturated air and equal to the saturated adiabatic lapse rate in saturated air (and vertical movement due to buoyancy forces is small compared with horizontal movement). These conditions are approximately fulfilled in the surface boundary layer as long as winds are sufficiently strong to ensure turbulent mixing. In very light wind conditions, and especially in calm conditions with marked low-level inversions, a neutrally stable layer is not established and the theory cannot be applied. Assuming that the atmosphere is neutrally stable in the surface boundary layer, then the theoretical variation of the wind speed with height is given by the following equation:

$$u = \frac{u_*}{k} \ln \frac{z}{z_o}$$

where: u is the wind speed at height z;
k is von Karman's constant, approximately 0.38;
u_* is the "friction velocity";
z_o is the roughness length, which depends on the nature (roughness) of the surface concerned.

This equation is known as the "logarithmic wind law" or the "Prandtl equation" and produces the well-known logarithmic wind speed profile.

3.1.2.2 The logarithmic wind law fits the observed wind speed profile in the surface boundary layer very well as long as the condition of neutral stability is fulfilled. In cases where the surface boundary layer is unstable, the shear in wind speed with height will be less than that predicted by the above equation; when conditions are stable the shear will be higher than predicted by the equation (see Figure 3-1 a))[3].

3.1.2.3 An extreme case of the stable condition, which can involve the whole of the friction layer, occurs when the stability is so marked (e.g. due to the formation of a strong low-level radiation inversion at night) that turbulent mixing and momentum transfer from the large-scale flow above the inversion cease. This results in surface winds becoming light or calm, and as the wind flow at the top of the inversion is effectively cut off from the retarding effects of friction at the surface, a wind speed maximum develops at the top of the inversion (see Figure 3-1 b))[4,5]. Under certain circumstances, for example, if the airstream is deflected across broad plains by a mountain chain, the wind speed maximum is concentrated into a comparatively narrow band resembling a jet stream. Such wind speed maxima are commonly referred to as "low-level jet streams" - as the maximum speed can exceed 60 kt the description seems fitting. This terminology was first used to describe the jet-like low-level wind maxima frequently encountered over the Great Plains in the United States and similar examples have been reported from elsewhere in the United States, in Scandinavia and along the east coast of Saudi Arabia. In these circumstances the shear below the jet can be significant and is proportional to the strength of the inversion[6]. The level of maximum wind is generally below 500 m (1 600 ft) and thus of considerable interest to aviation.

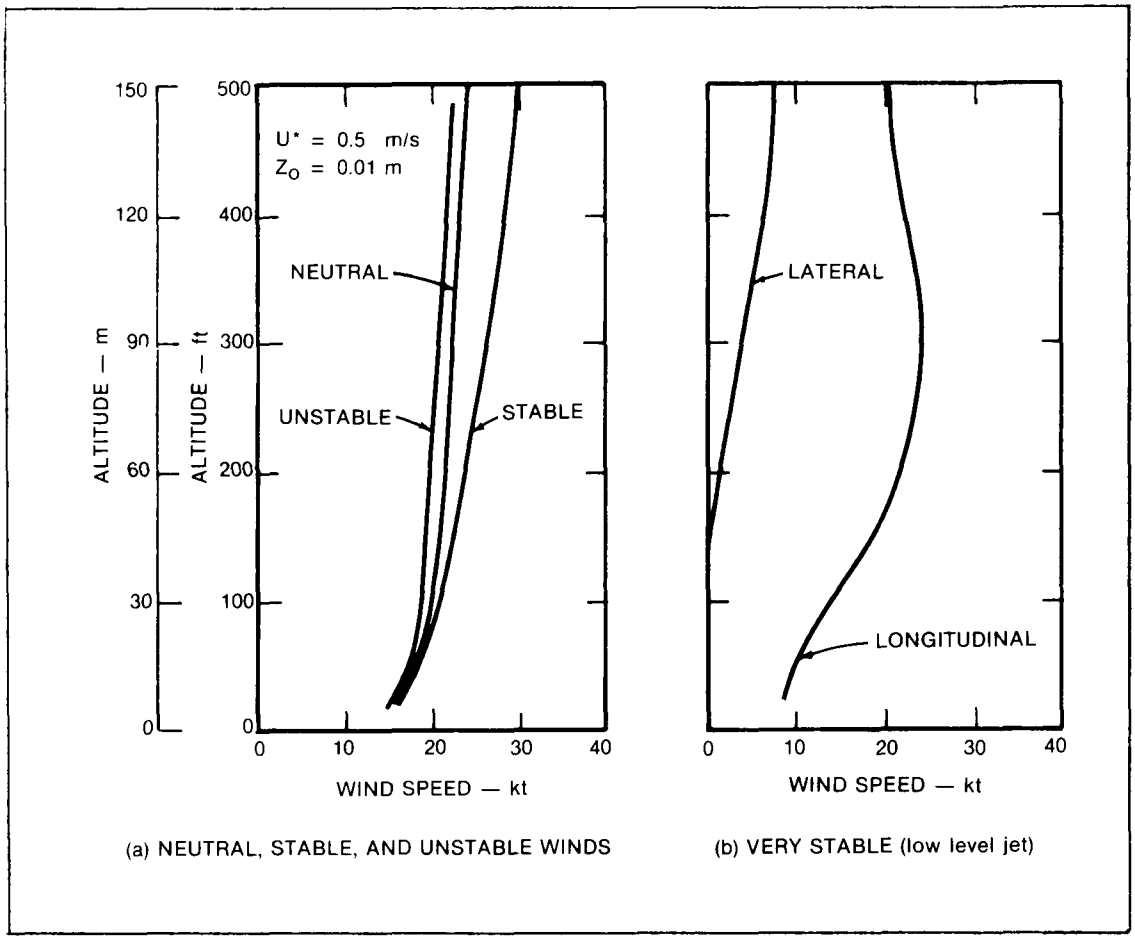


Figure 3-1. Wind profiles from atmospheric boundary layer effects (from Ellis and Keenan, 1978)

3.1.2.4 The logarithmic wind law is not simply of academic interest, as it also provides a wind shear model for use in the simulator certification of automatic landing systems* and in the training of pilots. It must be stressed, however, that in all cases in using this model in a simulator, the change in wind shear with height will be gradual and continuous: in simulated landings into a surface headwind there will always be a decreasing headwind on descent and, in simulated take-offs into a surface headwind the headwind will always increase with height; by definition there will never be a change in wind direction within the layer. Nevertheless, even allowing for such limitations, the

* See the Airworthiness Technical Manual, Doc 9051, Part III, Section 8, Chapter 7, Appendix A.

model does represent well the average conditions which the pilot is most likely to encounter in the lowest levels of the atmosphere below 100 m. In the logarithmic profile, wind shear is greatest below 30 m (100 ft) and decreases with height, the shear intensity may exceed 5 kt/30 m in the first 15 m (50 ft) decreasing to less than 1 kt/30 m above 100 m (330 ft). The question of the development of simulator models based upon more abnormal wind shears is discussed in Chapter 7.

3.1.3 The Ekman layer

3.1.3.1 Above the surface boundary layer, from about 100 m (330 ft) up to about 600 m (2 000 ft), the effect of friction on the wind decreases rapidly with height and the horizontal pressure gradient and coriolis forces become increasingly dominant. As in the case of the surface boundary layer, the wind speed between 100 m (330 ft) and 600 m (2 000 ft) increases with height as the effect of friction decreases. However, the wind direction does not remain constant with height, as was assumed in the surface boundary layer, but veers (backs) with height in the northern (southern) hemisphere.

3.1.3.2 The theory to explain these effects mathematically was first developed by Ekman and is applicable to the atmosphere between about 100 m (330 ft) and about 600 m (2 000 ft), a layer which has since come to be known as the Ekman layer. The equation which Ekman derived, when applied to the atmosphere, may be written as follows[7]:

$$u = V_g - V_g \sqrt{2} \sin a \, e^{-Bz} \cos \left(Bz + \frac{\pi}{4} - a\right)$$

and

$$v = V_g \sqrt{2} \sin a \, e^{-Bz} \sin \left(Bz + \frac{\pi}{4} - a\right)$$

where: u and v are the horizontal components of the wind at height z;
V_g is the geostrophic wind;
a is the angle between the actual wind at anemometer level and the geostrophic wind; and
B is a constant comprising viscosity and coriolis parameters.

3.1.3.3 Throughout the Ekman layer a balance is achieved between the friction, horizontal pressure gradient and coriolis forces. At the bottom of the Ekman layer the three forces are of equal orders of magnitude and the balanced flow is achieved by the wind blowing across the isobars towards lower pressure. The angle of this cross-isobar flow decreases exponentially with height as the effect of friction diminishes, until a level is reached where the frictional effect is negligible, a balance is achieved between the horizontal pressure gradient and coriolis forces and the wind blows along the isobars.

3.1.3.4 The level at which the wind blows along the isobars is referred to as the geostrophic-wind level or simply the top of the friction layer. At this level and above, the winds computed using Ekman's theory are very close to the geostrophic wind. According to the theory, the angle of the cross-isobar flow in the Ekman layer is a maximum of 45° at or just above the surface, decreasing exponentially above about 100 m to 0° at the top of the friction layer. If the computed winds in the Ekman layer are plotted in the form of a hodograph, the end points of the wind vectors describe an equiangular, spiral as shown in Figure 3-2, which is known as the Ekman spiral.

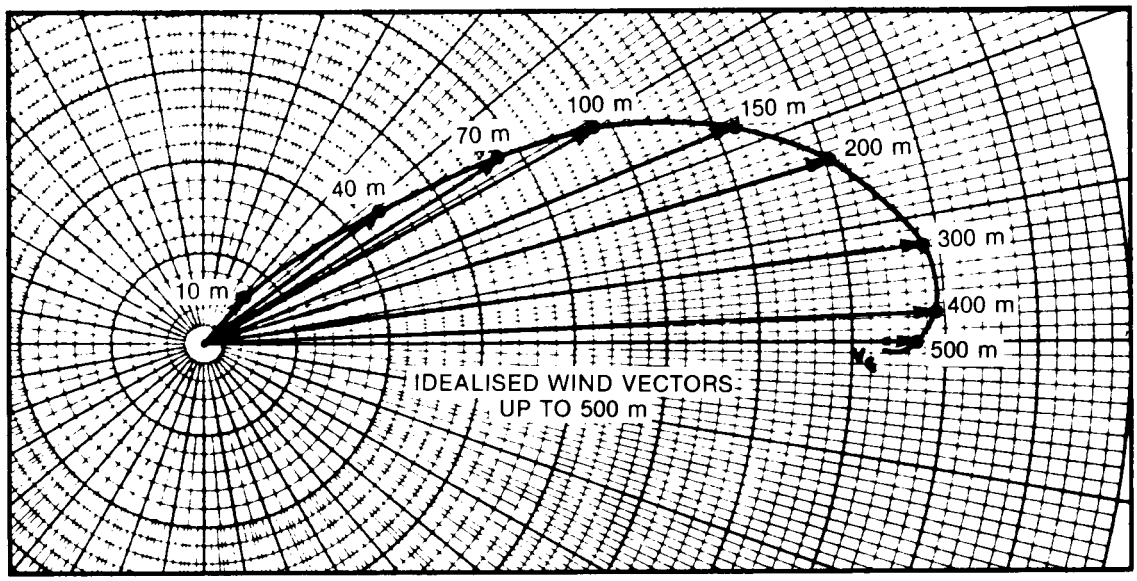


Figure 3-2. Ekman spiral

3.1.3.5 In practice, it is found that the wind speed does generally increase with height in the Ekman layer, the wind does blow at an angle across the isobars, the angle does decrease with height and the wind does veer (back) with height in the northern (southern) hemisphere. However, the idealized spiral shown in Figure 3-2 is rarely achieved and, outside of the equatorial regions where the coriolis force is close to zero and the wind can blow at virtually any angle to the isobars, the angle of cross-isobar flow rarely exceeds 30°. A combination of the logarithmic and Ekman wind profiles provides an adequate representation of the "normal" wind shear (i.e. outside the influence of specific wind shear producing meteorological phenomena) from the surface to about 600 m (2 000 ft).

3.1.4 Wind profile models applicable to non-neutrally stable conditions

3.1.4.1 Other models have been derived empirically which represent atmospheric wind profiles under atmospheric conditions where stability is not neutral[8,9,10]. The best-known of these is the "power law" which links wind speeds at two levels of the atmosphere through a stability parameter as follows:

$$u = u_1 \left[\frac{z}{z_1}\right]^{\gamma}$$

where: u, u_1 are wind speeds at heights z, z_1, respectively; and
γ is a parameter which depends on the stability, surface roughness and height with a value between 0 and + 1 determined empirically.

The power law is generally used under adiabatic conditions with strong wind speeds for the layer from 10 m to 200 m.

3.2 WIND FLOW AROUND OBSTACLES

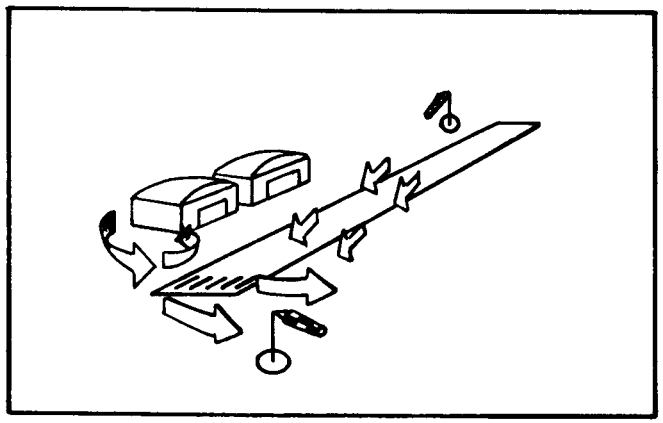
3.2.1 A combination of strong surface winds and obstacles to the prevailing wind flow situated upwind of the approach or departure path, such as large buildings, low hills or close-planted stands of tall trees, can create localized areas of low-level wind shear. In these circumstances the wind shear is usually accompanied by clear-air turbulence. The effect that the obstacles have on the prevailing wind flow depends on a number of factors, the most important of which is the speed of the wind and its orientation relative to the obstacle and the scale of the obstacle in relation to the runway dimensions.

3.2.2 The most commonly encountered wind shear of this type, particularly at smaller aerodromes, is that caused by large buildings in the vicinity of a runway. Although the height of buildings is restricted in proportion to their distance from the edge of the runway strip, to ensure that they do not constitute an obstacle to aircraft, their lateral dimensions tend to be rather large and, for many reasons, they tend to be grouped together in the same area. This means that whilst the buildings (hangars and fuel storage tanks, etc.) are comparatively low, they present a wide and solid barrier to the prevailing surface wind flow. The wind flow is diverted around and over the buildings (see Figure 3-3 a)) causing the surface wind to vary along the runway. Such horizontal wind shear, which is normally very localized, shallow and turbulent, is of particular concern to light aircraft operating into smaller aerodromes but has also been known to affect larger aircraft[11].

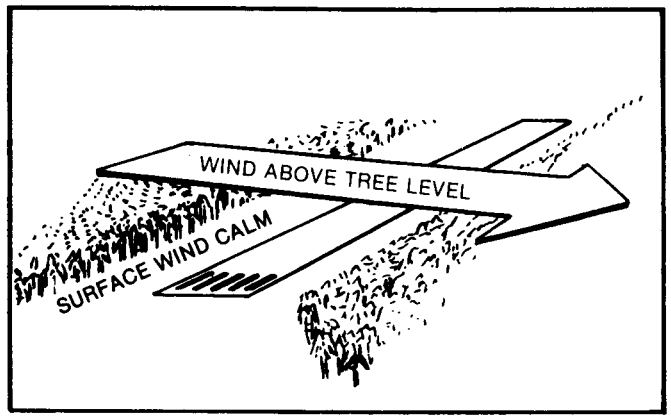
3.2.3 Airfields sometimes are literally carved out of extensive coniferous forests or coconut plantations, with the result that the runway is effectively situated within a "tunnel" of trees. Even when the treeline is beyond the runway strip and hence poses no obstacle to aircraft, because the height of the forest or plantation canopy can reach 30 m (100 ft) the surface wind along the runway often bears little or no relationship to the prevailing wind above the forest canopy. Most frequently the surface wind is light and variable or calm irrespective of the prevailing wind (see Figure 3-3 b)).

3.2.4 Of more general interest is the case of runways which, of necessity, have been built in narrow valleys or alongside a range of low hills. In this case, the scale of the obstacle is such that it can affect the low-level wind flow over a large area. Where a range of low hills lies alongside a runway, the height of the range may not be sufficient to divert the flow, but as the airflow is forced over the hills it acquires a vertical component (downwards) which, depending upon the proximity of the hills to the runway, can cause localized low-level downdrafts along the runway (see Figure 3-3 c)). Where the hills or mountains are sufficiently high to divert the low-level wind flow, the surface wind may be funnelled along the runway (see Figure 3-3 d)). In special cases where there are hills along both sides of the runway, the funnelled wind flow may exhibit a venturi-like effect, which results in an acceleration in the surface wind[12].

3.2.5 Strong surface winds at aerodromes where there are no substantial obstacles to the wind flow can also cause an increase in wind shear. This is because, in the layers of the atmosphere nearest the ground, the strong wind increases mechanical turbulence. This in turn transfers momentum throughout the layer and decreases the wind shear near the ground but with a corresponding increase in wind shear at higher levels of the surface boundary layer.



a)



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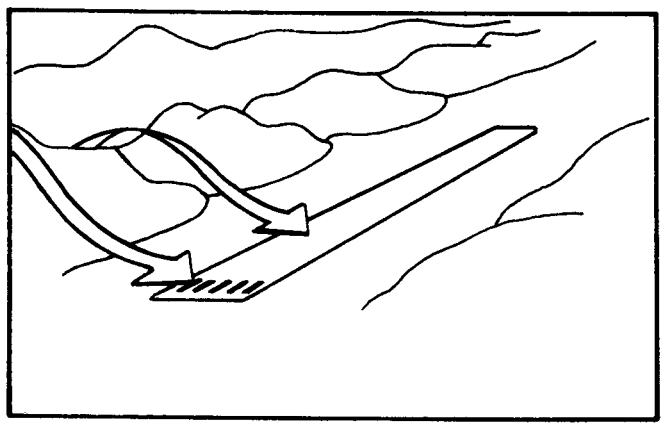

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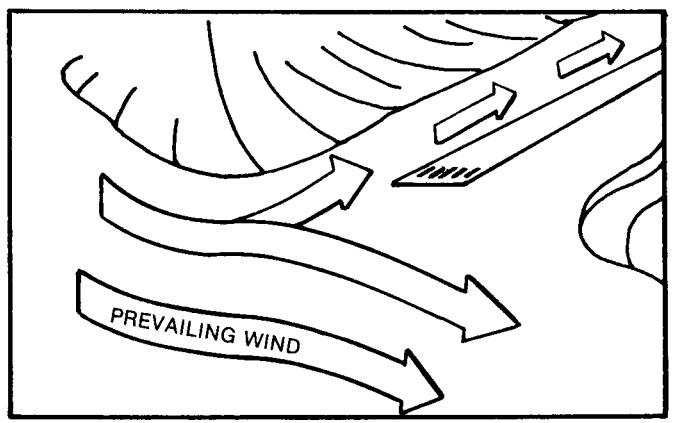


d)

Figure 3-3. Wind flow around obstacles

3.2.6 The wind shear described in 3.2.1 to 3.2.4 is due to the mechanical effects of obstacles interfering with the prevailing wind flow. Under certain circumstances, in addition to the mechanical effect, the thermodynamic properties of the atmosphere can influence the wind flow around obstacles, thereby creating special wind shear conditions.

3.2.7 The most common of these conditions, called a katabatic wind, occurs at night over sloping ground when there is no cloud and a weak pressure gradient - especially anticyclonic. The wind is formed due to the downslope gravitational flow of colder, denser air in contact with the slope below the warmer, lighter air at the same level but some distance away from the surface of the slope. Low-level wind shear and turbulence will be present along the leading edge and the top of the colder air as it moves downhill and on occasion the onset may be sudden, resembling a weak gust front (see 3.5.2). The cold, dense air collects as a "pool" at the bottom of the valley, forming a temperature inversion near the ground. If the surface temperature inversion is sufficiently strong, the prevailing winds above the surface may glide over the top of the "stagnant pool" of cold air lodged in the valley bottom. This produces wind shear at some height above ground level along the top of the inversion. The effect occurs over a wide range of scales, from the so-called valley or drainage winds at the smallest scale to the fjord winds of Norway, the Mistral of southern France, the bora of the Adriatic and the continental-scale strong outflow winds of Greenland and Antarctica[13]. The development of these large-scale effects normally requires other factors in addition to the katabatic effect, such as intensely cold air at high elevations, optimum orientation of the isobars and hence prevailing wind flow and, in the case of the Mistral, the venturi effect of the Rhone valley which can accelerate the cold north-westerly downslope wind to 70 kt or more.

3.2.8 The simple case of a surface wind flow being forced over a range of low hills in proximity to a runway was mentioned in 3.2.4 above. On a larger scale, when the wind flow is forced over a mountain range, depending on the speed and stability of the airstream a series of standing waves may be formed in the wind flow on the leeside of the mountains[14]. Particular mountain ranges which have unique features (especially steep leesides) and favourable meteorological conditions, such as the Rockies in the United States, are notorious for producing marked lee waves. The meteorological conditions most suitable for the formation of lee waves include:

a) a stable layer of air sandwiched between two less stable layers, one near the ground and the other at a higher level;

b) a wind in excess of 15 kt blowing within 30° either side of the normal across the ridge line;

c) little or no wind direction shear in the stable layer; and

d) sea-level pressure differential across the mountain barrier.

If the lee waves which develop are of sufficient amplitude, a closed rotor flow or eddy may be formed beneath a wave crest. In extreme conditions such a rotor flow can penetrate to ground level and can reverse the prevailing surface wind directly below the rotor (see Figure 3-4). Under such extreme conditions, instances have been recorded where surface gusts generated by the rotor were in excess of 100 kt, e.g. during "wind storms" near Boulder, Colorado[15]. The factors necessary for the development of such extreme conditions are not yet fully understood, but it has been suggested that some form of natural resonance and amplification may play a significant role. When the

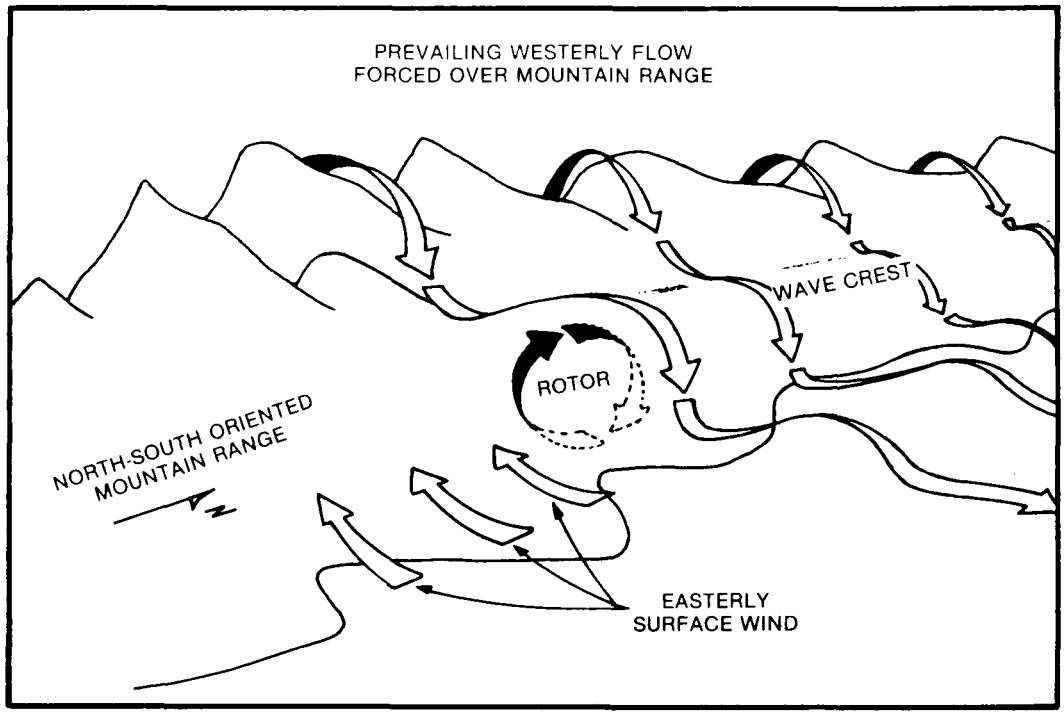


Figure 3-4. Lee waves

airstream is sufficiently moist, a very turbulent "rotor cloud" forms in the upper parts of the closed eddy. Such stationary wave systems produce marked downdrafts along the mountain edge and also downdrafts of lesser magnitude at some considerable distance from the mountainside in the secondary and tertiary waves of the series which form downwind of the mountain.

3.2.9 Another effect which can be produced when wind flow is forced over a mountain range is the "föhn wind" which blows down the leeside of the mountains (e.g. "Chinook" in Western Canada and "Santa Ana" in California). In most cases the prerequisite for the development of such a downslope wind is that the airstream forced over the mountains is sufficiently moist for clouds and precipitation to form along the windward slopes. In these conditions the ascending air cools at the saturated adiabatic lapse rate and, provided that water is removed by precipitation on the windward slopes, much of the adiabatic warming which occurs as the air moves down the leeside of the mountains is at the dry adiabatic lapse rate. Consequently, as the air reaches the ground it is as a noticeably warm, dry wind. The onset of the föhn wind can be very sudden, causing strong gusty winds at aerodromes situated in its path. In conditions where there is a strong temperature inversion near the ground, the föhn wind glides along the top of the inversion, producing wind shear along the inversion zone between 100 and 500 m above ground level. There is also evidence that a föhn wind can develop without the formation of precipitation on the upslope side of the mountain range. In these cases it is considered that the warm, dry downslope wind originates from a level above the mountain ridge line, possibly due to the formation of a standing lee wave as described in 3.2.8.

3.2.10 Whilst on the subject of atmospheric waves, it is appropriate to mention another type of wave, encountered in certain parts of the world, which is not stationary but propagates as a gravity wave in the lower levels of the atmosphere, particularly in

the early morning. This type of wave is most frequently observed in the Gulf of Carpentaria in northern Australia where it is referred to as a "morning glory"[16]. The name is thought to derive from the spectacular roll cloud or series of roll clouds, which accompany the propagating wave. A cross-section of relative streamlines associated with a typical morning glory is shown in Figure 3-5[17]. Whilst the gusts recorded in the surface winds during the passage of a morning glory do not usually exceed 10 m/s (20 kt), the onset is sudden, the wind direction does shift rapidly (often through 180°) and there are marked downdrafts within the wave itself[18]. The wave propagates fairly steadily, generally at more than 10 m/s (20 kt) and a sharp pressure jump occurs at the passage of the wave. The cause of this type of wave is not yet fully understood but is thought to be linked to a trigger disturbance, such as a sea-breeze front, gust front or cold front being propagated along a nocturnal inversion which acts as a wave guide ahead of the front itself. This phenomenon clearly has the potential to affect aircraft performance during landing and take-off operations. Whether in fact such phenomena have contributed at all to aircraft accidents remains to be confirmed, but some researchers believe that they are implicated[19].

3.3 WIND FLOW ASSOCIATED WITH FRONTAL SURFACES

3.3.1 Frontal surfaces are transition zones separating air masses of different temperature and hence of different density. When two such air masses come into contact, equilibrium is attained so that the colder and more dense air lies as a wedge below the warmer and less dense air with the boundary between them inclined at a small angle to the horizontal. The inclination of the frontal surface is due to the earth's rotation, but the extent of the inclination also depends on the contrast in the distribution of temperature and wind along the boundary between the two air masses - the greater the contrast the steeper the slope. The dynamics of frontal surfaces dictate that there is a discontinuity in the wind velocity across the surface, particularly in the lower levels of the atmosphere; a frontal surface is thus, by its very nature, a wind shear zone.

3.3.2 The intersection of the frontal surface with the horizontal plane indicates the position of the frontal surface at a particular level; the intersection with the earth's surface is referred to as a surface front or simply as a front. Fronts are classified according to their movement and the resultant temperature changes

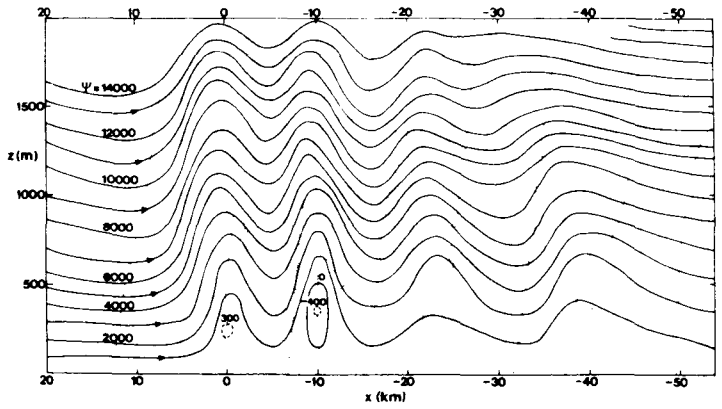


Figure 3-5. Cross-section of the relative streamlines normal to the cloud line in the "morning glory" of 4 October 1979 as deduced from double theodolite wind data (from Smith and Goodfield, 1981)

experienced at a location across which the front passes, a cold (warm) front being defined as a front along which cold (warm) air replaces warmer (colder) air at the surface. The relatively strong fronts having sharp transition zones and thus marked wind velocity discontinuities are the ones most likely to produce wind shear which could affect aircraft[20]. The average slope of a cold front ranges from 1/50 to 1/100, but due to friction with the ground, the cold, dense air near the surface is retarded - this can produce even steeper slopes in the lowest levels of the atmosphere including, in certain circumstances, a "nose" where the cold air just above the surface advances ahead of the cold air at ground level. Warm fronts are more shallow with typical slopes ranging from 1/100 to 1/300 or even shallower down to ground level. The typical slopes mentioned above indicate that, except in very strong cold fronts near the ground, the slope of even the steepest front tends to be shallower than the usual 3° glide slope (~ 1/20) and much shallower than usual climb-out flight paths.

3.3.3 It will be clear from the foregoing that the warm front slopes forward in the direction of motion of the front, whilst the cold front slopes backward in the opposite direction to the motion (see Figure 3-6). The implication this has for an aerodrome through which the fronts are moving is that the vertical wind shear across the frontal surface occurs:

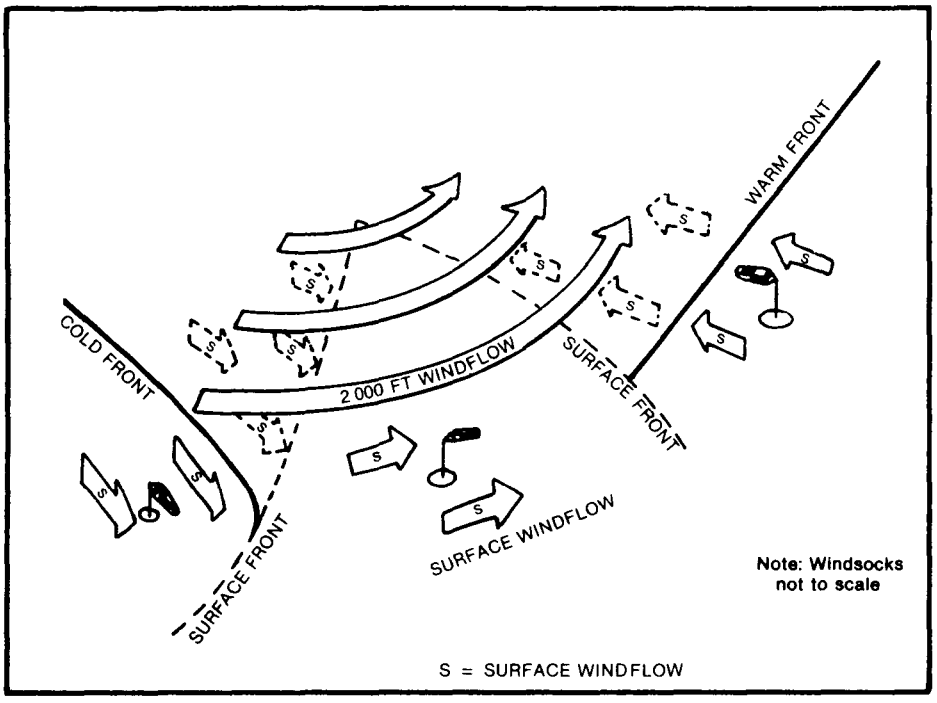
a) above the aerodrome ahead of the warm front with the level of maximum wind shear lowering to ground level as the warm front approaches; and

b) at and behind the cold front, with the level of maximum wind shear rising above the aerodrome from ground level following passage of the cold front.

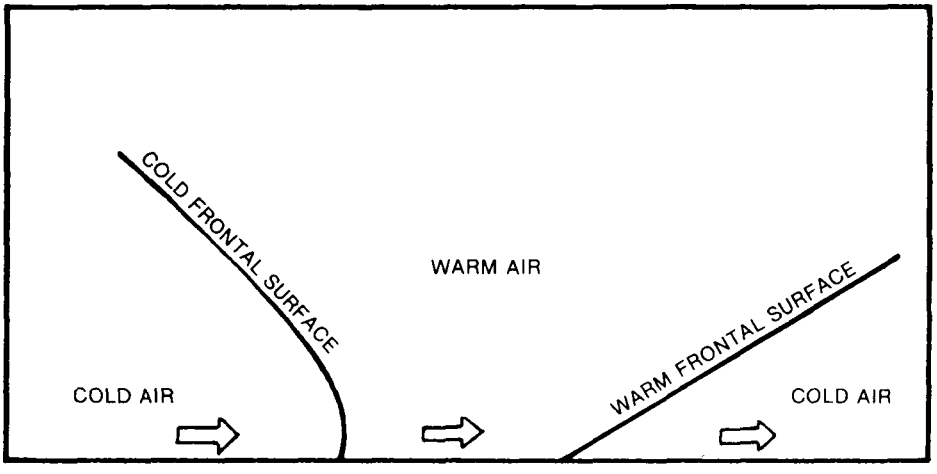
At ground level there is also horizontal wind shear across the front although, given the usual speed of movement of fronts across an aerodrome, this is likely to be short-lived. The more significant shear from the aviation point of view is the vertical wind shear across the frontal surface above an aerodrome which is ahead of an approaching warm front or behind a receding cold front. As warm fronts tend to move more slowly than cold fronts, wind shear conditions existing ahead of a surface warm front can affect an aerodrome longer than those existing behind a cold front. The wind shear discussed here is simply related to the frontal surface itself and takes no account of any wind shear produced by thunderstorms, etc., which may develop along the front. The effect of frontal vertical wind shear on an aircraft will depend on the width of the frontal surface (transition zone) and the transit time of the aircraft flying through the zone which in turn depends on the relative slopes of the flight path and the frontal surface and the aircraft ground speed.

3.4 LAND/SEA BREEZE

3.4.1 Over land areas adjacent to large bodies of water, such as the sea or large inland lakes, there is a well-marked diurnal variation in the surface wind. This effect is due to the temperature gradient which develops in daytime between the air over the heated land and the water-cooled air offshore and is particularly noticeable when the prevailing low-level wind flow is light and there are sunny days and clear nights. The surface wind blows from the water towards land during the daytime as a sea or lake breeze, often setting in rather abruptly in the morning (see Figure 3-7), and reverses at night, becoming a land or offshore breeze blowing from the land towards the water. In addition to the abrupt change in the surface wind, the onset of the sea breeze is often marked by a drop in temperature and a rise in humidity. The direction of the sea



a) Three-dimensional diagrammatic view of windflow around warm/cold frontal system up to 2 000 ft, northern hemisphere (vertical scale exaggerated)



b) Cross-sectional diagrammatic view across warm/cold frontal system (vertical scale exaggerated)

Figure 3-6. Frontal surfaces

breeze initially is approximately at right angles to the shoreline with speeds of 10 to 15 kt although in tropical areas these may exceed 20 kt. The sea breeze is much stronger than the land breeze and may penetrate as far as 48 km (30 miles) inland by mid-afternoon and extend up to 360 m (1 200 ft) above ground level. The sea breeze dies away during the evening as radiational cooling over the land reduces the temperature gradient and may be replaced by a light, shallow land breeze before dawn.

3.4.2 The sea breeze is essentially a shallow cold front because colder air is replacing warmer air; however, the slope and temperature gradients more closely resemble those of a warm front than of a cold front[21]. Wind shear in the sea breeze occurs predominantly at the surface along the leading edge as the front penetrates inland, although wind shear of lower magnitude will exist at higher levels. The extent of the sea breeze effect at any particular location is influenced considerably by the surrounding topography and thus may be of a very localized nature. Where the sea breeze is strong and penetrates some distance inland, the coriolis force begins to take effect and the wind eventually develops a component parallel to the coastline. At the time of maximum development of the sea breeze, in the late afternoon, the front may be marked by a line of convergence and vigorous convection which in favourable circumstances can give rise to lines of showers or even thunderstorms. A number of subtle effects can be produced by the land/sea breeze depending on local topography, such as the development of convergence lines and associated thunderstorms inland along a peninsula or the intensifying effect of a "concave" coastline on the offshore convergence due to the land breeze.

3.5 THUNDERSTORMS

3.5.1 General

3.5.1.1 Thunderstorms are probably the most impressive day to day manifestation of the power of nature which can be witnessed by most people throughout the world. The name "thunderstorm" is an all-embracing term which can include a number of phenomena produced by mature cumulonimbus clouds, such as thunder and lightning, torrential rain, hail, strong winds and tornadoes, etc. Most of these phenomena present great danger to aircraft. The tremendous energy involved in the development of a severe thunderstorm can be of a similar order of magnitude as a nuclear explosion, which is one reason some

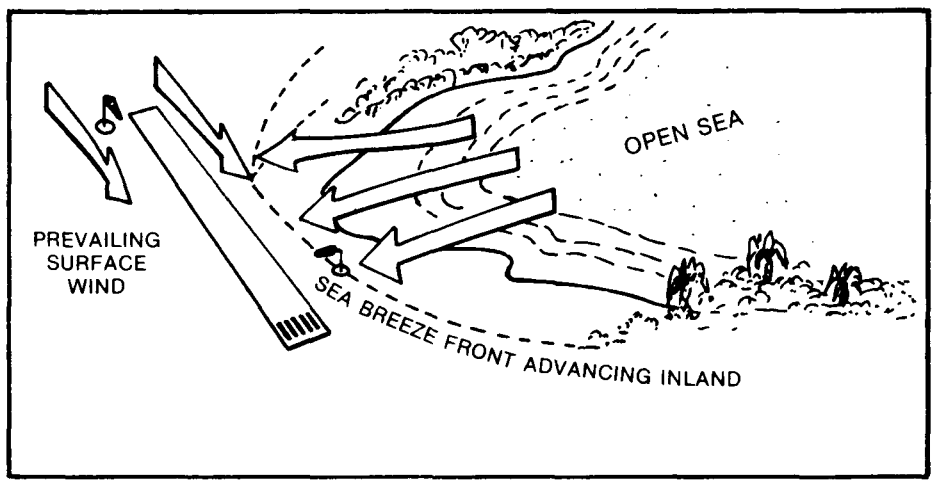


Figure 3-7. Sea breeze front

meteorologists might be seen to smile when such explosions are suggested as having affected the weather.

3.5.1.2 The cumulonimbus, as a towering mass of cloud rising on surging air currents, represents a particularly violent and spectacular form of atmospheric convection. When the atmosphere becomes unstable, from whatever cause, it undergoes convective overturning. A common example would be thermals due to solar heating on sun-facing slopes. Under favourable conditions, convection produces sufficiently strong localized updraft areas for the formation of cumulonimbus clouds and thunderstorms. Thunderstorms, historically, have been classified into two main types according to the source of the instability, as follows:

a) air mass or heat thunderstorms; and

b) frontal thunderstorms.

The former have a pronounced diurnal variation, occurring most frequently in the afternoon and evening over land due to solar heating. They also occur more or less at random over an area where the air mass is homogeneous and conditions are uniformly favourable. However, whilst random development is the norm, it does not require much to produce organized development within the homogeneous air mass. Such organization might be caused by orographic lifting along a mountain range or uplift along a line of converging low-level winds, such as along the intertropical convergence zone or in the spiralling bands of convergence associated with tropical cyclones. Frontal thunderstorms occur mainly in association with cold fronts and frontal depressions where the necessary uplift is provided by low-level convergence and the cold air undercutting the warm air as described in 3.3.1. Thunderstorms can also develop due to low-level convergence along sea-breeze fronts in the afternoon over land and along the retreating land-breeze front over the sea or large inland lakes before dawn.

3.5.1.3 Thunderstorms are usually composed of a cluster of several cells, each of which behaves as a unit of convective circulation, including both updrafts and downdrafts. Each cell goes through its own life cycle in a period of from one-half to one hour; these life cycles can be divided naturally into three stages (see Figure 3-8) depending upon the direction and magnitude of the predominating vertical air flow in the cell as follows:

a) cumulus or growing stage characterized by updrafts throughout the cell;

b) mature stage characterized by the presence of both updrafts and downdrafts; and

c) dissipating stage characterized by weak downdrafts throughout the cell.

Cell development within a thunderstorm can proceed at different rates, with some cells not completing their life cycle and others growing faster at their expense. In cases where two cells develop in close proximity to one another and where one is stronger, there is often a tendency for the cells to merge[22].

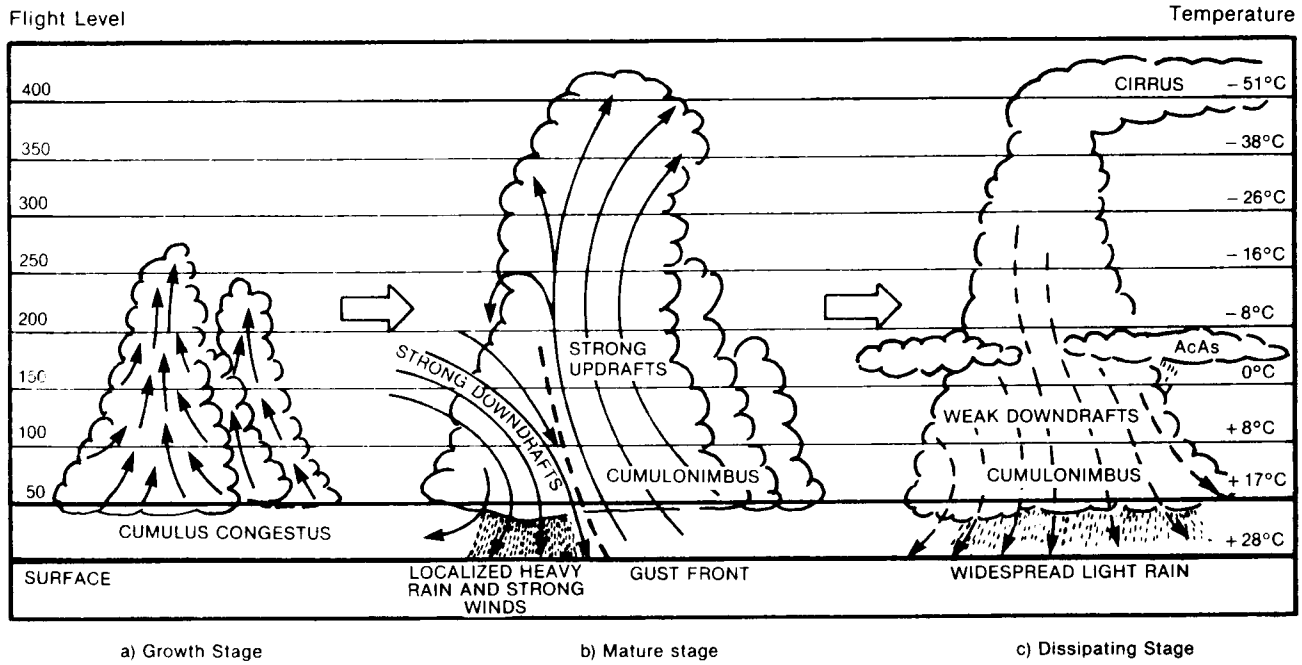


Figure 3-8. Life cycle of a thunderstorm

3.5.1.4 The air flow structure in and around a thunderstorm has been understood, at least in a general way, since the 1940s, particularly following the important "Thunderstorm Project" conducted in the United States in 1946-47[23], and more recent research has served largely to confirm these general ideas. In the past decade or so the use of multiple Doppler radars to monitor the air flow both in clear air and in cloud (see 5.1.2.3.3) and the computer simulation[24] of thunderstorm dynamics has enabled researchers to analyse the structure of the air flow in extremely fine detail (see Figure 5-12). As might be expected, the results show the thunderstorm to be a complex yet elegant and efficient thermodynamic mechanism. The detailed structure of the mature thunderstorm cell consists of a system of well organized and synergistic updrafts and downdrafts which intertwine and interact so as to exploit most efficiently the excess energy available from local heat and moisture surpluses. The fact that the air flow within and around mature thunderstorms is concentrated into such strong air currents is of extreme importance to aviation.

3.5.1.5 The cellular structure and the degree of cellular organization exhibited by thunderstorms has proved to be a feature which frequently is identifiable on radar (particularly Doppler radar) and relates, in a reasonably systematic way, to the severity of the thunderstorm[25]. In general, the more organized the cellular structure the more severe the thunderstorm. This feature provides the basis for a rather more detailed classification of thunderstorms than has hitherto been possible, with one such possible classification shown in Figure 3-9. The degree to which the cells of a thunderstorm become organized, which in turn relates to the intensity of the storm, ultimately depends on a number of interrelated meteorological factors including the stability of the atmosphere, the airflow convergence and divergence at various levels of the atmosphere and the wind flow profile with height. Recent research indicates that of

these factors, wind profile (i.e. the wind shear in the vertical) and instability are perhaps the most critical in determining the intensity of the storm[66]. Given sufficient instability, low-altitude convergence and humidity in the atmosphere, the intensity of a thunderstorm tends to increase according to the extent that the wind increases and veers (northern hemisphere) with height. With increasing vertical wind shear, the storm type tends to change from short-lived and loosely organized single cells through organized multicells to "supercell (unicellular) storms". There is, however, a natural upper limit, and in conditions of extremely high values of vertical wind shear, the storm cell can be so severely sheared that the cellular organization finally breaks down. There appears to be an optimum combination of instability and vertical shear which is particularly favourable for the development of supercell storms[26,27,67]. As indicated in Figure 3-9, such storms can cause tremendous damage both directly in the form of extensive hail, and indirectly, due to the severe downbursts and tornadoes which they spawn (see 3.5.5).

3.5.1.6 The localized updraft areas on which the initiation of thunderstorm development depends are generated and maintained by any one or all of a number of sources, including surface heating, low-level air flow convergence and frontal or orographic lifting, etc. The height to which the updrafts penetrate and the formation of cloud depend mainly upon the stability, humidity and wind profile of the atmosphere. In a developing thunderstorm cell, as the updrafts rise above the cloud base the cloud water droplets grow rapidly by coalescence and condensation and begin to freeze until eventually the droplets become so heavy that they fall back through the updraft becoming even heavier as they sweep up more ascending water droplets. This is the origin of the downdraft currents which at this stage are accelerating under the influence of gravity. However, as the downdrafts reach lower levels, drier air is entrained into the downdraft current from outside the cloud, especially from around the freezing level, which causes evaporation from the descending droplets, rapidly cooling the surrounding air and thus further accelerating the downdraft current[28]. Those water droplets in the downdraft which do not evaporate completely fall out of the base of the cumulonimbus cloud as heavy, localized rain accompanied by strong, gusty winds from the descending cold air current. Downdrafts which are strong enough to penetrate below the cloud base spread out horizontally in all directions just before reaching the ground as a cold current the leading edge of which resembles a shallow cold front, usually referred to as a "gust front". Downdrafts reaching the ground need not always be accompanied by heavy rain, although these latter are probably the most common type. Even when the descending water droplets evaporate entirely within the cloud or in the air just below the cloud base as "virga", the associated downdraft may still penetrate below the cloud base and reach ground level. The updraft and downdraft currents, especially those associated with severe storms are of immense importance to aviation. These features are examined in some detail in the remainder of the chapter.

	Type of thunderstorm			
	Air mass		Frontal	
Cellular structure	Loosely organized	Organized multicellular	Organized multicellular	Highly organized unicellular
Intensity	Moderate	Moderate to severe	Severe	Severe to very severe
Damaging phenomena likely to be associated with thunderstorm of particular concern to aircraft landing or taking off	Local strong gusty winds, downbursts possible but uncommon	Gust front, downbursts, waterspouts over large bodies of water, local hail	Gust front, downbursts, microbursts, waterspouts over large bodies of water, hail, tornadoes	Gust front, downbursts and microbursts, families of tornadoes, extensive hail
Examples	Random air mass development typically over maritime/oceanic areas or localized development near mountains, etc.	Often organized in lines especially in tropics (squall lines). Lines in tropical cyclones	Mainly frontal extratropical. May be organized in lines or mesoscale groups	Mainly frontal in mid latitude continental areas. "Supercell storms"
Movement	Generally with mean flow. Can be largely stationary when development occurs near mountains	With mean flow but sequential cell development can occur on one favoured flank giving impression of movement in that direction	With frontal movement, new cell development at gust fronts especially between existing cells	Most frequently to right of mean flow (occasionally splits into two storms). Infrequently remains stationary with disastrous local damage

Figure 3-9. Classification of thunderstorms

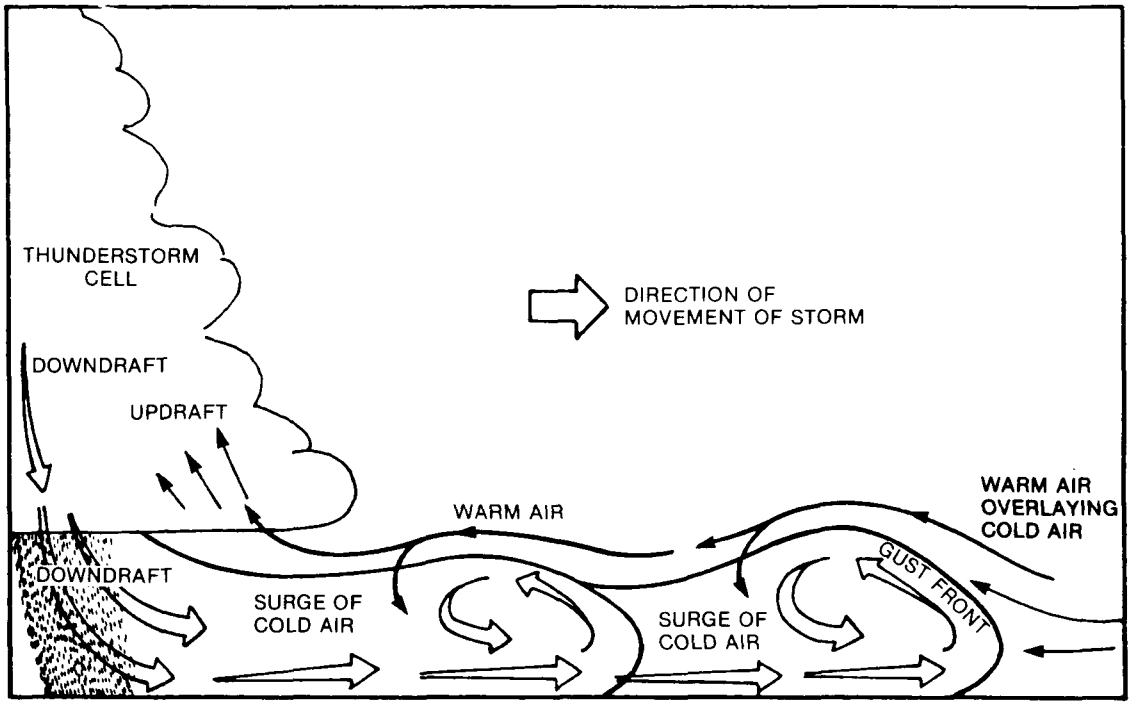


Figure 3-10. Cross section of typical gust front (after ICAO "gust front turbulence and wind shear" poster No. P621)

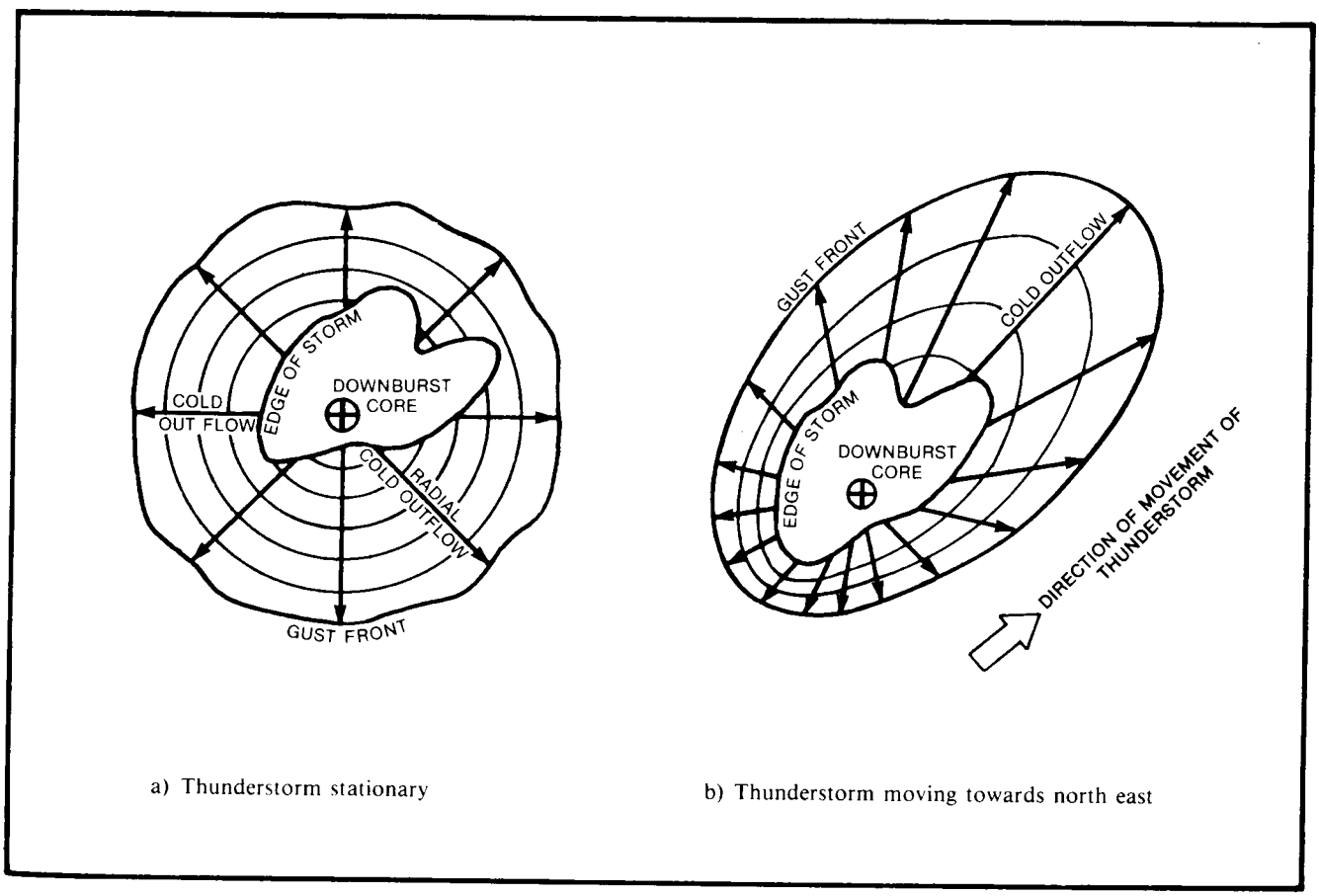
3.5.2 The gust front

3.5.2.1 Although the over-all effects of the gust front have long been known to meteorologists and pilots and the term itself has been used since at least the early 1960s, detailed knowledge of the structure of the system is relatively recent[29]. The gust front is the leading edge of the cold, dense air from a thunderstorm downdraft which reaches the ground and spreads out in all directions, undercutting the surrounding warmer and less dense air (see Figure 3-10). In this respect it resembles a shallow cold front except that the associated wind speeds, wind shear and turbulence are generally far higher in the gust front. The gust front initially travels along the ground equally in all directions; however, if the thunderstorm cell itself is moving, as is generally the case, the gust front advances furthest and fastest ahead of the storm in the direction of the storm's movement (see Figure 3-11). This effect may be accentuated if, as often happens, the cold downdraft strikes the ground at an angle instead of vertically, thus favouring a particular direction for the advance of the cold outflow. There is marked horizontal wind shear at ground level following the passage of the leading edge of the front, and as the front may move as far as 20 km ahead of the parent storm cell, such a sudden change in the surface wind may take pilots completely by surprise. The change in surface wind direction is often as much as 180° and the speed of the gusting winds following passage of the front can exceed 50 kt.

3.5.2.2 Thunderstorms often develop in organized lines, especially in the tropics, and the gust fronts formed from such squall lines tend to be longer-lived and move much faster and further from the parent storms (up to 35 km) than those generated by individual thunderstorms. Extremely well-organized squall lines are a typical feature of the rainy season throughout West Africa.[30] The depth of the cold air in the gust front can reach up to 1 000 m (3 200 ft) and there can be vertical wind shear all along

the dividing surface between the cold and warm air. As in the case of a cold front, friction tends to slow down the cold air nearest the ground, thus permitting the cold air at about 200 m (600 ft) above ground level to push ahead, forming a "nose". Within the nose, circulations or vortices develop in which, and in the wake of which, wind shear and turbulence are particularly intense. A cell may produce a series of downdrafts and associated surges of cold air, each forming a nose and each following in the wake of its predecessor.

3.5.2.3 Although gust fronts normally form and travel in clear air with nothing visible to mark their development and passage, sometimes the overriding warm air, if sufficiently moist, produces a line of smooth, shiny, almost meringue-like roll cloud above the gust front nose which, girding the base of the storm and advancing ahead of the rain belt, always looks particularly turbulent and threatening. In certain regions the downdrafts, and especially the vortices within the gust front nose, cause rising dust or sand which forms into a spectacular travelling wall of sand. Such instances are the well-known "Haboobs" of the Sudan and the "Andhi" of northwest India[31]. There are cases of gust fronts having been observed as a thin but distinct line or arc (sometimes referred to as an "angel") on ground-based weather radar and squall lines have been



a) Thunderstorm stationary

b) Thunderstorm moving towards north east

Figure 3-11. Plan views of typical gust fronts

observed on satellite pictures. Gust fronts can best be detected by use of Doppler radar, although for this method to be effective automated detection techniques have to be employed and these are still undergoing development (see 5.1.2.3.3.3)[32].

3.5.3 The downburst

3.5.3.1 The explanation for the development of strong downdrafts in mature thunderstorm cells given in 3.5.1.6 accounts reasonably well for the majority of downdraft and gust front phenomena actually observed, but there are at least two phenomena for which the explanation is not entirely satisfactory. The first is that, occasionally, very heavy and localized rainfall occurs in a thunderstorm with few if any associated downdrafts reaching the ground and no strong, gusty surface winds. The second is far more important as it lies at the other extreme: sometimes the downdraft wind speeds observed and inferred from tree damage surveys have reached extremely high values and yet the associated rainfall intensity appeared no higher than in the usual downdrafts.

3.5.3.2 The detailed survey of damage caused by winds during a thunderstorm, showing the directions in which trees, corn, wheat, etc. had been felled by the wind, was employed as early as 1947 by Faust. From these surveys he was able to infer the characteristics and intensity of the winds concerned. This technique was also employed by Fujita, who when examining a particularly severe outbreak of tornadoes in 1974, observed that some distance away from the tornado paths, trees in forests were blown over in radial directions, as if they had been blown outward. It was suspected that these trees were pushed or felled by strong winds which blew outward from the outburst centre (see Figure 3-12)[33]. Byers and Fujita (1976) classified such an intense downdraft as a "downburst", defined as "a localized, intense downdraft with vertical currents exceeding a downward speed of 12 ft per second or 720 ft per minute at 300 ft above the surface"[33]. By 1978, Fujita had generalized the definition to the following: "a strong downdraft inducing an outward burst of damaging winds on or near the ground". From the extent of the tree damage associated with such downbursts, it was clear that very strong winds could reach ground level and that the area affected was comparatively small, certainly small enough to be missed completely by normal operational observing systems.

3.5.3.3 A number of explanations have been proposed to account for the marked differences (e.g. downdraft and outflow speeds) between the ordinary thunderstorm downdraft as described in 3.5.1.6 and the downburst as postulated, and since conclusively found, by Fujita. At one extreme, the downburst is considered to be a "super-downdraft" originating at very high levels in the thunderstorm, whilst at the other extreme the downburst is said to originate in the middle levels of the atmosphere. The latter explanation does appear to agree with observation and simulation of the "supercell storms" (see 3.5.6.1). An interesting comparative review of the various explanations is given by Wolfson[34], but she concludes that, while all are plausible, none of the mechanisms proposed has so far been demonstrated to be the actual cause of downbursts. A comprehensive review of the current (1985) state of knowledge on the downburst can be found in Fujita's book "The Downburst" (see bibliography).

3.5.3.3 Increased attention was focused on the hazardous nature of downbursts, especially with respect to aviation, following the Eastern Airlines B727 Flight 66 accident at New York's John F. Kennedy International Airport on 24 June 1975. A detailed analysis of the thunderstorms which had occurred over the airport at the time of the accident was prepared by Dr. Fujita, in which he put forward a scenario based on

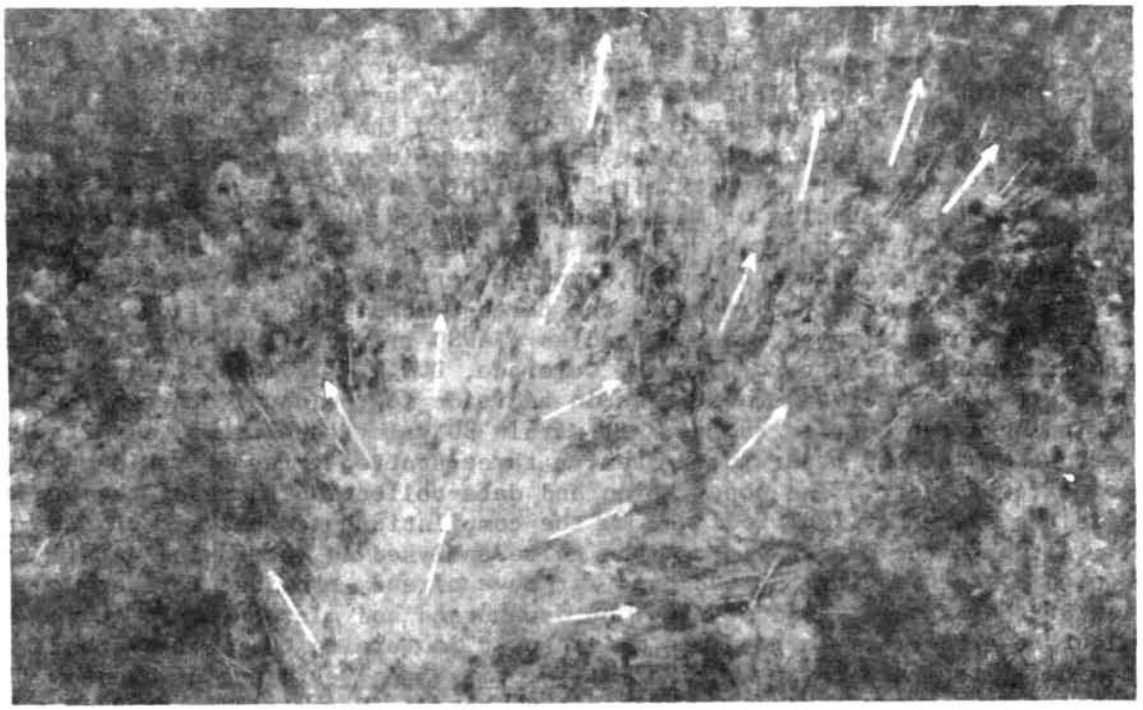


Figure 3-12. Over 300 trees blown over by an intense outburst near Beckley, West Virginia, U.S.A. Similar patterns of trees were photographed by the author at numerous locations along the paths of tornadic thunderstorms of 3 April 1974, the day of the super-outbreak tornadoes (from Fujita, 1976)

the existence of a series of downbursts to account for the sequence of events on that fateful day. He concluded that "the research results and the speculation regarding the phenomena presented in this paper suggest the existence of downburst cells in specific thunderstorms. These cells are likely to be characterized by spearhead [radar] echoes, a definition newly introduced in this paper. About 2 per cent of the echoes in the New York area, the principal site involved in this research, were spearhead echoes."[33]

3.5.4 The microburst

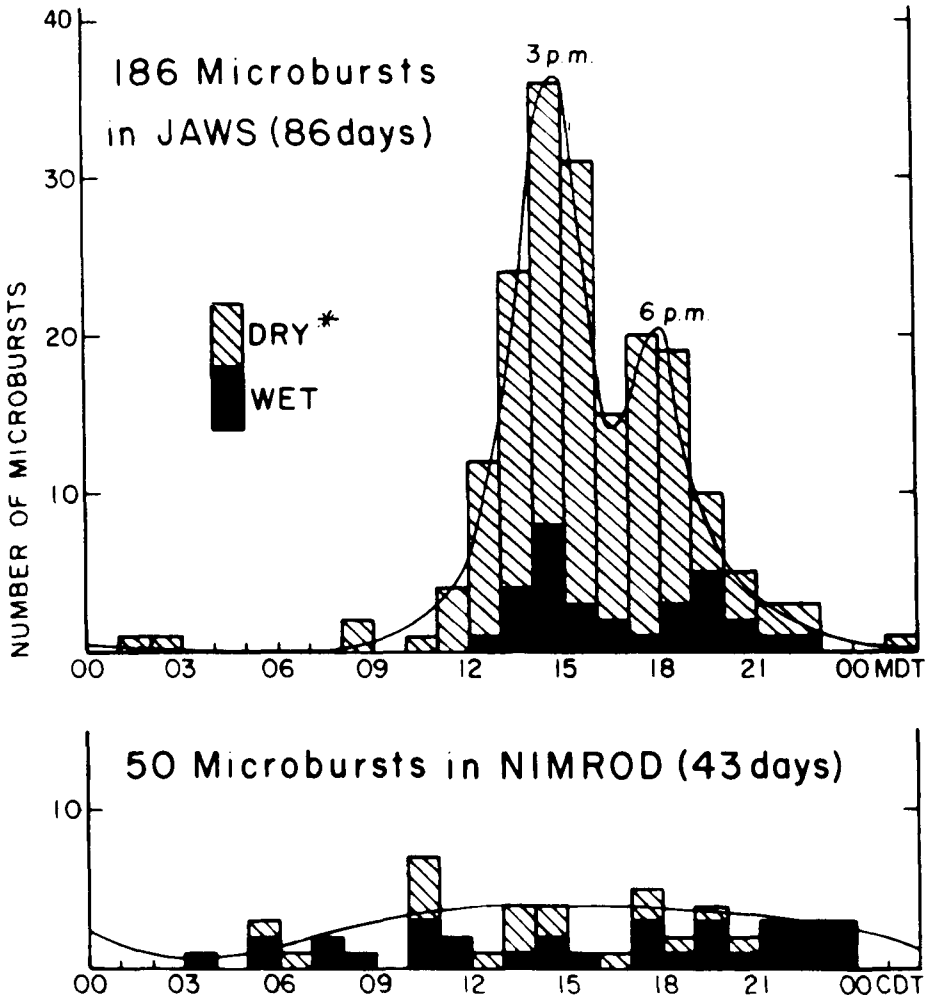
3.5.4.1 In the course of further research, it became apparent from the examination of damage patterns following downbursts that, embedded within the main downburst outflow field, often there was evidence of smaller but even more intense downbursts. These small but very intense downbursts were given the name "microbursts" by Fujita and defined as "a downdraft that induces a sudden outflow of damaging horizontal winds at the surface with a horizontal extent between 0.4 and 4 km"[35]. The small scale of the microburst, both in space and time, renders it almost impossible to observe with present observation systems. Unfortunately, this particular scale also happens to be the most important from the point of view of aviation, lending considerable urgency to research on thunderstorm dynamics. Microbursts can occur singly or in "families", may or may not

be accompanied by rain and, although they are most frequently associated with severe thunderstorms, can be produced by any convective cloud.

3.5.4.2 In order to advance this research, a two-year data collection project called project NIMROD (Northern Illinois Meteorological Research on Downburst)[35] was mounted jointly in 1978 by the University of Chicago and the National Weather Service in the United States. During this period, the existence of downburst phenomena was confirmed and the first measurements of air flow within microbursts were obtained by Doppler radar; due to the spacing of the three radars used, however, only single-Doppler analysis was possible*. The next objective was to obtain data on the actual winds in and around downbursts/microbursts by using, among other things, multiple Doppler radars in sufficiently close proximity to measure the three-dimensional wind flow. To meet this objective the Joint Airport Weather Studies (JAWS) project (1982-84) was organized at Stapleton International Airport, Denver, Colorado, U.S.A.[36]. This project employed an impressive array of observing facilities in addition to the usual observation network, including three Doppler radars, all within 30 km of each other, a portable automated mesonetwork (PAM) observing system, a three-station array of rawinsondes, instrumented aircraft, etc. The observation and data-collection phase of the project took place in the summer of 1982 followed by the compilation and analysis of data phase in 1983-84. Although the data will continue to be analysed in increasing detail for some time to come, the results published so far have already provided further confirmation of the existence and severity of downbursts and microbursts. At the same time, as might be expected, the downburst/microburst is turning out to be rather more complex than had first been thought. There is, for example, evidence of even smaller and more intense structures embedded within microbursts. These tend to produce a long and narrow pattern of damage within the over-all outflow much the same as tornado damage. Fujita has coined the term "burst swath" to describe these structures.

3.5.4.3 A total of at least 236 microburst "fish", so to speak, were caught in the NIMROD and JAWS observation "nets", and their diurnal frequency during the projects is shown in Figure 3-13. The frequency of microbursts causing selected maximum surface wind speed differences measured in the 186 JAWS microbursts is given in Figure 3-14. "Dry" microbursts accounted for 36 per cent of those observed in the NIMROD project and 83 per cent of those observed in the JAWS project[37]. The high percentage of dry microbursts was rather surprising, although the climatology of the area concerned is noted for its high-base thunderstorms developing in comparatively dry upper air conditions. In the more humid areas, e.g. in the south-east United States, the majority of microbursts are of the "wet" variety. An example of the wind fields associated with one JAWS microburst is given in Figure 3-15[38], indicating the possible existence of a vortex ring around the microburst which could explain the rapid intensification of the downdraft and account for its concentrated and localized nature. It has been suggested that a series of such vortex rings may be formed as shown in Figures 3-16[39,40]. The probable sequence and scale of events in the development of a microburst, as derived from the analysis of the JAWS data, is illustrated in Figure 3-17[41]. Of particular interest is the short lifespan of the microburst, which generally reaches maximum intensity within 10 minutes. As a direct follow-up and practical application of the results of the JAWS project, the U.S. National Centre for

* As is explained in Chapter 5, in order to measure all three components of the actual wind remotely by Doppler radar, at least two radars must observe the same volume of the atmosphere simultaneously. One radar alone simply provides data on the radial velocity of the air in relation to the radar.



* Wet microbursts: Equal to or greater than 0.01 inches of rain during the period of peak winds.

Dry microbursts: Less than 0.01 inches of rain between both the onset of high winds and the end of the microburst winds including the calm period if any.

Figure 3-13. Diurnal variation of surface microbursts of all intensities measured at the 27 PAM stations (from Fujita and Wakimoto, 1983)

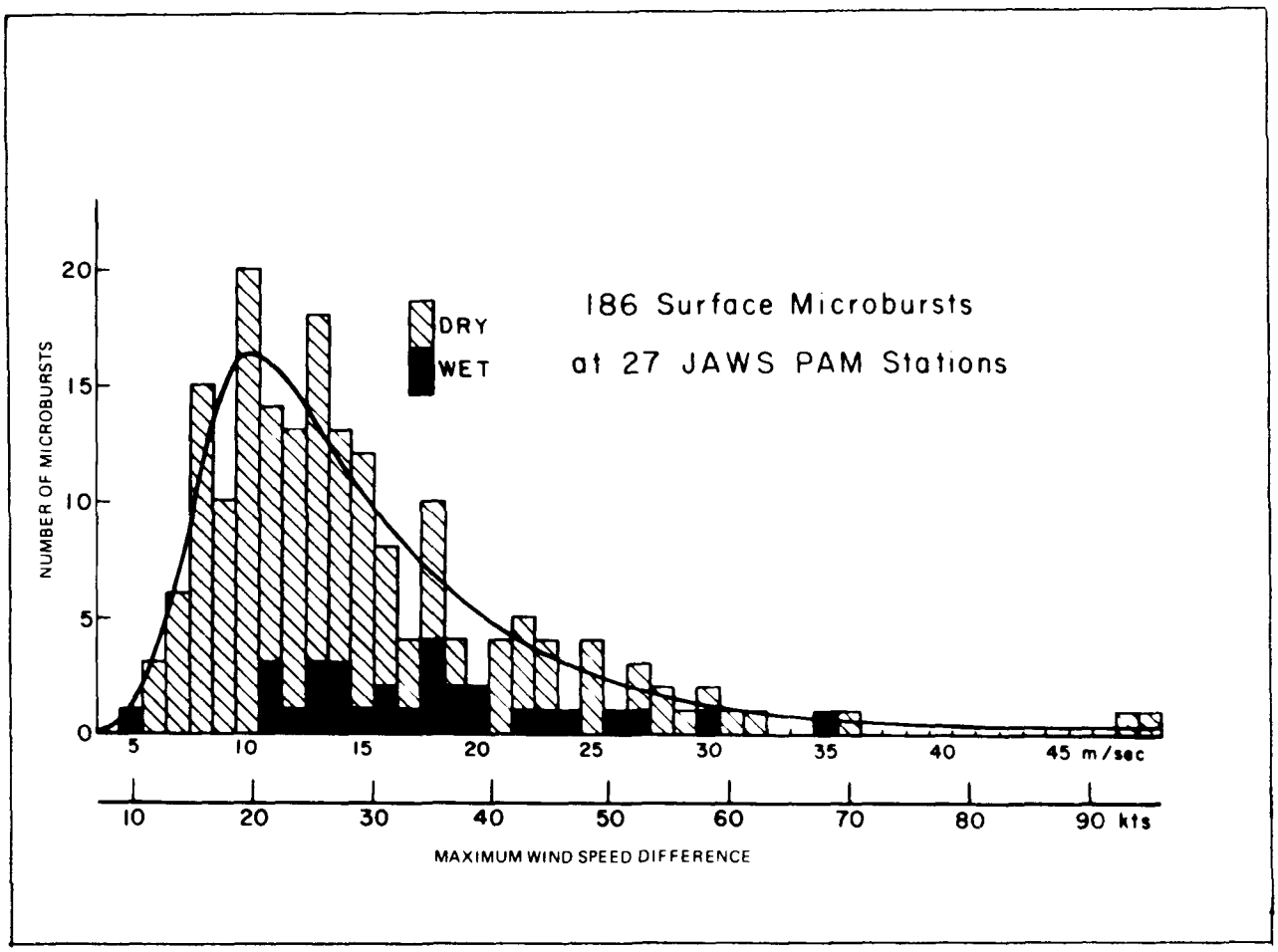


Figure 3-14. Frequency of surface microbursts as a function of the maximum wind speed difference measured at the 27 PAM stations (from Fujita and Wakimoto, 1983)

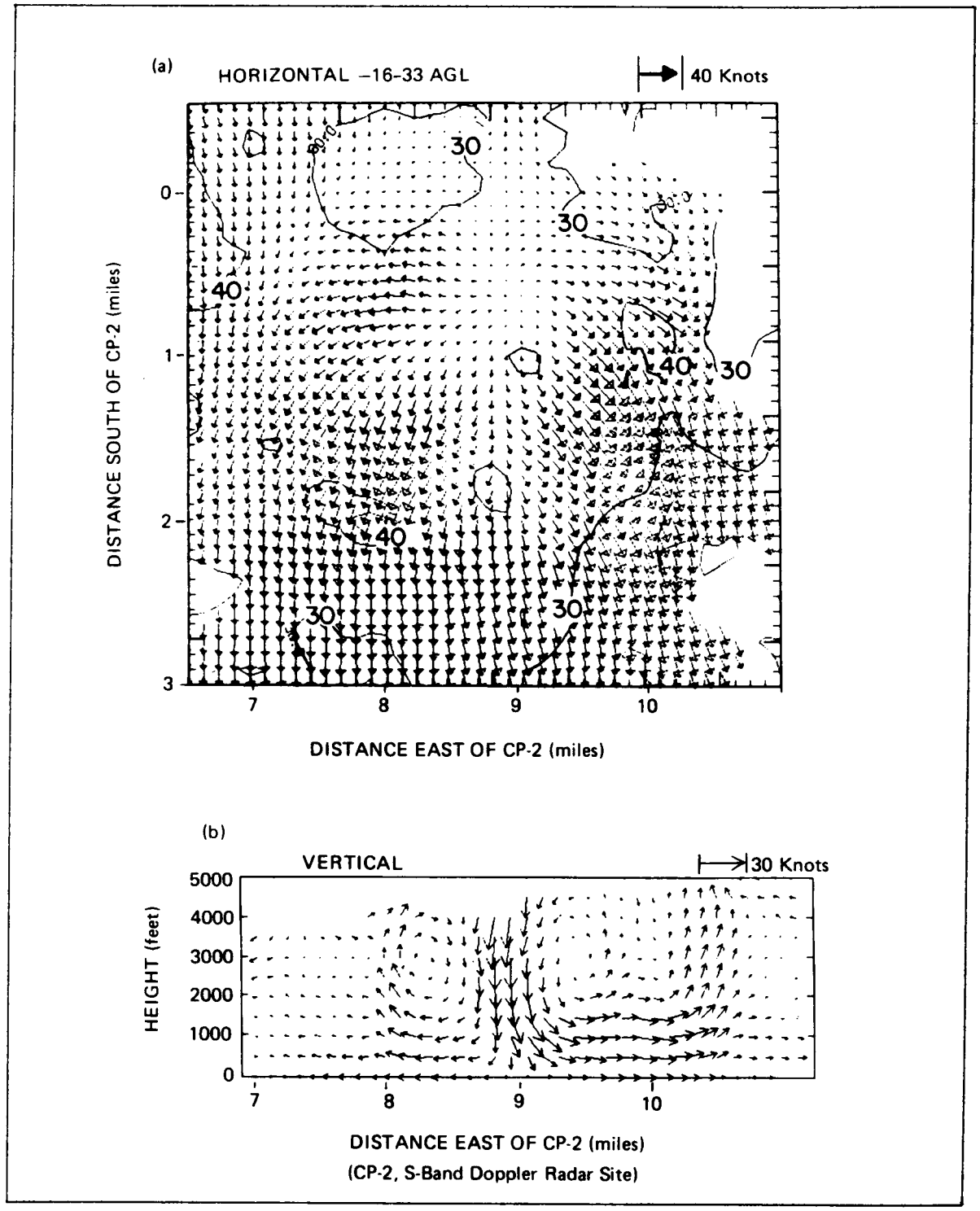
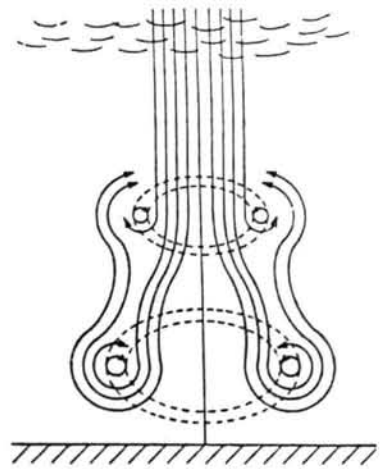
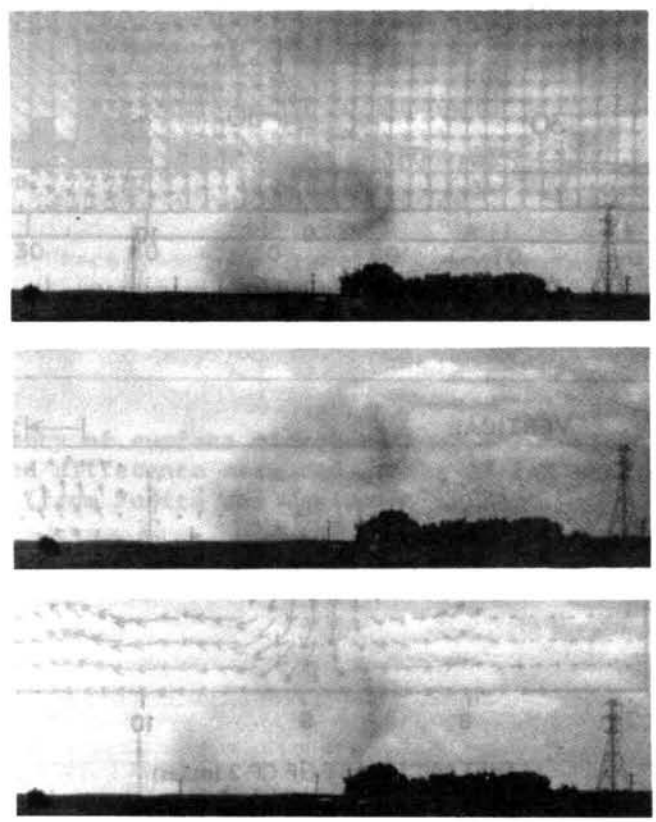


Figure 3-15. Velocity fields with respect to the ground, based on a dual Doppler analysis for a microburst occurring at 1452 MDT on 14 July 1982. Contours are radar reflectivity factors (dBZ_e) (from Wilson and Roberts, 1983)



a) Thunderstorm downburst - vortex ring flow model
(from Woodfield and Vaughan, 1984 after Caracena)



b) Vortex ring circulation associated with leading edge of
a microburst (from Fujita & Smith, University of Chicago, 1983)

Figure 3-16

Atmospheric Research (NCAR) and the FAA carried out a program of research termed CLAWS (Classify, Locate, Avoid Wind Shear) aimed at improving aircraft safety. CLAWS concentrated on detection and forecasting of microbursts at Denver's Stapleton Airport in order to provide pilots and air traffic services units with real-time advisory forecasts of wind shear and develop the necessary operational procedures[42]. In the course of the project (between 2 July and 15 August 1984 and from 1100 to 2000 local time) the following advice was issued:

Microburst advisories	30
Line of microbursts advisories	5
Wind shift (or gust front) advisories	32
Tornado advisories	1

Advice given to ATC concerning wind shifts on the runways was of considerable assistance to controllers in choosing appropriate runways for take-off or landing. The initial analysis of the project according to McCarthy and Wilson (1985)[42] was as follows:

a) the capability of Doppler radar to provide advance warning of microbursts and wind shifts was clearly demonstrated;

b) pilots clearly stated their need for accurate quantitative estimates of actual wind shear along the approach/departure runways, rather than a semi-qualitative indication of microburst location;

c) the area of aviation microburst warnings could be greatly reduced to the immediate region of the aircraft approach/departure operations.

A report on the operational aspects of the project has been produced by the FAA[43]. The report concluded that CLAWS provided the FAA with the opportunity to gauge the operational usefulness of two very simple Doppler radar-based products for control tower use, i.e. the microburst and gust front advisories. The project demonstrated the usefulness of these two products at Stapleton Airport - even in their present, primitive forms. It also provided a pool of operational experience in the use of these products.

3.5.4.4 In addition to the continued analysis of the mass of data collected during the JAWS project, further research on microbursts is planned under a new project termed "MIST" (MIcroburst and Severe Thunderstorm). This project, which is to be conducted jointly by the National Aeronautics and Space Administration (NASA), the University of Chicago and the Marshall Space Flight Centre at Huntsville, Alabama, U.S.A. will employ up to 5 multiple Doppler radars and 55 PAM observing stations, as well as rawinsondes launched hourly during storm days (see 6.4).

3.5.5 The tornado

3.5.5.1 Strong and dangerous though the winds generated by microbursts undoubtedly are, the accolade for the generation of the strongest surface winds of all must go to the tornado. In many respects the tornado is the antithesis of the microburst, in that the former results from an extremely concentrated low-pressure system whose vortex literally sucks in the surrounding air, whilst the latter is a localized high pressure system in which the low-level winds diverge from the microburst centre. The generalized structure and scale of the various pressure systems which produce damaging surface winds, their classification in the context of commonly accepted planetary scales and the

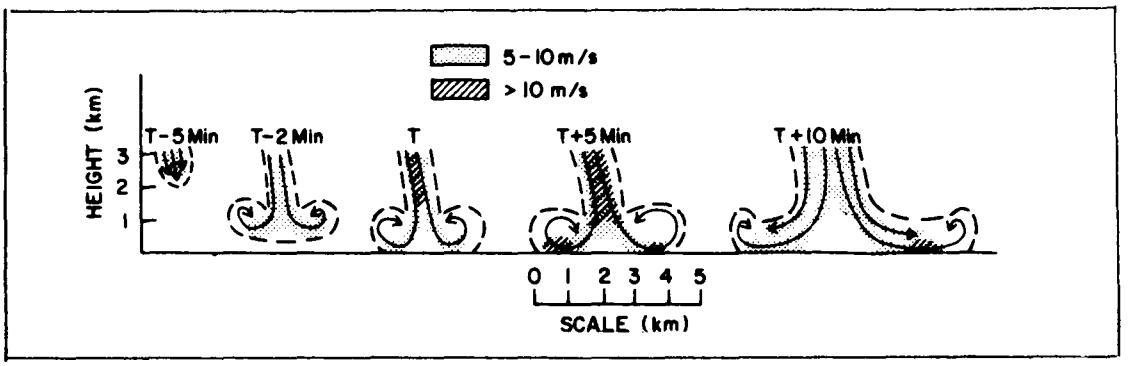
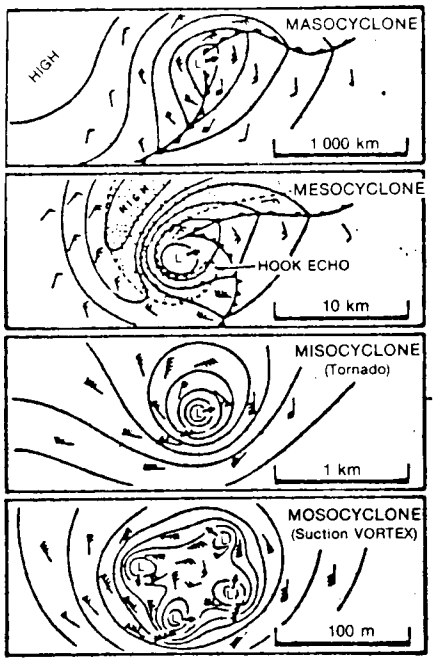


Figure 3-17. Vertical cross-section of the evolution of the microburst wind field; T is the time of initial divergence at the surface. The shading denotes the vector wind speeds (from Wilson, Roberts, Kessinger and McCarthy, 1984)

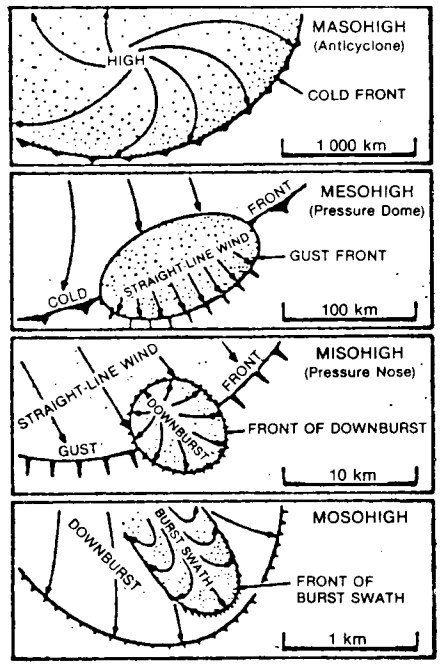
expected maximum wind speeds as proposed by Fujita (1981) are shown in Figure 3-18[44]. In this figure the maximum wind speeds are also related to the "F-scale" which is based on the scale of damage caused by six classes of wind speed F0 (18-32 m/s) through F5 (117-142 m/s).

3.5.5.2 Tornadoes are produced in the concentrated and persistent updrafts of severe thunderstorms. Such severe thunderstorms are generally of the same type as those which produce microbursts, with tornadoes forming in the updrafts and microbursts and gust fronts forming in the downdrafts. There is, of course, considerably more to it than this, because tornadoes do not necessarily develop in all severe thunderstorms. Indeed, one of the most important questions facing research meteorologists today is why some severe thunderstorms generate tornadoes whilst others do not. A good description of a tornado given by Snow[45] is as follows: "A tornado is a vortex: air rotates around the tornado's [vertical] axis about as fast as it moves towards and (upwards) along the axis. Drawn by greatly reduced atmospheric pressure in the central core, air streams into the base of the vortex from all directions through a shallow layer a few tens of metres deep near the ground. In the base the air turns abruptly to spiral upwards around the core and finally merges, at the hidden upper end of the tornado, with the air flow in the parent cloud. The pressure in the core may be as much as 10 per cent less than that of the surrounding atmosphere: about the same difference as that between sea level and an altitude of 1 km. Winds in a tornado are almost always cyclonic." The sheer destructive power of a tornado is the result of a proportion of the vast amount of energy available in a severe thunderstorm being concentrated in an area usually no more than several hundred metres in diameter. The highest wind speed actually measured in a tornado was 67.5 m/s (135 kt)[44]; however, the analysis of tornado damage to engineered structures whose structural strength is known, the analysis of films of the motion of debris rotating in the tornado and the study of Doppler wind speed spectra indicates that maximum wind speeds almost certainly approach or even exceed 100 m/s (200 kt)[46 47].

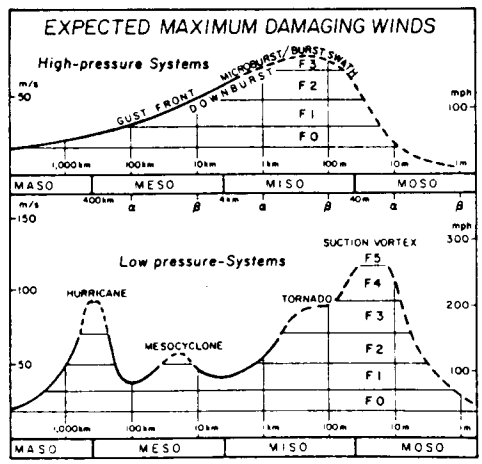
3.5.5.3 Most tornadoes (and all strong ones) form within "mesocyclones"* (see Figure 3-18 a)), which frequently are also associated with reports of heavy hail and damaging downburst winds[27]. As all mesocyclones do not produce tornadoes, the presence of a mesocyclone is clearly a necessary but not sufficient condition for tornado development.



a) Maso-, meso-, miso- and moso-cyclones in the context of generalized planetary scales. Sequence follows order of vowels a, e, i, o and u (from Fujita, 1981)



b) Maso-, meso-, miso- and mosohighs in the context of generalized planetary scales (from Fujita, 1981)



c) Expected maximum wind speeds plotted as functions of the scales of high- and low-pressure systems. It should be noted that the highest outburst winds occur in the misoscale downburst (microburst) while the maximum wind speed of tornadoes does not exceed 90 m/s outside the swaths of embedded suction vortices (from Fujita, 1981)

Figure 3-18

3.5.5.4 There is evidence from the analysis of tornado wind damage that there are intense, organized "suction vortices" even within the parent tornado. A model of such a tornado proposed by Fujita[44] is shown in Figure 3-19 (their scale is also indicated in Figure 3-18 a)). Frequently, a tornado first becomes visible as a "funnel cloud" hanging below the parent thunderstorm cloud. Usually the funnel cloud is cone-shaped but it can take many different forms, including long trailing rope-like features. Tornadoes developing over water take the form of "waterspouts"** and these have a far wider distribution throughout the world than tornadoes over land[48].

3.5.5.5 It would seem to be stating the obvious to say that tornadoes represent an extreme case of wind shear and a hazard to aircraft landing and taking off. It might also seem equally obvious that such hazards might be mitigated to some extent by the fact that:

a) tornadoes are generally visible and aircraft can be expected to be able to manoeuvre around them; and

b) although tornadoes have been reported from many areas of the world, they are most frequent in the central and south-eastern parts of the United States and therefore constitute a "known hazard" in those areas.

Whilst there is some truth to the foregoing it would be most unwise to take too lightly the danger which tornadoes pose to aviation, because tornadoes are not always visible. For example, they can form in the updrafts along the gust front ahead of a storm or can be embedded in cloud or heavy rain; they can also occur at night (see Chapter 4). Moreover, if a tornado moves across an aircraft's flight path, a hazard can still be present if the aircraft encounters the disturbed air and wind shear in the wake of the vortex or the tornado vortex in cloud (see 4.2.3.10).

3.5.6 The supercell storm

3.5.6.1 In 3.5.1.5 and in Figure 3-9, mention has been made of "supercell" storms. The main features which distinguish supercell storms from other severe thunderstorms are:

a) their unicellular nature;

b) the persistence of this predominant single cell in a quasi-steady state for comparatively long periods of time;

c) the extremely vigorous updrafts and downdrafts in the cell, both of which support the other in an almost life-like symbiotic relationship;

---

* A mesocyclone is a mesoscale cyclonic vortex with core diameter between 3 and 9 km which frequently produces a recognizable radar "signature".

** Waterspouts are of two types: one develops downward from cumulonimbus clouds and may be considered as a tornado over water; the other type builds upwards as a column of rotating water from the sea surface and is not directly associated with a cloud but more akin to the "dust devils" over land.

d) a tendency to move to the right of the mean wind flow; and

e) the phenomenal damage which can result from the associated hail and, in certain regions of the world, from the families of tornadoes and microbursts[49].

The term "supercell" was coined by Browning as long ago as 1962 in connexion with a very severe hailstorm which caused extensive damage near Wokingham, England in July 1959. The typical structure of a supercell storm, which has been developed in some detail since the advent of multiple Doppler radar observation of such storms and computer simulation[26], is shown diagrammatically in Figure 3-20[50].

3.5.6.2 Perhaps the single most important feature of the supercell storm is the very intense and quasi-steady state updraft fed by moist, potentially unstable air from low levels on the storm's right flank. The maximum speeds in the updraft have been estimated as being well in excess of 40 m/s (78 kt or nearly 8 000 feet/minute) and the updraft may persist and maintain a distinct identity for up to two hours. The air in the updraft also tends to rotate cyclonically as it rises, creating particularly favourable conditions for the formation of tornadoes.

3.5.6.3 The downdraft is most frequently encountered on the left flank of a supercell storm (i.e. in relation to direction of movement of the storm), fed by dry, potentially cold air from medium levels, with speeds similar to those in the updraft. It has been postulated that when the gust front produced by the downdraft propagates at roughly the same speed as the storm, the result could be a quasi-steady region of low-level convergence underneath the updraft which forces continuous uplifting of moist low-level inflow air along the right flank of the storm, thus sustaining the updraft.

3.5.6.4 The atmospheric prerequisites for the development of supercell thunderstorms given sufficiently unstable conditions are, as mentioned in 3.5.1.5, the wind veering (northern hemisphere) and increasing with height (shear $> 0.001\ s^{-1}$) and reasonably strong, but not too strong, winds at all levels. Very dry air aloft is conducive to the formation of severe hail. It is fortunate that supercell storms are not of widespread or frequent occurrence because the hail, microbursts and tornadoes associated with such storms present extreme danger to aircraft landing and taking off.

3.5.6.5 Recent research into incidents in which aircraft have encountered severe clear-air turbulence (CAT) and/or wind shear at cruise levels, which resulted in temporary loss of control causing an uncontrolled descent, indicates that such regions often lie downwind from an area of severe thunderstorms between flight levels 350 and 450. Whilst much more work needs to be done on this problem, initial indications are that the turbulence and wind shear may be caused by the severe thunderstorm tops, perhaps by interaction between the developing tops and nearby jet streams or the tropopause inversion. There are also grounds for believing that vortices or waves can develop for some distance downwind of thunderstorm tops[51]. It has been pointed out that, whereas aircraft flying into wind might expect to have some warning of wave-like disturbances ahead (i.e. upwind) as they first encounter the dissipating waves or vortices, those crossing, or travelling with the air stream, would have no such warning. Researchers at NASA's Ames Research Centre in California are attempting to develop a model for use on flight simulators which can reproduce the effects on different types of aircraft.

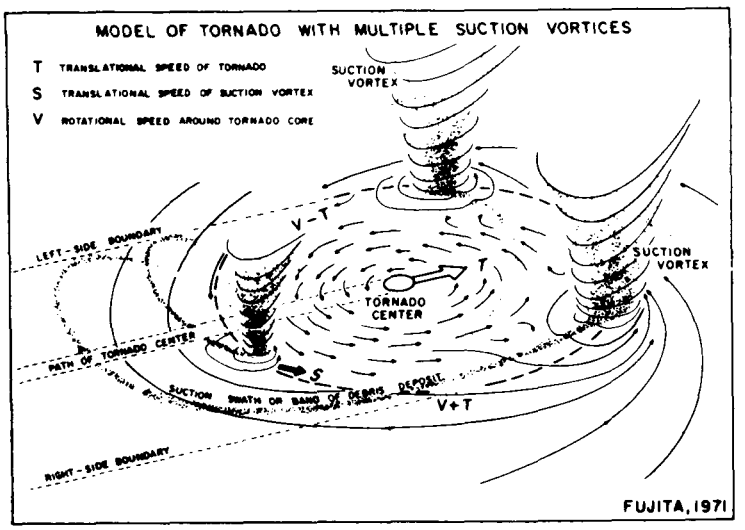


Figure 3-19. A model of a tornado with multiple suction vortices (from Fujita, 1971)

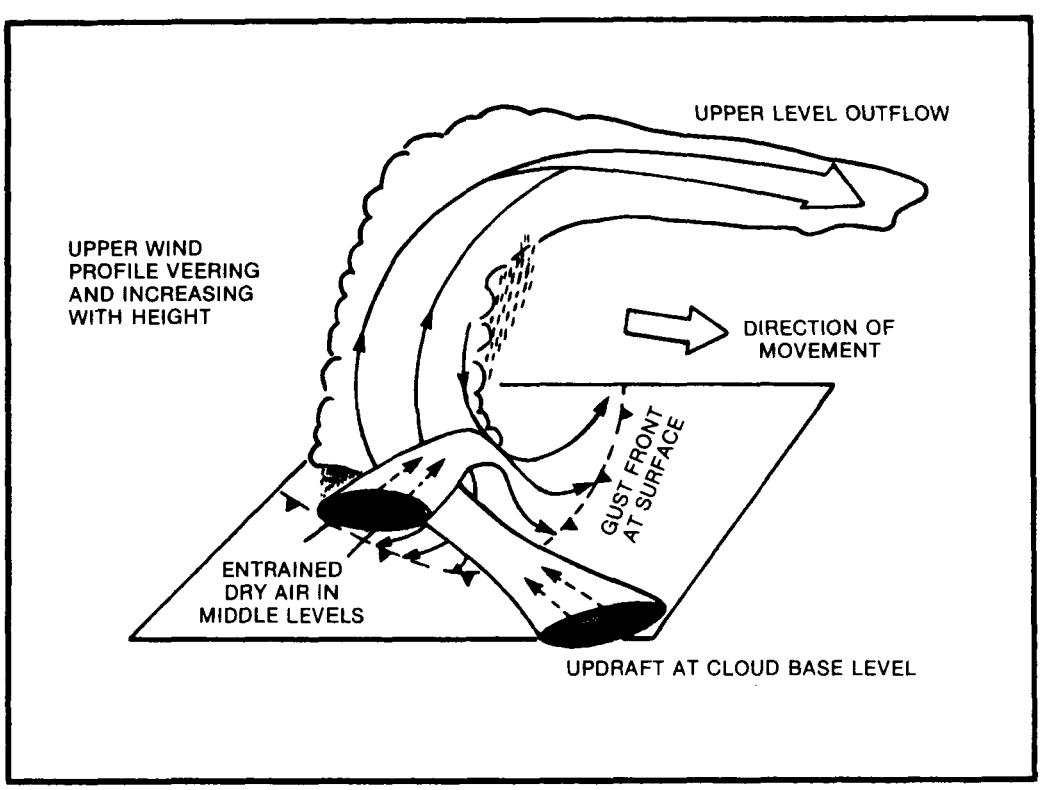


Figure 3-20. Diagrammatic structure of a "supercell" thunderstorm (after A.J. Thorpe, 1981)

3.6 CLIMATOLOGY OF CONVECTIVE WIND SHEAR

3.6.1 The annual frequency distribution of thunderstorms throughout the world is shown in Figure 3-21[52] and a more detailed illustration of the distribution over the United States shown in Figure 3-22[53]. The thunderstorm regions of the United States and their associated diurnal and seasonal variation of thunderstorm activity are shown in Figure 3-23[54]. The world distribution of accidents/incidents where microbursts were confirmed or suspected to have been a factor is shown in Figure 3-24[55] and the paths of confirmed violent tornadoes reported over the United States during the period 1880-1982 are shown in Figure 3-25[56]. Reference to Figure 3-21 shows that thunderstorms are most frequent over tropical continental regions. It is well known, however, that the distribution of tornadoes does not follow this pattern. Although tornadoes occasionally occur in many regions of the world and waterspouts over lakes and oceans are probably of even wider distribution, most tornadoes occur in the central and south-eastern parts of the United States. The world-wide distribution of microbursts is not known, mainly because they are generally not visible directly and even their effects, such as forest or crop damage on the ground, are not likely to be recognized as having been due to a microburst unless detailed aerial damage surveys are made. Microbursts as such have only achieved notoriety in the past ten years or so due to their having been implicated in a number of aircraft accidents/incidents, and their apparent distribution is consequently weighted towards busy air traffic terminal areas. Although microbursts are fairly common, their relatively small size and short duration ensures that the probability of an aircraft encountering one during landing or take-off is low, but as several major accidents indicate, by no means insignificant.

3.7 STATISTICS OF LOW-LEVEL WIND SHEAR IN THE VICINITY OF AERODROMES

3.7.1 A considerable body of world-wide data on low-level wind shear in the vicinity of aerodromes has been derived from the airborne integrated data systems (AIDS) on board British Airways (BA)[57] and Royal Dutch Airlines (KLM)[58] [59] wide-bodied jet aircraft (BA B747s and KLM B747s and DC10s). Up to 1984, the data base comprised 10 000 landings by KLM aircraft of which so far 8 573 have been analysed* and selected data published, and 9 136 landings by BA aircraft all of which have been analysed and the results published. A similar project was initiated in the Federal Republic of Germany whereby AIDS data was collected from Deutsche Lufthansa Airbus A300 aircraft for a period of one year, stored and then analysed[61].

3.7.2 The data from the BA landings have been analysed by the Royal Aircraft Establishment (RAE), Bedford, United Kingdom using discrete gust methods. The statistics on the one in a thousand probability of encountering wind shears with particular patterns of headwind speed changes calculated from over 9 000 BA landings are shown in Figure 3-26[57]. With respect to the KLM data, detailed analysis pertaining to 1 909 landings at Schiphol Airport, Amsterdam and an analysis of world-wide "worst-case airports" have so far been published. From this data various probability statistics

* The analysis of the remainder has since been published by the Netherlands National Aerospace Laboratory (1984) together with an assessment of various airborne wind shear detection equipment. The publication is available in Dutch with a summary in English.[60]

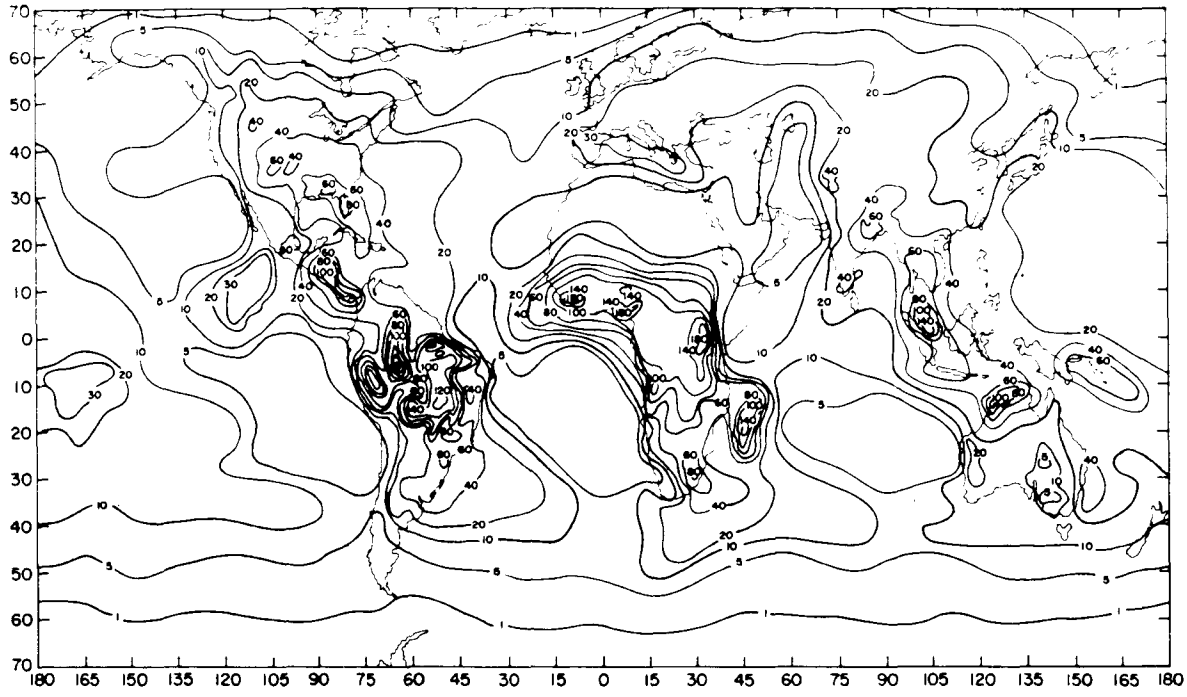


Figure 3-21. Average annual world-wide thunderstorm days (source: WMO Publication No. 21 TP21, 1956)

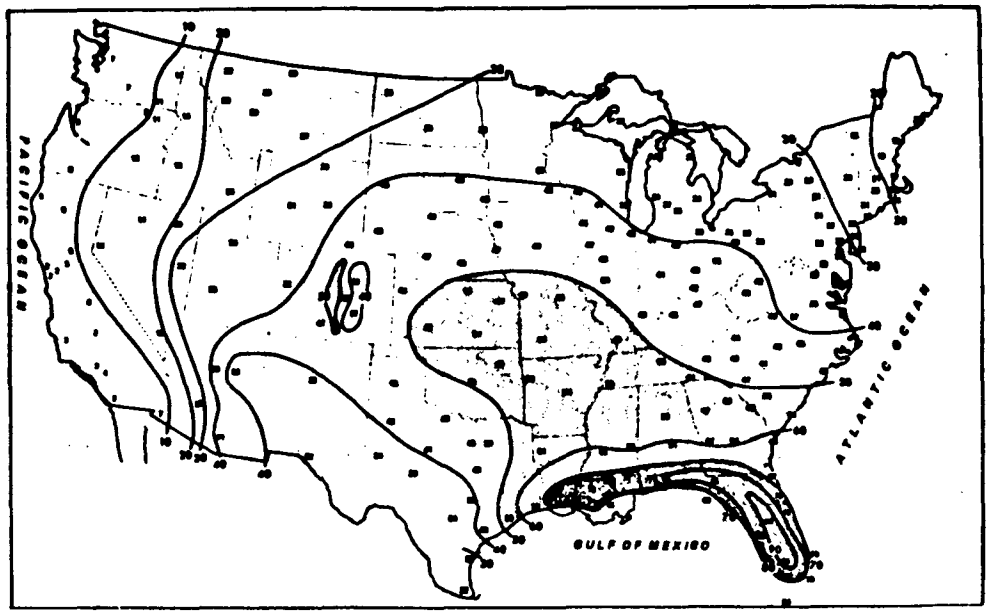


Figure 3-22. Mean number of days per year with thunderstorms, 1951-1975 (from Court and Griffiths, 1982)

Region	Spring		Summer		Fall		Winter	
	t	a	t	a	t	a	t	a
West Coast	A	H	–	–	A/N	L/M	A/N	M
Inter-Montane	A	H	A/N	H	A	A	–	–
Western Plains	A/N	M/H	A/N	M/H	A/N	M/H	–	–
Central	N	L	N	L	N	L	–	–
Great Lakes	N	L	N	L	N	L	N	L
Northeast	A	M	A	M	A	M	–	–
Southeast	A	L/M	A	H	A	M	N	L
Peninsula Florida	A	M	A	H	A	H	A	L
Gulf Coast	M/A/N	L	M/A	M/H	M/A	M	N/M	L

t - timing: M - morning, A - afternoon, N - night

a - amplitude: L - low (≤0.5), M - medium (0.5-1.0), H - high (>1.0)

Figure 3-23. Thunderstorm regions of the United States (from Easterling and Robinson, 1985)

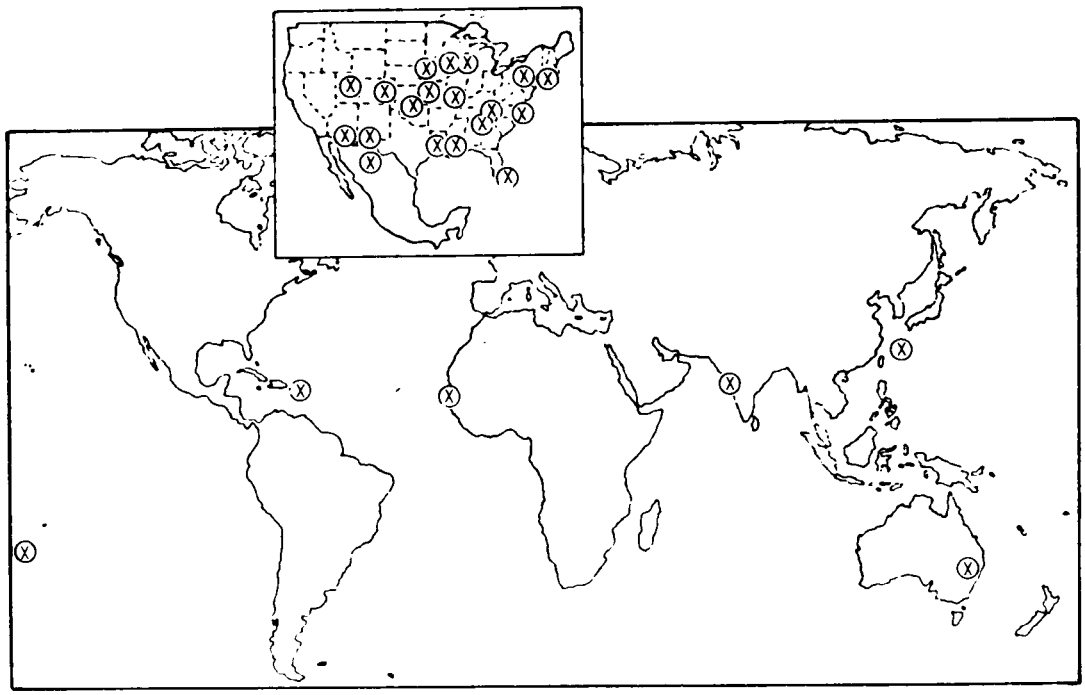


Figure 3-24. Distribution of accidents/incidents in which microbursts have been confirmed or suspected (from McCarthy and Wilson, 1984)

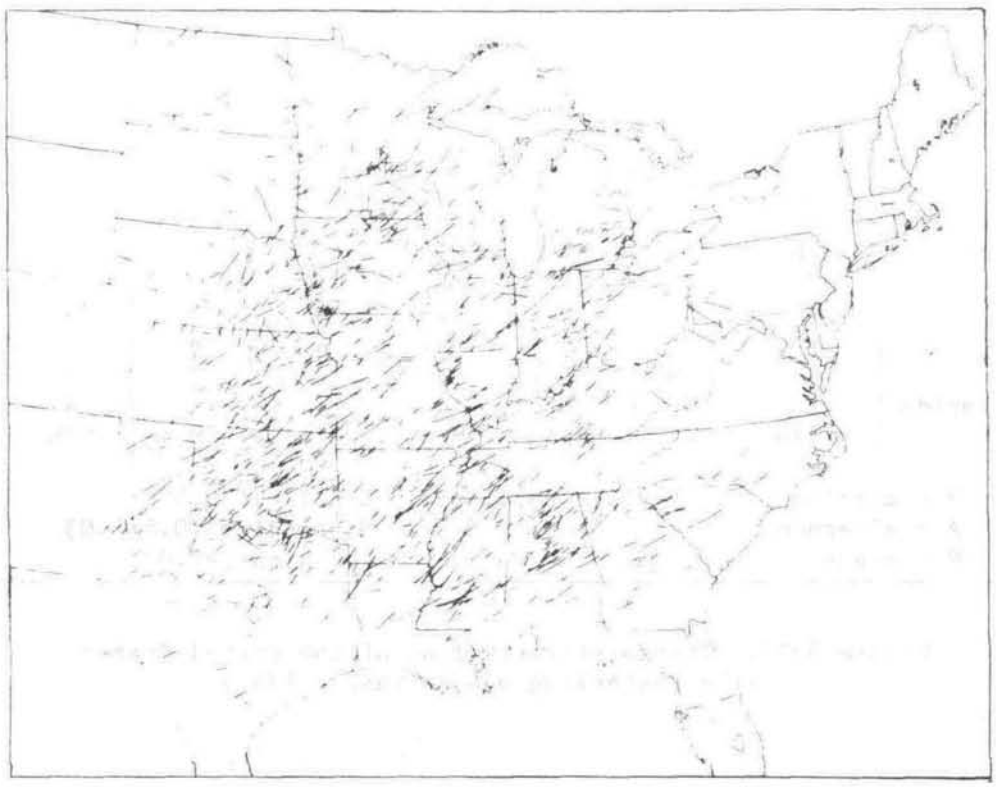


Figure 3-25. Paths of 972 confirmable violent (F4/5) tornadoes, 1880-1982 (from Grazulis and Abbey, 1983)

have been calculated: Figure 3-27[58] shows the probability density distribution of along-track-wind change per 30 m height and Figure 3-28[58] shows probabilities of exceeding given wind shear values, all of which are applicable to Schiphol Airport, Amsterdam.

3.7.3 One of the main reasons for mounting these projects was to provide data from which realistic wind shear models could be derived for use in testing aircraft control and display systems and airborne systems designed to detect and warn of low level wind shear. At the same time, of course, they provide invaluable data on the types and intensity of wind shear at many aerodromes throughout the world. Readers interested in wind shear at specific aerodromes are advised to consult the original papers by Woodfield and Woods (1984)[57] and by Haverdings (1981)[59]. It would be useful, however, to quote three pertinent paragraphs from the Woodfield and Woods paper in which the variation of wind shear at different aerodromes is discussed:

> At any level of exceedance the airport with the largest wind shears has speed changes of no more than about twice that of the airport with the smallest shears. The lowest shear levels among these airports were at Nairobi (NBO), Kuala Lumpur (KUL) and Singapore (SIN). Landings at NBO are mainly just after sunrise when weather activity is often at its

Nominal Ramp Length, m	Ramp Lengths for 1 000 Landings	Speed change (Ramp length)⅓ (m/s)/m ⅓	Ramp Length m	Speed Change kt	Gradient kt/100 m
305	30 000	– 1.04	200 300 400	– 11.8 – 13.5 – 14.9	– 5.9 – 4.5 – 3.7
609	15 000	– 0.85	400 600 800	– 12.2 – 13.9 – 15.3	– 3.0 – 2.3 – 1.9
1 218	7 500	– 0.78	800 1 200 1 600	– 14.1 – 16.1 – 17.7	– 1.8 – 1.3 – 1.1

Figure 3-26. Single-ramp wind shears with a 1 in 1 000 landings probability - world-wide data (from Woodfield and Woods, 1984)

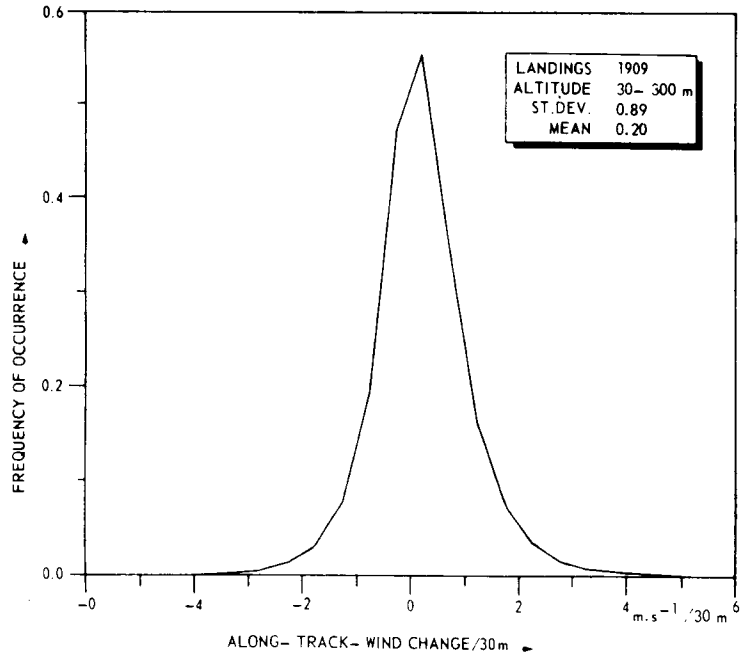


Figure 3-27. Probability density distribution of along-track wind change/30 m for Schiphol, for a height range of 30 to 300 m, based on AIDS data of November 1977-1978 (from Haverdings, 1980)

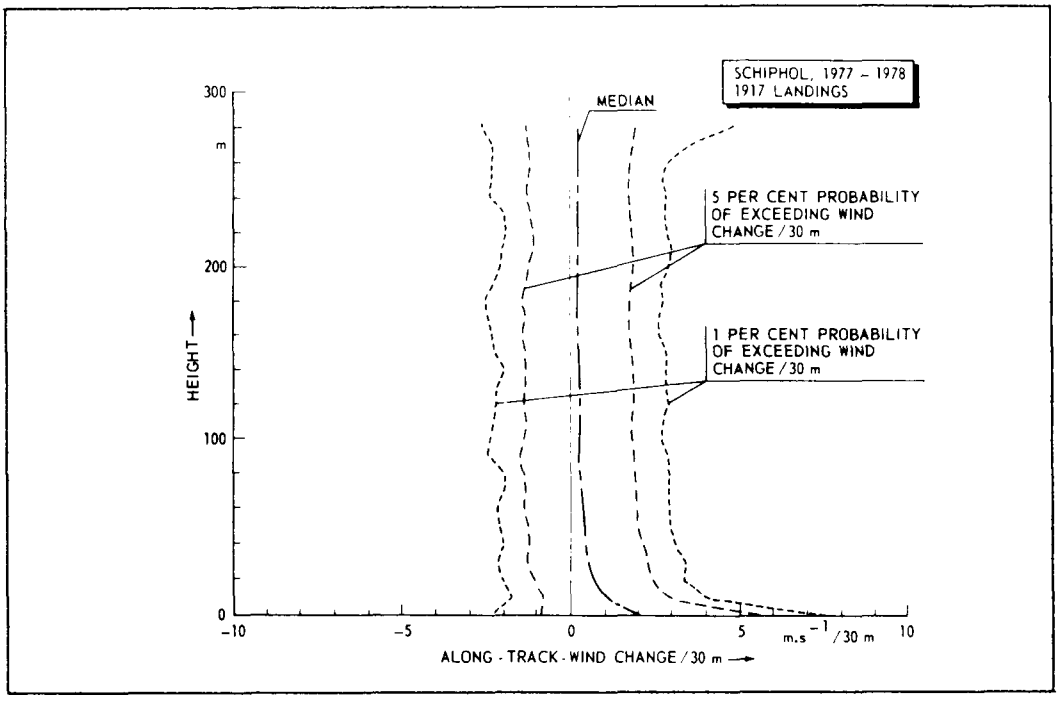


Figure 3-28. 50%, 5% and 1% probabilities of exceeding along-track wind change/30 m per landing, versus height (from Haverdings, 1980)

quietest. KUL and SIN on the other hand have landings during the late afternoon and are also renowned for their levels of thunderstorm activity during the summer.

The largest shear levels were at Hong Kong (HKG, RW 31 only), New York (JFK) and London (LHR) for single ramps and Hong Kong (HKG RW 31 only) for double ramps. Hong Kong is surrounded by rugged mountainous terrain and is well known for the high level of turbulence on the approach. Only approaches to Runway 31 could be analysed because of the offset instrument landing system and the late heading change of 50 degrees required for landings on Runway 13. In general the shape of the distributions are well established, even with only just over 100 landings at an airport. The large event in the distribution for double ramps at San Francisco (SFO) is expected to become part of the general pattern if a larger sample is taken.

Thus, as the hub airport [for British Airways], LHR is one of the airports with large wind shears and as the over-all selection of airports is representative of a wide variety of conditions around the world, the over-all distributions are believed to be representative of most international route systems.

Haverding[59] lists the "worst-case" airport sequence, from highest to lowest fraction of wind shear landings as JFK New York, Houston, Montreal, Schiphol (Amsterdam), Dubai, Singapore and Bangkok (based on 300 landings or more).

3.7.4 The Kingdom of the Netherlands' National Aerospace Laboratory (NLR) has also analysed the world-wide KLM data using the discrete gust method. It is expected that data will be exchanged between the RAE and NLR and that data from other sources, such as Lufthansa, will be included. Altogether the data base is likely to comprise over 20 000 landings world-wide over a wide range of seasonal conditions. Data on large wind shears are still being collected as an ongoing project under the United Kingdom Civil Aviation Airworthiness and Data Recording Programme (CAADRP). This will provide additional "extreme" data for the possible future improvement of wind shear intensity classification (see 5.2.2).

3.8 WAKE VORTICES

3.8.1 Wind shear is of course generated behind every aircraft in flight, mainly as wing tip vortices which take the form of two counter-rotating cylindrical vortex tubes trailing behind the wing tips. Such vortices are severe when generated by large, wide-bodied jet aircraft and the vortices generated by aircraft taking off can pose a significant hazard to aircraft following too closely behind. Although wake vortices are a special case of wind shear, they are not normally treated in the same way, because the effect of such vortices on aircraft landing and taking off can be avoided by the application by ATS units of appropriate separation minima. Details of wake vortices and guidance on the procedures used by ATS units to apply aircraft separation minima to minimize the potential hazards of wake turbulence and wind shear are given in Attachment L to the Procedures for Air Navigation Services - Rules of the Air and Air Traffic Services (PANS-RAC) (ICAO Doc 4444). Research is being conducted in a number of States (e.g. the United Kingdom, the United States and the Kingdom of the Netherlands) into the development of a "wake vortex avoidance system" which, based upon relevant real-time meteorological information, would permit air traffic controllers to assess when the vortices are likely to have cleared the runway, which would in turn contribute to reducing average landing intervals between aircraft (i.e. recommended wake vortex separation minima) to cope with the traffic increases expected in the future[62,63]. It should be noted, however, that whilst such experiments have tended to confirm the technical feasibility of such a system, in fact for a number of practical reasons it has not so far been possible to establish it operationally.

3.9 AERODYNAMIC PENALTIES OF HEAVY RAIN

3.9.1 It has been postulated by some researchers[64] that in a number of aircraft accidents where wind shear was cited as having been involved (e.g. the Eastern 066 accident at John F. Kennedy International in 1975), much of the deterioration in aircraft performance that occurred may be accounted for by the aerodynamic penalties due to heavy rain. It is suggested that heavy rain can affect aircraft performance in at least four ways, as follows:

a) raindrops striking the aircraft impart a downward and rearward momentum;

b) a thin film of water from the rain over the airframe increases the aircraft mass;

c) this film of water can be "roughened" by subsequent drop impact and surface stresses which can produce lift/drag penalties compared to the dry, smooth aerofoil; and

d) depending on aircraft orientation, raindrops striking the aircraft unevenly impart a pitching moment.

3.9.2 Following analysis of this hypothesis using computational hydrodynamics the researchers reached the following conclusions:

a) momentum penalties become significant for rainfall rates approaching 500 mm/h (extremely heavy rain);

b) drag/lift penalties could be very significant for rainfall rates exceeding 100 mm/h (heavy rain).

Aircraft landing simulations are reported to indicate that a 400 mm/h rainfall rate, encountered on the approach, may produce an aircraft performance deterioration equivalent to a wind shear of 9 kt/100 ft. It has also been suggested that the combination of some or all of the foregoing effects could temporarily raise the stalling speed of the aircraft, possibly above the speed at which the stall warning system (stick shaker) would normally operate. Although the magnitude of the effect of heavy rain on aircraft performance has not been established, the United States Committee on Low-Altitude Wind Shear and its Hazard to Aviation recommend that investigations should continue (see Appendix C).

3.9.3 Aside from the ongoing debate regarding the aerodynamic penalties of heavy rain, it should be noted that there have been cases where aircraft have penetrated severe thunderstorms and have experienced a total loss of thrust from all engines. An example is the DC-9 which crashed in 1977 while making an emergency landing after losing all engine power in flight; the United States National Transport Safety Board attributed this to the direct ingestion of massive amounts of water and/or hail in a severe thunderstorm which, in combination with thrust lever movement, induced severe stalling and major damage to the engine compressors[65]. Research is also being undertaken to assess if the angle-of-attack sensor vanes used for stall warning, the wind shear warning systems and the transmission/reception characteristics of the weather radar radome could be affected by rain. It has been suggested that errors could be caused by the sensor vanes aligning partially with the angle of approaching rain, which at normal aircraft approach speeds is likely to be around 8° from the horizontal.

Chapter 4

EFFECT OF LOW-LEVEL WIND SHEAR ON AIRCRAFT PERFORMANCE

4.1 GENERAL

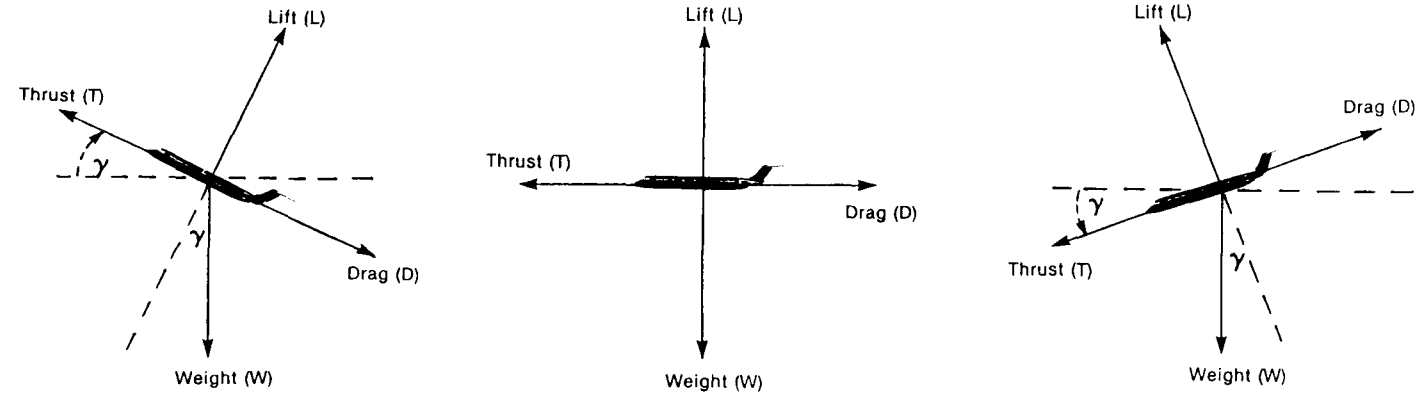
4.1.1 In order to understand the effect that wind shear has on aircraft performance, it is helpful first of all to pause for a moment to review some of the basic principles of flight. The main forces acting on an aircraft in flight are shown in Figure 4-1, these being the thrust provided by the engine(s), the weight of the aircraft, the lift provided primarily by the wings, and the drag. The figures are slightly simplified; for example, it is assumed that the thrust acts in exactly the same direction as the flight path. This simplification renders the arguments much easier to understand without materially affecting the conclusions drawn.

4.1.2 When the forces acting on the aircraft are in equilibrium, for steady non-accelerating flight there is no resultant force and hence the sum of all the upward forces normal to the flight direction must equal the sum of all the downward forces normal to the flight direction. Similarly, the sum of all the forces acting forward along the direction of flight must equal the sum of all the forces acting rearward along the direction of flight. The aircraft is then in equilibrium and in accordance with Newton's first law of motion will continue in this state, whether climbing, descending or maintaining level flight, until such time as the balance of the forces is disturbed.

4.1.3 Although these are simple equations, it is possible to draw important conclusions from them. In level non-accelerating flight, the thrust has to balance the drag and the lift balance the weight (Figure 4-1 b)). In non-accelerating climbing flight the thrust also has to balance part of the weight ($W\sin\gamma$), so more thrust is required than for level flight and the thrust requirement is proportional to the angle of climb. The possible angles of climb can be derived by simplifying Equation (1) in Figure 4-1. For the usual small angles of climb $\sin\gamma \simeq \gamma$ and Equation (1) becomes:

$$T = D + W\gamma$$

$$\text{and } \gamma = \frac{T - D}{W}$$



a) Climb

b) Level flight

c) Descent

Notes.— 1) Assuming steady, unaccelerated flight, and thrust acting along flight path,
2) Assuming angle of climb or descent is γ,
3) Resolve forces normal to and parallel to the flight path:

$T = D + \sin \gamma$ ..... (1)

$L = W \cos \gamma$ ..... (2)

$T = D$ ..... (3)

$L = W$ ..... (4)

$T + W \sin \gamma = D$ ..... (5)

$L = W \cos \gamma$ ..... (6)

Figure 4-1. Forces acting on an aircraft in flight

Thus the angle of climb depends directly on the excess of thrust over drag and inversely on the weight. In the case of non-accelerating descending flight (Figure 4-1 c)), Equation (5) shows that less thrust is required than for level flight because part of the weight ($W\sin\gamma$) now acts in the same sense as the thrust.

4.1.4 At this point the question may be asked - what has all this to do with wind shear? The answer lies in a close examination of what each of the four main forces acting on an aircraft comprises. The weight is simply $W = mg$ (mass of the aircraft x acceleration due to gravity), the thrust T is the direct force produced by the engine(s), the lift (L) and the drag (D) are found to be proportional to the air density (ρ), the area of the wing (S) and the square of the velocity of the air over the wings (V), i.e. L and D are proportional to ρ, S and V^2. The constants of proportionality C_L and C_D, called the lift and drag coefficients respectively, such that:

$$L = \tfrac{1}{2} C_L \rho S V^2 \text{ and}$$

$$D = \tfrac{1}{2} C_D \rho S V^2$$

depend on, among other things, the angle of attack (α) of the wing. Looking at these equations it may be seen that lift and drag depend on the angle of attack (through C_L) and the square of the airspeed and it will be shown that wind shear can affect both angle of attack and airspeed, which in turn affects lift and drag which ultimately disturbs the equilibrium of the aircraft (see Appendix D).

4.1.5 Effect of wind shear on airspeed

4.1.5.1 On the face of it, the statement that "wind affects airspeed" seems to contradict the rule stressed in basic pilot training that "wind only affects ground speed and drift"[1]. This apparent contradiction may have caused confusion in some pilots' minds and perhaps contributed to their difficulty in understanding the serious effect that wind shear can have on aircraft performance. The two statements can be reconciled if the word "transient" is introduced into the first statement so that it reads "wind (i.e. change in the wind) has a transient effect on airspeed", and account is taken of the longitudinal stability of the aircraft which seeks to restore the original trimmed airspeed. This means that in steady wind conditions or in conditions where the horizontal wind changes gradually, the wind has no effect on airspeed and the following well known equation holds true:

ground speed (GS) = true airspeed (TAS) $\pm$ wind speed along the ground track (WIND).

In wind shear conditions, however, the horizontal wind (the along-track wind is the important factor in this situation, i.e. for landing/take-off the headwind or tailwind encountered) is certainly not steady nor is it changing gradually but may be changing rapidly through a comparatively short distance. If an aircraft encounters such a rapid headwind/tailwind change, due to inertia it clearly cannot accelerate or decelerate instantaneously to recover the original trimmed airspeed and for a short but finite period of time the airspeed changes in accordance with the wind change. This "transient" change in airspeed changes the lift and drag and disturbs the equilibrium of the forces acting on the aircraft. The gradual wind change situation can be illustrated as follows:

140 kt ground speed and no wind

140 kt (GS) = 140 kt (TAS) - 0 (WIND)

a gradual change to a 20 kt headwind becomes

120 kt (GS) = 140 kt (TAS) - 20 kt (WIND)

The ground speed adjusts continually to the changing wind regime and there is no effect on airspeed. An illustration of the sequence of events during an encounter with a rapid wind change, however, is as follows[2]:

140 kt ground speed and no wind

140 kt (GS) = 140 kt (TAS) - 0 (WIND)

a rapid shear to 20 kt headwind temporarily becomes

140 kt (GS) = 160 kt (TAS) - 20 kt (WIND)

when equilibrium is re-established and trimmed airspeed regained (i.e. aircraft has decelerated with respect to the ground)

120 kt (GS) = 140 kt (TAS) - 20 kt (WIND)

as in the previous sample above.

The way in which the aircraft restores equilibrium by virtue of its longitudinal stability is dealt with in 4.1.8 below.

4.1.5.2 The disturbance of the equilibrium of forces acting on the aircraft creates a resultant force so that instead of Equation (1) being written $T = D + W\sin\gamma$ or $T - D - W\sin\gamma = 0$ (i.e. no resultant force), once the equilibrium is disturbed the equation must be written $T - D - W\sin\gamma = F$ (resultant force) and the application of a resultant force to the aircraft immediately causes an acceleration. This is because Newton's second law of motion states that "the rate of change of momentum of a body is proportional to the force acting on the body and is in the direction of the applied force". The law is more commonly encountered as F = ma (mass x acceleration) or $F = \frac{W}{g}a$. Under the transient effect of wind shear when the equilibrium is disturbed. Equations (1) to (6) would be rewritten[3]:

$$\left.\begin{array}{ll} \text{(climb)} & T - D - W\sin\gamma \\ \text{(level flight)} & T - D \\ \text{(descent)} & T + W\sin\gamma - D \end{array}\right\} = \frac{W}{g} \cdot \text{acceleration along the flight path}$$

$$\left.\begin{array}{ll} \text{(climb/descent)} & L - W\cos\gamma \\ \text{(level flight)} & L - W \end{array}\right\} = \frac{W}{g} \cdot \text{acceleration normal to the flight path}$$

The aircraft accelerates in the direction in which the disturbing (resultant) force acts until equilibrium is once more attained. The underlining emphasizes the fact that, although equilibrium is indeed re-established, the aircraft is unavoidably flying on a new flight path and, in accordance with Newton's first law of motion, will remain on the new flight path until the equilibrium is disturbed again. The aircraft always seeks a flight path which will result in equilibrium between the forces acting upon it. In other words, wind shear changes the flight path of the aircraft and in order for the aircraft to return to the intended flight path the pilot would have to intervene. The initial changes in flight path due to transient airspeed changes caused by wind shear are shown in Figure 4-2. These effects are produced by shears in the horizontal wind such as might be encountered in strong wind profiles near the ground (especially low-level jet streams), frontal systems, etc. It should be noted at this point that as far as the transient wind shear effect on airspeed is concerned, a decreasing headwind has exactly the same transient effect on the airspeed (a decrease) as an increasing tailwind. Similarly, an increasing headwind has exactly the same transient effect on the airspeed (an increase) as a decreasing tailwind. Additional considerations apply once equilibrium is re-established particularly in the case of a landing aircraft and these are discussed in 4.2.2.4.

4.1.6 Effect of wind shear on angle of attack

4.1.6.1 In 4.1.4 it was stated that wind shear can affect the angle of attack. It will be recalled that in 2.1.1, attention was drawn to special cases in the atmosphere where the vertical component of the wind is not zero (or very small) and may even predominate over the head/tailwind and crosswind components. Such cases include mountain waves (see 3.2.8) and especially downbursts associated with convective clouds (see 3.5.3). The following discussion will concentrate on the wind shear effect of downbursts, as these are undoubtedly the most important wind shear hazard, but the arguments apply equally well to any situation where the vertical component of the wind predominates over the horizontal components and changes rapidly.

4.1.6.2 In level (non-turning) flight, an aircraft is flown at a pitch attitude which provides for an angle of attack (α) of the wing appropriate to the airspeed. The relationship between the angle of attack and the airspeed assumes that the air is striking the leading edge of the wing horizontally (i.e. negligible upward or downward component) and indeed, more often than not this is the case. If an aircraft is flying in a downdraft or updraft, however, the air is no longer striking the wing horizontally but at a small angle to the horizontal which depends on the relative magnitudes of the airspeed and the vertical component of the wind (downdraft or updraft). Hence, the angle of attack has effectively been changed without any change in the pitch attitude[4]. This is illustrated in Figure 4-3, which shows how the angle of attack is reduced by a downdraft whilst the pitch attitude angle remains unchanged. The example given is a downdraft of 10 kt (1 000 ft/min) and an aircraft with an airspeed of 140 kt reducing the angle of attack by approximately 4 degrees with no change in pitch attitude. It should be noted that whilst downdraft speeds of 10 kt are probably fairly typical of most downdrafts, peak downdraft speeds in excess of 50 kt have been measured in severe thunderstorms.

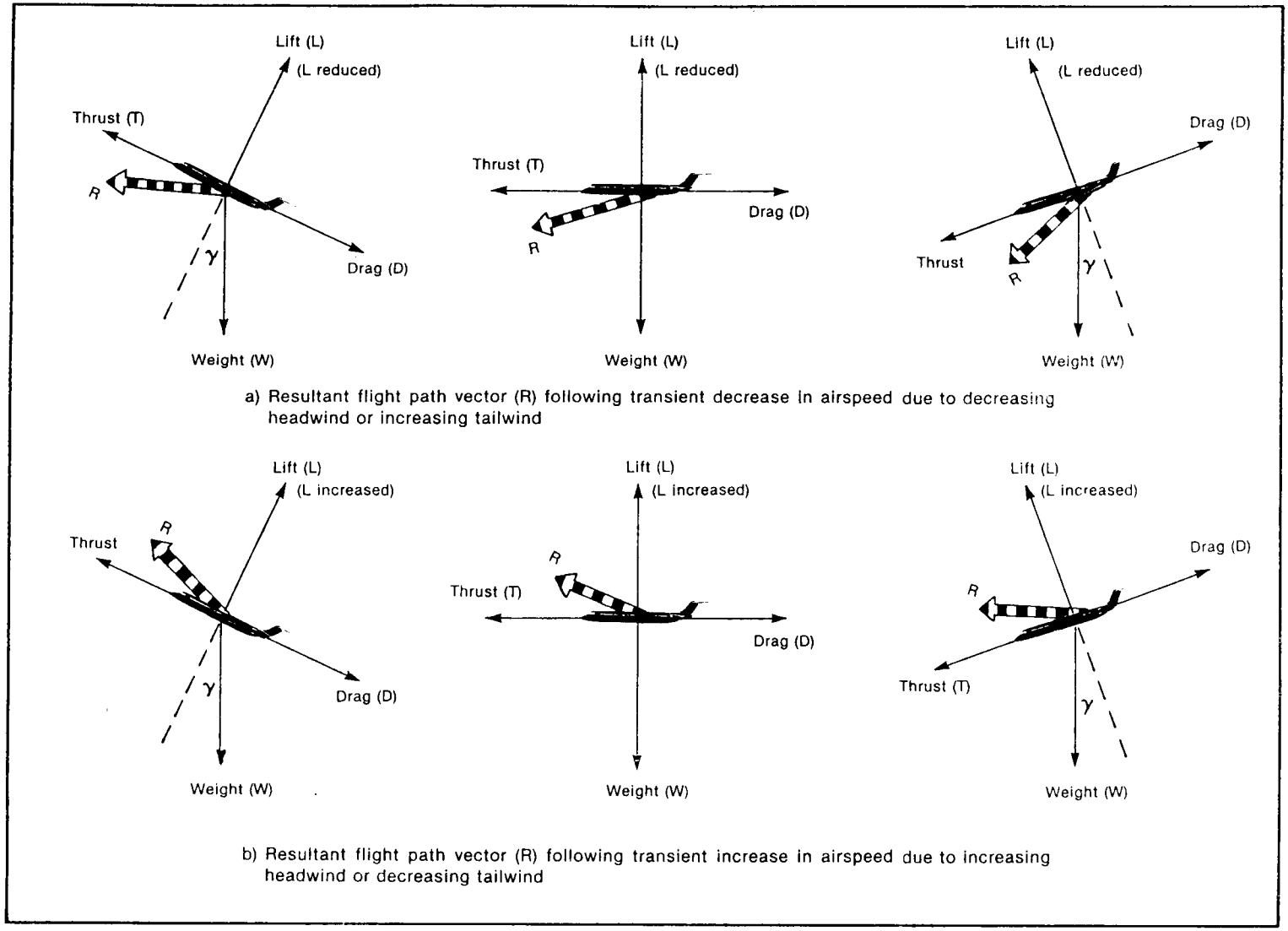
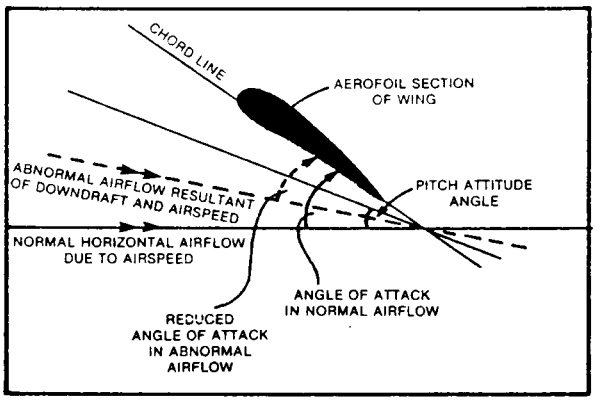
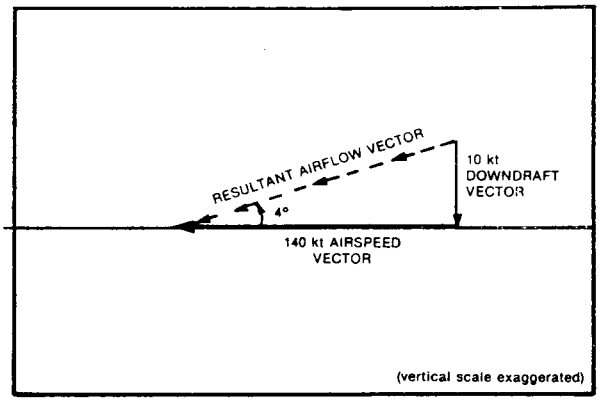


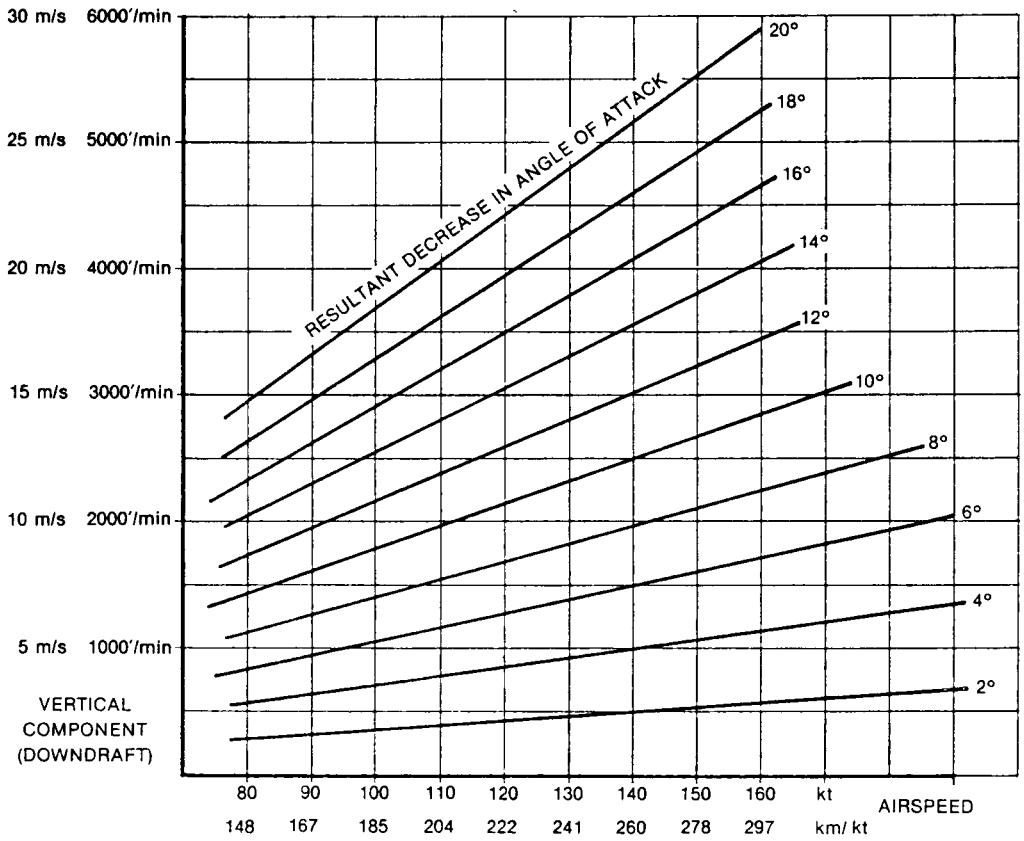
Figure 4-2. Resultant flight path vector due to shear in the horizontal wind



a) Angle of attack reduced due to downdraft but pitch attitude angle remains unchanged



b) 4° reduction in angle of attack due to 10 kt downdraft at airspeed of 140 kt



c) Decrease in angle of attack resulting from various combinations of airspeed and vertical component of the wind (downdraft)

Figure 4-3. Reduction of angle of attack due to sharp-edged downdraft

4.1.6.3 As in the case of a change in airspeed due to wind shear dealt with in 4.1.5.1, a change in angle of attack due to a downdraft/updraft is a transient change pending the restoration of the original trimmed angle of attack by the longitudinal stability of the aircraft. A downdraft causes a transient reduction in angle of attack which in turn causes a reduction in lift coefficient and disturbs the equilibrium of the forces acting on the aircraft, thus causing a resultant force acting below the intended flight path (see Figure 4-4). An updraft acts in the opposite sense. A downdraft thus has the same initial effect on an aircraft as a decreasing headwind or increasing tailwind and an updraft the same initial effect as an increasing headwind or decreasing tailwind. However, the downdraft/updraft effect is due to a transient change in angle of attack whilst the headwind/tailwind effect is due to a transient change in airspeed. Equilibrium is re-established by the longitudinal stability following the disturbance but the aircraft will be flying on a new flight path. Additional considerations apply once equilibrium has been re-established which are dealt with in 4.2.2.4.

4.1.7 Effect of crosswind shear

4.1.7.1 It will not have passed unnoticed that, so far, consideration has been restricted to the shear in headwind/tailwind components of the wind and its effect on airspeed and to the shear in the vertical components of the wind (downdraft/updraft) and its effect on angle of attack. As already mentioned in 2.1.2, because runways are oriented, as far as practicable, in the direction of least crosswind component, the

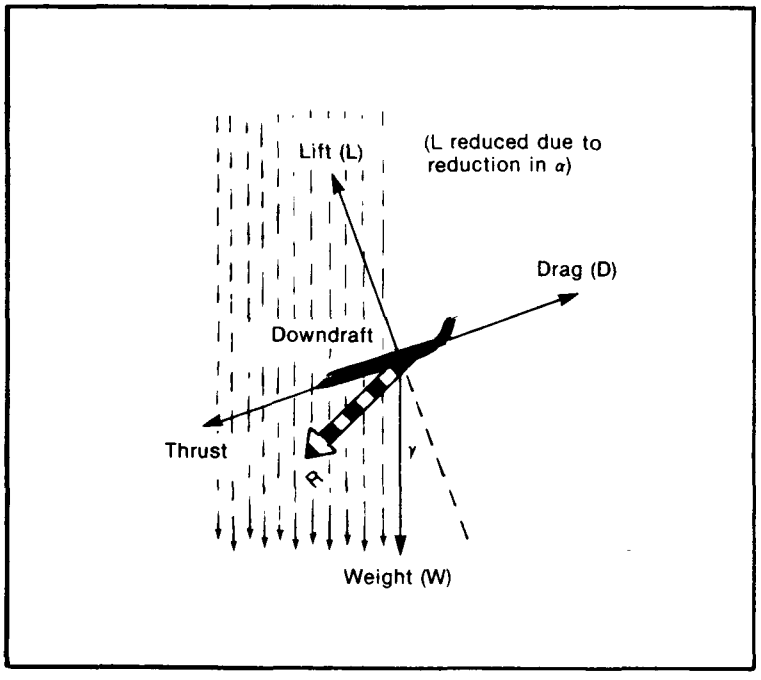


Figure 4-4. Resultant flight path vector due to shear in the vertical component of the wind (downdraft) - hypothetical sharp-edged steady downdraft

shear in the headwind/tailwind components and the special cases of shear in the vertical components of the wind (e.g. downbursts) tend to dominate discussions of wind shear. This does not mean to say that there is no crosswind component shear or that any such shear has no effect on the aircraft. In fact there is nearly always some crosswind component shear involved, but generally speaking it does not affect the airspeed and angle of attack and hence does not alter the equilibrium of forces on the aircraft in the vertical plane. It does affect the drift and sideslip angles, causing added complications for the pilot in an already complex situation. Some of these complications are discussed in 4.2.2.6.

4.1.8 Restoration of equilibrium due to longitudinal stability

4.1.8.1 In order to complete this general introduction to the effect of wind shear on aircraft performance, it is necessary to consider how the aircraft restores the equilibrium conditions after a disturbance, such as might be caused by wind shear. The restoring effect is referred to as the stability of the aircraft. The stability of an aircraft is its ability to return to a given condition of flight after having been slightly disturbed from that condition. The aircraft is normally designed to be stable in all three axes (pitch, roll and yaw). In the case of a disturbance due to wind shear we are particularly interested in the stability about the pitch axis or the longitudinal stability. Longitudinal stability ensures that if the angle of attack is changed, restoring forces will immediately and automatically come into play to return the angle of attack to its original value[6]. The detailed analysis of these forces is a very complex matter and will not be dealt with here. However, it is as well to state that, as far as longitudinal stability is concerned, the restoring forces are mainly due to the tailplane or horizontal stabilizer. For the particular flight conditions with which we are mainly concerned (straight level, climbing or descending flight, i.e. essentially non-turning flight), for every angle of attack there is an equivalent indicated airspeed, hence the aircraft also has "speed" stability. This means that an aircraft will generally pitch down and accelerate to recover a loss of airspeed and pitch up and decelerate to shed an increase in airspeed (i.e. to regain the original trimmed airspeed).

4.1.8.2 The "natural" responses of an aircraft to wind changes are usually identified in standard textbooks for an aircraft with controls fixed. In these circumstances, airspeed changes produce a lightly damped oscillation in airspeed and height called a phugoid with an oscillation period of about 40 seconds. The rather unusual term "phugoid" was coined by the aerodynamicist Lanchester, who worked at the beginning of this century. He derived the term from two Greek words meaning literally "flight-like", but unfortunately he used the Greek word for "flight" in the sense of "fugitive" instead of "flight of a bird" as intended. If the phugoid oscillation were left uncontrolled, the aircraft could not fly satisfactorily at low speed such as at take-off and landing, but would behave in a swooping manner frequently observed in paper model aeroplanes. Fortunately the period of the phugoid is very long and it can be controlled by the normal pilot action of holding a steady pitch attitude. Changes in angle of attack, for example, from downdrafts or updrafts (see Figure 4-3) produce a well damped oscillation in pitch with a period of about five seconds which is usually referred to as the short period oscillation[7].

4.1.8.3 If the pitch attitude is held fixed by the pilot, then the aircraft's response to an airspeed change is a non-oscillatory return to the original speed (speed stability). Again, under pilot control the response to a downdraft/updraft is also a non-oscillatory return to the original angle of attack. The degree of speed stability depends on how close the original speed is to the minimum power speed at which there is neutral speed stability. Typical take-off and landing speeds are close to minimum power speeds in the normal flap and undercarriage positions. In these circumstances, the speed stability is weak and airspeed changes caused by wind shear will persist unless corrected by pilot response on throttle and/or pitch controls[7].

4.2 AIRCRAFT PERFORMANCE IN PARTICULAR WIND SHEAR CONDITIONS

4.2.1 In this and the following sections, the meteorological and aerodynamic theory dealt with so far is applied to practical situations involving particular wind shear conditions, and to the techniques recommended for use by pilots in the event of an inadvertent encounter with such conditions. It will be seen that the conclusion which emerges is that an encounter with wind shear should be avoided as far as possible. The question may be asked - why then spend so much time analysing the phenomenon and its effect on aircraft in such detail? The answer is that the analysis of the meteorological aspects, besides assisting aeronautical meteorologists, also provides a firm basis for assisting pilots in recognizing and thus avoiding potential wind shear situations. Knowing the range of wind shear types and intensity which have been recorded helps to give the pilot a healthy respect for the phenomenon. Knowledge of the aircraft response to wind shear helps the pilot to understand what is happening and explains the reasons for the techniques recommended to deal with an inadvertent wind shear encounter, some of which might appear different than "normal" flying practices. It should be borne in mind, therefore, that the following discussions are not provided to encourage pilots to attempt to fly in known or suspected wind shear conditions, on the contrary, the overwhelming advice is AVOID AVOID AVOID.

4.2.2 Headwind/tailwind wind shear

4.2.2.1 Situations in which shears in the headwind/tailwind (i.e. headwind/tailwind components normally in relation to runway orientation) might be encountered near the ground include landing or taking off in strong wind gradients (especially low-level jet streams), through frontal surfaces and in the vicinity of thunderstorms. The effect on aircraft of wind shear associated with thunderstorms, such as might be caused by gust fronts and downbursts, etc., is dealt with in 4.2.3 as it involves shear in the vertical component of the wind (downdraft/updraft) in addition to headwind/tailwind shear. Wind shear associated with low-level wind gradients (or profiles) and frontal surfaces is described in 3.1 and 3.3 respectively. To all intents and purposes, a frontal surface may be considered a special case of a wind profile, at least as far as its effect on an aircraft is concerned. Wind profiles vary considerably in respect of the rate of change of wind speed with height (measured, for example, in kt/100 ft) and in the total magnitude of the wind speed change (measured, for example, in kt) from the top of the layer to the bottom. In general, wind shear is only a problem when both of these characteristics are significant. It should be noted that both of these characteristics of the shear layer, i.e. intensity (rate of change of wind speed with height) and the total wind speed change, reflect the state of the atmosphere at a particular time and place and exist quite independent of an aircraft being there or not. Both characteristics have an effect on aircraft landing or taking off but that is not

the whole story because it is easy to see that the effect will also depend on how fast the aircraft transits the shear layer, i.e. the rate of encounter measured, for example, in knots per second[8]. In the example given in 2.4.3, the wind shear intensity is given as 4.2 kt/100 ft and the rate of descent of the aircraft is 13 ft/s, hence the wind encountered by this aircraft will decelerate by

$\frac{4.2 \times 13}{100} = 0.546$ kt every second[9]. The approximate airspeed changes in different wind shear intensities and aircraft rates of descent on a 3° glide slope are shown in Figure 4-5. The total wind shear over the layer in this example from 1 000 ft AGL to 500 ft AGL is 21 kt and, assuming for the sake of argument that this is a headwind change in relation to the runway orientation, for a landing aircraft the shear would cause a deceleration in the airspeed of 21 kt at a rate of 0.546 kt/s. The phase of the operation has to be specified because the same wind gradient has opposite effects on take-off and landing. In the example of wind shear cited above, the headwind is decreasing along the glide slope for a landing aircraft but increasing along the climb-out path for an aircraft taking off.

4.2.2.2 For an aircraft landing into a rapidly decreasing headwind or increasing tailwind the airspeed decelerates at approximately the same rate as the deceleration of the headwind or acceleration of the tailwind. As shown in Figure 4-2 a), this causes the aircraft to fly below the glide slope. The new descent angle established due to the transient imbalance of the forces acting on the aircraft will be maintained so long as the shear continues and the rate remains the same and the pilot does not intervene. Landing in an increasing headwind or decreasing tailwind causes an acceleration in the airspeed equivalent to the rate of shear and the aircraft flies above the glide slope. The two effects are very similar to what would happen if the engines were suddenly to lose or gain respectively the equivalent amount of thrust sufficient to establish the new descent angle below or above the glide slope. The flight path is said to "improve" if the aircraft goes above the no-shear (or intended) flight path and to "deteriorate" if it goes below the no-shear flight path. However, it is debatable whether any deviation from the glide slope could be classed as an "improved" flight path. Other ways of describing the same effects are increasing performance shear (increasing headwind, decreasing tailwind) and decreasing performance shear (decreasing headwind, increasing tailwind).

4.2.2.3 From the pilot's point of view, the actual sequence of events which might be observed from the flight deck instruments will depend to a large extent on the particular combination of circumstances including the shear itself, the height of the onset of shear above ground, the aircraft configuration and the pilot's actions. The sequence of events is relatively straightforward, however, if the response of the aircraft is considered with fixed controls. With these constraints the sequence is one of airspeed change immediately with the onset of the shear followed by diverging altitude and pitch attitude profiles as shown in Figures 4-6 and 4-7. In decreasing headwind (increasing tailwind) situations the aircraft reaction (due to longitudinal stability), and the pilot's natural reaction to the drop in airspeed, is to pitch over to recover the lost airspeed. During landing and take-off, however, it is the deteriorating flight path which is critical so near the ground and obstacles, not the airspeed so long as the latter remains sufficiently above the stall speed.

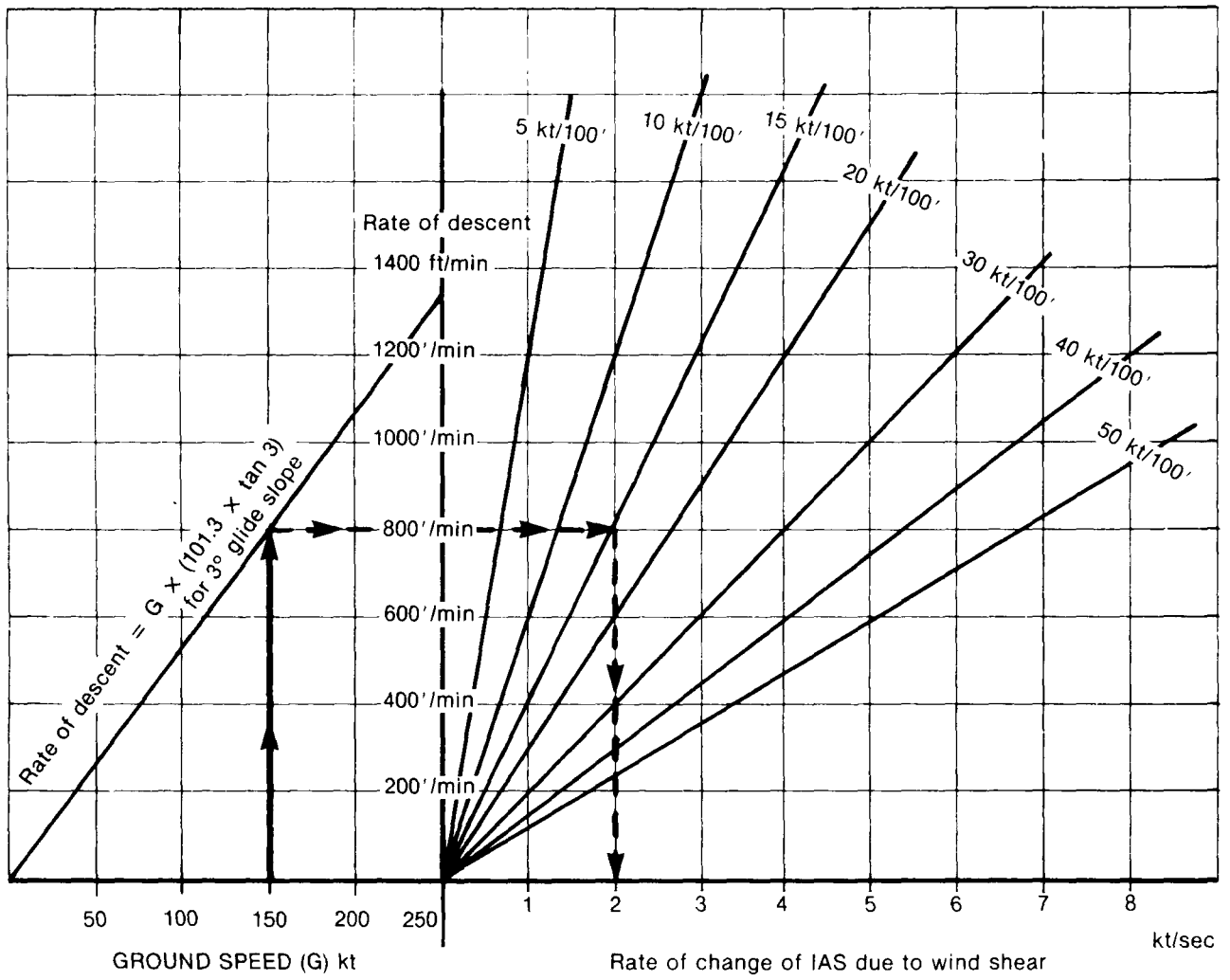


Figure 4-5. Rate of change of IAS due to wind shear and aircraft rate of descent (after Lord, 1978)

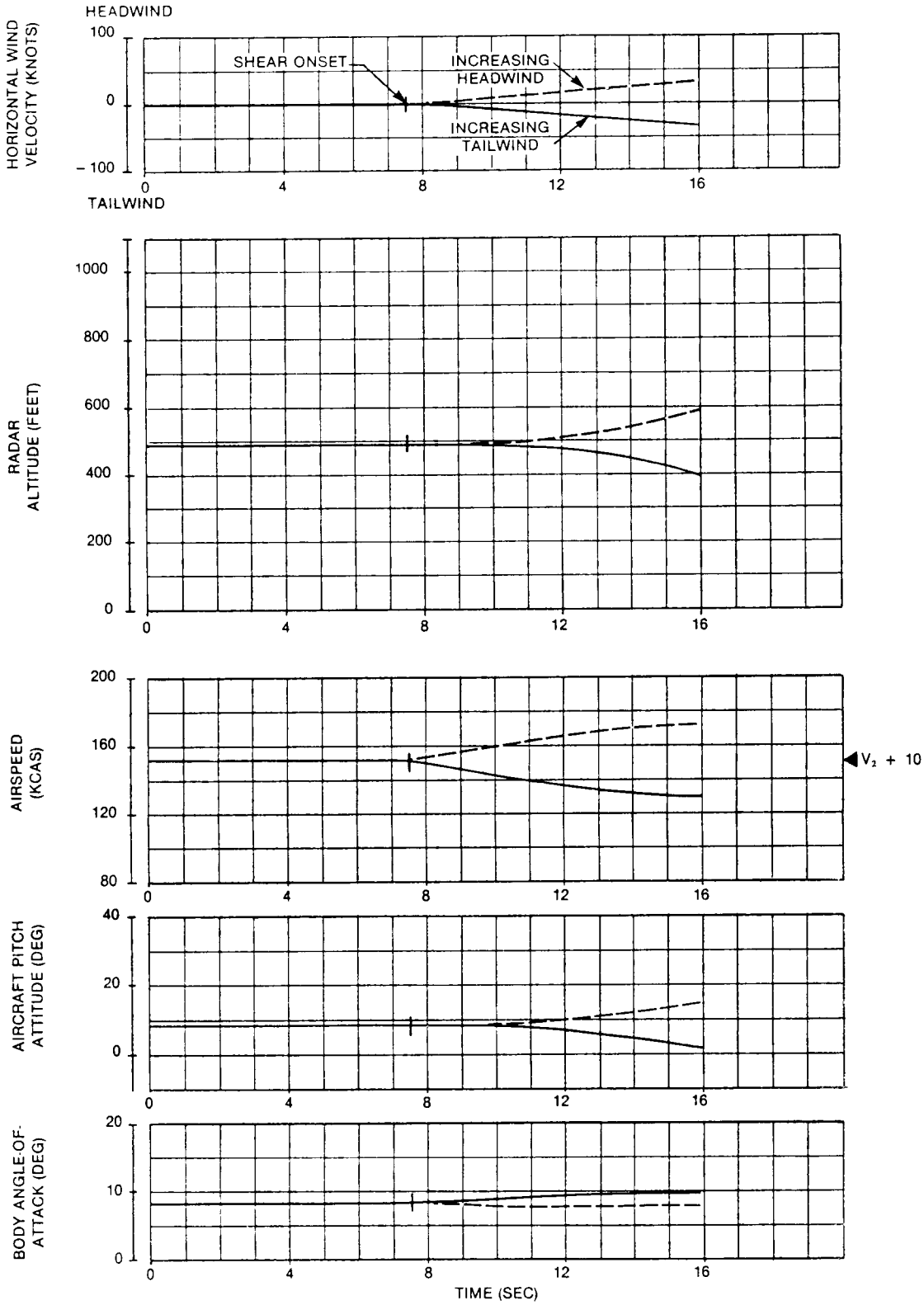
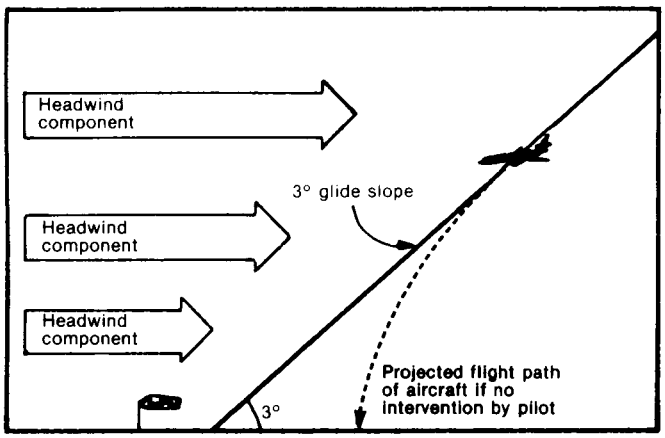
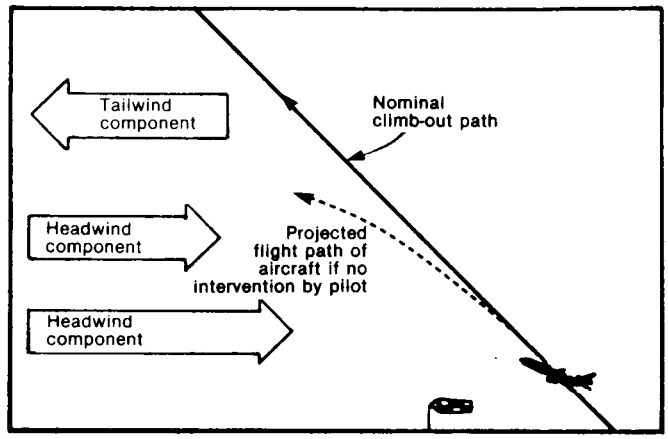


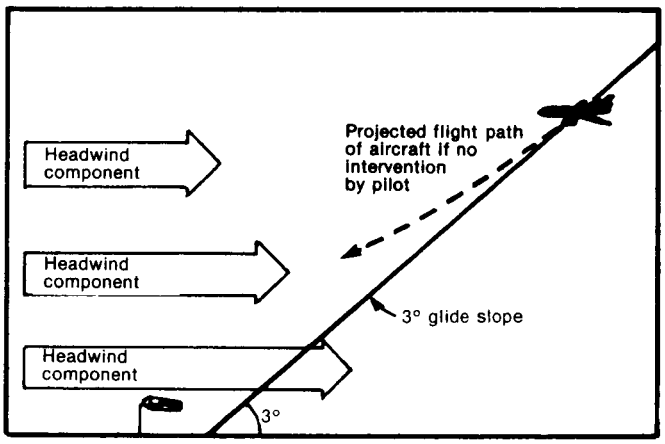
Figure 4-6. Initial aircraft fixed control response to headwind/tailwind shear components (from FAA Wind Shear Training Aid, 1987)



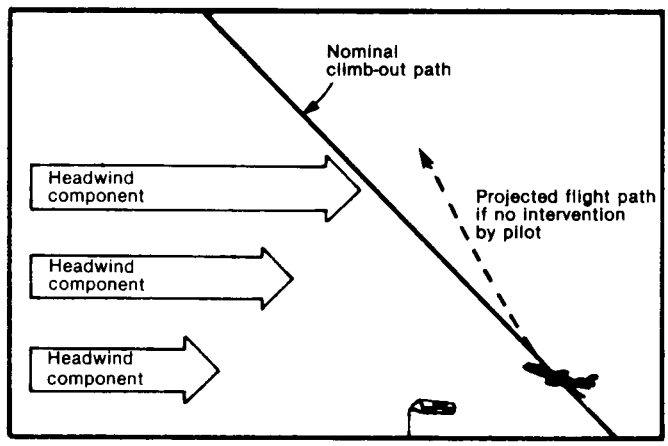
a) Landing in decreasing headwind



b) Take-off in decreasing headwind



c) Landing in increasing headwind



d) Take-off in increasing headwind

Figure 4-7. Effect of head (tail) wind shear on aircraft assuming no intervention by pilot

4.2.2.4 The techniques recommended for use by pilots to control the flight path are dealt with in the next section, but in order to continue this discussion of the effect of particular wind shear situations, a limited preview of the reasoning behind the techniques is necessary. The pilot uses elevator (pitch attitude hence angle of attack) and thrust controls to vary the aircraft's speed and altitude and hence rate of climb/descent. These are also therefore the principle means by which the pilot can control the flight path when faced with an inadvertent encounter with wind shear. The effects on the aircraft of the elevator and thrust controls are interdependent and it is not possible to state the effect when one control is altered without also specifying the action taken with the other control. An increase in thrust results in a forward acceleration which, depending on elevator control, may provide a rate of climb, or an acceleration (increase in airspeed), or a combination of both. It was explained earlier that for an aircraft one of the important characteristics of the wind shear is the rate of encounter. In a decreasing performance wind shear, if the pilot can accelerate the aircraft by increasing thrust at the same rate the airspeed is decelerating he can compensate for the shear. A typical acceleration capability for a jet transport aircraft in the landing configuration is 3 kt/s, which means that such an aircraft could maintain level flight at constant airspeed in a 3 kt/s decreasing performance wind shear. It should be noted, however, that wind shear intensity can exceed this capability. Of course if the shear rate changes so must the application of thrust. This presents an added complication because if the shear ceases above ground level during landing, i.e. the wind remains constant with height from the bottom of the shear layer to touchdown, the aircraft will now be landing in a steady wind and the thrust change necessary when exiting the shear layer in order to stay on the glide slope will depend on whether the wind to touchdown is a headwind or a tailwind. The relative wind experienced by a landing aircraft in various steady wind conditions is shown in Figure 4-8. It will be seen that when landing into a headwind or tailwind the angle of attack and the speed of the relative wind are changed compared to the still air conditions. The pilot adjusts thrust and pitch attitude accordingly to remain on the glide slope. In a headwind the aircraft is at a higher pitch attitude, shallower flight path angle and lower vertical speed than with no wind, and a higher thrust level is required to fly the glide slope. Conversely, when landing in a tailwind the aircraft is at a lower pitch attitude, steeper flight path angle and higher vertical speed than in no wind, and less thrust is required to maintain the glide slope[2].

4.2.2.5 In addition to the use of thrust to control the flight path, the pilot can also use pitch control to change the angle of attack. This enables the pilot to trade energy between potential (altitude) and kinetic (speed) and vice versa[4]. Altitude can be traded for speed by pitching the aircraft over, thus accelerating the aircraft but losing altitude in the process, and speed can be traded for altitude by pitching the aircraft up, thus decelerating the aircraft but gaining altitude. Of course, this is a one-shot affair, as the aircraft at any one time possesses a finite total amount of energy comprising potential (depending on its altitude) plus kinetic (depending on its speed). Trading one for the other does not change the total energy. An increase or decrease in thrust, however, does change the total energy and as such has a "permanent" effect on the flight path. Notwithstanding the "temporary" nature of the effect of pitch attitude changes, an energy trade can assist in controlling the flight path and it also has one particular advantage in that the response (i.e. effect on the flight path) of the aircraft is almost immediate. The limit of available thrust is obviously the maximum thrust available from the engines. There is also an upper limit, called the stalling angle, to which the angle of attack may be increased to trade speed for altitude but above which lift no longer increases but actually decreases rapidly. This brings us back to the second characteristic of wind shear of importance to aircraft referred to in 4.2.2.1, namely the total wind speed change across the shear layer. The

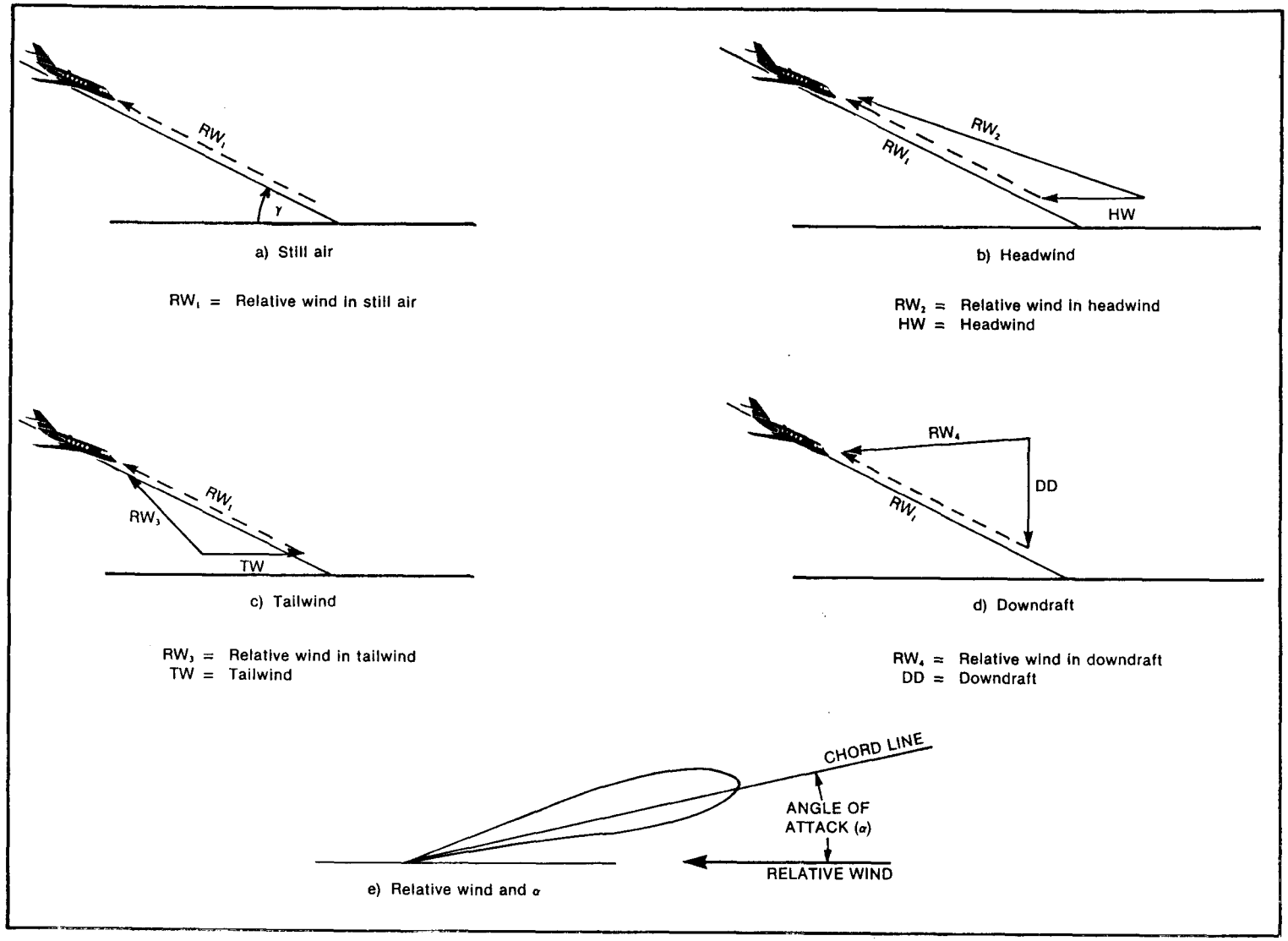


Figure 4-8. Relative wind experienced by an aircraft landing in various steady wind conditions

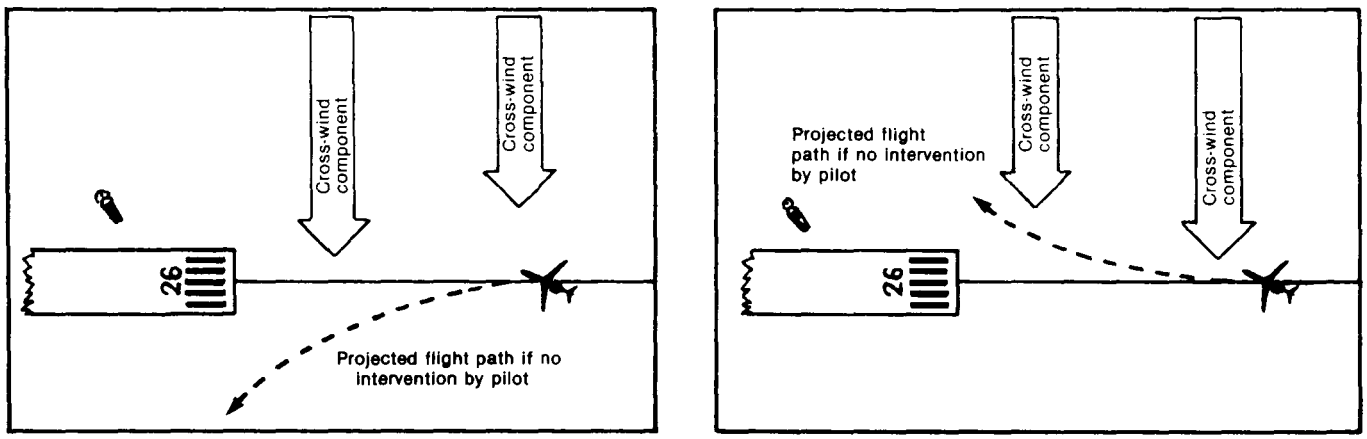
total wind speed change is important in comparison to the speed margin above the low-level flight stalling speed, which is the lowest speed at which level flight can be maintained (typically about 20 per cent, or about 25 kt, for a jet transport aircraft). The techniques recommended in the next section employ both thrust and pitch attitude adjustments to maintain control of the flight path. In order that readers do not gain a false impression, it is as well to point out that whilst most profile shears may well seem to be within the capability of an aircraft in retrospect, i.e. from analysis of detailed profiles after the fact, during a real encounter with wind shear the pilot has no idea how strong the shear ahead of the aircraft is going to be or for how long it will operate. Consequently, if certain parameters are exceeded (as discussed in 4.3.4), a go-around is executed.

4.2.2.6 The effect on an aircraft of a shear in the crosswind component was referred to in 4.1.7. A crosswind shear has a direct initial effect on drift and sideslip angles, causing the aircraft to yaw and roll but with no initial effect on airspeed and altitude. The aircraft rolls away from the shear, yaws towards the shear and drifts laterally away from the intended flight path as shown in Figure 4-9. Consequently, normal roll and yaw flying techniques are sufficient to counter the effects of crosswind shear. It may of course be necessary to initiate a go-around due to severe crosswind shear, but again the techniques which apply for strong but steady crosswinds will also apply to severe crosswind shear. It should be noted that winds indicated by an inertial navigation system are in degrees true whilst the surface wind given by ATC is in degrees magnetic. At aerodromes having a large magnetic variation, allowance must be made for this in determining the likely shear[5]. Changing crosswind components occurring together with headwind/tailwind shears do of course add considerably to pilot workload in an already highly dynamic and difficult situation.

4.2.3 Shear in vertical wind components (updrafts/downdrafts)

4.2.3.1 Wind shear due to strong and rapidly changing vertical components of the wind (updrafts/downdrafts) is by far the most hazardous wind shear situation for aircraft. The general effect of updrafts and downdrafts on aircraft is described in 4.1.6, where it is pointed out that downbursts/microbursts associated with convective cloud are the main culprits. In a downburst (a microburst being simply a concentrated form of a downburst) as described in 3.5.3 and 3.5.4, strong downdrafts penetrate through the base of the cloud and reach very close to ground level before spreading out radially along the ground. Intense microbursts are thought to form an annular vortex around the base of the downdraft just above ground level (see Figures 3-15 and 3-16). The effect of a downburst on an aircraft unfortunate enough to encounter one depends on the aircraft configuration, the intensity of the downburst, and where the downburst is located (laterally and vertically) in relation to the flight path. Three typical cases showing downbursts over the glide slope and offset on either side of the glide path are shown in Figure 4-10.

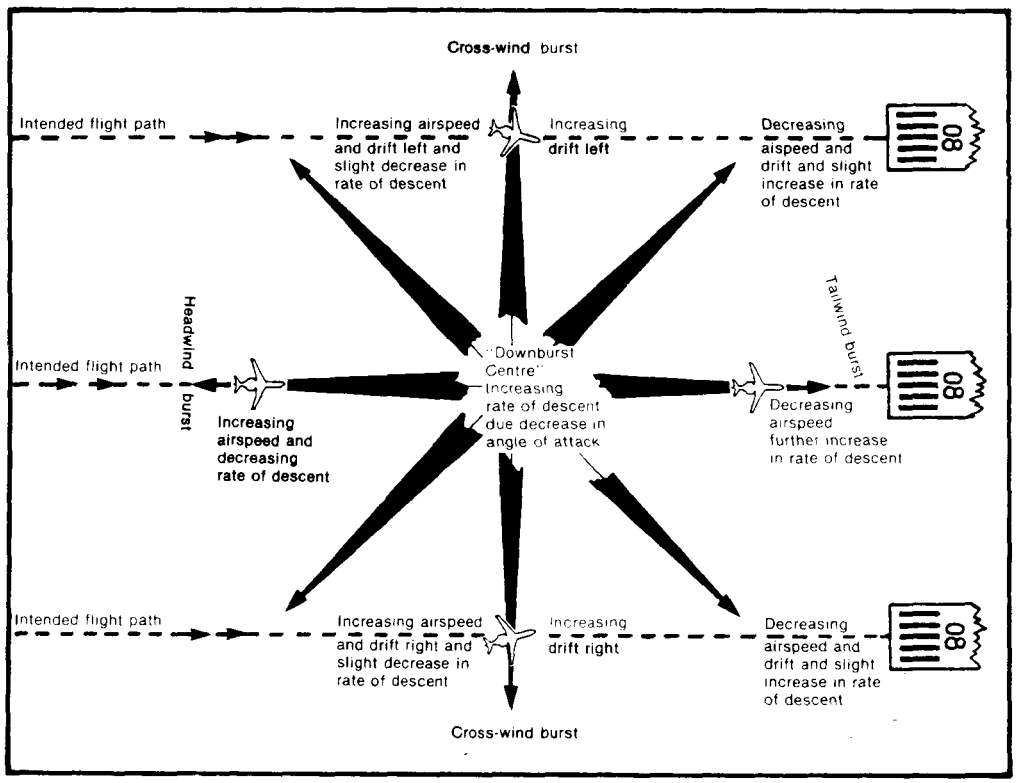
4.2.3.2 The first case to consider is an aircraft penetrating a downburst which occurs more or less on the flight path, for example, on the glide slope as shown in Figure 4-10 a). As the aircraft encounters the downburst it usually first meets an increasing headwind and possibly vortices or rotors in the outflow. There are cases, however, where the downburst shaft is not vertical and, depending on the inclination, this can reinforce the outflow on one side of the downburst and weaken the outflow on the opposite side. This means that the increasing headwind may not be encountered in every case. The increasing headwind causes an increase in airspeed, the aircraft pitches up and flies above the glide slope or climb-out path. It should be noted at



a) Increasing right to left cross-wind component

b) Decreasing right to left cross-wind component

Figure 4-9. Effect of crosswind shear on an aircraft, assuming no intervention by pilot



b) Downburst right of glidepath

a) Downburst on glide path

c) Downburst left of glidepath

Figure 4-10. Effect on aircraft landing through downburst at three locations with respect to glide path, assuming no intervention by pilot (plan view)

this point that although the pilot can counter this and regain the intended flight path by decreasing thrust, if (as will be discussed later) the pilot suspects that the headwind increase is due to a downburst, decreasing thrust is not advisable, and instead it is recommended that a go-around be initiated immediately. As the aircraft reaches the centre of the downburst the headwind disappears and is replaced by the downdraft (vertical component), the angle of attack decreases as the relative wind changes in response to the change from headwind to downdraft (see Figure 4-8 d) and continues to decrease further for as long as the speed of the downdraft increases[10]. This causes the aircraft to pitch down and fly back through and below the glide slope or climb-out path. As the aircraft exits the downburst, the downdraft is replaced by an increasing tailwind which causes a decrease in airspeed and a further deterioration in the flight path. Once inside the vertical shaft of the downburst core the aircraft descends at the speed of the downdraft (i.e. "drifting" downwards in the new vertical wind regime in a manner similar to lateral drift in crosswinds, although the downdraft case will of course be far more severe). To counter the steady downdraft it is necessary to generate an equivalent rate of climb by increasing thrust and pitch attitude. The sequence of events, assuming no intervention by the pilot, is shown in Figure 4-11 and the initial aircraft fixed control response to the downdraft and tailwind shears is shown in Figure 4-12.

4.2.3.3 If the downburst is offset to either side of the flight path (Figure 4-10 b) and c)) the immediate effect on the aircraft, though still potentially serious, will not normally be quite as severe as when the aircraft passes more or less directly under the downburst. This is because in these cases there will be rather less vertical component but more crosswind component to contend with. However, due to the fact that downbursts/microbursts often occur in "families", even if the aircraft is fortunate enough to skirt the edge of a downburst, a go-around is still recommended in case other downbursts are encountered, which might just as easily occur directly ahead of the aircraft. The sequence of increasing airspeed, decreasing and variable angle of attack and decreasing airspeed in a downburst, all of which could be encountered in as

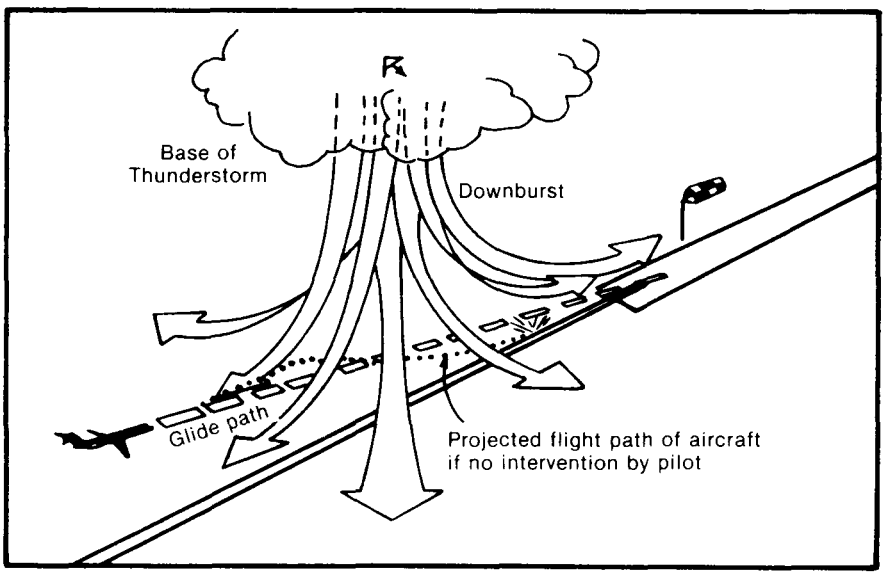


Figure 4-11. Landing through a downburst results in a change in flight path (after Melvin, 1977)

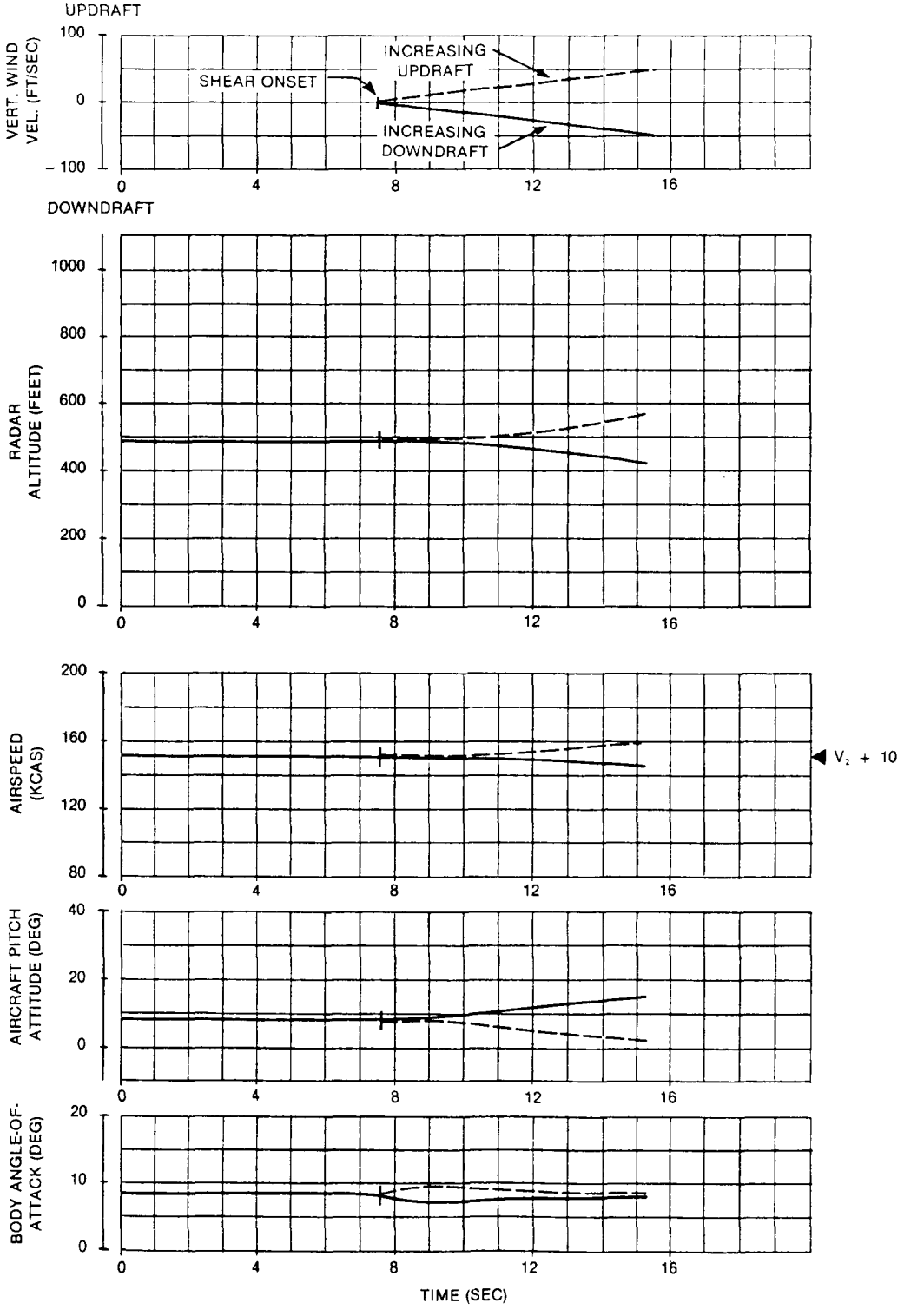


Figure 4-12. Initial aircraft fixed control response to vertical (updraft/downdraft) components (from FAA Wind Shear Training Aid, 1987)

little as 30 seconds, presents an extremely complex and dangerous situation for the pilot. Downbursts can also be encountered when the aircraft is still on the runway prior to lift-off. In these circumstances it hardly matters exactly where the downburst hits on the runway as all cases will cause serious problems for the pilot. If the downburst hits ahead of the aircraft, although initially the airspeed will build up quicker than normal due to the headwind from the outflow, after lift-off the aircraft will still have to transit the ensuing downdraft and tailwind outflow. This can present the worst possible combination of circumstances, because at take-off the aircraft is already operating close to or at maximum thrust levels and more than likely at a comparatively high mass. The pilot has to decide whether or not there is sufficient runway length to make an accelerated stop or whether to proceed with the take-off. A similar situation can arise if the downburst occurs behind the aircraft prior to lift-off. In this case, the sudden tailwind can make it impossible for the aircraft to accelerate to reach the necessary airspeed for take-off in the runway length available. These and other problems and measures which pilots can take to deal with them are discussed in some detail in 4.3.

4.2.3.4 In Chapter 3, 3.5.2, the main characteristics of the gust front are described. The gust front may be encountered a considerable distance away from the parent thunderstorm, especially in the case of gust fronts generated by squall lines. Gust fronts can cause sudden and totally unexpected changes in the surface wind during landing and take-off. Most aircraft encounters with gust fronts tend to be as an increasing headwind and hence increasing performance shear mainly due to the fact that the aircraft is normally operating into wind. However, there have been cases of gust fronts causing strong and unexpected crosswind shear and there is no reason to discount completely the possibility of a gust front causing an increasing tailwind, especially on take-off.

4.2.3.5 Mention was made in 3.5.5.5 of the possible consequences to an aircraft passing through a tornado or the wake of a tornado. A particular case of this, well documented by Roach and Findlater (1983), concerned the loss of a Fokker F-28 aircraft which took off from Rotterdam at 1604 UTC on 6 October 1981 bound for Eindhoven. According to the subsequent investigation, Roach and Findlater state that: "There were thunderstorms in the area and the aircraft flying at 900 m (3 000 ft) entered one of them a few minutes after take-off. After a short period of moderate turbulence in cloud the aircraft suddenly encountered extreme turbulence in which the starboard wing detached and, at 1612 UTC, the aircraft crashed near Moerdijk, about 25 km south east of Rotterdam, with the loss of all occupants." A tornado was reported just west of Moerdijk a few minutes before the crash and a police launch managed to take a series of photographs of the tornado and, less than one minute later, the smoke from the crash. The Kingdom of the Netherlands Civil Aviation Authority showed, from this and other evidence, that it was very likely that the aircraft encountered the tornado circulation in cloud shortly after the tornado funnel had lifted from the ground.

4.3 AIRCRAFT PERFORMANCE IN WIND SHEAR AND THE TECHNIQUES AVAILABLE TO PILOTS TO RECOGNIZE AND COPE WITH SUCH SITUATIONS

4.3.1 General

4.3.1.1 Before a pilot can apply the recovery techniques described later in this section he must be able to recognize that the aircraft is encountering wind shear. There is an unavoidable time lag between the pilot first seeing the signs, recognizing them for what they are, applying the appropriate recovery techniques and the aircraft responding accordingly. Reducing the time lag to a minimum is a question of early recognition of the wind shear condition by the pilot and the unhesitating application of the recommended wind shear recovery techniques.

4.3.1.2 Recognition and reaction times are largely a function of training, by giving the pilot the knowledge to spot quickly the first sign of wind shear and the confidence to apply recovery techniques without hesitation. Recognition also plays a major part in enabling the pilot to avoid an encounter with wind shear and subsequent discussions will therefore be organized in the following sequence: RECOGNITION - AVOIDANCE - PRECAUTION - RECOVERY. The sequence of pilot decisions and actions with respect to wind shear is shown in flow chart format in Figure 4-13. Indications that an aircraft is encountering wind shear may be derived from the flight deck instruments, from special on-board wind shear warning equipment, from wind shear warnings or other pilots' wind shear reports, or from external meteorological clues. Moreover, whether, and how quickly, the pilot will in fact recognize the instrument and meteorological signs for what they are depends upon a number of factors, such as whether the pilot has been forewarned to expect wind shear and is therefore alert to the possibility, and the extent to which wind shear has figured in the pilot's training (in particular the frequency and recency of wind shear training on a simulator, see Chapter 7).

4.3.2 Recognition of wind shear

4.3.2.1 External meteorological clues

4.3.2.1.1 Recognition of external meteorological clues to the possible presence of low-level wind shear near an airport permits the pilot to make an early decision to avoid an encounter by going around or by delaying the approach or take-off until conditions improve. Even if the decision is made to continue, the recognition of external wind shear signs should alert the pilot to pay very close attention to the progress of the landing/take-off by reference to the flight deck instruments. External clues which may be directly visible to the pilot include the following:

- virga, i.e. precipitation falling from the base of a cloud but evaporating before reaching the ground (especially under convective cloud), as downdrafts may still exist and reach the ground even though the precipitation itself has evaporated (see 3.5.1.6);

- lenticular cloud (smooth lens-shaped altocumulus) indicating the presence of standing waves, usually downwind from a mountain (see 3.2.8);

- roll cloud girding the base of a thunderstorm and advancing ahead of the rain belt, indicating the presence of a gust front (see 3.5.2.3);

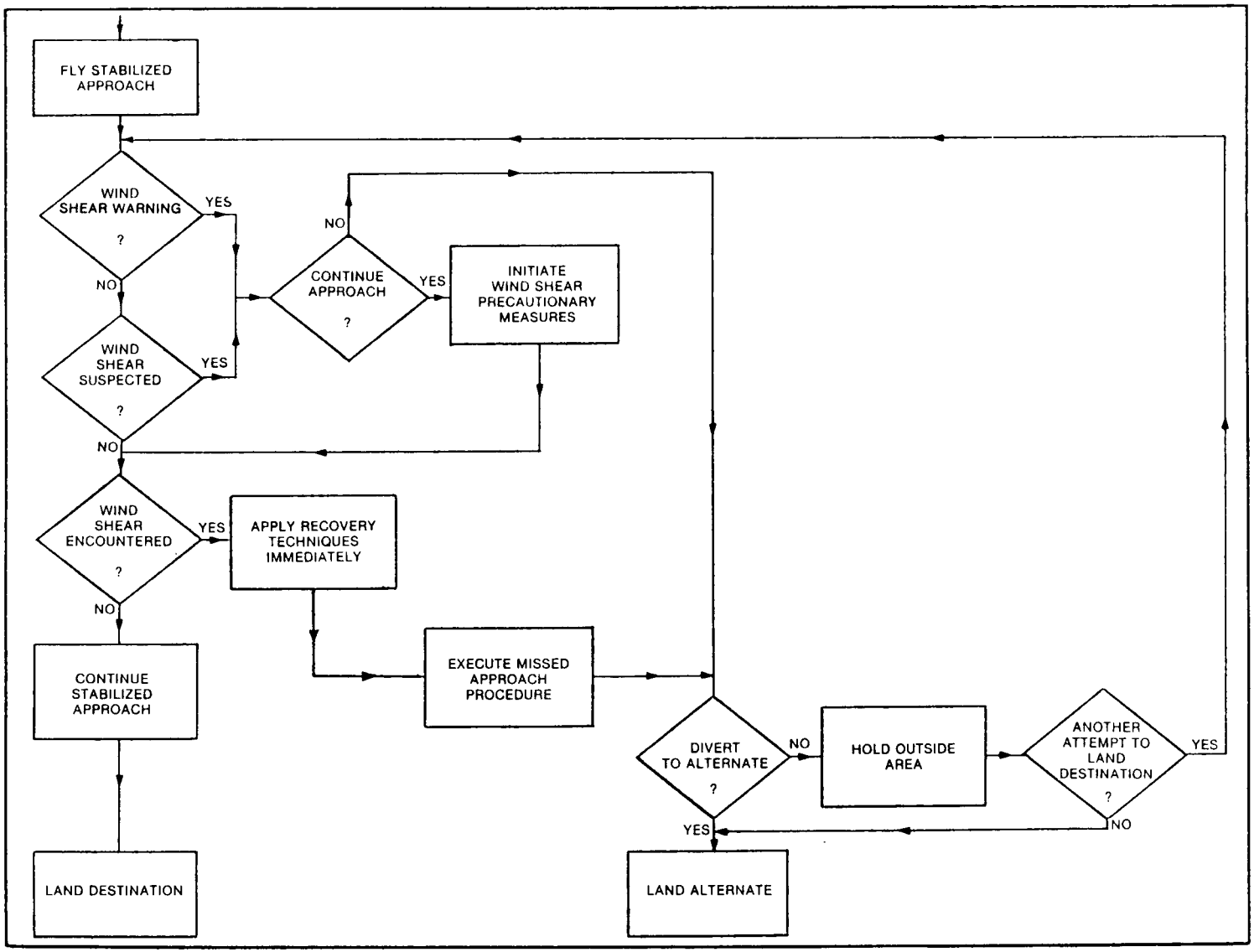


Figure 4-13. Flow chart sequence of pilot decisions and actions with respect to wind shear

- strong, gusty surface winds, especially where the aerodrome is located near hills or where there are comparatively large buildings near the runway, indicating the possibility of local wind shear and turbulence (see 3.2.1);

- areas of dust raised by wind, particularly when in the form of a ring below convective clouds, indicating presence of a downburst (see 5.1.2.1.1 and Figure 3-16);

- wind socks responding to different winds;

- smoke plumes sheared, with upper and lower sections moving in different directions;

- thunderstorms, which should always be assumed to have the capability of producing hazardous wind shear.

The implication of any of the foregoing for landing and take-off operations at an aerodrome would have to be assessed on a case-by-case basis, depending on the proximity of the phenomena to landing and take-off corridors, etc.

4.3.2.1.2 The wind shear warnings which may be issued at an airport are described and examples given in Chapter 5. These serve to alert the pilot to the possibility of wind shear and permit appropriate action to be taken. These warnings are likely to be based to a large extent on pilot reports, due to the continued difficulty in observing wind shear from the ground (see Chapter 3). It behoves all pilots, therefore, wherever possible, to make reports of wind shear during the approach and landing and during take-off and climb-out in line with the examples given in Chapter 5.

4.3.2.2 Indications from flight deck instrumentation and/or airborne equipment

4.3.2.2.1 As far as "flight deck" clues are concerned, these may be derived from the behaviour of flight deck instruments and, in aircraft so equipped, from dedicated airborne wind shear warning systems. The recognition of a wind shear situation from the behaviour of the flight deck instruments during the approach to land is rendered much easier if the pilot always flies a stabilized approach as a normal routine. A stabilized approach with, as far as practicable, constant airspeed, descent rate (vertical speed) and pitch angle assists the pilot in recognizing quickly any abnormal deviations in these parameters. This technique involves establishing the aircraft on the glide slope as early as possible in the landing configuration and flying the appropriate airspeed, pitch attitude and hence rate of descent by the smooth application of thrust/elevator control down to the flare. It is extremely difficult to recognize any but the most extreme deviations in airspeed, glide slope holding and descent rate due to wind shear if the aircraft is not flying a stabilized approach. This is perhaps no more than good airmanship, but it is a habit which could save valuable seconds in a wind shear encounter and should be encouraged from ab initio training.

4.3.2.2.2 The indications of wind shear which the pilot should be watching for when scanning the instruments are significant changes in airspeed, position relating to glide path on landing and vertical speed (climb/descent rate) and thrust setting. Significant changes to the thrust setting required to maintain a flight path are often the first indication of wind shear. Monitoring of thrust settings is therefore extremely

important especially if auto-throttle is being used. Abnormal and sudden deviations from the intended flight path may also be noticed on the vertical speed indicator, the glide slope indicator, the altimeter or from the ground proximity warning system. Airborne weather radar may assist in the detection and avoidance of convective cells. All of the foregoing alerting clues would be available to pilots of most transport aircraft and, on those aircraft equipped with airborne wind shear warning systems, additional warning should be available to the pilot. Given any of these indications of the presence of low-level wind shear during the approach to land, the pilot has to decide whether or not to delay the approach or, if encountering wind shear, to go around. Prior to take-off the the pilot will be largely dependent on external indications of wind shear and based on these a decision will have to be made whether or not to delay the take-off. The presence of wind shear may also be detected by the abnormal buildup of airspeed during the take-off roll. If wind shear is detected during the early stage of the take-off roll it may be advisable to abandon the take-off.

4.3.2.2.3 Subjective guidelines for evaluating relative and cumulative probabilities for the various convective wind shear observational clues as an aid to the pilot in making appropriate avoidance decisions have been developed as part of the FAA Wind Shear Training Aid (see Table 4-1). The probabilities are classified as follows:

HIGH PROBABILITY: Critical attention need be given to this observation. A decision to avoid (e.g. divert or delay) is appropriate.

MEDIUM PROBABILITY: Consideration should be given to avoiding. Precautions are appropriate.

LOW PROBABILITY: Consideration should be given to this observation, but a decision to avoid is not generally indicated.

4.3.2.2.4 In Table 4-1, the probability for each single observation is given. Wind shear clues, however, should be considered cumulative, and if more than one clue is observed, the total probability rating may be increased to reflect the total set of observations, as shown in the following example:

Example.- Nearing destination, VIRGA is seen descending from high based clouds over the airfield (MEDIUM PROBABILITY). Commencing approach, a PIREP is received indicating that another flight just experienced a 10 kt airspeed loss on final approach to the same airport (MEDIUM PROBABILITY). Therefore, it would be appropriate to raise the total avoidance decision weighting to HIGH PROBABILITY (indicating a decision to avoid is appropriate).

4.3.2.2.5 The guidelines in Table 4-1 apply to operations in the airport vicinity (within 3 miles of take-off or landing along the intended flight path below 1 000 ft AGL). Although encountering the weather conditions described in Table 4-1 above 1 000 ft may be less critical in terms of flight path, such encounters may present other significant weather-related risks. Pilots are therefore urged to exercise caution when determining a course of action. Use of Table 4-1 should not replace sound judgement in making avoidance decisions.

Table 4-1. Microburst wind shear probability guidelines
(from FAA Wind Shear Training Aid, 1987)

Observation	Probability of wind shear
Presence of convective weather near intended flight path:	
- with localized strong winds (tower reports or observed blowing dust, rings of dust, tornado-like features, etc.)	High
- with heavy precipitation (observed or radar indications of contour, red or attenuation shadow)	High
- with rain shower	Medium
- with lightning	Medium
- with virga	Medium
- with moderate (or greater) turbulence (reported or radar indications)	Medium
- with temperature/dew point spread between 17 and 28 degrees Celsius	Medium
On-board wind shear detection system alert (reported or observed)	High
Pilot report of airspeed loss or gain:	
- 15 kt or greater	High
- less than 15 kt	Medium
LLWAS alert/wind speed change:	
- 20 kt or greater	High
- less than 20 kt	Medium
Forecast of convective weather	Low

Note.- These guidelines apply to operations in the airport vicinity (within 3 miles of the point of take-off or landing along the intended flight path and below 1 000 ft AGL). The clues should be considered cumulative. If more than one is observed the probability of weighting should be increased. The hazard increases with proximity to the convective weather. Weather assessment should be made continuously.

CAUTION.- Currently no quantitative means exists for determining the presence or intensity of microburst wind shear. Pilots are urged to exercise caution in determining a course of action.

4.3.3 Precautionary measures

4.3.3.1 If, after carefully assessing all the available information, the pilot decides to continue the approach to land or to proceed with the take-off, preparation should be made for possible encounters with wind shear by taking the precautionary

actions specified in aircraft operations manuals and airline company flight manuals. Pilots should not proceed on the assumption that their particular aircraft can cope with all wind shears, as experience has shown that this is clearly not the case. An example of such measures is given in the abstract from the B737 operations manual in Appendix D under "prevention". The precautionary measures for approach and landing are aimed at configuring the aircraft for landing but with the maximum practicable reserve held for any recovery techniques or go-around which may have to be applied by selecting appropriate landing flap positions for the particular circumstances and carrying extra airspeed for wind correction up to a given maximum, etc. In the same way, precautions for take-off include use of maximum thrust and use of the longest suitable runway. The precautionary measures and recovery techniques described in this chapter are taken from the techniques developed as part of the FAA Wind Shear Training Aid (1987)[12]. The training aid was developed by Boeing as the prime contractor with Douglas and Lockheed participating in the development of technical conclusions assuring applicability "over the broadest range of United States manufactured jet transports" (see list in 4.3.3.3 below). The training aid contains the following disclaimer and idemnity notice:

"DISCLAIMER AND INDEMNITY NOTICE

This document, Wind Shear Overview for Management, and its companion documents, Pilot Wind Shear Guide, Example Wind Shear Training Programme, Wind Shear Substantiating Data, and video presentations A Wind Shear Avoided and Wind Shear - What the Crew Can Do were prepared pursuant to Federal Aviation Administration Prime Contract DFTA01-86-C-00005 with the Boeing Company as a training aid for flight in wind shear conditions. The information contained herein and in the companion materials was derived from information originally developed for the Boeing 727, and provides a base-line training programme with additional recommendations, developed and approved by Boeing, Douglas or Lockheed for their respective aircraft, regarding how that programme might be adapted for use in specific commercial transport aircraft manufactured by Boeing (727, 737, 747, 757 and 767), Douglas (DC-9, MD-80 and DC-10) and Lockheed (L-1011). Any use of this wind shear overview for management for any purpose related to aircraft or conditions other than those specified above is not authorized and may result in improper aircraft operation, loss of aircraft control, injury and loss of aircraft and life. Any use, adaptation and/or use after adaptation of the material in this wind shear overview for management by any entity for any purpose related to aircraft, conditions or to training programmes other than those specified above shall be completely at the risk of the entity responsible for using, adapting and/or using the adaptation of this wind shear overview for management, and such entity by such use, adaptation and/or use after adaptation assumes such risk and waives and releases all claims it may have against the Boeing Company, McDonnell Douglas Corporation, Lockheed Corporation, United Airlines, Aviation Weather Associates, Helliwell, Inc., their divisions, subsidiaries, affiliates and their officers, directors, subcontrators and employees from any liability whatsoever, whether based on contract (including but not limited to express and implied warranty claims), tort (including but not limited to negligence and strict liability claims) or otherwise, arising from such use, adaptation and/or use of such adaptation. Any such entity (including without limitation any manufacturer of other aircraft or operator with another training programme but not the United States Government) which uses this wind shear overview for management or adapts and/or uses an adaptation thereof with respect to

such other aircraft, conditions or training programme thereby agrees to indemnify and hold harmless the Boeing Company, McDonnell Douglas Corporation, Lockheed Corporation, United Airlines, Aviation Weather Associates, Helliwell, Inc., their divisions, subsidiaries and affiliates and their officers, directors, agents, subcontractors and employees from any liability whatsoever, whether based on contract (including but not limited to express and implied warranty claims), tort (including but not limited to negligence and strict liability claims) or otherwise, arising from such use, adaptation and/or use of such adaptation.

Notwithstanding any other provision of this contract to the contrary, the FAA shall accept the items delivered hereunder with the disclaimer affixed by contractor and agrees not to remove such disclaimer for any reason whatsoever."

4.3.3.2 Avoidance is the best precaution. However, there are situations when wind shear clues do not clearly dictate a delay, but can be interpreted to mean that conditions are right for wind shear activity. In these instances, pilots should consider the next step of flight crew actions - the use of precautions. A number of precautionary techniques have been developed which crews can take to lessen the effect of wind shear should an unsuspected severe wind shear be encountered on take-off or approach. These precautions include consideration of thrust setting, runway selection, flap selection, airspeed, use of autopilot, auto-throttle and flight director. They were developed by detailed analysis and piloted simulation of several microburst wind shear encounters. In many cases, trade offs were involved and no "best" recommendation for all conditions could be developed.

4.3.3.3 Use of precautions along with even the best recovery piloting skills cannot guarantee a successful escape from many microburst wind shears. It is important to realize that the recommended precautions each have a relatively small effect on the outcome of an inadvertent wind shear encounter. Therefore, use of precautions should not replace sound pilot judgement in deciding whether or not it is safe to proceed. Use of precautions should not bias a go/no-go decision in the go direction.

4.3.3.4 Take-off precautions

Thrust setting

4.3.3.4.1 Maximum rated take-off thrust should be used for take-off. This shortens the take-off roll and reduces over-run exposure. Full thrust also provides the best rate of climb, thus increasing altitude available for recovery if required. Lastly, full thrust take-offs may eliminate resetting thrust in a recovery, thereby maximizing acceleration capability and reducing crew work-load.

Runway selection

4.3.3.4.2 Use the longest suitable runway that avoids suspected areas of windshear. The choice of a suitable runway involves consideration of exposure to obstacles after lift-off and crosswind and tailwind limitations. This assures maximum runway available to accelerate to rotation speed and may result in more ground clearance at the end of the runway and during the climb profile. Should the decision be made to reject the take-off, more runway is available on which to stop the aircraft.

Take-off flap selection

4.3.3.4.3 The choice of take-off flap setting is dependent on the aircraft type. The following flap settings should be considered unless limited by obstacle clearance and/or climb gradient:

Aircraft type	Take-off flap setting
B727	15
B737	5 to 15
B747	20
B757	20
B767	20
DC-9-10	10 or 20
DC-9-20,-30,-40,-50	5 or 15
MD-80	5 or 15
DC-10	5 or 20
L-1011	10 to 22

Studies of available take-off flap settings showed that the greater flap setting provided best performance for wind shear encounters on the runway. However, lesser flap settings showed the best performance for in-air wind shear encounters. The take-off flap settings given above offered somewhat better performance over a wide range of conditions; however, it must be pointed out that the performance difference between flap settings is small.

Increased airspeed

4.3.3.4.4 Increased airspeed at rotation improves the ability of the aircraft to negotiate a wind shear encountered after lift-off. Increased airspeed improves the flight path, reduces potential exposure to flight near stick-shaker speeds, and reduces pilot work-load.

4.3.3.4.5 Delaying rotation to a higher airspeed may appear to increase the risk of overrunning available runway. However, because of the manner in which increased rotation speed is calculated, it is simply using the runway as if the aircraft was loaded to the field length limit mass for that runway. If the take-off is at field length limit conditions, the risk of overrunning the available runway is increased because there is no extra runway available. The overrun exposure is also increased if the wind shear reduces the airspeed below the minimum airspeed required for lift-off at the maximum available (body contact) attitude. However, initiating rotation no later than 2 000 ft from the end of the usable runway surface reduces the probability of overrun and maximizes the available energy after lift-off.

4.3.3.4.6 If increased V_R is to be used, the technique for scheduling and using increased rotation airspeed is:

1) Determine V_1, V_R and V_2 speeds for actual aircraft gross mass and flap setting. Set airspeed "bugs" to these values in the normal manner.

2) Determine field length limit maximum mass and corresponding V_R for selected runway.

3) If field length limit V_R is greater than actual gross mass V_R, use the higher V_R (up to 20 kt in excess of actual gross mass V_R) for take-off. Airspeed bugs should not be reset to the higher speeds.

4) Rotate to normal initial climb attitude at the increased V_R and maintain this attitude. This technique produces a higher initial climb speed which slowly bleeds off to the normal initial climb speed.

WARNING.- If wind shear is encountered at or beyond the actual gross mass (bug) V_R, do not attempt to accelerate to the increased V_R, but rotate without hesitation. In no case should rotation be delayed beyond 2 000 ft from the end of the usable runway surface (see 4.3.4, recovery techniques).

4.3.3.4.7 If increased airspeed was not used prior to lift off, accelerating to higher than normal airspeed after lift off is not recommended. Reducing pitch attitude at low altitude to accelerate might produce a hazard if wind shear is encountered.

Flight director

4.3.3.4.8 Do not use speed-referenced flight directors unless they are equipped with wind shear recovery guidance.

WARNING.- A speed-referenced flight director which does not have wind shear recovery guidance may command a pitch attitude change to follow target airspeeds regardless of flight path degradation. This guidance may be in conflict with the proper procedures for wind shear recovery. Such flight directors must be disregarded if a recovery is required and, time permitting, switched off by the pilot not flying (PNF).

4.3.3.4.9 Some flight directors are equipped with a selectable pitch attitude mode. If normal procedures utilize this feature, the selectable pitch attitude mode may be effectively used in a wind shear encounter provided the selected attitude is within the acceptable range. However, if an attitude other than the selected attitude becomes necessary, the flight director should be disregarded and, time permitting, switched off by the PNF.

Summary

Take-off precautions

- Use maximum rated take-off thrust
- Use longest suitable runway
- Consider using recommended flap setting
- Consider using increased rotation airspeed
- Do not use speed referenced flight director

4.3.3.5 Approach precautions

Stabilized approach

4.3.3.5.1 A stabilized approach should be established no later than 1 000 ft AGL to improve wind shear recognition capability.

Thrust management

4.3.3.5.2 Minimize thrust reductions. Rather than immediately compensating for an airspeed increase by reducing thrust, a brief pause to evaluate speed trends is prudent. If a tailwind shear occurs and recovery is initiated, the additional airspeed and earlier availability of thrust (due to engines accelerating from a higher RPM) will be advantageous. If auto-throttles are engaged, ensure that inappropriate thrust reductions do not occur. In the absence of a tailwind shear, this procedure may result in a higher than normal approach speed which may have to be accounted for on landing.

Runway selection

4.3.3.5.3 Use the most suitable runway that avoids the area of suspected wind shear and is compatible with crosswind and tailwind limitations. A longer runway provides the greatest margin for increased ground roll due to unanticipated winds and possible resulting high ground speed at touchdown. A precision (instrument) approach and other aids to glide path monitoring (VASI, etc.) are also desirable, as they can enhance wind shear recognition by providing timely, accurate flight path deviation information.

Landing flap selection

4.3.3.5.4 The choice of landing flap setting is dependent on aircraft type. The following flap settings should be considered:

Aircraft type	Landing flap setting
B727	30
B737	30
B747	25 to 30
B757	30
B767	30
DC-9	*
MD-80	28
DC-10	35
L-1011	33

* Minimum flap setting for particular model

Studies of wind shear encounters using all available landing flap settings have shown that the flap settings recommended above provided the best over-all recovery performance for a wide range of wind shears.

Increased airspeed

4.3.3.5.5 Increased airspeed on approach improves climb performance capability and reduces the potential occurrence of flight at stick shaker during recovery from an inadvertent wind shear encounter.

4.3.3.5.6 If available landing field length permits, airspeed may be increased by up to a maximum of 20 kt. This increased speed should be maintained to flare. Touchdown must occur within the normal touchdown zone - do not allow the aircraft to float down the runway.

4.3.3.5.7 As many variables are involved, it is not practical to provide exact guidance on the effect of 20 kt extra speed on actual stopping distance. Surface wind can be a major factor since stopping distance is affected by ground speed rather than airspeed. If increased airspeed is used and an increasing performance shear is encountered, a go-around may be necessary due to insufficient landing field length for the higher approach speed. Furthermore, if a pilot can be reasonably certain that wind changes (due to topography or unique local conditions) will not result in decreasing performance, it may be inappropriate to use increased approach speed.

4.3.3.5.8 Other factors affecting stopping distance, such as availability and effectiveness of thrust reversers, tire and brake condition, runway surface conditions, etc., must also be taken into consideration. On a dry runway with no adverse factors present, landing field length may accommodate 20 kt extra speed at touchdown. In other cases greater field length may be required. If in doubt, use the longest suitable runway which does not expose the aircraft to greater hazard from possible shear.

WARNING.- Increased touchdown speeds increase stopping distance. An additional 20 kt at touchdown can increase stopping distance by as much as 25 per cent and in some cases may exceed brake energy limits.

Flight director and/or autopilot and auto-throttles

4.3.3.5.9 During approach it is desirable to utilize the flight director, autopilot and auto-throttles to the maximum extent practicable. These systems may relieve pilot work-load, allowing the crew more time to monitor instruments and weather conditions. However, use of autoflight systems, and in particular of the auto-throttle, only provides benefits if properly monitored. In the absence of proper monitoring, these systems may mask onset of shear through lack of pilot awareness of control inputs being made.

Summary

Approach precautions

- Stabilize approach no later than 1 000 ft AGL
- Minimize thrust reductions
- Use most suitable runway
- Consider using recommended flap setting
- Consider using increased approach speed
- Use autoflight systems during approach

4.3.3.6 Follow established standard operating techniques

4.3.3.6.1 In an effort to aid crews in the early recognition of a wind shear encounter, a series of recommendations has been formulated under the general heading of standard operating techniques (SOTs). These SOTs fall into two general headings of crew awareness and crew co-ordination.

4.3.3.6.2 The need for emphasis on SOTs came from recognition that in most take-off wind shear accidents, the aircraft pitch attitude was reduced below the attitude that would maintain level flight. This was done when the aircraft was already descending toward the ground and indicates lack of flight path awareness on part of the crews involved. This lack of awareness was also observed during piloted simulator studies of wind shear encounters. Traditional training programmes and routine flying may not have reinforced proper flight path control and concern for altitude loss. However, flight path control should be the primary focus when dealing with wind shear. Techniques such as strict adherence to airspeed must be modified in favour of maintaining flight path by controlling pitch attitude.

4.3.3.6.3 The SOTs that follow emphasize flight path and pitch attitude for operations near the ground. Following the SOTs results in better crew performance during day-to-day operations, as well as during wind shear encounters. In both take-off and approach to landing, crew awareness and co-ordination are vital for timely wind shear recognition, particularly at night or in marginal weather conditions.

Crew awareness

4.3.3.6.4 It is important for crews to remain alert for any change in conditions, remembering that wind shear can be quick to form and to dissipate. The shears that proved to be the most deadly were those which caught crews by surprise.

4.3.3.6.5 Crews should be aware of normal vertical flight path indications so that wind shear induced deviations are more readily recognized. On take-off, this would include attitude, climb rate, and airspeed buildup. On approach, airspeed, attitude, descent rate and throttle position provide valuable information. Awareness of these indications assures that flight path degradation is recognized as soon as possible.

4.3.3.6.6 During take-off and approach, be alert for airspeed fluctuations. Such fluctuations may be the first indication of wind shear. Control column forces significantly different than those expected during a normal take-off or go-around may result if airspeed is below target or airspeed buildup is low during rotation and lift-off. Vertical flight path displays should be used to cross-check flight director commands.

4.3.3.6.7 During take-off while at relatively low altitude (below 1 000 ft AGL), the SOTs require awareness and use of normal climb-out pitch attitude and less emphasis on strict airspeed control. Know the all-engine initial climb pitch attitude. Rotate at the normal rotation rate to this attitude for all take-offs. Minimize pitch attitude reductions in response to low airspeed until terrain and obstruction clearance is assured.

4.3.3.6.8 On approach, avoid large thrust reductions or trim changes in response to sudden airspeed increases as an airspeed decrease may follow. Closely monitor vertical flight path instruments, such as vertical speed, altimeters and glide slope displacement. In addition, comparison of ground speed and airspeed indications can provide additional information for timely wind shear recognition. Achieve a stabilized approach no later than 1 000 ft AGL.

4.3.3.6.9 High work-load and distractions in the approach phase, particularly in marginal weather, may divert attention away from instruments that provide early recognition of flight path deterioration. Additionally, gradual application of thrust on approach may mask a decreasing airspeed trend.

4.3.3.6.10 Crews should be prepared to execute the recommended recovery procedure immediately if deviations from target conditions in excess of the following occur:

Take off/approach:

1) ± 15 kt indicated airspeed

2) ± 500 FPM vertical speed

3) ± 5° pitch attitude

Approach:

1) ± 1 dot glide slope displacement

2) unusual throttle position for a significant period of time.

These values should be considered as guidelines only. Exact criteria cannot be established. In certain instances where significant rates of change occur, it may be necessary to initiate recovery before any of the above criteria are exceeded. Other situations may exist where brief excursions, particularly in airspeed, resulting from known or anticipated local wind effects may not be an indication of significant hazard. The PF is responsible for assessing the situation and using sound judgement to determine the safest course of action.

Crew co-ordination

4.3.3.6.11 The PF should focus attention on flying the aircraft. In a wind shear encounter, appropriate action should be taken in response to call-outs. The PNF should focus attention on airspeed, vertical speed, altitude, pitch attitude, glide path deviation and thrust. If any significant deviations from normal indications are detected, the PNF should immediately call out the deviation. Call-outs in the cockpit should be standardized and easy to understand to ensure timely recognition.

Example.- "Vertical speed 1 200 down - airspeed 115 decreasing - glide slope one dot low."

Standard operating techniques summary

Take-off

- know normal attitudes, climb rates, airspeed buildup
- know/use all-engine initial climb attitude
- make continuous rotation at normal rate
- cross-check flight director commands
- minimize pitch attitude reductions
- monitor vertical flight path instruments, call out deviations (PNF)
- know recovery decision guidelines

Approach

- know normal attitudes, descent rates, airspeeds, throttle position
- cross-check flight director commands
- avoid large thrust reductions
- monitor vertical flight path instruments, call out deviations (PNF)
- know recovery decision guidelines

4.3.4 Wind shear recovery technique

4.3.4.1 General

4.3.4.1.1 The primary objective of a recovery technique is to keep the aircraft flying as long as possible in the hope of exiting the shear. A wide variety of techniques have been considered to establish the one technique which best meets this objective. The best results were achieved by pitching toward an initial target attitude while using necessary thrust. Several factors were considered in developing this technique.

4.3.4.1.2 Studies show wind shear encounters occur infrequently and that only a few seconds are available to initiate a successful recovery. Additionally, during high stress situations pilot instrument scan typically becomes very limited - in extreme cases, to only one instrument. Lastly, recovery skills will not be exercised on a day-to-day basis. These factors dictate that the recovery technique must not only be effective, but simple, easily recalled, and have general applicability.

4.3.4.1.3 Extensive analysis and pilot evaluations have been conducted. Although a range of recovery attitudes (including 15° and the range of all-engine initial climb attitudes) provides good recovery capability for a wide variety of wind shears, 15° was chosen as the initial target pitch attitude for both take-off and approach. Additional advantages of 15° initial target pitch attitude are that it is easily recalled in emergency situations and it is prominently displayed on attitude director indicators.

Note 1.- L-1011 target attitudes:

Take-off = 17.5°
Approach = 15°

Note 2.- Operators using pre-calculated target pitch attitudes such as all-engine attitude for normal take-offs and go-arounds may use these attitudes in place of the recommended initial target recovery attitude.

4.3.4.1.4 While other more complex techniques may make slightly better use of aircraft performance, these techniques do not meet simplicity and ease of recall requirements. Evaluations show that the recommended technique provides a simple, effective means of recovering from a wind shear encounter.

4.3.4.1.5 A detailed discussion of the recommended recovery technique follows. Recovery both during take-off after lift-off and recovery during approach are discussed together in the following section since the technique for both situations is identical. The recovery technique for encounters during take-off on runway is presented later.

4.3.4.2 Encounter during take-off, after lift-off and encounter on approach

4.3.4.2.1 Wind shear recognition is crucial to making a timely recovery decision. The recommended recovery procedure should be initiated any time the flight path is threatened below 1 000 ft AGL on take-off or approach. The guidelines for unacceptable flight path degradation are repeated below:

Take-off/approach:

1) ± 15 kt indicated airspeed

2) ± 500 FPM vertical speed

3) ± 5° pitch attitude

Approach:

1) ± 1 dot glide slope displacement

2) unusual throttle position for a significant period of time.

4.3.4.2.2 Again, these should be considered as guidelines, since exact criteria cannot be established. In every case, it is the responsibility of the pilot flying to assess the situation and use sound judgement in determining the safest course of action. In certain instances where significant rates of change occur, it may be necessary to initiate recovery before any of the above are exceeded.

4.3.4.2.3 If wind shear is inadvertently encountered after lift-off or on approach, immediately initiate the recommended recovery technique. If on approach, do not attempt to land. (However, if on approach and an increasing performance shear is encountered, a normal go-around, rather than the recovery manoeuvre, may be accomplished.) The technique for recovery from a wind shear encounter after lift-off or during approach is the same for both cases. This technique is described as follows:

Thrust

4.3.4.2.4 Aggressively apply necessary thrust to ensure adequate aircraft performance. Disengage the auto-throttle if necessary. Avoid engine overboost unless required to avoid ground contact. When aircraft safety has been ensured, adjust thrust to maintain engine parameters within specified limits.

Pitch

4.3.4.2.5 The pitch control technique for recovery from a wind shear encounter after lift-off or on approach is as follows:

- At normal pitch rate, increase or decrease pitch attitude as necessary toward an initial target attitude of 15°. The autopilot/flight director should be turned off by the PNF unless specifically designed for operations in wind shear, or unless using a pitch-selectable flight director with desired attitude commanded.

- Always respect stick shaker. Use intermittent stick shaker as the upper pitch limit. In a severe shear, stick shaker may occur below 15° pitch attitude.

- If attitude has been limited to less than 15° to stop stick shaker, increase attitude toward 15° as soon as stick shaker stops.

- If vertical flight path or altitude loss is still unacceptable after reaching 15°, further increase pitch attitude smoothly in small increments.

- Control pitch in a smooth, steady manner (in approximately 2 degree increments) to avoid excessive overshoot/undershoot of desired attitude.

- Once the aircraft is climbing and ground contact is no longer an immediate concern, airspeed should be increased by cautious reductions in pitch attitude.

Configuration

4.3.4.2.6 Maintain flap and gear position until terrain clearance is assured. Although a small performance increase is available after landing gear retraction, initial performance degradation may occur when landing gear doors open for retraction. While extending flaps during a recovery after lift-off may result in a performance benefit, it is not a recommended technique because:

1) Accidentally retracting flaps (the usual direction of movement) has a large adverse impact on performance.

2) If landing gear retraction had been initiated prior to recognition of the encounter, extending flaps beyond a take-off flap setting might result in a continuous warning horn which distracts the crew.

Additional considerations

4.3.4.2.7 If autopilot/flight director systems specifically designed for operation in wind shear are engaged during approach, they should be used during the recovery manoeuvre. These systems may aid in recovery from an inadvertent wind shear encounter. However, due to limited time available to recognize and respond, do not engage the autopilot or auto-throttle if these systems were not engaged prior to recovery.

WARNING.- A flight director and/or autoflight system which is not specifically designed for operation in wind shear may command a pitch attitude change to follow target airspeeds or a fixed pitch attitude regardless of flight path degradation. This guidance may be in conflict with the proper procedures for wind shear recovery. Such systems must be disregarded if recovery is required and, time permitting, switched off by the PNF.

4.3.4.2.8 Use of autopilot control wheel steering (CWS) has not been fully evaluated for its effectiveness in a wind shear encounter. One consideration regarding CWS is that it is usually a single-channel autopilot mode and as such has reduced control authority. In any case, if CWS is used during a wind shear encounter, its use should be discontinued if it produces difficulty in achieving the desired attitude.

4.3.4.2.9 Some flight directors are equipped with a selectable pitch attitude mode. If normal procedures utilize this feature, the selectable pitch attitude mode may be effectively used in a wind shear encounter, provided the selected attitude is within the acceptable range. However, if an attitude other than the selected attitude becomes necessary, the flight director should be disregarded and, time permitting, switched off by the PNF.

4.3.4.2.10 Avoid stabilizer trim changes in response to short term wind shear produced airspeed/stick force changes. However, stabilizer trim should be used to trim out stick force due to thrust application.

4.3.4.2.11 Throughout recovery, the PNF should call out vertical flight path deviations using the barometric altimeter, radio altimeter, or vertical speed indicator as appropriate. For example, "sinking 500, altitude 200, climbing 400, altitude 300, etc." Operators of aircraft requiring a flight engineer may incorporate the second officer into the call-out process.

4.3.4.2.12 Rapidly changing winds may cause rapid excursions in pitch and roll with little or no pilot input as well as varying the attitude for stick shaker activation.

4.3.4.2.13 As soon as possible, report the encounter to the tower, as aircraft following may not have the performance required to recover from the same wind shear encounter. The wind shear also may be increasing in intensity, making flight through it even more dangerous. (The pilot reports for wind shear encounters are dealt with in Chapter 5.) Pilots and controllers must be aware that their timely actions may prevent an impending disaster - seconds may save lives!

Summary

After lift-off/on approach wind shear recovery technique

- Thrust
  - apply necessary thrust
- Pitch
  - adjust toward 15°
  - increase beyond 15° if required to ensure acceptable flight path
  - always respect stick shaker
- Configuration
  - maintain existing configuration

4.3.4.3 Encounter during take-off on runway

4.3.4.3.1 Recognition of wind shear is difficult during the take-off roll since airspeed is changing rapidly. In addition to visual clues described previously, unusual airspeed fluctuations, slow or erratic airspeed buildup may be indications of a wind shear encounter.

4.3.4.3.2 The go/no-go criteria based on engine failure decision speed (V_1) may not be valid for wind shear conditions, since ground speed can be much higher than airspeed (Figure 4-14). It therefore may not be possible to stop the aircraft on the runway during a rejected take-off. The ability to lift-off is a function of airspeed; the ability to stop is largely a function of ground speed.

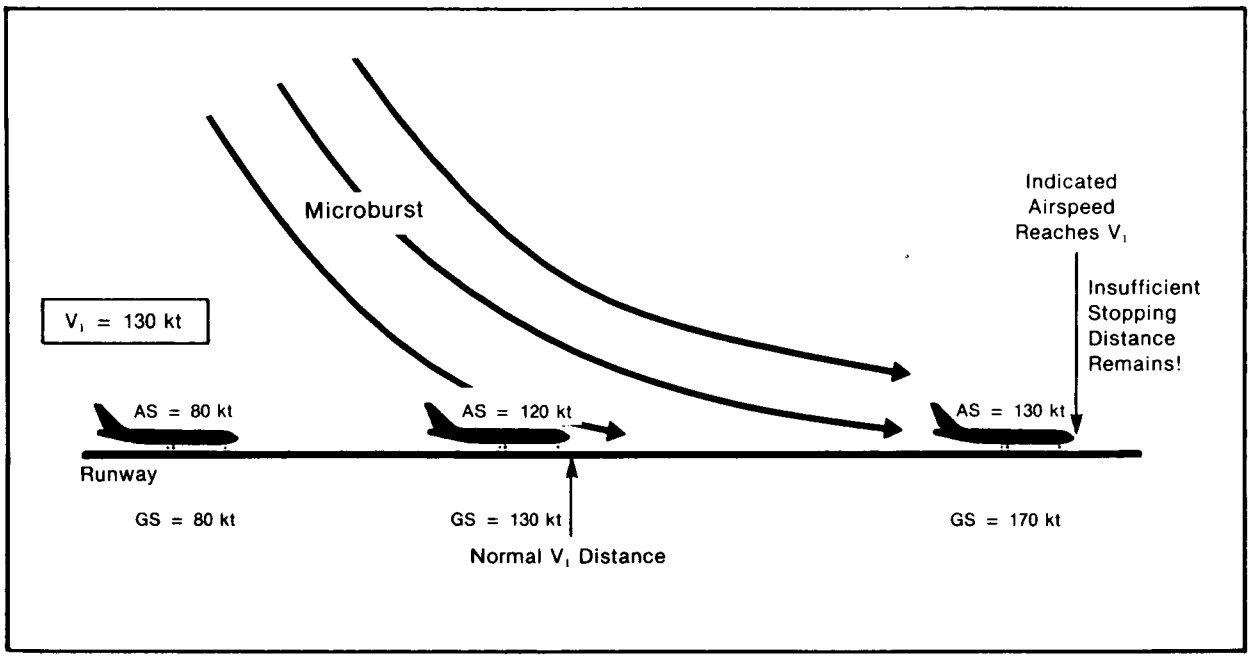


Figure 4-14. Wind shear effects on go/no-go decision point. V_1 decision speed may not be attained until insufficient runway remains to abort take-off (from FAA Wind Shear Training Aid, 1987)

Prior to V_1

4.3.4.3.3 The take-off should be rejected if unacceptable airspeed variations occur below indicated V_1 and the pilot decides that there is sufficient runway remaining to stop the aircraft.

After V_1

4.3.4.3.4 The take-off must be continued if V_1 has been reached.

Thrust

4.3.4.3.5 Aggressively apply necessary thrust to ensure adequate aircraft performance. Avoid engine overboost unless necessary to ensure aircraft safety. When aircraft safety has been ensured, adjust thrust to maintain engine parameters within specified limits. Overboost thrust alone, however, is NOT sufficient to offset the effects of an inadvertent wind shear encounter. Proper pitch attitude control is the most important factor in recovery from wind shear.

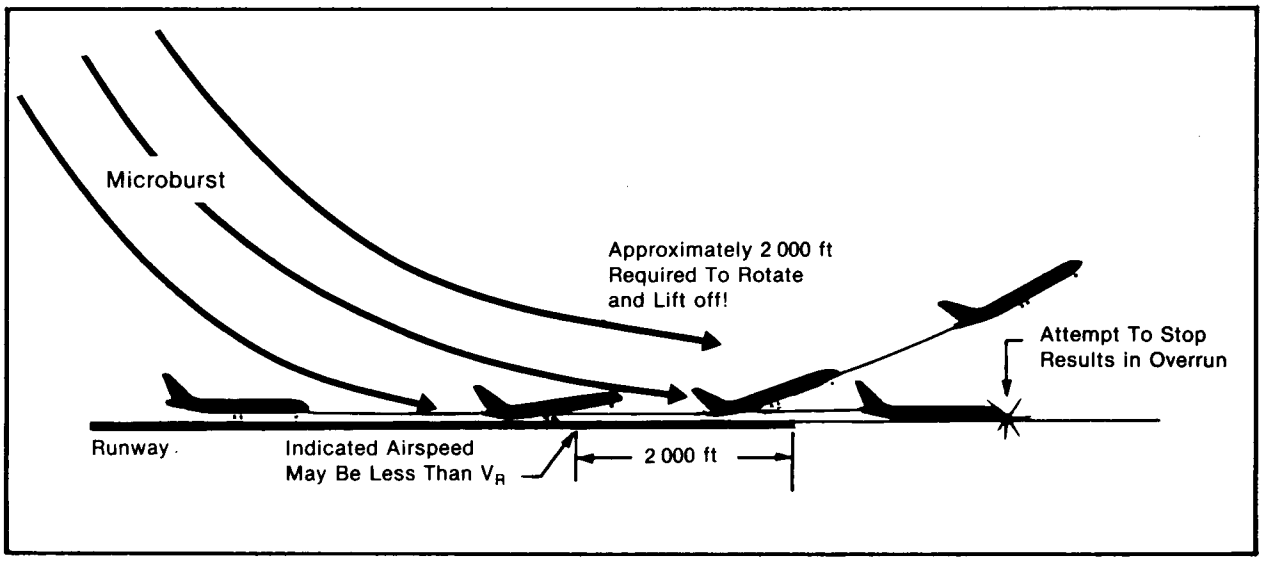


Figure 4-15. Wind shear effects on rotation decision. Wind shear effects may force rotation at speeds below V_R. Rotation should begin no later than 2 000 ft from runway departure (from FAA Wind Shear Training Aid, 1987)

Pitch

4.3.4.3.6 When V_R is reached, rotate at normal rate toward 15° pitch attitude. In severe wind shear encounters, however, V_R might not be reached and the option to reject the take-off may not exist. If this is the case, rotation must be initiated no later than 2 000 ft from the end of the usable surface (Figure 4-15).

Note.- Transport category aircraft typically can lift off 5 to 10 kt prior to V_R (except B727, which cannot lift off prior to V_R).

4.3.4.3.7 Pitch attitude and rotation rate should not be restricted to avoid aft body contact since all available pitch attitude may be required to lift off in the available runway. Once airborne, follow the "after lift-off recovery technique" discussed earlier.

Take-off (on runway)
recovery technique

- Thrust
  - apply necessary thrust
- Pitch
  - rotate toward 15° (no later than 2 000 ft remaining)
  - increase beyond 15° if required to lift off

Note.- After lift-off follow after lift-off recovery technique.

4.3.4.3.8 The runway remaining during take-off can be identified on runways having appropriate marking and lighting. While the markings discussed are usually to assist landing aircraft, they can also be used to determine runway remaining during a take-off. Figure 4-16 illustrates the markings and lighting typical of ICAO and FAA precision approach runways. For an aircraft departing from left to right in the figure, the first pair of single hash marks on either side of the centre line indicates 3 000 ft of runway remaining (i.e. 1 000 ft until rotation must be initiated). As take-off continues, the 2 000 ft remaining point is denoted by the first pair of double hash marks encountered. Note that the spacing of all hash marks is in 500 ft intervals from the departure end threshold.

4.3.4.3.9 Another indication of runway remaining may be the runway lighting. ICAO/FAA precision approach runways have edge lights which are yellow rather than white for the last 2 000 ft of runway when viewed in the take-off direction. In addition, centre line lighting can be used to identify the length of runway remaining. The crew in an aircraft taking off from left to right in Figure 4-16 would see white centre line lights until 3 000 ft from the end of the runway (1 000 ft until rotation must take place). From 3 000 ft to the 1 000 ft remaining point the centre line lights alternate white and red. The centre line lights are all red for the last 1 000 ft of runway. A line of red lights perpendicular to the runway indicate the end of usable runway surface.

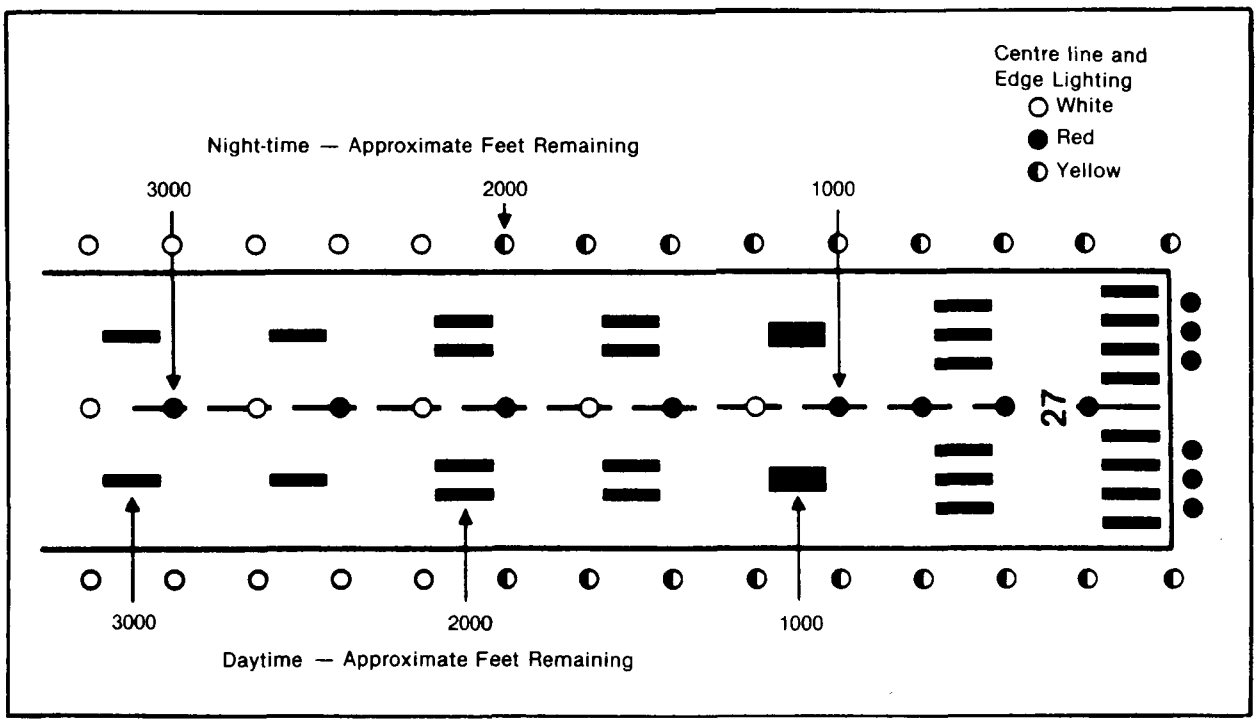


Figure 4-16. ICAO/FAA precision approach runway markings and lighting (from FAA Wind Shear Training Aid, 1987)

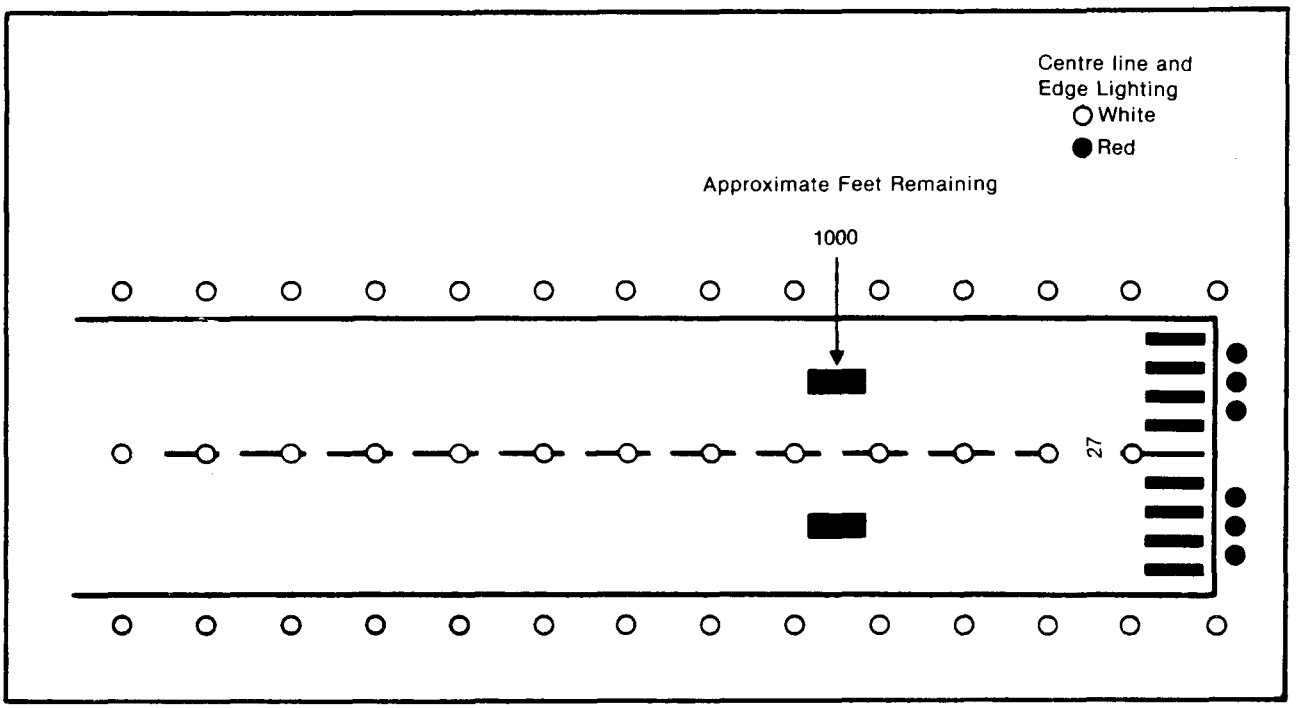


Figure 4-17. FAA non-precision approach runway markings and lighting (from FAA Wind Shear Training Aid, 1987)

4.3.4.3.10 Figure 4-17 illustrates the markings and lighting on an FAA non-precision approach runway. The main indicator of distance remaining on these runways is the fixed distance markings on either side of centre line approximately 1 000 ft from the runway threshold. For runways with these markings, pilot judgement and/or familiarity with specific features along the runway are required to estimate the 2 000 ft remaining point.

4.3.4.3.11 Runway markings and lighting on an ICAO non-precision runway are shown in Figure 4-18. This figure represents the optimum configuration that might appear. Most ICAO non-precision approach runways would include some but not necessarily all of these features. ICAO non-precision runways have single hash marks on either side of runway centre line at intervals of approximately 500 ft (150 m) starting from the runway threshold. Fixed distance markers may also be present approximately 1 000 ft (300 m) from the threshold. In addition, runway edge lights may be colour coded similar to precision approach runways, with yellow rather than white lights for approximately the last 2 000 ft (600 m) of the runway.

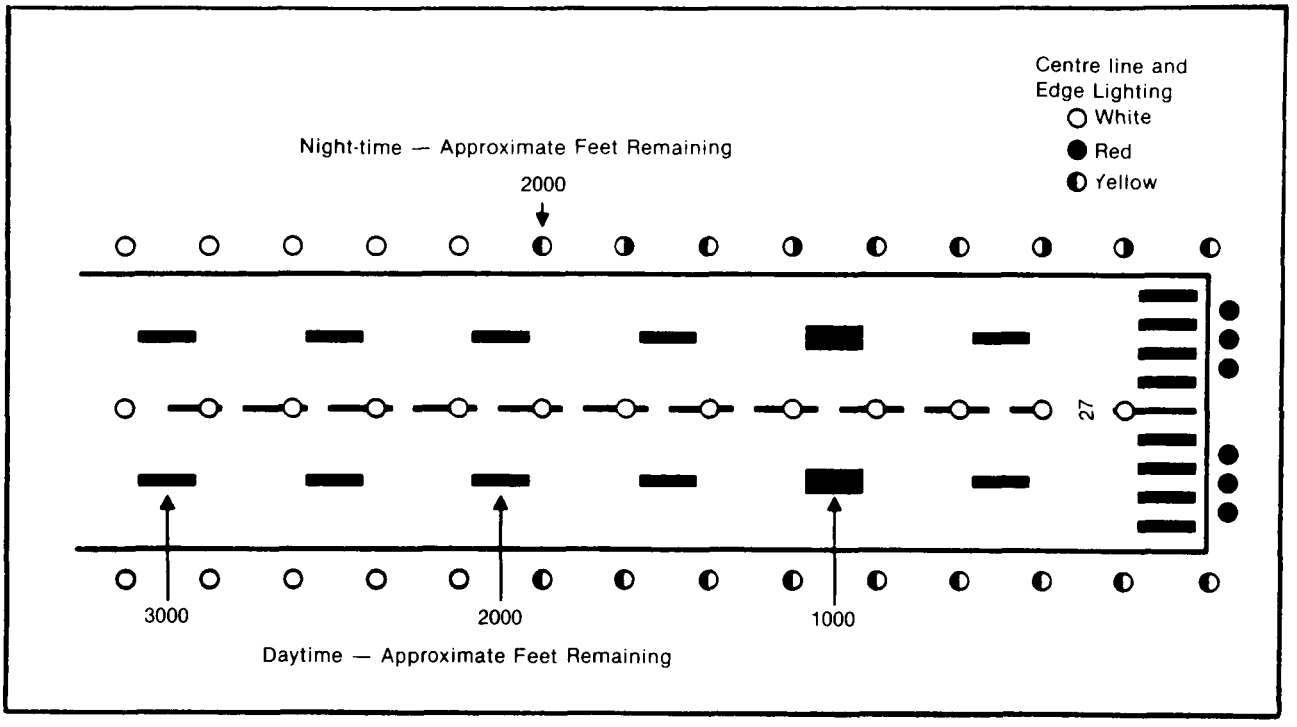


Figure 4-18. ICAO non-precision approach runway markings and lighting (from FAA Wind Shear Training Aid, 1987)

4.3.4.4 Non-recommended recovery techniques

4.3.4.4.1 Many wind shear recovery techniques were evaluated while establishing the technique recommended on the preceding pages. The techniques which follow are NOT recommended, since they may reduce the chances for surviving a wind shear encounter:

- Attempting to maintain target airspeed does not utilize full climb capability of the aircraft.

- Attempting to pitch directly to stick shaker does not maximize use of available aircraft energy, and results in a degraded flight path and increased exposure to stall.

- Attempting to fly at best lift/drag angle-of-attack does not utilize the short-term maximum gradient capability of the aircraft.

- Retracting flaps during approach recovery (as in the normal go-around procedure) reduces margins to stick shaker and has an adverse effect on the initial climb capability of the aircraft.

- Use of inertial reference ground speed emphasizes control of speed which is contrary to the recommended recovery technique. In addition, this "ground speed" technique is oriented toward compensating for the wind shear and continuing the approach rather than immediately

initiating the recovery manoeuvre. While this technique is not appropriate for microburst encounters, it may be suitable for use in other types of wind shears.

- Use of "dive" technique (lowering the aircraft nose in an attempt to accelerate, then pulling up at some predetermined minimum altitude) exposes the aircraft to potentially higher intensity horizontal winds, produces lower minimum recovery altitudes, requires high pitch rates and complicates the recovery procedure.

Again, the best recovery results are achieved by properly controlling pitch attitude in conjunction with thrust application.

Chapter 5

OBSERVING, FORECASTING AND REPORTING OF LOW-LEVEL WIND SHEAR

5.1 OBSERVING WIND SHEAR - GROUND-BASED AND AIRBORNE OBSERVATIONS

5.1.1 General

5.1.1.1 The statement of operational requirements (see Appendix A) calls for information on low-level wind shear to be provided to the pilot. The source of this information may be observation (from the ground or in the air) or forecasting. As mentioned in the foreword, the real-time operational detection and observation of low-level wind shear continue to be among the more intractable problems facing aviation meteorology. In view of the fact that it is necessary to monitor changes in all three components of the wind along the climb-out and approach paths in order to observe or detect and measure wind shear hazardous to aircraft operations, the difficulty in developing suitable remote-sensing equipment is understandable.

5.1.1.2 The situation is beginning to improve, however, and remote-sensing equipment, both airborne (Doppler LIDAR) and ground-based (Doppler radar), has reached a stage of development where it is available for use in wind shear research. At present, in the case of the ground-based equipment, the techniques are not sufficiently mature, and the equipment is still too expensive for general use at aerodromes. In the meantime, recourse has to be made to a variety of different methods of observation, mostly indirect, to detect the presence and, where possible, measure the intensity of wind shear.

5.1.2 Ground-based observations

5.1.2.1 Visual observation of wind shear

5.1.2.1.1 Wind shear itself of course cannot be seen, but very often its effects can. Mention has already been made of some of the ways in which evidence of the existence of wind shear may be deduced from other meteorological information. The list of clues would include:

- adjacent cloud layers moving in different directions
- smoke plumes sheared and moving in different directions
- roll cloud ahead of an approaching squall line

- strong, gusty surface winds affecting trees, flags, etc.
- windsocks around an aerodrome responding to different winds
- dust* (especially in the form of a ring) raised by downdrafts beneath convective cloud
- dust raised in gust front ahead of squall line
- virga, especially when associated with convective cloud
- lenticular cloud indicating standing waves, etc.
- funnel clouds
- waterspouts
- tornadoes.

Not all of these wind shear effects would necessarily have any significance for aircraft landing and taking off; this would need to be assessed on a case-by-case basis in the light of prevailing local circumstances. Many of the effects would be visible both from the ground and in the air and, as mentioned in Chapter 4, could be useful clues to warn the pilot of possible wind shear.

5.1.2.2 Observation of wind shear using regular meteorological instruments

5.1.2.2.1 Anemometers. The use of anemometers to observe and measure wind shear in the horizontal plane (e.g. along a runway) was referred to in Chapter 2. At many aerodromes, in order to provide surface wind information which is representative of critical sections of the runway, such as take-off areas and touchdown zones, it is necessary to install a number of anemometers. Such multiple anemometer installations provide an immediate source of information on horizontal wind shear. This idea provided the basis for the development of a dedicated wind shear warning system (i.e. the low-level wind shear alert system (LLWSAS)), details of which are given in 5.1.2.3.1. A number of States have also installed remote-sensing anemometers on existing television masts and towers located in the vicinity of the aerodrome in order to observe and measure wind shear in the vertical. In Finland and Sweden such installations, together with tower-mounted temperature sensors to detect and measure the intensity of low-level inversions, form the basis of wind shear warning systems (see 5.3.5.1). In Hong Kong[47], anemometers have been installed on hills situated near the approach path to provide information for wind shear warnings.

5.1.2.2.2 Balloon soundings. Another obvious source of wind shear information is from rawinsonde and pilot balloon ascents. It should be noted, however, as mentioned in 2.5.3, that each of the winds derived from these sources is already an average wind over a layer and represents only a very small sampling of the atmosphere in space and time. The rawinsonde ascent also facilitates the detection of low-level temperature inversions, which under certain circumstances indicate the presence of wind shear (see

* There have also been reports of possible microbursts occurring in snow conditions where, in addition to the attendant wind shear effects, there was also "white-out" reduction in visibility due to the high surface winds.[1]

3.1.2.3 regarding low-level jet streams). For the most part, while wind data from balloon soundings will be most useful to indicate profile wind shear (vertical), it is unlikely to be of much assistance in detecting wind shear associated with convective clouds (gust fronts, downbursts, microbursts, etc.). However, whilst sounding data is likely to be of limited use operationally for observing wind shear, it is of considerable assistance in forecasting conditions favourable for the development of wind shear (see 5.2).

5.1.2.2.3 Ground-based weather radar. Occasionally the leading edge of a gust front, especially when produced by squall lines, can be seen on conventional weather radar (especially on 10 cm radars but also on 3 cm radars) as a thin but very distinct arc or line. Such an echo is often referred to as a "radar angel" and although some echoes can be attributed to massed flying insects or flocks of birds, etc., most are simply caused by strong temperature or moisture gradients causing relatively abrupt changes in the refractive index of the air. The arc or line echoes caused by gust fronts mark the leading edge of the cold downdraft air and the echoes often maintain their identity for up to an hour in some instances as they move across the radar scope at the speed of the gust front. Unfortunately, not all gust fronts produce identifiable radar angels, as their formation seems to depend on a comparatively rare combination of atmospheric and radar reflective variables. Moreover, at ranges beyond about 50 km the radar signal travels above the rather shallow gust front and therefore is incapable of detecting it. However, if one is seen and tracked on radar, the forecaster is in a very good position to forecast how and when the gust front will affect the aerodrome concerned (see 5.2.5.1.2). A number of radar processing techniques are available which enable the meteorologist to assess the severity of thunderstorm echoes and which may be used to infer the likelihood of their producing any or all of the wind shear phenomena hazardous to aviation. These techniques are generally based upon the reflectivity of the radar signal and the display of contours of radar reflectivity factor (dBZ)*. One such technique, used in the United States and called the radar echo-contouring system, uses an automatic video integrator and processor (VIP) and the six contour levels produced are commonly referred to as VIP levels (dBZ). These methods are discussed in more detail in 5.2.5.1.2.3. The radar scan may be made in the horizontal plane (plan position indicator (PPI)) or in the vertical plane (range height indicator (RHI)).

5.1.2.2.4 Weather satellites. Gust fronts have also been observed reasonably frequently on weather satellite pictures. The feature most readily observed is the roll cloud (stratus) which often forms above the gust front nose (see 3.5.2.3), especially in the case of gust fronts formed from squall lines. A particularly good example of such a picture is the extensive arc of cloud moving radially outwards from a cluster of cumulonimbus clouds shown in Figure 5-1[2]. This particular picture poses something of a problem because, whilst arc section L'L of the picture is indeed roll cloud (stratus) associated with the gust front, from comparison of the infra-red and visual pictures, that part of the arc of cloud labelled L'U seems to be cirrus cloud.

5.1.2.3 Equipment specifically designed to detect and measure low-level wind shear

5.1.2.3.1 Low-level wind shear alert system (LLWSAS)

5.1.2.3.1.1 The LLWSAS system[3] comprises five surface wind sensors located at strategic points around the perimeter of the aerodrome, a centre-field surface wind

* dBZ is decibels relative power.

sensor and microprocessor and display units which continually monitor and compare the vector difference between perimeter and centre-field surface wind observations. The perimeter sensors measure instantaneous wind and the observations are sampled by the central control unit every ten seconds. The centre-field sensor produces a two-minute running mean surface wind as a reference against which the perimeter surface wind values are compared.

5.1.2.3.1.2 Displays are located in air traffic control (ATC) units which give a continuous indication of the centre-field surface wind and, depending on the wind speeds involved, a gust factor. The control unit continually compares the perimeter winds with the centre-field wind and, if the vector difference between them is more than 15 kt, the perimeter wind is also displayed and an audiovisual alarm is triggered. The controller can select for display any or all of the perimeter winds at any time.

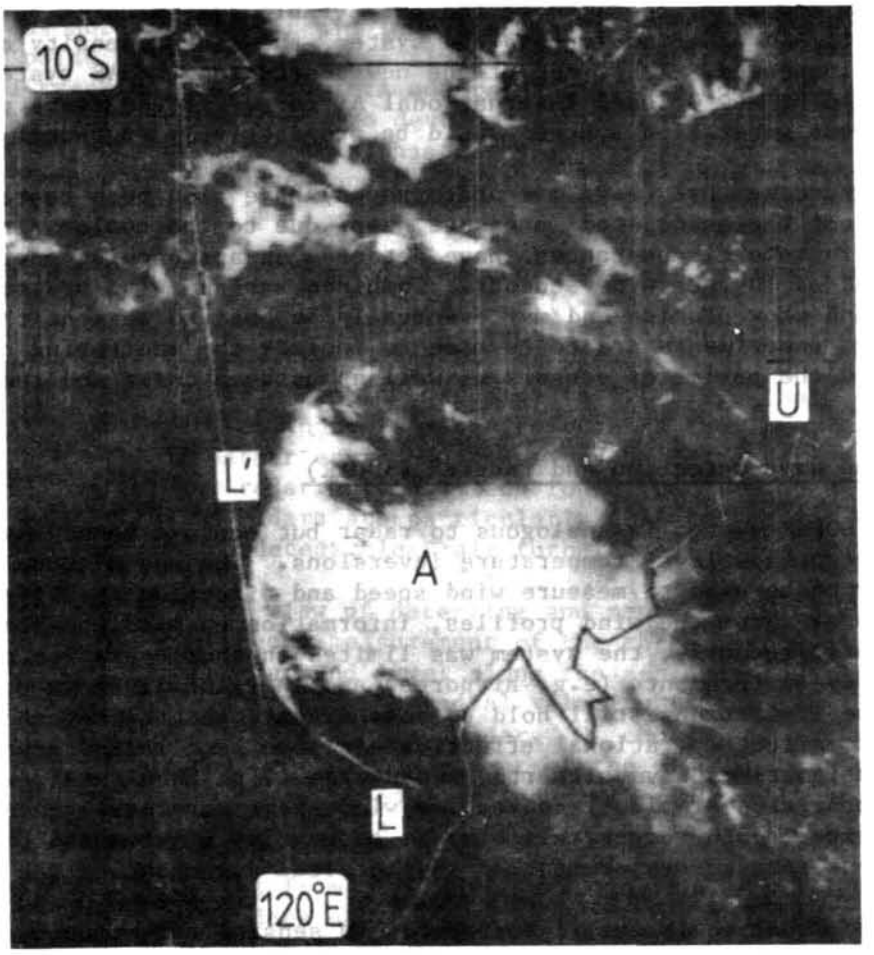


Figure 5-1. Weather satellite picture of arc cloud
(from Kingswell, 1984)

5.1.2.3.1.3 The LLWSAS system was designed and installed following several aircraft accidents during the mid-1970s, and is now in operation at over 60 aerodromes in the United States and eventually will be installed at over 100 aerodromes. It was originally intended to detect gust fronts as they crossed the aerodrome perimeter and in this respect the system works well. Following further research into low-level wind shear associated with convective cloud it has become increasingly apparent, however, that gust fronts are only part of the problem - the prime culprits seem to be the precursors of the gust front which develop above ground level, i.e. downbursts and microbursts, rather than the front itself. In this respect, LLWSAS is limited because it can only detect horizontal wind shear at ground level, which precludes detecting shear along the glide or climb-out paths; given the current temporal and spatial resolution of the system, microbursts could easily occur between two perimeter sensors without affecting either of them.

5.1.2.3.1.4 Nevertheless, despite these limitations the LLWSAS system does detect some wind shears and, in any case, seems to be the only viable system using currently available equipment. In order to improve the system, the sensor density and sensor response is to be increased. The first of the new generation LLWSAS systems will be installed and tested at New Orleans International Airport. If the tests prove successful, the first generation systems would be progressively upgraded.

5.1.2.3.1.5 Pressure sensors (e.g. microbarographs) have also been tested as perimeter instruments to detect the associated "pressure jump" due to the cooler air of gust fronts, etc. and, in some circumstances, have detected an approaching gust front up to three minutes ahead of surface wind sensors. Combined surface wind/pressure sensors have been tested and show promise and may eventually be used to augment the LLWSAS system. Similarly, experiments are to be made to include the monitoring of vector differences between the perimeter sensors as well as between these and the centre-field sensor.

5.1.2.3.2 Sound wave detection and ranging (SODAR)

5.1.2.3.2.1 The SODAR system is analogous to radar but employs sound waves (~ 1 500 Hz) to detect low-level temperature inversions. The use of Doppler techniques enables the system to be used to measure wind speed and direction at different levels in the lower atmosphere. From the wind profiles, information on wind shear may be computed and displayed. Until recently, the system was limited in that operation could deteriorate in noisy environments (e.g. airports) and in rainfall above specified intensities. These limitations still hold to some extent, but the threshold values at which they begin to affect operational effectiveness have been raised appreciably. The SODAR data integration times have hitherto ranged from 10 to 20 minutes, which is far too long for the provision of timely convective wind shear warnings. Recent developments are expected to reduce this time to below five minutes and the use of three-axis SODAR has enabled measurement of the vertical component of the wind.

5.1.2.3.2.2 Current SODAR equipment is restricted to sensing the atmosphere directly above the observing site, although further development is under way to permit the SODAR sound beam to be pointed at an angle which, if successful, could open the way to continuous monitoring of all three components of the wind profile along the climb-out and approach paths at aerodromes[5]. The equipment is especially suitable for observing area-wide and non-transitory wind shear such as low-level jet streams associated with strong temperature inversions[6]. SODAR is used operationally at aerodromes in a number of locations, including Canada, Denmark, France, Hong Kong and Sweden. Turesson and Dalquist have reported on the use of multiple SODAR installations to observe and

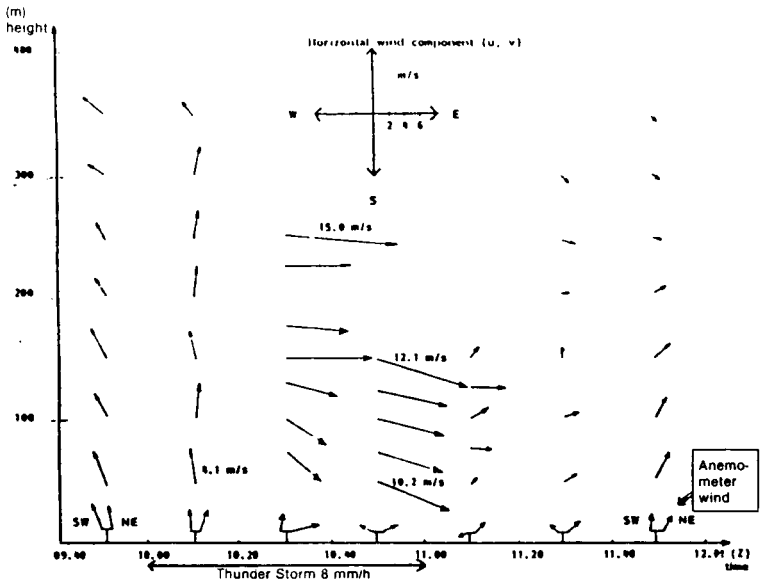
measure, with a data integration time of 20 minutes, a downburst which occurred at Copenhagen Airport; the resulting wind shear is shown in Figure 5-2[4].

5.1.2.3.3 Doppler radar

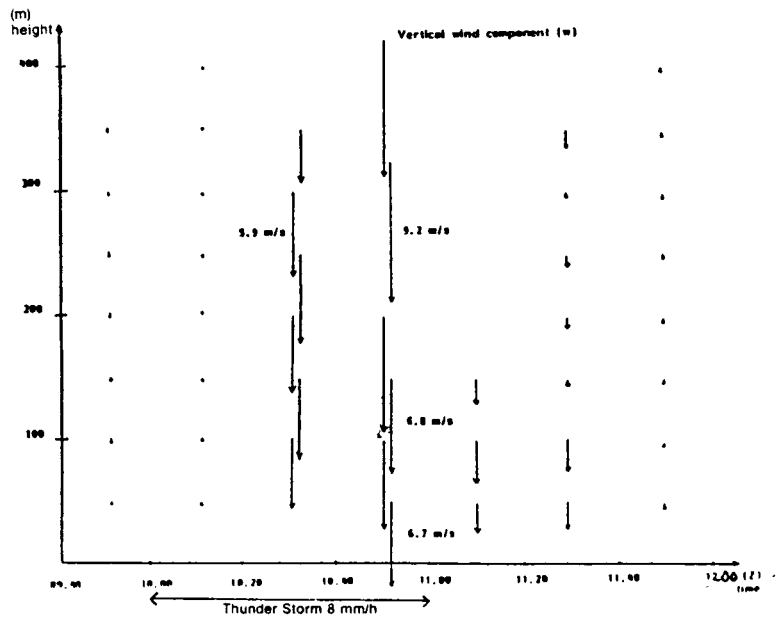
5.1.2.3.3.1 Conventional weather radars compute and display on a screen the range and direction of targets reflecting the transmitted radar beam. The fact that the reflected beam from moving targets differs slightly in phase/frequency from the transmitted beam and that the phase/frequency shift is proportional to the velocity of the target to/from the radar has hitherto been only of incidental interest. This phenomenon, known as the "Doppler shift" does, however, permit the elimination from ATC radar of obscuring stationary targets (permanent echoes such as hills, etc.) by means of moving target indicator (MTI) circuits. In the past 20 years or so, the Doppler frequency shift phenomenon has been increasingly exploited for the measurement of the radial velocity spectrum of the moving reflecting targets. Development of such microwave coherent Doppler radars has not only been rapid in recent years but, more importantly, has advanced to the point where the direct analysis of thunderstorm clouds is now possible by detecting and tracking cloud droplets and rain/hail/snow and also tracers in "clear air"[7]. This has enabled researchers to develop sophisticated three-dimensional models of the thunderstorm and, in particular, has markedly improved our understanding of the associated gust fronts, microbursts and tornadoes, all of which are of prime concern to aviation[8].

5.1.2.3.3.2 In order to detect targets of meteorological interest, weather radars usually operate at wavelengths of 3 to 10 cm (3.2 (X-band), 5.5 (C-band) and 10 cm (S-band) are the most common). For a Doppler radar, a target with radial velocity of 1 m/s would produce a frequency shift of 62 Hz, 36 Hz and 20 Hz for radar wavelengths of 3.2, 5.5 and 10 cm respectively. Mention was made in 5.1.2.2.3 that, occasionally, refractive index inhomogeneities in the atmosphere such as the interface between the cold gust front air and the warmer environment air may be detected and tracked as radar angels on normal 3 cm weather radar. It has been found that frequency-modulated, continuous-wave (FM-CW) 10 cm radars are particularly well suited for detecting radar angels and can even be used to detect clear-air turbulence.

5.1.2.3.3.3 From the point of view of detecting and measuring wind shear at aerodromes, the ideal is continuous measurement of the three components of the wind up to about 500 m (1 600 ft) above ground level along the approach and climb-out paths. As mentioned earlier (see 3.5.4.2), only the radial velocity (along radii to and from the radar) may be derived from a single Doppler radar. Of course, if the radar is scanning vertically, information on the vertical component of the wind at that point, i.e. downdrafts/updrafts, may be obtained. By scanning azimuthally at a given elevation angle, an almost sinusoidal variation in Doppler velocity is obtained as the antenna scans upwind, across wind, downwind and across wind during each rotation. It is possible to obtain wind profiles from this data, assuming the winds in the area are uniform. At first sight, this does not seem to be of much use in detecting wind shear where the wind field is not likely to be uniform, but it has been found that many wind shear-producing phenomena, such as gust fronts, microbursts and tornadoes, may be identified from their single-Doppler radar "signatures" (i.e. patterns in the radial velocity gradient). This is not a totally foolproof method at present because, for a number of reasons, not all microbursts, etc., exhibit identifiable signatures and, in any case, the identification techniques themselves require considerable subjective skill and experience. Moreover, when observing the lowest levels of the atmosphere, the Doppler radar signal is still subject to considerable degradation due to ground clutter.



a) Horizontal wind component of 9 June 1984 at Copenhagen Airport - measurement by Doppler SODAR with integration time of 20 minutes.



b) Vertical wind component profile of 9 June 1984.

Figure 5-2. Wind shear measures by Doppler SODAR at Copenhagen (from Turesson and Dahlquist, 1985)

5.1.2.3.3.4 In order to measure directly all three components of the wind, in theory three spatially separated Doppler radars are needed, sensing the same volume of the atmosphere simultaneously. In practice it is possible to use two Doppler radars to obtain directly the two horizontal components of the wind (northerly and easterly components) and derive the vertical component indirectly. The JAWS project employed three Doppler radars (see 3.5.4.2) to obtain a complete three-dimensional analysis of the wind structure of microbursts.

5.1.2.3.3.5 It seems unlikely that in the near future any but the most wind-shear prone aerodromes would be in a financial position to install and operate two dedicated Doppler radars. In view of this it seems clear that, aside from the multiple-Doppler radar installations which will still be essential for research projects, much effort will be concentrated on the refinement of the single-Doppler radar techniques, particularly concerning the automatic processing and recognition of the various Doppler velocity "signatures" associated with wind shear phenomena hazardous to aviation and on the elimination of obscuring ground clutter.

5.1.2.3.3.6 Considerable progress has been made in a number of States in the development of ground-based continuous-wave infra-red Doppler LIDARs (LIght Detection And Ranging) capable of measuring winds up to a height of about 1 km. Due to the narrow, collimated beam, LIDAR measurements are less affected by ground clutter, enabling data to be obtained within a few metres of the surface. In the Federal Republic of Germany, such a system has been developed which is especially suitable for continuous measurement of the wind profile in real time and hence for monitoring many non-convective types of wind shear such as low-level jet streams[9].

5.1.3 Observing wind shear from the air

5.1.3.1 Use of standard flight deck instruments

5.1.3.1.1 The use of standard flight deck instruments to observe wind shear was dealt with in some detail in the previous chapter in connexion with the recognition of wind shear by pilots. It was mentioned that an indication of the presence of wind shear could be obtained from the air speed indicator, vertical speed indicator and altimeter installed on all aircraft and, on aircraft so equipped, from the attitude indicator, horizontal situation indicator, ground proximity warning system (mode 1 indicating excessive descent rate and modes 3 and 5 indicating altitude loss after take-off and below glide slope deviation respectively), the stall warning system (stick shaker) and the INS ground speed and wind speed and direction readout.

5.1.3.2 Airborne wind shear warning equipment

5.1.3.2.1 Wind shear warning systems based on the monitoring of aircraft performance

5.1.3.2.1.1 One system, which has been commercially available for a number of years, uses input data from conventional aircraft sensors such as the pitot head (airspeed), vertical gyro (pitch attitude) and stall warning airflow sensor (angle of attack), together with additional data from special horizontal and vertical accelerometers which form part of the warning system itself. Using this data the system computer calculates, instant by instant, the shear in the vertical and horizontal components of the wind and, taking into account any compensatory actions by the pilot, displays the energy loss or gain due to the shear, and at a preset threshold, provides an audio alert. The threshold is set at a headwind loss/tailwind gain of 3 kt/sec or (in a downdraft) a

decrease in angle of attack of 0.15 radians (8.6°) or any combination of the two which provides the equivalent signal level (deceleration of 0.15 g).

5.1.3.2.1.2 Another system, which became available commercially in 1986, provides a wind shear detection and warning capability as part of a performance management system. The system is being developed in two phases, with Phase I providing detection and alerting components and Phase II providing guidance to the pilot (the latter was expected to become available during 1987). The system utilizes information from the air data sensors and from dedicated accelerometers forming part of the performance management computer. The data input comprises pitch angle, angle of attack, true airspeed, vertical acceleration and longitudinal acceleration. The system computer makes continuous comparisons between inertial and air mass accelerations and the rate of change of these relative accelerations. This permits warning the aircrew as soon as any significant deviations occur which indicate the presence of wind shear.

5.1.3.2.1.3 Although these systems have the limitation that they only warn of wind shear as the aircraft is actually entering the shear, they are able to detect the wind shear a few seconds before a pilot would normally recognize the condition which, in a wind shear encounter, can be critical. The latest versions of these instruments not only provide warning of wind shear but also give pitch attitude guidance, which is important in a downburst situation due to the fact that the angle of attack no longer relates directly to pitch attitude and therefore extreme body angles may be necessary to achieve the desired angle of attack (see 4.2.3.2 and Figure 4-5). It is also reported that one aircraft manufacturer plans to introduce a wind shear detection system in 1988 which will feed data into the auto-throttles and autopilot. It will also be available for retrofitting to older aircraft with appropriate commands being displayed on the flight director.

5.1.3.2.2 Modified vertical speed indicators

5.1.3.2.2.1 Two companies have each developed a modification of the conventional vertical speed indicator (VSI) which uses output of vertical speed and airspeed from the air data computer to calculate the rate of change of energy of the aircraft. This value is displayed on the VSI, in one case by means of a second pointer on the instruments and, in the other case by means of two dots which move around the outer perimeter of the dial. In both cases the acceleration or deceleration of the aircraft is proportional to the separation between the conventional VSI pointer and the energy rate indicator (whether a pointer or dots), enabling the pilot to assess how much thrust is required in a particular situation. Changes in the horizontal wind components are indicated by a rapid separation of the two pointers and changes in the vertical wind component (e.g. downbursts) are indicated by both pointers showing a sudden increased rate of descent (or ascent in an updraft). Should either pointer indicate a rate of descent in excess of a preset value (e.g. 1 000 ft/min), the pilot knows the aircraft is encountering wind shear and can act accordingly. One of the systems also includes a digital angle of attack readout.

5.1.3.2.2.2 Both instruments indicate wind shear only as the aircraft encounters it and there is also the usual instrument lag. Nevertheless, as in the case of the performance monitoring wind shear warning systems, the instruments do indicate wind shear a few seconds before a pilot would normally recognize it and these seconds can be critical. Another advantage of all of the foregoing systems is that they simply modify an existing flight deck instrument which already forms part of the pilots' normal scan pattern (i.e. VSI or flight director).

5.1.3.2.3 Doppler LIDAR

5.1.3.2.3.1 The United Kingdom Royal Aircraft Establishment (RAE) at Bedford and the United States National Aeronautics and Space Administration have been studying the use of Doppler LIDAR for airborne measurement of wind speed and direction[10 11 12]. Doppler LIDAR operates on exactly the same principle as Doppler RADAR (see 5.1.2.3.3) but employs coherent infra-red light produced by a CO_2 infra-red laser. In the RAE system, called the laser true airspeed system (LATAS) the laser beam is focused 500-600 m ahead of the aircraft and measures the motion of the air at this point relative to the moving transmitter. In this way the system is able to advise the pilot of likely airspeed changes due to wind shear about four seconds ahead of the aircraft. The instrument is actually measuring the motion of aerosol particles in the air relative to the aircraft and along the flight path (headwind/tailwind) so it is not capable, as currently designed, of measuring the vertical and crosswind components of the wind (e.g. downburst). However, if the LATAS system were used in a conical scan mode, the vertical and cross-track components of the wind ahead of the aircraft could also be measured. The scanning beam may also be directed upwards or downwards along the intended flight path during landing and take-off. The system has been installed on the RAE HS125 research aircraft for the past three years; this aircraft also took part in the JAWS project (see 3.5.4.2). The system is reportedly rugged, reliable and lightweight, requires minimal maintenance, adjustment and calibration and can measure "airspeed" up to 800 m ahead of an aircraft in clear air or in cloud. The performance is considerably better below 20 000 ft (6 km) where aerosols are normally plentiful, and although the signal return decreases above this level, wind measurements have been made up to the operating ceiling of the HS125 (43 000 ft (13 km)).

5.1.3.2.4 Airborne Doppler radar

5.1.3.2.4.1 Doppler radars have been flight-tested as possible wind shear detection systems, but due to the comparatively large size and weight of the equipment (radar and processing units), the tests so far have been restricted to large transport aircraft, e.g. C-130 Hercules[13,14,15]. The likelihood of being able to scale down the equipment at a reasonable cost seems small in the immediate future, although NASA is starting the development of a small, low power airborne Doppler radar which may become available within five to ten years. Doppler techniques are available as an option on some commercially available airborne weather radars. These are able to measure and process the different radial velocities of raindrops ahead of the aircraft and from this information deduce and display areas of turbulence.

5.1.3.2.5 Head-up display (HUD)

5.1.3.2.5.1 Head-up displays have been regular equipment on fighter aircraft for many years but have only recently been installed on some commercial aircraft. HUD is a system for presenting essential guidance and control information to the pilot reflected from a partially mirrored but otherwise transparent glass plate mounted at an angle between the pilot's eyes and the cockpit windscreen. The pilot is able to see the usual outside view through the glass plate and windscreen, but at the same time symbolic guidance and control information is projected onto the glass plate, a percentage of which is reflected towards the pilot and thus directly superimposed on the pilot's outside view. Control information is always directly in view without the pilot having to look down, adjust focus and scan a number of different flight instruments. In addition to the usual symbolic information provided on conventional HUDs, tests have been undertaken in a number of States on providing specific flight path indicators, for example a "flight path indicator" (FPI) symbol representing the touchdown point on the

runway projected from the existing flight path and a "potential flight path" (PFP) symbol which indicates acceleration or deceleration of the aircraft (assuming the flight path indicator is maintained on the aiming point, e.g. by elevator adjustment). When the two symbols are superimposed, the aircraft is neither accelerating or decelerating, and wind shear is indicated when the symbols separate on the display[16]. Most pilots taking part in the tests indicated that the HUD was of considerable assistance in coping with the simulated wind shear conditions.

5.1.3.2.6 Modified inertial navigation systems (INS)

5.1.3.2.6.1 One major inertial navigation system manufacturer has developed a modification to the conventional INS which displays wind components throughout the approach and landing phase. The modified system calculates the wind component and, using an accelerometer, also computes vertical sink rate. If wind shear is detected, the numerical readout displays a set of flashing figure eights.

5.1.4 FAA Integrated Wind Shear Programme (sensors)

5.1.4.1 Mention was made in the foreword of the FAA's "Integrated Wind Shear Programme". Two components of the programme are the "ground sensors sub-programme" and the "airborne wind shear detection and avoidance sub-programme". The former includes the development and implementation of improvements to the present LLWSAS (see 5.1.2.3.1) to be called ALWAS (Advanced LLWSAS) and the development and commissioning of the "Next Generation Weather Radar (NEXRAD)" (see 6.2.1) and the terminal Doppler radar (TDR) (see 6.2.2). The airborne component comprises the development of forward-looking airborne wind shear sensors (see 5.1.3.2.3 and 5.1.3.2.4) and the improved utilization and integration of present-position sensors (see 5.1.3.2.1.1).

5.2 FORECASTING WIND SHEAR

5.2.1 General

5.2.1.1 The lack of operational equipment to observe or detect and measure wind shear, referred to in the previous section (see 5.1.1.1), renders the forecasting of wind shear extremely difficult. Generally speaking, the only viable approach at present is to attempt to forecast the occurrence of the meteorological phenomena which are known to produce wind shear on the understanding that significant wind shear may or may not in fact occur, and even if it does occur its intensity cannot be predicted. This difficulty also means that detailed climatological statistics regarding the frequency, distribution and intensity of low-level wind shear in the vicinity of aerodromes are also lacking.

5.2.1.2 From this rather bleak prospect it would seem that matters could only improve and indeed the problem is beginning to yield to the concentrated research efforts which have been expended during the past few years. Progress has been most noticeable along two fronts: the first is the increasing use of Doppler radar for research into the structure and dynamics of thunderstorms and their associated wind shear, and the second is the routine accumulation of a world-wide data base of wind shear encountered during landing and take-off derived from the airborne integrated data system (AIDS) installed on most large jet transport aircraft (see 3.7). These efforts are gradually providing a clearer understanding of wind shear and, in particular, have permitted attention to be focused on the specific types of wind shear which appear to be the most dangerous for aircraft.

5.2.1.3 In the meantime, at most aerodromes recourse has to be made to various forecasting "rules of thumb" which have been developed on the basis of meteorological theory and extensive knowledge of the area concerned. An example of such a set of rules, employed by the United Kingdom Meteorological Office during wind shear forecasting trials in 1977, and of the current set of rules derived from these, used operationally in 1985, is given in Appendix F. A similar set of rules, modified as necessary for different conditions, are currently used by the United States National Weather Service[17].

5.2.1.4 A weather forecast for a particular area normally provides information on the phenomena expected under three main headings: "type", "time" and "intensity", i.e. which phenomena are expected, when and for how long, and how strong they will be. In the case of a wind shear forecast, the question of intensity is of critical importance. A simple forecast or a report of wind shear in the approach path at some point in time alerts pilots on approach and, in this respect alone, provides useful information, but what the pilot really needs to know is the severity of the shear in order to gauge its likely effect on the aircraft. In view of the importance of the intensity of the wind shear, before going further into the various methods currently used to forecast wind shear this is an appropriate point to look at the many problems associated with classifying wind shear in terms of intensity.

5.2.2 Wind shear intensity

5.2.2.1 In Chapter 2, various methods for calculating wind shear were discussed and the different units currently used were examined. Historically, wind shear, as the vector difference between two winds at different points in space, has usually been calculated in units of speed per given distance, e.g. knots per 100 ft or m/sec per 30 m. It would seem at first glance that the classification of wind shear intensity in terms of a number of classes, bounded by empirically derived values in knots/100 ft or m/s/30 m, would be a straightforward matter. This approach was followed at the Fifth Air Navigation Conference (Montreal, 1967) where the interim criteria for wind shear intensity given in Table 5-1 were recommended. This original table gave wind shear intensities in four classes from light to severe in terms of knots per 30 m; qualitative criteria in terms of the effect each class of wind shear is likely to have on aircraft control were added later.

5.2.2.2 In those days it was thought that the predominant wind shear threat was associated with fronts, including gust fronts from thunderstorms, and extreme wind profiles near the ground and these could easily be visualized in terms of wind speed gradients. It has since become evident, however, that this relatively simple approach to wind shear intensity classification is not entirely satisfactory for the following reasons:

Table 5-1. Interim criteria for wind shear intensity recommended by the Fifth Air Navigation Conference (Montreal, 1967)

Light	-	0 to 4 kt inclusive per 30 m (100 ft)
Moderate	-	5 to 8 kt inclusive per 30 m (100 ft)
Strong	-	9 to 12 kt inclusive per 30 m (100 ft)
Severe	-	above 12 kt per 30 m (100 ft)

a) it is found that the same wind shear intensity (as proposed in Table 5-1) can affect each aircraft type differently; what might be considered severe for one type of aircraft is only considered moderate for another. This is especially true in respect of aircraft in widely different mass categories;

b) the effect that wind shear has on an aircraft depends, among other things, on the speed of passage through and hence time of exposure to the shear;

c) information on wind shear intensity given in units of speed/distance is not of direct assistance to the pilot flying a 3° glide slope, because a pilot does not think in such units and they do not relate to any of the usual flight deck instruments. A pilot thinks in terms of airspeed, and thus, changes in airspeed are accelerations or decelerations in kt/s or g units;

d) the most hazardous wind shear is that associated with thunderstorms, such as microbursts, where all three components of the wind are changing at the same time; and

e) the boundary values of the intensity classes relating to shear in the horizontal components of the wind given in Table 5-1 (i.e. excluding downdrafts) do not seem to have been substantiated following the analysis by the RAE Bedford of AIDS data from over 9 000 landings world-wide of British Airways B747 aircraft. In this context, the aircraft encountered wind shear conditions classed as severe in accordance with the criteria in Table 5-1 but which in fact had evidently presented little or no problem for the pilot in landing the aircraft[18].

5.2.2.3 The fact that there are a number of unresolved problems associated with the interim criteria for wind shear intensity had two main effects. Firstly, it is impossible for the time being to use the qualifying terms "light", "moderate", "strong" and "severe" in relation to wind shear in the provisions covering wind shear in ICAO Annex 3 - Meteorological Service for International Air Navigation (Chapters 4, 5 and 7). Consequently, the provisions in Annex 3 require reports, forecasts and warnings of wind shear without qualification with respect to intensity. Nevertheless, it is recognized in Note 2 following 7.4.4 of Annex 3 that "pilots, when reporting wind shear, may use the qualifying terms 'moderate', 'strong' or 'severe', based to a large extent on their subjective assessment of the intensity of the wind shear encountered." Secondly, although a number of proposals have been made for improving the interim criteria, details of which are dealt with below, the tendency seems to be to avoid the issue altogether by basing future warning systems (whether airborne or ground-based) on the computation of the expected aerodynamic response of individual aircraft types to standard simulator wind shear models (these latter proposals are also dealt with below).

5.2.2.4 One proposal to improve the wind shear intensity criteria has been made by Woodfield and Woods in their paper analysing world-wide wind shear data derived from over 9 000 landings of British Airways B747 aircraft[18]. Their proposal is based on the fact that, in practice, aircraft are going to be affected by two main wind shear factors. The first is the rate of change of wind speed in the shear compared to the acceleration that can be achieved by the aircraft with the excess thrust margin

available (typically 3 kt/sec for large jet transport aircraft in the approach configuration). The second factor is the total magnitude of the wind speed change relative to the speed margin above stalling speed (typically 20 per cent of V_{REF} or around 25 to 30 kt for large jet transport aircraft). In general, wind shear will only be a problem if the rate of change of wind speed and the magnitude of the shear are significant. This can be illustrated by considering two extremes: at one extreme an aircraft can cope with even a 100 kt wind speed change if the rate of change is only 0.1 kt/sec; similarly, at the other extreme, with only a 5 kt wind speed change even a rate as high as 10 kt/sec presents no problem.

5.2.2.5 Further, consideration of aircraft response suggests that when the rate of change of wind speed is greater than the acceleration available using full thrust, then the magnitude of the wind speed change will dominate the aircraft response. Conversely, when the rate of change of wind speed is low, the magnitude will not be of significance. On this basis, the researchers suggest that the rate of change of headwind and the ratio of the total change in headwind to the aircraft's normal approach speed could be taken as the main factors in determining intensity criteria. They suggest that the wind shear intensity factor "I" be as follows:

$$I = \frac{dV}{dt} \cdot \left(\frac{\Delta V}{V_{app}}\right)^2 = \frac{1}{V_{app}} \left|\frac{\Delta V}{R^{1/3}}\right|^3$$

where $\frac{dV}{dt}$ = rate of change of wind speed;

ΔV = total change of wind speed;

R = ramp length (distance (m) over which wind speed change occurs or time exposed (s) if airspeed known); and

V_{app} = normal approach speed;

The primary parameter turns out to be $\frac{\Delta V}{R^{1/3}}$ or the "normalized" wind shear. Suggested forms of intensity boundaries are shown in Figure 5-3[18]. The researchers recommend that such intensity criteria should be tested in the appropriate flight simulators.

5.2.2.6 A different approach to the problem of wind shear intensity has been suggested by Swolinsky[48]. He points out that the intensity factor proposed by Woodfield and Woods[18] (see 5.2.2.5 above) does not take into account changes in the vertical component of the wind. Swolinsky's proposal is based upon energy considerations (potential and kinetic) for approach/landing and is termed the "energy height error" (ΔH_E) as follows:

$$\Delta H_E = \frac{(V^2 - V^2_{Ref})}{2g} + H - H_{Ref}$$

(where V, V_{Ref} are the airspeed at height H and reference approach speed at the reference height H_{Ref} respectively).

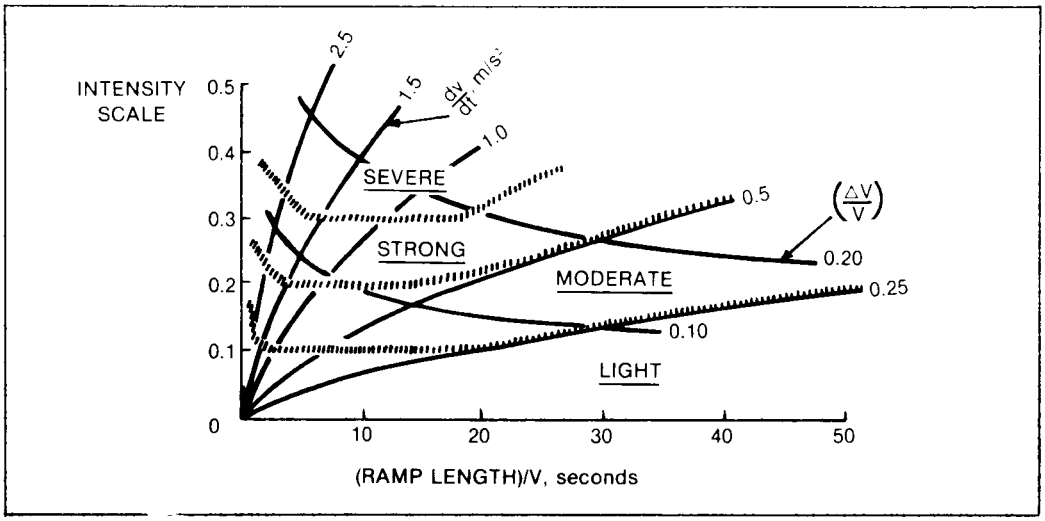


Figure 5-3. Suggested form of intensity boundaries (from Woodfield and Woods, 1984)

5.2.2.7 One way to avoid the problem of general wind shear intensity classification is to develop procedures for approving airborne wind shear detection systems based upon aircraft type response to a set of simulated "severe" wind shear models. The United States is following this course of action and has issued an Advisory Circular AC 120-41 dated July 1983 - "Criteria for Operational Approval of Airborne Wind Shear Alerting and Flight Guidance Systems"[19]. The circular contains a set of two-dimensional wind shear models (i.e. wind values only in the plane of the approach path, although all three components of the wind are specified) derived from accident reconstruction data, meteorological data and other sources against which an airborne detection system may be flown on the simulator. For the purposes of this procedure, severe wind shear is defined as:

> "Severe.- A wind shear of such intensity and duration which, if encountered, would exceed the performance capability of a particular aircraft type, and cause inadvertent loss of control on ground contact if the pilot did not have information available from an airborne wind shear alerting and flight guidance system which meets the criteria in paragraph 4 b)." [emphasis added]

Paragraph 4 b) of the advisory circular reads as follows:

> "Airborne wind shear alerting and flight guidance system. A device or system which identifies the presence of severe wind shear phenomena and provides the pilot with timely alert and flight guidance for the following:
>
> 1) approach/missed approach to permit the aircraft to be flown using the maximum performance capability available without inadvertent loss of control, stall, and without ground contact;
>
> 2) take-off and climb-out to permit the aircraft to be flown during initial or subsequent climb-out segments using maximum performance capability available without inadvertent loss of control or ground contact with excess energy still available."

The foregoing implies that there is another class of wind shear intensity beyond "severe" which cannot be safely transited even with the use of airborne wind shear detection systems.

5.2.2.8 The utilization of airborne wind shear detection systems will, it is stated in the advisory circular, enhance safety to an even greater margin over that which is provided by forecasting techniques and ground-based detection equipment, by affording the pilot early and reliable recognition of wind shear phenomena, and by permitting the pilot to use all remaining performance capability if required. The wind fields to be used as test data will be continually updated by the FAA as new information is received (for example, from JAWS data, etc.). The United States Committee on Low-Altitude Wind Shear has suggested that future wind field definitions in the Advisory Circular should include "wind profiles that may exceed the performance capability of a specific airplane"[20].

5.2.3 Transitory and non-transitory wind shear

5.2.3.1 From the forecasting standpoint, low-level wind shear may be conveniently classified into two types, either transitory or non-transitory. Whilst this division is to some extent artificial and by no means absolute, most wind shear can be recognized as being predominantly one type or the other (see Table 5-2). Non-transitory wind shear, which might be associated with, for example, marked low-level temperature inversions, mountain waves or air flow around obstacles, etc., tends to affect a particular area and persist for relatively long periods (measured in hours) and is currently being forecast operationally in a number of States with some degree of success. On the other hand, transitory wind shear, such as might be associated with convective clouds and especially thunderstorms, is normally short-lived (measured in minutes), of small scale, fast-moving and very intense, making it extremely difficult to forecast. Unfortunately, for a number of reasons, the transitory type of low-level wind shear, especially that associated with thunderstorms, is by far the more hazardous for aviation.

Table 5-2. Classification of wind shear for forecast purposes

Wind shear type	
Transitory	Non-transitory
Convective (including gust fronts, downbursts, microbursts and tornadoes)	Air mass frontal surfaces (mainly)
Gravity waves (mainly)	Sea breeze frontal surfaces (mainly)
	Mountain waves
	Obstacles to prevailing wind flow
	Low level jet streams

5.2.4 Forecasting non-transitory wind shear

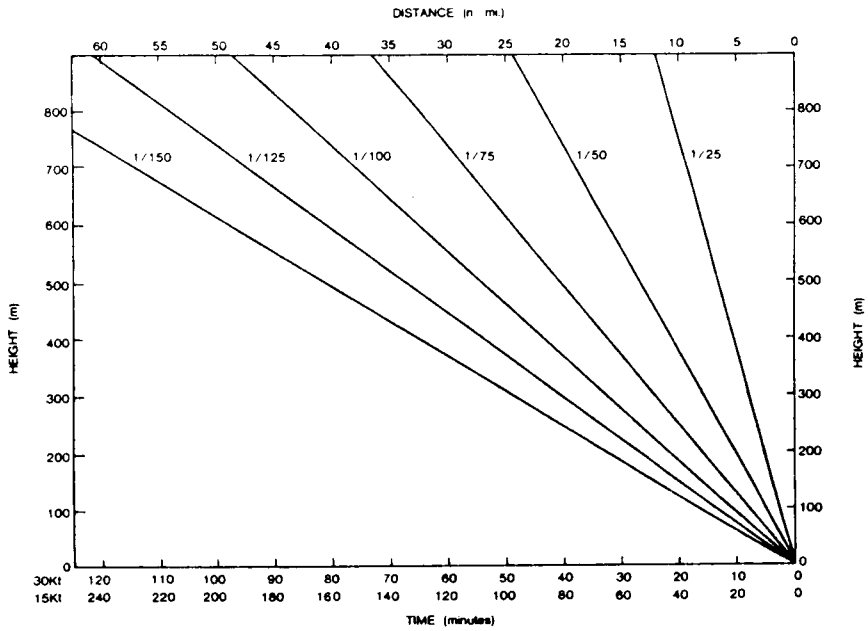
5.2.4.1 Forecasting wind shear associated with air mass fronts

5.2.4.1.1 Forecasting the development and movement of frontal surfaces is based on mature techniques which have been used successfully for many years. The fact that low-level wind shear occurs with the passage of a frontal surface (i.e. not considering wind shear related to frontal thunderstorms) simply adds one more phenomenon to an already long list of phenomena of interest to aviation which are likely to be associated with fronts. One particular aspect of frontal analysis which has perhaps received added emphasis due to the need to forecast low-level wind shear is the slope of the frontal surfaces. A detailed description of the nature of wind shear associated with frontal surfaces is given in Chapter 3, 3.3.1 to 3.3.3 and 3.4.1 to 3.4.2. From this description it is evident that, from the point of view of wind shear, the most important features of frontal surfaces are the intensity of the front, its speed of movement and the slope of the surface.

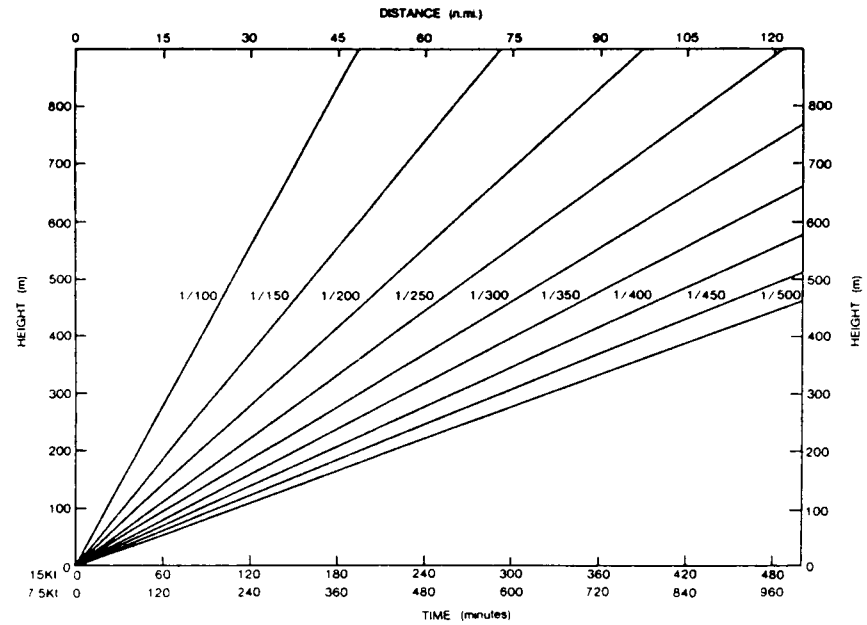
5.2.4.1.2 Techniques for identifying the location, development and movement of air mass fronts are too well known to require repetition. Historically, these techniques were based upon the detailed synoptic analysis of surface and upper air observations. In the past 20 years or so, synoptic analysis has been considerably augmented by using information from polar-orbiting and, especially in the past five years, geostationary weather satellites. The former provide information relevant to a particular location every six hours whilst the latter provide quasi-continuous observation. The geostationary satellites (e.g. GOES), in addition to providing cloud pictures every 30 minutes, also provide multi-spectral images in real time of the distribution of atmospheric temperature and water vapour and approximately hourly vertical profiles of temperature and moisture. Access to this wealth of data enables very accurate broad-scale frontal analyses to be made. These techniques are further supplemented on the local scale by the use of radar to monitor the development, intensity and movement of precipitation areas (both convective and non-convective) associated with the fronts.

5.2.4.1.3 Once the front has been located and, by monitoring sequential positions, its speed and direction of movement calculated in relation to the aerodrome concerned, the next step is to determine the slope of the front in the region of special interest to aviation, i.e. below 500 m (1 600 ft) above ground level. The simplest method is to locate the surface position of the front at a particular time on the surface chart and determine from rawinsonde/satellite data the height above ground of the frontal surface at the same time some distance ahead of a surface warm front or behind a surface cold front. More detailed analysis may be necessary using cross-sections (especially isentropic*) through the frontal surface. Isentropic analyses in the past were notoriously labour-intensive, but recently the preparation of such analyses in real time by mini-computer has become a reality. Given the speed of movement and the slope, some idea may be obtained of the time it will take for the shear along the frontal surface to pass across and clear the vicinity of an aerodrome, especially approach and climb-out corridors. An example of simple but effective nomograms to assist in this regard are shown in Figure 5-4[17]. Only two typical speeds and a selection of typical slopes are shown for each front, but it is a straightforward matter to derive information for other speeds and slopes using proportion and interpolation respectively.

* Such cross-section analysis has been dealt with in detail by Saucier in "Principles of Meteorological Analysis", 1955.



a) cold front



b) warm front

Figure 5-4. Height of warm and cold fronts versus distance/time from airport for various slopes (from Badner, 1979)

5.2.4.1.4 The question arises whether all fronts need to be treated in such detail or if there are some criteria to determine which fronts are likely to contain low-level wind shear (i.e. non-convective) of significance to aviation. The shear across the frontal surface is certainly proportional to the intensity of the front which, in turn, is proportional to the temperature gradient across the front. A critical temperature gradient of 5°C per 50 NM has been suggested and used successfully in this regard[17]. Experience in analysing hundreds of fronts at a particular aerodrome would eventually permit the fine tuning of such criteria. An indication of significant frontal surface wind shear may also be given by the vector difference in the winds across the front and the speed of movement of the front. In this context, a vector wind difference of magnitude 20 kt per 50 NM has been suggested and simple nomograms to calculate the magnitude of the vector difference directly from two winds using the relationship discussed in Figure 2-2 II b), i.e. $a = \sqrt{b^2 + c^2 - 2bc \cos A}$, are normally provided to assist the forecaster. Similarly, significant wind shear is usually present in fronts moving at 30 kt or more. There are of course two aspects to be considered with respect to criteria based upon speed of frontal movement. Whilst fronts moving at speeds of 30 kt or more (usually steeply sloped cold fronts) do tend to exhibit marked frontal wind shear, the fact that they are moving so quickly means that any wind shear effect below 500 m (1 600 ft) is likely to affect the aerodrome for only a short period of time. This means, perhaps somewhat paradoxically, that the slower-moving fronts, including warm fronts, although exhibiting less marked (non-convective) frontal wind shear conditions, by moving very slowly or even becoming quasi-stationary, can have a more marked effect over-all on aircraft operations (e.g. numerous missed approaches) than the intense, fast-moving cold fronts.

5.2.4.1.5 A quantitative estimate of the wind shear across the frontal surface may be made by analysis of the wind fields and wind profiles in the vicinity of the front. In the unlikely event that a rawinsonde/pilot balloon station happens to be situated at an appropriate location in relation to the frontal surface, the wind shear may be calculated directly as shown in Chapter 2, note being taken of the unavoidable deficiencies of this method. Otherwise, or in addition, the wind fields in the vicinity of the front must be analysed. In this context, it has been found that the geostrophic wind measured in the warm sector is a good estimate of the wind speed and direction immediately above both cold and warm frontal surfaces below 500 m (1 600 ft); this provides an estimate of the "upper" wind for the shear calculation for cold and warm fronts. Ahead of the warm front, in the "cool" air mass, the average surface winds are sufficiently representative of the wind below the frontal surface (this provides an estimate of the "lower" wind for the shear calculation for a warm front). In the case of a cold front, the geostrophic wind in the cold air behind the front is found to be more representative of the wind below the frontal surface than the surface winds (this provides an estimate for the "lower" wind for the shear calculation for a cold front). All the foregoing "upper" and "lower" wind vectors used for the calculation of frontal shear should be resolved into components parallel to and normal to the orientation of the most probable runway concerned, or the final calculated vector difference should be so resolved[17]. In this way the shear magnitude relates directly to headwind/tailwind (airspeed) changes and crosswind (drift angle) changes likely to be encountered by aircraft operating from that runway.

5.2.4.1.6 Following the foregoing procedures, a forecast may be prepared giving advice of expected wind shear at an aerodrome between the surface and 500 m (1 600 ft) and the expected period of validity, if possible, indicating the vector difference in knots expected across the front in terms of headwind/tailwind and crosswind for a particular runway[21].

5.2.4.2 Forecasting wind shear associated with sea breeze fronts

5.2.4.2.1 As mentioned in 3.4.2, although the sea breeze involves cool air displacing warm air, the slope of the frontal surface and the temperature gradients more closely resemble those of a shallow warm front rather than a cold front (virtually a warm front moving backwards!). In view of this, the procedures and criteria for the analysis of wind shear associated with warm fronts given in the previous section may be used to analyse sea breeze fronts. There are, however, a number of additional considerations, the main one being that the sea breeze is not advected steadily across a synoptic chart as is the case with air mass fronts, and its formation must be forecast every 24 hours. The formation of the sea breeze is by no means automatic and is subject, to a large extent, to the over-all synoptic situation and also to subtle local influences (e.g. topography). Thus there are more variables, such as whether the front will form at all and if so, at what time, how far inland it will penetrate and how deep the air from the sea or lake will be. Once the sea breeze front has formed, the procedures already described for the analysis of a warm front may be applied. The availability of detailed information on the vertical profile of wind, temperature and humidity through the sea breeze front is critical to the forecasting of the associated wind shear. This, in turn, depends upon the availability of nearby representative rawinsonde/pilot balloon/SODAR data. In addition, in accurately forecasting sea breeze effects, there is no substitute for local knowledge and experience on the part of the forecaster.

5.2.4.2.1 A particularly good example of an actual case of a sea breeze front near Boston is shown in Figure 5-5[27]. In estimating the wind shear across the frontal surface in this case, the surface wind at Providence (PVD) is taken as typical of the warm air above the frontal surface (although use of the gradient wind would have been better and would perhaps have been slightly stronger than the 30 kt at the surface), and the surface wind at Boston (BOS) taken as typical of the wind below the frontal surface. The magnitude of the vector difference between them (wind shear) is at least 40 kt. The surface temperatures (°F) are also plotted alongside the station circle in Figure 5-5. Aside from the shear in the wind speed above the surface, the sudden change in surface wind direction at the passage of the front could also be very important at an aerodrome. Although clearly of most concern to coastal aerodromes, it should be borne in mind that intense sea breeze fronts are capable of penetrating up to 50 km inland under suitable conditions.

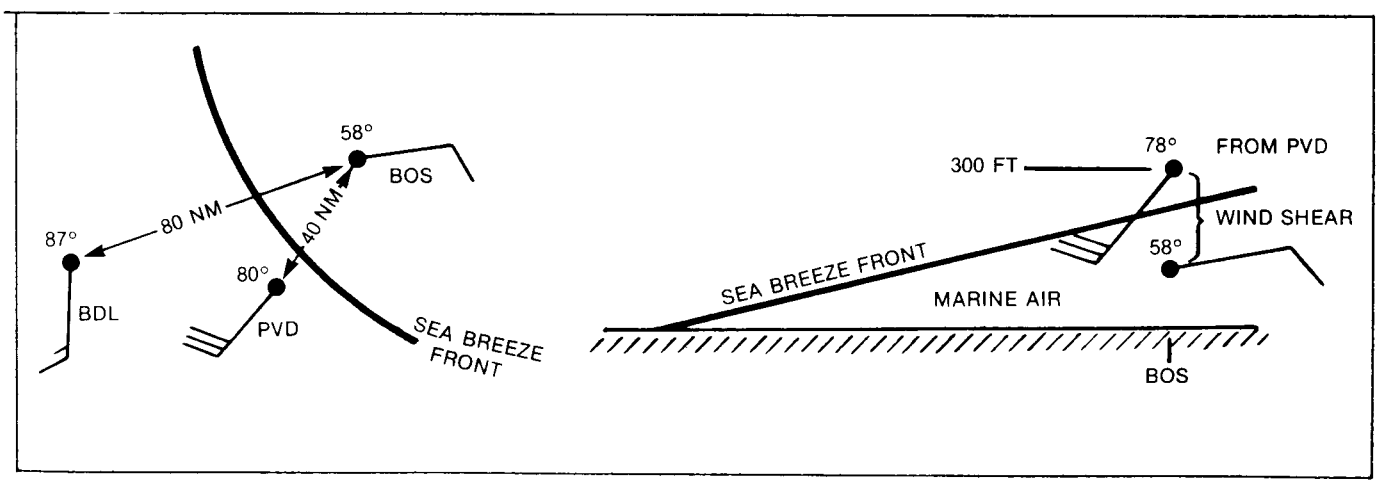


Figure 5-5. Wind shear associated with a sea breeze (from Badner, 1979)

5.2.4.3 Forecasting wind shear due to wind flow around obstacles

5.2.4.3.1 Although terrain-induced wind shear is notorious for its variability in intensity and for this reason is usually accompanied by clear-air turbulence, from the forecasting standpoint it is best considered as non-transitory because, given certain favourable meteorological conditions, this type of wind shear tends to develop at specific locations in relation to the obstacles and to exist there for as long as these particular meteorological conditions persist (see 3.2). Forecasting such wind shear requires, in addition to the general synoptic forecasts of wind in the area, a detailed knowledge of the local topography and its effect on the prevailing winds. The susceptibility of an aerodrome to terrain- or building-induced wind shear is best determined using the following techniques:

a) inspection of the aerodrome and its vicinity and analysis of available climatological records by an experienced aviation meteorologist;

b) gradual build-up of experience in analysing local area wind flow under different conditions by the local forecasters (such experience should be consolidated as a local technical research paper at the earliest opportunity);

c) conducting field trials using strategically sited anemometers (analysis of these results can be taken to virtually any level of complexity)[23];

d) soliciting low-level wind and wind shear/clear-air turbulence reports from pilots operating into the aerodrome and correlating these reports with the ambient conditions at the time;

e) discussions with tower controllers, who have to pay close attention to the vagaries of the surface wind by watching both anemometer displays and wind socks, etc.; and

f) in special cases where the expense* is warranted (e.g. Rock of Gibraltar), hydrodynamic tests can be run on scale models or computer simulations made.

5.2.4.3.2 There are numerous ways in which the climatological data and field trial data may be analysed, ranging from routine wind frequency analysis to sophisticated spectral analysis. One method by which effective results may be achieved reasonably quickly is to calculate the mean gust factors for each installed anemometer (either permanent installations or temporary field trial installations). There are various ways of doing this but perhaps the simplest is to calculate the mean and standard deviation of the ratio of gust speed to mean speed, monthly or annually. An example of such an analysis (annual) is shown in Figure 5-6 for Seychelles International Airport[25]. In this example it is immediately evident that south-westerly winds are very gusty indeed. This agrees well with the fact that there is high ground in relatively close proximity to the west of the anemometer site.

5.2.4.3.3 Once the nature and prevalence and, where possible, the average intensity of terrain- or building-induced wind shear in the vicinity of an aerodrome are known and

* Whilst such experiments are normally expensive, this is not always the case; see, for example, reference 24 for analysis of wind flow over Cyprus.

the particular meteorological conditions which are necessary and sufficient for its development have been determined, a set of empirical forecasting "rules of thumb" specific to each aerodrome can be prepared to assist forecasters. A brief summary of the characteristics of such non-transitory wind shear at particular aerodromes should also be included in the State aeronautical information publication.

5.2.4.4 Forecasting wind shear associated with mountain waves

5.2.4.4.1 Wind shear associated with mountain waves is really a special case of wind flow around, or at least over, obstacles, details of which were given in 3.2.8 and 3.2.9. In general it is of concern only to aerodromes situated on the lee side of high and long mountain ranges which are oriented across the prevailing winds (e.g. the Rockies in Canada and the United States). Mountain waves normally form at levels above 500 m (1 600 ft) as stationary wave trains of decreasing amplitude streaming downwind from the ridge line or specific mountain peaks. There are circumstances, however, when the wave train amplitude is sufficiently large to affect the wind flow below 500 m (1 600 ft). In such circumstances, the downslope wind on the lee side of the mountain range forms part of the first (and therefore largest amplitude) wave which reinforces the usual föhn wind effect (see 3.2.9). This can result in the sudden onset of very strong, gusty and noticeably warm dry surface winds. Such gusts have been known to exceed 100 kt in extreme cases. The presence of a marked low-level temperature inversion at ground level may prevent this wind from actually reaching the surface, thereby producing a shear zone at the top of the inversion layer. In extreme cases the amplitude of the waves may be sufficient to form separate and very turbulent rotor flows with or without attendant rotor cloud under the first and possibly subsequent wave crests. These rotor flows have been known to extend down to ground level and reverse the usual surface wind (see Figures 3-4 and 5-7). Intense rotor flows may contain downdrafts/updrafts as strong as 50 kt (5 000 ft/min)[22].

5.2.4.4.2 Normal föhn-type downslope winds and mountain waves can both be forecast, although it is often very difficult to forecast the actual wind speeds and wind shear quantitatively[26,27]. The presence of lenticular clouds and rotor clouds are of course an immediate indication of the existence of mountain waves. As far as forecasting is concerned, a set of empirical "rules of thumb" must be prepared for each location, which will normally include criteria based upon:

a) the critical wind speed at the mountain ridge (probably in excess of 15 kt) with wind speed increasing with height;

b) a stable upwind layer or an inversion below the 600 hPa level and preferably sandwiched between two less stable layers;

c) light winds in the stable layer;

d) removal of moisture on the windward side of the mountain range as precipitation; and

e) sea level pressure differential across the mountain range.

A simple yet effective nomogram for forecasting the development and intensity of mountain waves can be based on two of these factors - sea level pressure difference across the mountain range against wind speed normal to the mountain range[28,29]. With north-south orientated mountain ranges, marked mountain waves can be triggered by a passing cold front.

° / kt	350° 010°	020° 040°	050° 070°	080° 100°	110° 130°	140° 160°	170° 190°	200° 220°	230° 250°	260° 280°	290° 310°	320° 340°	VRBL
1 To 3													
4 To 6	1.72	1.70	1.74	1.71	1.95	1.92	2.00	2.17	2.08	1.83	1.95	1.86	2.15
7 To 10	1.51	1.61	1.73	1.60	1.63	1.82	2.01	2.08	2.04	1.83	1.78	1.59	2.01
11 To 16	1.46	1.70	1.88	1.53	1.59	1.74	1.96	1.82	1.77	1.82	1.68	1.49	0
17 To 21	1.63	1.43	0	1.76	1.73	1.69	1.76	0	1.71	1.78	1.62	1.52	0
22 To 27	0	0	0	0	0	1.64	0	0	1.66	1.76	0	0	0
28 To 33	0	0	0	0	0	0	0	0	1.61	1.52	0	0	0
34 To 40	0	0	0	0	0	0	0	0	0	0	0	0	0
41 To 47	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5-6. Mean gust factor for various classes of wind speed (kt) and direction, Seychelles International Airport (from Climate of the Seychelles, 1979)

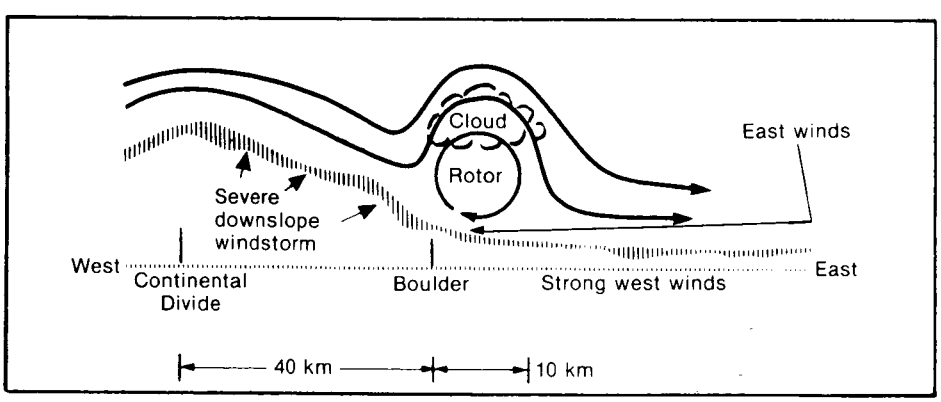


Figure 5-7. For January 24, 1982, schematic vertical cross-section through Boulder, Colo., U.S.A., believed representative of the mean flow field from about 0900-1800 MST. While winds from a general easterly direction prevailed in a zone around Boulder, strong west winds were observed 2-3 km above ground level in the stratocumulus clouds which systematically formed just west of Boulder (from Zipser & Bedard, 1982)

5.2.4.5 Forecasting wind shear associated with katabatic winds

5.2.4.5.1 This type of wind flow is likely to be of particular concern to aerodromes situated in a valley. The meteorological situation favouring its development (see 3.2.7) includes calm, clear nights under anticyclonic conditions. The onset and strength of the local katabatic wind can normally be forecast reasonably accurately on the basis of empirical rules drawn up for each specific location. Aside from its obvious importance in the forecasting of surface wind changes at the aerodrome, except in extreme cases the katabatic wind itself does not normally constitute a problem at most aerodromes. In extreme cases, such as in areas where inland plateaus are adjacent to coastal regions, and especially in winter under strong anticyclonic conditions, the air over the coast is markedly warmer than the intensely cold air over the plateau. If the pressure gradient is so disposed that it forces the cold air down the slopes of the plateau, very strong, gusty and accelerating cold winds blow across the coastal plain and out to sea, occasionally reaching speeds in excess of 100 kt (e.g. the "bora" of the Adriatic).

5.2.4.5.2 Significant local wind shear (above ground level) due to the normal downslope katabatic winds is only likely to occur if the surface inversion which develops at night is sufficiently strong to prevent mixing in the lowest levels of the atmosphere[30]. In these conditions a "stagnant pool" of cold air forms in the valley bottom which eventually prevents the succeeding downslope wind from reaching the surface, thus causing it to glide along the top of the inversion. This creates a situation where the surface wind at the valley bottom is mostly calm or light with a shear zone at the top of the inversion (usually between 75 m (250 ft) and 150 m (500 ft) above ground level)[31]. After sunrise the inversion rises and weakens and the shear zone rises also. The winds above the inversion often increase after sunrise with the result that, as the wind shear zone rises, it may also intensify just after sunrise. An estimate of the wind shear can be derived from the vector difference between the winds at the ridge and the surface wind at the valley bottom. Anything in excess of 5 kt/30 m is likely to be significant to aircraft operations.

5.2.4.6 Forecasting wind shear associated with the low-level jet stream

5.2.4.6.1 Under certain conditions, a strong super-geostrophic wind develops at low levels, especially over broad continental plains bordered by mountain barriers. The term "low-level jet stream" is used to describe this phenomenon because it develops as a long, narrow band of strong winds with streamlines and isotachs resembling those of jet streams found at higher levels of the atmosphere. As described in 3.1.2.3, the axis of the low-level jet stream is generally to be found below 500 m (1 600 ft) although the axis does tend to rise steadily after its initial formation. The formation of the jet stream depends upon a number of factors, the most important of which is rapid nocturnal cooling at the surface. This being so, its formation occurs after sunset and reaches a maximum around sunrise[32], times which, depending on the longitude of the aerodrome, may or may not coincide with the availability of detailed low-level temperature and wind data from rawinsondes launched around 0000 and 1200 UTC. The use of Doppler SODAR (see 5.1.2.3.2.2) is particularly appropriate for monitoring the development of the low-level inversion and the measurement of the low-level wind profile hour by hour directly above the aerodrome.

5.2.4.6.2 A number of empirical forecasting rules have been developed for use at aerodromes affected by low-level jet streams. If information is available from a local rawinsonde ascent around the time of formation of the low-level jet stream, then fairly detailed rules may be developed. Otherwise the following general rules proposed by Badner[17] for use in the United States may be applied:

a) There should be little cloud cover, with daytime heating producing an unstable lapse rate near the ground during the afternoon. An inversion near the 850 hPa level is desirable to cap the low-level instability. These conditions can be determined from the previous rawinsonde ascent and the maximum temperature during the afternoon.

b) Surface winds should be from the southerly sector with near geostrophic speed, as determined from isobaric spacing on afternoon surface maps ≥ 20 kt. The pressure gradient should not relax below the spacing sufficient to produce the maximum 20 kt wind speed during the night.

c) Wind speed should decrease with height above the low-level inversion in the lowest 900 m (3 000 ft) layer around sunset. This may be evident from the latest available upper winds.

d) The approximate vector difference between the observed surface wind direction and speed near sunset, and the geostrophically measured direction and 1.5 times the speed measured from the pressure gradient on the latest available surface analysis chart can be determined.

If the vector difference exceeds 30 kt, then significant wind shear could occur. Next assume that a minimum vector difference of 30 kt in the layer from the surface wind observation level to the low-level jet stream's presumed height of 360 m (1 200 ft) is necessary to produce an average vertical wind shear loss of 4 kt/30 m, $30 \text{ kt}/350 \text{ m} = 30 \times \frac{30}{350} = 30 \times .086 = 2.6 \text{ kt}/30 \text{ m}$. This average shear in the layer 350 m thick suggests that the shear will be at least twice as much in the lowest 90 m (300 ft).

5.2.5 Forecasting transitory wind shear

5.2.5.1 Forecasting wind shear associated with convective clouds

5.2.5.1.1 General

5.2.5.1.1.1 Low-level wind shear associated with convective clouds and especially mature thunderstorms is of critical importance to aviation but is extremely difficult to forecast. The forecasting of convective cloud, especially thunderstorms, in the area of interest is of course a necessary condition but, as far as low-level wind shear is concerned, is not a sufficient condition. The many different types of low-level wind shear of concern to aviation which may be associated with thunderstorms are described in detail in Section 3.5, including gust fronts, downbursts, microbursts and tornadoes. However, all thunderstorms do not necessarily produce such wind shear and sometimes non-thunderstorm convective cloud does produce it.

5.2.5.1.1.2 If convective cloud and especially thunderstorms are forecast to affect an aerodrome, then the occurrence of low-level wind shear associated with the cumulus or cumulonimbus clouds is clearly a possibility and should be understood to be so by pilots. If severe thunderstorms, organized lines or large areas of thunderstorms are forecast, then the likelihood of the occurrence of any or all of the critical types of low-level wind shear referred to above increases markedly. However, the more extreme manifestations of the thunderstorm such as microbursts and tornadoes, which in theory could accompany any severe storm, tend to be especially prevalent in certain parts of the world which appear to be particularly favourable for their development. Forecasting the development of thunderstorms has always been one of the most important tasks of the meteorologist and the necessary forecasting techniques are well known and, especially on the synoptic scale, reasonably successful. The forecasting of severe thunderstorms on the local scale has received increasing emphasis over the past decade or so, mainly due to the threat to life and the horrendous local damage that the associated high winds, torrential rain, hail and tornadoes can inflict on the community. The techniques that are being developed are rapidly blurring the distinction between observations and forecasts - because they are largely based on a detailed knowledge of the minute-by-minute state of the atmosphere at a given location, and the "forecast" which results may, at the extreme, constitute no more than a critical few minutes' "warning". These techniques have since come to be known under the general heading of "nowcasting", a term which has been explained by Browning[33] as follows:

> "The term nowcasting symbolizes an observations-intensive approach to local forecasting with the timely use of current data, in which remote sensing plays a dominant role. ... The very word, nowcasting, evokes a vivid picture of an approach to prediction that is more than usually dependent on the description of the present state [of the atmosphere]. ... The weather phenomena which are the subject of the nowcast are associated with mesoscale systems. The mesoscale lies between the synoptic scale and the cumulus scale: hence its name. It can be anything between a few kilometres and several hundred kilometres, with time scales between one hour and a day. Fronts, thunderstorm systems, and various kinds of local terrain-induced effects, all occur on the mesoscale."

The World Meteorological Organization[34] has defined "nowcasting" as forming a subset of "short-range forecasting" and being "a description of current weather and a 0-2 hour forecast". This is substantially also the definition of a "trend-type landing forecast" as provided for in Annex 3, 6.3.4 which renders nowcasts especially suitable for aviation purposes.

5.2.5.1.1.3 For severe thunderstorms and/or thunderstorms organized in lines or areas (both of which may also include individual severe thunderstorms), effective local forecasting techniques for thunderstorm development (changes in intensity and extent) and movement, whether nowcasting or otherwise, are generally based upon information from any or all of the following:

a) direct visual observation;

b) weather radar (from single 3 cm radar installations through to organized networks of 10 cm radars);

c) synoptic observations and aircraft reports;

d) observations received continuously in real time from mesoscale observing systems (including strategically sited automatic stations);

e) increased frequency/density of rawinsonde/pilot balloon ascents;

f) weather satellite data (including half-hourly pictures of cloud and water vapour distribution and vertical profiles of temperature and moisture);

g) Doppler radar (including multiple installations);

h) SODAR;

i) real-time lightning detection and location systems; and

j) automatic processing and display in real time of data from the foregoing sources[35].

5.2.5.1.2 Forecasting gusts, gust fronts, downbursts/microbursts and tornadoes

5.2.5.1.2.1 Without exception, all thunderstorms may be expected to produce gusts in the surface wind. A number of empirical forecasting rules are available for forecasting the likely maximum surface wind speed in gusts, especially for air mass thunderstorms, most of which are based on the estimation of the difference between the surface temperature before and after the onset of the gusty downdraft air from the thunderstorm. One such method, due to Fawbush and Miller, uses the latest available and representative sounding plotted on a standard thermodynamic diagram (e.g. tephigram). Wet-bulb temperatures are calculated and plotted as far as the freezing level. The point where the wet-bulb curve reaches 32°F (sometimes referred to as the "wet-bulb freezing level") is reduced to the surface along a saturated adiabatic line. The temperature of this latter point in °F is then subtracted from the observed surface temperature or forecast temperature (°F) prior to the onset of the thunderstorm. The difference is proportional to the maximum gust according to the graph shown in Figure 5-8*[36]. Forecasting the direction of the gusts is rather more difficult, but generally speaking the mean wind direction in the layer between 700 and 600 hPa gives a good indication. Observation of the movement of the storm on radar often assists in estimating the likely direction of the gusts[37]. Having forecast the probable maximum gust, there is of course no guarantee that such a gust will affect any particular area in the thunderstorm's path, such as an aerodrome.

5.2.5.1.2.2 The rules of thumb for forecasting gusts from thunderstorms described above generally apply to the immediate area around air-mass thunderstorms. Severe thunderstorms and frontal/squall line thunderstorms usually produce the rather more organized and propagating system of gusts known as a "gust front", which can produce much higher gust speeds and gusts which can travel as far as 35 km ahead of the parent storm or squall line (see 3.5.2). Gusts due to thunderstorms originate from the cold downdraft currents which penetrate the base of the cloud with or without accompanying heavy rain. The gust front originates from particularly strong downdrafts which reach the ground and which, when the diverging winds at the surface are of damaging intensity, are defined as "downbursts" by Fujita (see 3.5.3). Forecasting the probable maximum

* Sometimes referred to as the "Delta-T Index".

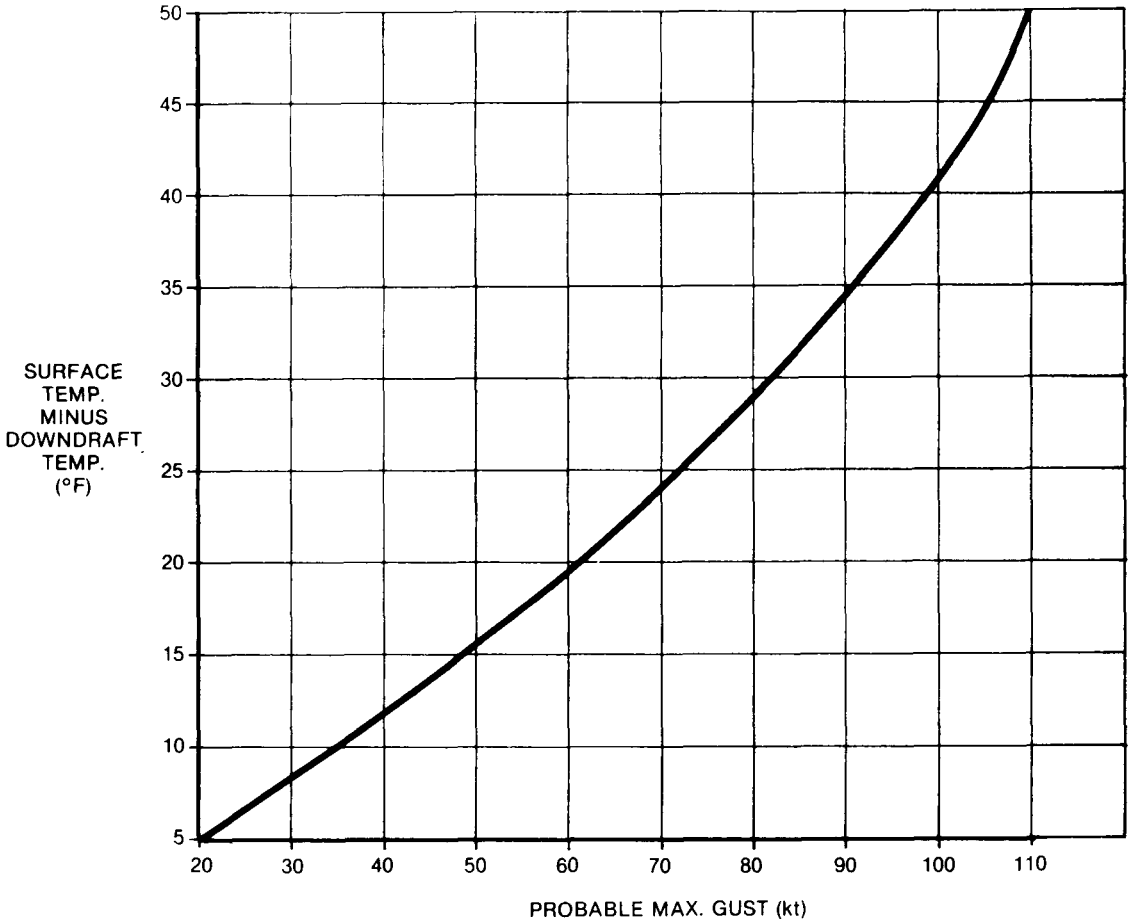


Figure 5-8. Empirical forecasts of probable maximum gusts (after George, 1960)

gust speed due to a gust front is difficult but if the speed and orientation of the gust front can be established, from observations of its passage across observing stations or from radar, etc., then the maximum wind normal to the gust front near the ground will be approximately 1.5 times the gust front speed. Deciding whether or not a thunderstorm will actually produce gust fronts is also difficult. It has been suggested that radar centre reflectivities from the thunderstorm greater than 40 dBZ (equivalent to rainfall of over one inch per hour) be used as a criterion[38]. Techniques for forecasting the development of downbursts dealt with below may also be applied, as gust fronts stem from downbursts. Gust fronts should always be expected ahead of squall lines and from organized areas of active thunderstorms. As mentioned in 3.5.2.3 and 5.1.2.2.3, occasionally the gust front shows on conventional weather radar, especially on 10 cm radar configured to receive weaker than usual returns (down to <10 dBZ). Tracking these radar echoes permits very accurate forecasts to be made; unfortunately all gust fronts do not produce such identifiable returns. Observation of gust front roll cloud on weather satellites (see 5.1.2.2.4 and Figure 5-7), although rare, can also provide the basis for an accurate forecast. The use of an array of wind and/or pressure sensors around the perimeter of an aerodrome to detect gust fronts, such as in the LLWSAS installed at many United States aerodromes, is described in detail in 5.1.2.3.1. This system was originally designed to provide short-term warning of gust fronts crossing the aerodrome perimeter and, for this purpose, the system works well.

5.2.5.1.2.3 Current "nowcasting" techniques for forecasting thunderstorms likely to produce downbursts (and hence gust fronts), microbursts and tornadoes depend to a large extent on the interpretation of conventional, i.e. non-Doppler, radar echo characteristics and cloud top pictures from geostationary weather satellite infra-red imagery. Conventional radar echo characteristics associated with severe thunderstorms have been analysed since the 1950s and the collection of identifiable types now includes "tall echoes," "hook echoes", "bow echoes", "comma echoes" and "spearhead echoes". The hook and the bow echoes and possible downburst areas are shown diagrammatically[39] in Figure 5-9 a), and the typical evolution of radar echoes through various stages and the location of downbursts is shown in Figure 5-9 b). The spearhead echo concept was introduced by Fujita and Byers in their analysis (1976) of the meteorological aspects of the Eastern Airlines accident at New York's John F. Kennedy International in June 1975. The plan and elevation views of a spearhead echo are shown diagrammatically in Figure 5-10[40]; comparison should also be made with Figure 3-11. Diagrams of the plan and elevation views of typical cloud tops seen from infra-red imagery of thunderstorms which produced downbursts are shown in Figure 5-11[39]. The identification of such radar echo patterns is not always a simple matter and their absence certainly does not preclude the development of severe thunderstorms. For details on the interpretation and forecasting of severe storms using these techniques reference should be made to the original technical papers given in references 17, 39, 41, 42, 43, 49, 50 and 51.

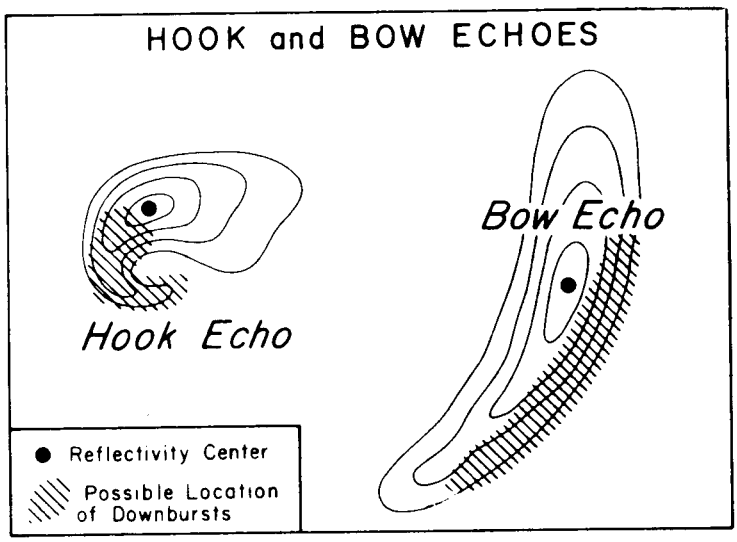
5.2.5.1.2.4 In 1982, Browning stated that "nowcasting" techniques were "in a state of flux"[33]. Considerable technical research effort is being expended on remote-sensing equipment, digitizing, processing and interactive display of radar satellite and sounding data and a similar research effort is being concentrated on the theoretical basis for predicting severe storms and their associated downbursts, microbursts and tornadoes (see Figure 5-12)[44]. These efforts are likely to produce results which will be incorporated gradually into the field of operational weather forecasting during the next few years. Some of the various alternatives which have been proposed for future systems for observing and forecasting low-level wind shear on an operational basis are discussed in Chapter 6.

5.3 REPORTING WIND SHEAR

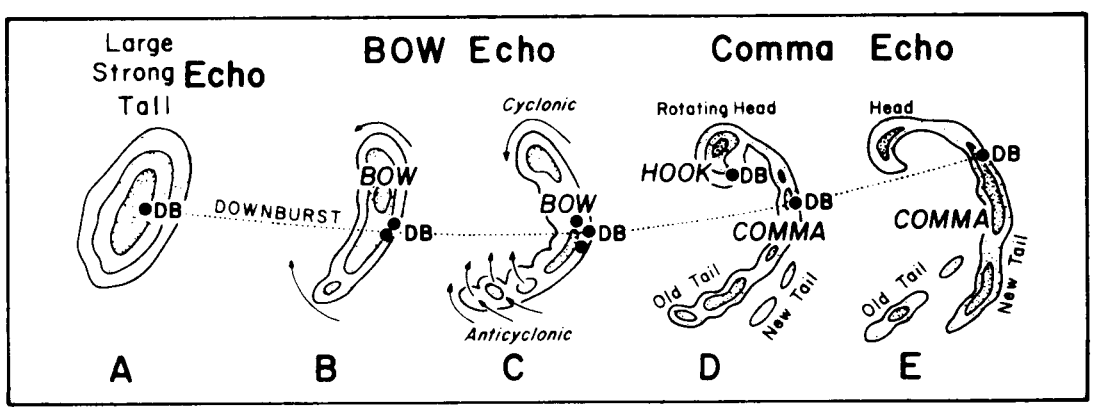
5.3.1 General

5.3.1.1 The first two paragraphs of the statement of operational requirements given in Appendix A deal with the need to provide pilots with information on low-level wind shear and turbulence. At first sight, the mechanics of providing available wind shear information to pilots would not seem to be very much different from those of providing information on any other hazardous low-level weather phenomena. In practice, however, there are several unusual difficulties, which are worth examining in order to give insight to operational personnel.

5.3.1.2 Information on low-level wind shear at aerodromes, at present, may be derived from pilots' reports during landing and take-off, from direct visual observations taken at the ground, from forecasts prepared on the basis of general meteorological information or from dedicated instruments or instrument systems specifically installed at an aerodrome for this purpose. The flow of wind shear information is shown diagrammatically in Figure 5-13. Essentially, the flow of information would also be applicable to other hazardous low-level weather phenomena reported by and to pilots.



a) Hook and bow echoes commonly observed during downbursts. A line echo wave pattern (LEWP) often includes a fast moving bow echo. The maximum reflectivity within a bow echo is frequently seen on the left side of the bow centre.



b) A typical morphology of radar echoes associated with strong and extensive downbursts. Some bow echoes disintegrate before turning into comma echoes. During the period of strongest downbursts, the echo often takes the shape of a spearhead or a kink pointing toward the direction of motion ("DB" indicates position of downburst).

Figure 5-9. Characteristics of radar echoes which produce downbursts (from Fujita, 1978)

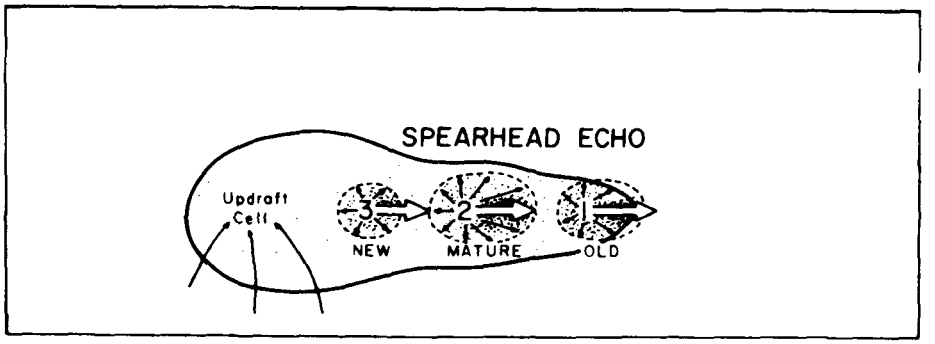


Figure 5-10. Plan view of the Fujita-Byers model of a spearhead echo (from Fujita, 1976)

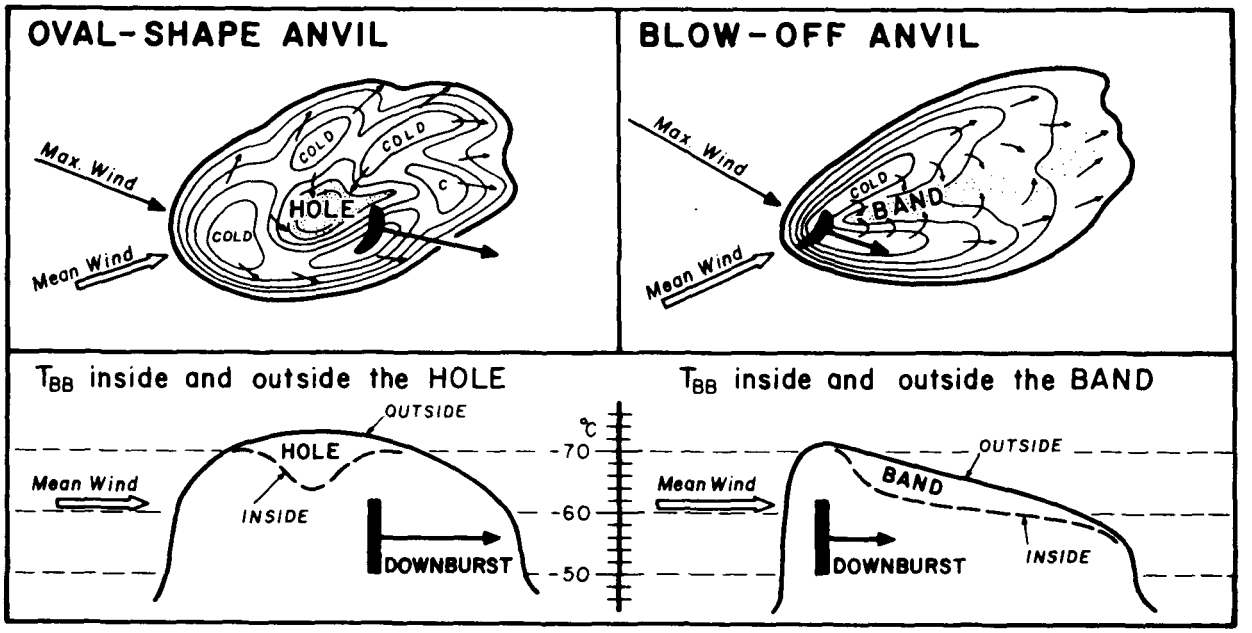


Figure 5-11. Schematic diagrams showing patterns and profiles of cloud-top temperature (T_{BB}). Mean wind denotes the mean layer wind 0 to 3 km or 3 to 6 km below the height of the maximum wind near anvil level. Based on the analyses of infra-red imagery for four downburst cases (from Fujita, 1978)

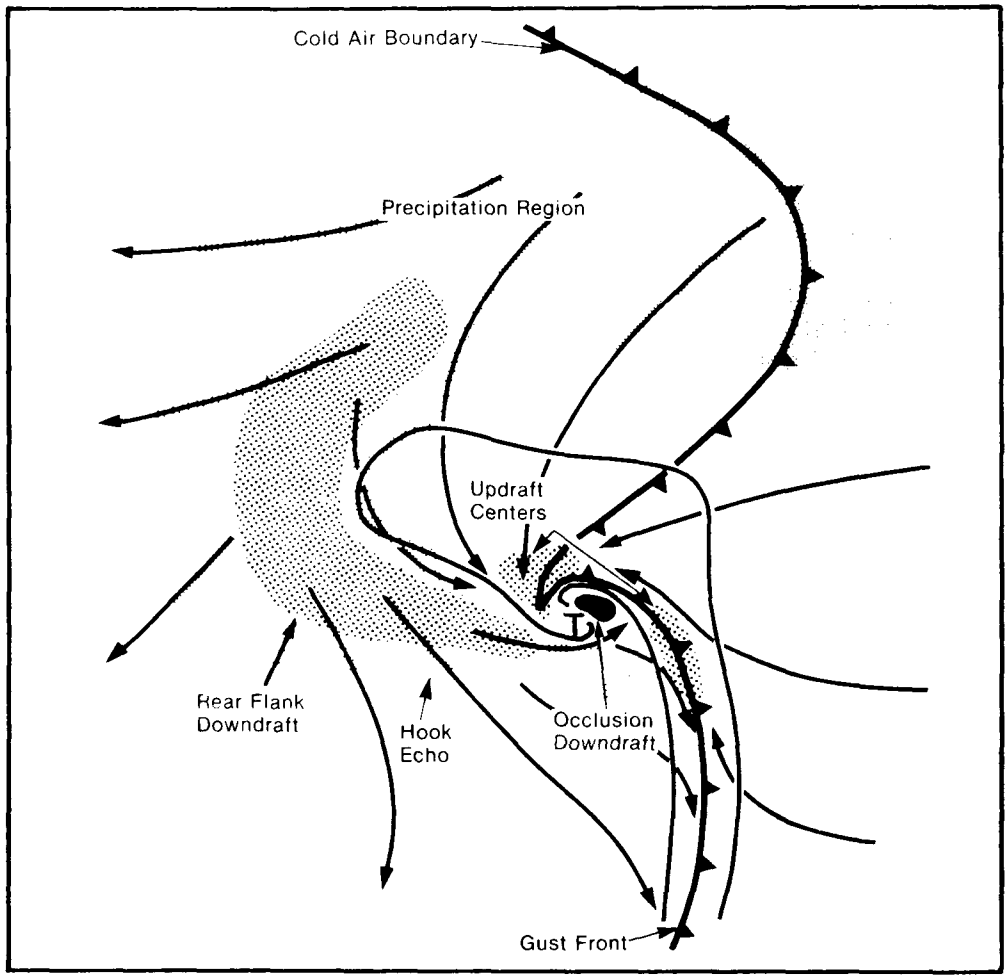


Figure 5-12. Model of tornadic thunderstorm; (T) indicates position of tornado (from Weisman, 1983)

5.3.1.3 The reasons for the particular difficulties in providing wind shear information to pilots may be grouped under two main headings: "time element" and "terminology". The time element is important because the most hazardous low-level wind shear is the transitory type which may be associated with any convective clouds but especially with thunderstorms. The lifespan of microbursts (the most hazardous invisible manifestation of thunderstorm wind shear) is generally less than 15 minutes. During the JAWS project (see 3.5.4.2), of 40 microbursts examined by Doppler radar, 50 per cent reached their maximum intensity within 5 minutes after first detection, while 95 per cent did so within 10 minutes from the time the diverging outflow reached the ground (see Figure 3-17). Some dissipated within 5 to 10 minutes, with maximum wind speed differential across the microburst increasing from 25 to 50 kt during this time. They are small scale events being only 1.8 km in diameter when first detected, growing to only 3.1 km on average in about 6.4 minutes. The foregoing illustrates the difficulty with the time factor: to be effective, a pilot report of wind shear and wind shear warnings must be passed to aircraft with the minimum possible delay.

5.3.1.4 Difficulties under the second heading, "terminology", stem largely from the intrinsic complexity of the subject and the lack of operational equipment capable of detecting and measuring wind shear in units and intensity classes which are directly understandable by a pilot in terms of the performance of the aircraft type concerned. Advising a pilot of, for example, freezing rain in the approach path provides sufficient information for the pilot to take appropriate action. Advising that wind shear is expected or reported in the approach path, whilst it does at least alert the pilot, also gives rise to a whole series of consequential questions in the pilot's mind, e.g. what type, what intensity, what height, etc. These are not trivial questions because the course of action the pilot should take depends upon their being answered.

5.3.1.5 Two examples of difficulties in terminology will suffice to illustrate this point. As described in Chapter 4, wind shear can either increase apparent aircraft performance (increasing headwind, decreasing tailwind, updrafts) or decrease apparent aircraft performance (decreasing headwind, increasing tailwind, downdrafts). What could be more simple, direct and informative than referring to such types of wind shear, respectively, as "positive wind shear" and "negative wind shear"? From the theoretical standpoint it is attractive and appropriate and from the pilots' standpoint it relates immediately to potential performance and is applicable to all aircraft. Unfortunately, "negative wind shear" in English can also be understood to mean "no wind shear", which could have disastrous results. Even inserting an additional word such as "type" (hence "negative-type wind shear") to alleviate this difficulty would not be foolproof because the single word "type" could be missed in transmission or even deliberately dropped due to the natural human temptation to shorten R/T phrases. Alternative terms which have been proposed by the ICAO Low Level Wind Shear and Turbulence (WIST) Study Group are "overshoot effect" and "undershoot effect" (see Appendix B). These are longer terms of course but are understood directly by pilots. Originally there was a difficulty associated with these terms - if the word "overshoot" was heard by a pilot it might have been taken to be an ATC instruction to overshoot. This potential source of confusion has since been eliminated by the introduction by ICAO of the terms "missed approach procedure" and "go around".

5.3.1.6 The difficulty in resolving the problem of wind shear intensity classification, dealt with in 5.2.2, means that qualifying terms such as light, moderate, strong and severe based upon agreed quantitative criteria are not currently recommended in Annex 3, Chapter 7 for use in the provision of wind shear warnings. The "interim wind shear intensity criteria" (see Table 5-1) recommended by the Fifth Air Navigation Conference (Montreal, 1967) are available as guidance and may be used by States at their discretion in the full knowledge that, although they have a number of disadvantages, recent analysis of world-wide wind shear data by the Royal Aircraft Establishment, Bedford (see 5.2.2.2 e)) indicates that the interim criteria, at least with respect to shear in the horizontal wind components, are probably on the conservative side[45].

5.3.2 Aircraft reports of wind shear

5.3.2.1 In view of the current lack of operational remote sensing equipment capable of detecting and measuring low-level wind shear, information on wind shear is largely based upon pilot reports, a situation which is duly acknowledged in 4.12.1 and 7.4.2 of Annex 3. Such pilot reports are to be made in accordance with 5.5.1 (and note thereto), 5.5.2 and 5.8.3 of Annex 3. This means that, as it may well be the only source of information, the reporting of wind shear by pilots is of vital importance in helping to safeguard other aircraft. Ideally, the maximum amount of relevant information should be given by pilots to help other pilots assess the likely effect of

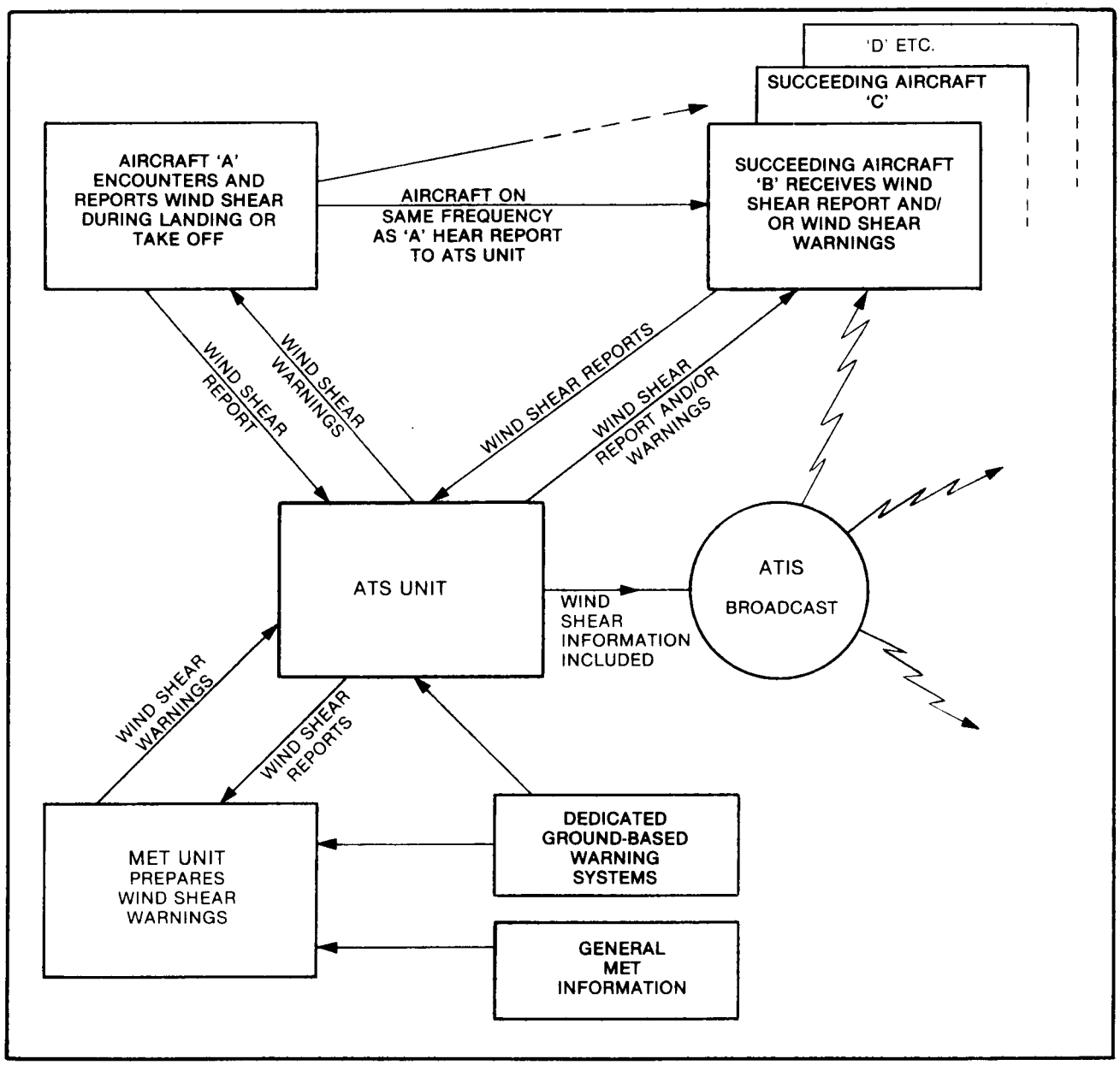


Figure 5-13. Flow of wind shear information between MET, ATS and pilots

the wind shear on their own aircraft. However, it must also be appreciated that a wind shear encounter is a dynamic event involving high cockpit workload in a very short space of time and that to expect pilots to report in detail in all circumstances is therefore unrealistic.

5.3.2.2 Guidance for pilots to assist them in framing wind shear reports has been developed with the assistance of the WIST Study Group. This guidance is based on the assumption that pilots will give as much relevant information as possible, taking into account cockpit workload at the time (and hence the resources available for framing and transmitting the report) as well as the particular equipment carried on board from which wind shear information may be derived. Subject to the foregoing caveat, pilot reports should contain the following information:

a) Description of the event as concisely as possible, including use of the term "wind shear" and a subjective assessment of the intensity using the terms "light", "moderate", "strong" and "severe" as appropriate (analogous to describing the wind shear on a (subjective) scale of 1 to 10 on the basis of aircraft reaction to the shear). Alternatively, factual plain-language reports (i.e. in the pilot's own words) regarding airspeed/ground speed changes and undershoot/overshoot effects may be made or, in circumstances where only minimum advice is possible, a simple report of "wind shear".

b) Aircraft type, in accordance with 5.8.3 of Annex 3.

c) Height or height band at which wind shear was encountered.

d) Phase of flight, if not obvious.

e) Appropriate detailed meteorological and/or operational information. In this context, aircraft equipped with suitable navigation systems encountering wind shear should, if possible, report other relevant information such as significant changes in wind direction and/or speed.

5.3.2.3 Guidance on the wind shear terms recommended for use in air/ground communications, which were also developed with the assistance of the WIST Study Group, is given in Appendix B. Example reports based on the foregoing guidance are as follows:

A. <u>Minimum reports where time and/or information is not available to give further detail</u>

"[call sign] WIND SHEAR B727 ON APPROACH (RW36)"; or

"[call sign] STRONG WIND SHEAR B727 ON APPROACH (RW36)"; or

"[call sign] WIND SHEAR DC10 ON APPROACH (RW28)"; or simply

"[call sign] WIND SHEAR"

B. Further amplified reports where sufficient time and information available

"[call sign] MODERATE WIND SHEAR TRISTAR AT 150 FT ON APPROACH (RW36) LOST 10 KT (AIRSPEED)"

"[call sign] STRONG WIND SHEAR B747 UNDERSHOOT EFFECT BETWEEN 300 FT and 600 FT TEMPORARILY UNABLE MAINTAIN CLIMB ON DEPARTURE (RW13)"

"[call sign] STRONG WIND SHEAR B707 ON APPROACH (RW26) WIND 350° 45 KT AT 500 FT BECOMING 230° 10 KT AT 200 FT"

5.3.3 Air traffic services reporting of wind shear

5.3.3.1 As shown in Figure 5-13, ATS units are the critical communications interface between aircraft, and between aircraft and MET units. On receipt of a pilot report of "wind shear", the ATS unit concerned should:

a) immediately relay the report to other aircraft concerned;

b) include a report in the automatic terminal information services (ATIS) broadcast (if available); and

c) pass the report to the associated MET unit.

5.3.3.2 The relay of pilot reports of wind shear to other aircraft and indeed the provision of wind shear information to pilots in general is covered in the Procedures for Air Navigation Services - Rules of the Air and Air Traffic Services (PANS-RAC), Part IV, 5.1 and 13.3 b) and Part V, 7.3 b). The pilot report should be relayed with content unchanged, although additional relevant factual information missing from the original report should be added if known (e.g. aircraft type, runway, etc.). The reports should be relayed using the following standard sequence, the contents of which will depend upon the detail of the original report:

a) "wind shear" - identifier;

b) aircraft type - added if not included in original report;

c) description of event - no change to report as received from pilot;

d) height wind shear encountered - no change to report as received from pilot;

e) phase of flight - no change to report as received from pilot;

f) runway - added if not included in original report;

g) time of encounter - no change to report as received from pilot; and

h) meteorological/operational information - no change to report as received from pilot.

An example of such a report is as follows:

"WIND SHEAR B747 REPORTED STRONG WIND SHEAR AT 300 FT ON APPROACH RWY 27 AT 0937 MAX THRUST REQUIRED"

5.3.3.3 The inclusion in the ATIS broadcast of available information on significant meteorological phenomena (i.e. including wind shear) in the approach, take-off and climb-out areas is covered in 4.3.5.1 17), 4.3.6.1 17) and 4.3.7.1 12) of Annex 11.

5.3.3.4 Relaying pilot reports of wind shear by ATS units to the associated MET office is covered in the PANS-RAC, Part II, 16.1. These reports form the basis for wind shear warnings prepared by the MET office (see 5.3.4 below).

5.3.3.5 The statement of operational requirements in Appendix A, 2.1 a) refers to the need for pilots to be provided with information of changes in the surface wind along the runway. The occurrence of horizontal wind shear along the runway, indicated by a highly variable surface wind and/or significantly different surface winds from multiple anemometers, may be caused by windflow around buildings, air mass fronts, sea breeze fronts and gust fronts, etc. (see Chapter 4), and can cause difficulty for pilots at touchdown and roll-out and during the take-off run. At aerodromes where this is a problem, 4.5.3 of Annex 3 recommends the installation of multiple sensors. In accordance with the PANS-RAC, information on surface wind and significant changes and variations thereto should be:

- passed by approach control to aircraft on first contact and at the commencement of final approach (Part IV, 13.1 b), 13.3 a));
- available at appropriate area control centres or flight information centres for transmission to supersonic aircraft (Part VI, 1.3.5.1 a) i);
- passed by aerodrome control to aircraft prior to their entering the traffic circuit (Part V, 7.4 b); and
- passed by aerodrome control to aircraft prior to taxiing and prior to take-off (Part V, 7.2 b) and 7.3 a)).

In this context, in Annex 3 "differences" in the surface wind refer to a change in the mean wind (i.e. a definite shift to a new prevailing wind) either at one anemometer or between multiple anemometers whereas "variations" in the surface wind refer to conditions where the surface wind (direction and/or speed) fluctuates about some mean value, but the mean itself does not change. An example of a report indicating a change in mean surface wind along the runway is as follows:

"FASTAIR 345 CLEARED TO LAND TOUCHDOWN WIND 270 DEGREES 7 KNOTS STOPEND WIND 160 DEGREES 15 KNOTS"

An example of a report indicating a fluctuating surface wind is as follows:

"FASTAIR 345 CLEARED TO LAND WIND 270 TO 350 DEGREES 10 TO 20 KNOTS GUSTING 30 KNOTS"

5.3.3.6 At some aerodromes (notably in the United States), a low-level wind shear alert system (LLWSAS) has been installed (see 5.1.2.3.1). In these circumstances local arrangements have been made to pass system-derived wind shear alerts from ATS units to aircraft. When a significant shear is detected (>15 kt vector difference) between a perimeter anemometer and the centre-field anemometer, an alert is sounded and both wind values are displayed and passed to the aircraft. Information on the actual vector difference is not passed to aircraft. Examples of such reports are as follows:

"WIND SHEAR (ALERT) CENTRE FIELD WIND 270 DEGREES 20 KNOTS WEST BOUNDARY WIND 180 DEGREES 25 KNOTS" or

"WIND SHEAR (ALERT) ALL QUADRANTS CENTRE FIELD WIND 210 DEGREES 14 KNOTS WEST BOUNDARY WIND 140 DEGREES 22 KNOTS"

5.3.3.7 Air traffic service units should continue to transmit information on wind shear conditions until it is confirmed that it is no longer significant for operations at the aerodrome, either from subsequent aircraft reports or by advice from the associated meteorological office. The cancellation of wind shear warnings by the meteorological office is covered in Annex 3, 7.4.5 and is discussed in more detail in 5.3.4.6 below. The ATS unit should continue to relay pilot reports of wind shear to other aircraft concerned until such time as the report(s) has(have) been incorporated into a wind shear warning by the associated meteorological office. Thereafter, the wind shear warning will be transmitted to all aircraft concerned until cancelled by the meteorological office.

5.3.4 Meteorological services reporting wind shear

5.3.4.1 Information on low-level wind shear at an aerodrome should be provided to ATS units, operators, etc. by the meteorological office designated to serve the aerodrome in the following manner:

a) in wind shear warnings (see Annex 3, 7.4.1 to 7.4.5 inclusive); and

b) in the supplementary information section of the routine and special meteorological reports (see Annex 3, 4.12.1, 4.12.3, 4.12.5, 4.13.1 k) and 4.13.2).

5.3.4.2 Wind shear warnings may be based upon aircraft reports received through an ATS unit (see 5.3.3.4 above), direct observations from conventional meteorological equipment (e.g. anemometer), forecasts of meteorological phenomena known to produce wind shear (e.g. convective cloud) and ground-based wind shear warning equipment (e.g. tower-mounted anemometers). The warnings should be prepared in abbreviated plain language and should be identified as "WS WRNG" for example:

"WS WRNG SURFACE WIND 320/10 WIND AT 60 M 360/25 in APCH"
[i.e. assuming actual winds are available]

When an aircraft report is used to prepare a warning or to confirm a warning previously issued, the corresponding aircraft report, including aircraft type, should be given unchanged, for example:

"WS WRNG B707 REPORTED MOD WS IN APCH RW34 AT 1510"

5.3.4.3 With respect to wind shear warnings based upon forecasts of relevant meteorological phenomena, it is difficult to be dogmatic as to the presentation preferred. In general, the provision of reliable quantitative forecasts of the wind shear associated with the phenomena will not be possible, which means that only qualitative statements can be made. Under such circumstances there is a temptation to include information which is not strictly relevant. This temptation should be avoided and the warning should always be made as concise as possible and should clearly indicate its "forecast" status by use of abbreviations such as FCST, EXP or POTENTIAL, etc.

5.3.4.4 The question of convective wind shear and non-convective wind shear must also be considered and these may have to be treated separately. Whilst it should be understood by pilots and ATS personnel that when thunderstorms are forecast, they will automatically contain wind shear as well as icing, turbulence, hail, etc., it is still necessary to draw attention to special situations, e.g. squall lines, severe storms, etc. Such a warning might be framed as follows:

"WS WRNG YUDO 1500 UTC LSQ WNW AP MOV E 20 KT WS EXP IN APCH AND TKOF ALL RWY NXT HR"

The manner in which convective wind shear warnings should be prepared and the procedures for their issuance should be agreed locally for each aerodrome or at least within each State by the ATS and MET authorities and the operators concerned. Little purpose would be served by having a plethora of wind shear warnings issued every day for each and every isolated thunderstorm. The authorities concerned must assess the situation at their aerodromes and draw up local procedures accordingly.

5.3.4.5 In the case of non-convective wind shear, the possibility of forecasting the meteorological phenomena concerned is much higher. Examples of such warnings might be as follows:

"WS WRNG YUDO 0900 UTC WS FCST APCH AND TKOF BLW 2 000 FT BTN 2100 UTC AND 0300 UTC DUE LOW LEVEL JTST"

"WS WRNG YUDO 0500 UTC WS FCST APCH AND TKOF BLW 1 000 FT BTN 0600 UTC AND 0900 UTC DUE STRONG SEA BREEZE FRONT"

Where non-transitory wind shear is a regular feature of the aerodrome climatology under well known and recurring meteorological conditions, such as local terrain-induced wind shear, etc., details should be included in the MET Section of States' AIPs as useful background information for pilots, and operators should include such information in the appropriate route guides.

5.3.4.6 In accordance with Annex 3, 7.4.5, wind shear warnings should be cancelled when aircraft reports indicate that wind shear no longer exists, or after an agreed elapsed time if no further reports are received. The criteria for cancellation of wind shear warnings should be defined locally for each aerodrome, as agreed between the ATS and MET authorities and the operators concerned. In this context, consideration should be given to the normal traffic mix at the aerodrome to ensure that, for example, wind shear warnings based on reports from light aircraft are not cancelled too soon simply because subsequent reports from heavy jet transport aircraft have not confirmed its existence (i.e. perhaps it is not of sufficient intensity to affect them). The importance of effective ATS/MET/operator co-ordination in this regard cannot be

over-emphasized. These matters are dealt with in more detail in the ICAO's Manual on Co-ordination Between Air Traffic Services and Aeronautical Meteorological Services (Doc 9377).

5.3.4.7 The inclusion of information on wind shear in the supplementary information section of the routine and special meteorological reports has been a recommended practice in Chapter 4 of Annex 3 for many years and considerably predates the 1983 introduction of wind shear warnings into Annex 3, Chapter 7. Observers are therefore fully familiar with the procedure and little specific advice is required here. It might, however, be pointed out that if the issuance of wind shear warnings is instituted at an aerodrome, care should be taken that local staff instructions/ procedures, etc. for "warnings" and those for the "inclusion of wind shear in supplementary information" are compatible and do not conflict in any way. One problem which should be borne in mind, if automatic processing and display of MET reports is planned at aerodromes, is that due provision should be made, in communication and display software, to permit the random inclusion in the reports of supplementary information of wind shear reports of varying length and in abbreviated plain language. This has been known to cause problems in the past and for this and other reasons, the compatibility of aviation figure codes for automatic processing is currently being reviewed by the WMO in consultation with ICAO. An example of such supplementary information in abbreviated plain language is as follows:

"SPECIAL YUDO 050/25 KT MAX 37 VIS 2500M TS 7/8 CB 500 FT MOD WS REPORTED B707 IN APCH RW08"

5.3.5 FAA Integrated Wind Shear Programme (terminal information)

5.3.5.1 This component of the programme deals with the development of procedures for the timely transmission of wind shear information to pilots in the terminal environment. It includes use of current systems such as LLWSAS (see 5.1.2.3.1) and weather radar (see 5.1.2.2.3) and future systems such as NEXRAD (see 6.2.1) and TDR (see 6.2.2).

5.3.6 Typical wind shear warning system

5.3.6.1 A final look at a typical "wind shear warning system", as established at Helsinki-Vantaa Airport in Finland, may serve to illustrate what can be achieved in practice to deal with a specific problem[46].

5.3.6.2 In Finland, in fact throughout Scandinavia as well as in other parts of the world, wind shear associated with low-level temperature inversions is a fairly common occurrence. The potential loss of performance by aircraft landing and taking off in these conditions due to encountering temperatures higher than the normal temperature lapse rate combined with rapidly changing head/tailwind components is a serious concern to the authorities. In order to deal with the problem, advantage was taken of an existing 1 000-ft high television transmitter mast some 20 km south-west of the airport to install wind, temperature and humidity sensors at selected levels. The data from these sensors is transmitted to the airport and analysed in real time by computer. The wind data from the television mast has been correlated with INS data reported from aircraft landing and taking off and the two sets of data correlated +0.85 for speed and +0.99 for direction. Warnings are issued for wind shear and for significant inversions (≥10°C as per the provisional requirement (Recommendation 3/5) formulated by the Eighth

Air Navigation Conference, Montreal, 1974). The warnings are displayed on the aerodrome closed-circuit television and comprise information on the actual winds at selected levels and the magnitude of the inversion as follows:

"WS WRNG
WIND AT 700 FT 160/30 KT
WIND AT 300 FT 090/05 KT
INVERSION 12°C BLW 900 FT"

The fact that a wind shear/inversion warning is in effect at any time is also given as a remark attached to the routine MET report which is also displayed automatically on the aerodrome closed-circuit television system. The warning system has been in routine operation since 1978 and has proved to be very useful. Similar systems are in operation elsewhere, e.g. in Denmark, Hong Kong, Sweden and the Union of Soviet Socialist Republics. In the case of Hong Kong, the anemometers are located on hills which are situated at strategic points along the approach path[43].

CHAPTER 6

RESEARCH AND DEVELOPMENT

6.1 GENERAL

6.1.1 There are under way or proposed a number of research and development projects concerned with dedicated wind shear warning systems, or with general meteorological research, which could assist in forecasting the phenomena known to produce wind shear. Progress has accelerated in the past few years, particularly in three fields which, taken together, promise the development of very powerful systems and techniques for the detection and forecasting of wind shear. The three fields of interest are remote-sensing equipment; high-speed automated data processing and analysis using powerful microcomputers and efficient algorithms, and interactive visual display techniques, all operating in real time. It is appropriate to look first at the various types of equipment being developed, then at some of the systems being proposed which use the equipment and at the application of such equipment and systems to forecasting wind shear.

6.1.2 Research is also being undertaken on the airborne equipment needed to assist pilots in wind shear encounters. One approach concerns the examination of the optimum trajectory which an aircraft should fly in order to recover and escape from wind shear. This approach is being followed by the Aero Astronautics Group of Rice University in the United States, which is examining the optimum trajectories and the guidance and control laws and pilot techniques to achieve the trajectories. This research is being funded by NASA Langley, the United States Air Line Pilots Association and Boeing Aerospace. It is expected that this research will be of considerable importance in design considerations for flight deck instrumentation to assist pilots in wind shear encounters[1].

6.2 EQUIPMENT CURRENTLY UNDER DEVELOPMENT OR PROPOSED

6.2.1 Next Generation Weather Radar (NEXRAD)

6.2.1.1 NEXRAD is an advanced (10 cm) pulsed Doppler radar currently being developed by the United States to meet a common requirement of principal users of meteorological data for information on the location, severity and movement of such weather phenomena as tornadoes, severe thunderstorms, heavy precipitation, tropical cyclones, hail, wind shear and turbulence. Each NEXRAD installation will provide

coverage for ranges in excess of 200 NM and heights of 60 000 ft at a rate of once every 3½ minutes. In view of the wide range of requirements to be met, the size of the coverage volume and hence the high data rate, NEXRAD will depend heavily on automated data processing to analyse the data and present it to users in real time. NEXRAD is not intended to be dedicated to wind shear detection and is therefore unlikely to be optimized for this task. Nevertheless, the clear improvement this radar is likely to make in identifying and forecasting the development and movement of severe thunderstorms, etc., will be of considerable assistance in the preparation of wind shear warnings. A progress report on the development of NEXRAD was published by Evans in June 1985[2].

6.2.2 Dedicated terminal Doppler radar for wind shear detection

6.2.2.1 In addition to NEXRAD, the United States FAA has proposed an automated terminal Doppler radar (TDR) dedicated to low-level wind shear detection for location at aerodromes. A number of alternatives are being considered, such as single or dual installations, on-airport or off-airport installations, pulsed Doppler radar or frequency-modulated, continuous wave (FM-CW) Doppler radar, wavelength of 3 cm, 5 cm or 10 cm. Each alternative has advantages and disadvantages. A single installation is obviously cheaper than a dual installation but it cannot measure wind velocities (speed and direction) in three dimensions as is the case with the dual installation (see 5.1.2.3.3.3 and 5.1.2.3.3.4); the effectiveness of the single installation thus depends on the development of sophisticated automated, high-speed algorithms for the detection in real time of wind shear "signatures" in the radial flow field[3 4 5]. Siting the radar on the aerodrome has the advantage of short data links and proximity to approach and take-off paths but also has problems with ground clutter from airport buildings, etc[6]. At large aerodromes the runway system is often so complex that it is impossible to point the radar antenna along all the glide slopes and take-off and climb-out paths. Pulsed Doppler radar transmits high-power, low duty-cycle pulses while the FM-CW Doppler radar transmits a low-power, full duty-cycle signal with linear frequency modulation. The FM-CW Doppler radar can transmit high average power over a broad signal bandwidth thereby achieving a higher sensitivity and resolution at short ranges than the pulsed Doppler radar. The high resolution possible contributes to significant ground clutter rejection, and permits the detection of smaller scale features of the wind flow, such as wingtip vortices and clear-air turbulence. Further studies will be necessary before the design can be finalized.

6.2.3 Wind profilers

6.2.3.1 Continuous measurement of winds (all three components) up to the tropopause may be made using vertically pointing VHF and UHF Doppler radars[7]. Of the two types, the UHF Doppler radar profiler is better suited to measuring winds in the boundary layer in near real time and could provide at least hourly profiles of wind in the vicinity of the aerodrome. Profilers are the subject of considerable research interest as their potential to augment and possibly replace the existing rawin network at a reduced recurrent cost, while at the same time producing more frequent and higher resolution wind profiles, could revolutionize mesoscale forecasting. Profiles would be particularly useful for detecting and monitoring non-transitory wind shear such as that associated with low-level jet streams but, aside from their use in providing additional data for forecasting severe thunderstorms, etc., they would not be suitable for detecting convective wind shear along the approach and take-off paths. A number of research institutions, particularly in the United States, have installed VHF and UHF Doppler radar profilers for test purposes and the results so far have been very encouraging.

6.2.3.2 Aside from data obtained from multiple Doppler radar installations, much of the low-level wind data used for research purposes is derived from the Airborne Integrated Data Systems (AIDS) installed on an increasing number of jet transport aircraft. This is particularly true in the case of post-accident investigations. There is also the possibility in the future that such data will become available in real time via various air and ground data links which are currently being examined for air traffic service purposes. This could provide landing and take-off wind profile information at an aerodrome on an operational basis.

6.2.4 Satellite-based scanning multi-channel microwave radiometer (SMMR)

6.2.4.1 SMMR equipment installed on the United States NIMBUS 7 experimental satellite measures microwave radiances transmitted from earth in five spectral bands in the wavelength region 0.8 to 2.8 cm. Clouds are generally very transparent to microwave radiation emitted from earth in the 0.8 cm band. It has been found, however, that radiation in this band is attenuated through cloud in proportion to the amount of precipitation-size ice particles in the clouds. This interesting effect has enabled researchers to monitor the 0.8 cm band (37 GHz) for particularly "cold" microwave radiation from cloud masses (i.e. large amounts of ice particles) and relate this to the development of severe convective activity. Results obtained so far have been encouraging and an "ice signature" has been identified even in spite of the fact that, as NIMBUS 7 is a polar-orbiting satellite, continuous monitoring of a particular area or cloud mass is not possible. It has been suggested by researchers that further research, perhaps including high-flying instrumented aircraft, may well indicate the need to consider installing such passive microwave sensors on board future geostationary weather satellites[8].

6.3 PROSPECTIVE SYSTEMS

6.3.1 Nowcasting

6.3.1.1 Future nowcasting systems are likely to be based upon a judicious mixture of the equipment discussed in 6.2 above, together with conventional radars, weather satellites and improved mesoscale observation networks. A number of States are already developing such systems, for example the prototype regional observing and forecasting service (PROFS) in the United States, the PROMIS-90 project for very short-range forecasting in Sweden, the automated meteorological data acquisition system (AMEDAS) in Japan and the FRONTIERS project in the United Kingdom.

6.3.1.2 These systems combine into a composite picture digitized radar data from an organized radar network (conventional or Doppler) and superimpose this data on the current atmospheric state as derived from weather satellites, rawinsondes and mesoscale observation networks, etc. The combined data is made available for visual presentation to the analyst in real time and in virtually any desired configuration. The analyst is able to intervene interactively through his display keyboard in order to produce nowcasts. A possible configuration for such a future system is shown in Figure 6-1[9]. From the point of view of wind shear, these systems will markedly assist in the forecasting of severe thunderstorms and thereby provide an improved framework for the local forecasting of low-level wind shear associated with such thunderstorms. It is also likely that, in the course of operating these systems, the recognition and classification of particular wind shear precursor patterns or signatures will be possible, which ultimately would have a direct bearing on wind shear forecasting.

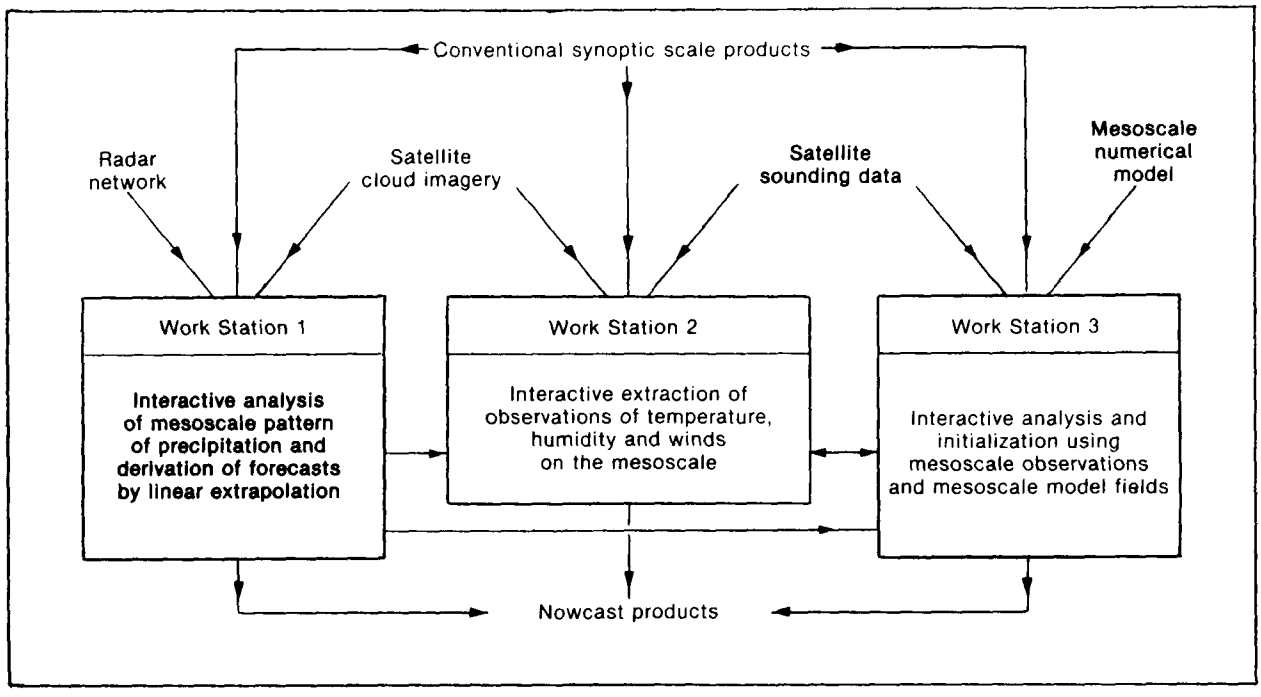
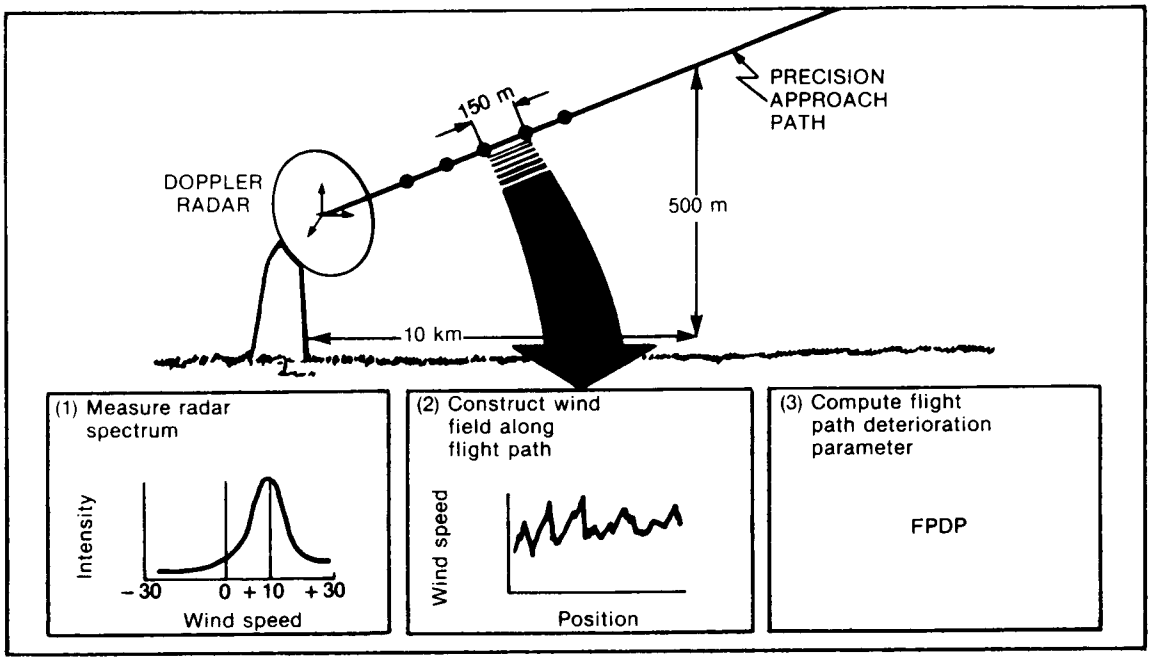


Figure 6-1. Possible configuration of video work stations in a future nowcasting and very short-range forecasting centre (from Browning and Collier, 1982)

6.3.2 Flight path deterioration parameter

6.3.2.1 The flight path deterioration parameter forms the basis of a system proposed and tested in various configurations by Frost, Kessel, McCarthy, Vern Norveil, Turkel et al. to provide aircraft with advance warning on approach or take-off of longitudinal low-level wind shear considered to be hazardous to that particular type of aircraft[10,11,12,13]. The system comprises a Doppler radar beamed along the glide slope/climb-out path linked to an on-line microprocessor containing a two-dimensional, three-degree-of-freedom model of an aircraft including pilot/autopilot control. The Doppler radar measures radial winds along the glide slope, the processor then computes the real-time wind shear spectrum, calculates the aircraft's projected flight path and finally determines deviations from the flight path given the observed and computed wind regime. These computations are all executed in real time and fast enough to permit a warning to be passed to approaching or departing aircraft. The system has so far only been tested on airline simulators, but these tests have led to various improvements, such as the inclusion of a response function specific to aircraft type. Of six flight path deterioration parameters tested, deviation in airspeed from the nominal approach speed has emerged as the most effective for the approach/landing phase. The tests also indicated that airspeed fluctuations seem to be more critical than glide slope deviations to pilots monitoring aircraft performance. As currently designed (see Figure 6-2)[13] the system might be considered rather conservative; however, the conclusion reached by McCarthy and Vern Norviel was that the purpose of the proposed Doppler radar/numerical model low-level wind shear detection and warning system is to identify potential wind shear quantitatively in the vicinity of an airport, sufficient to warn of potentially hazardous approach and departure conditions. The objective of the system is not to make a precise prediction as to whether an aircraft can penetrate the shear without a crash; in their opinion the variables are just too numerous to make that possible[10]. The system was tested on simulators at a number of frequencies and it was



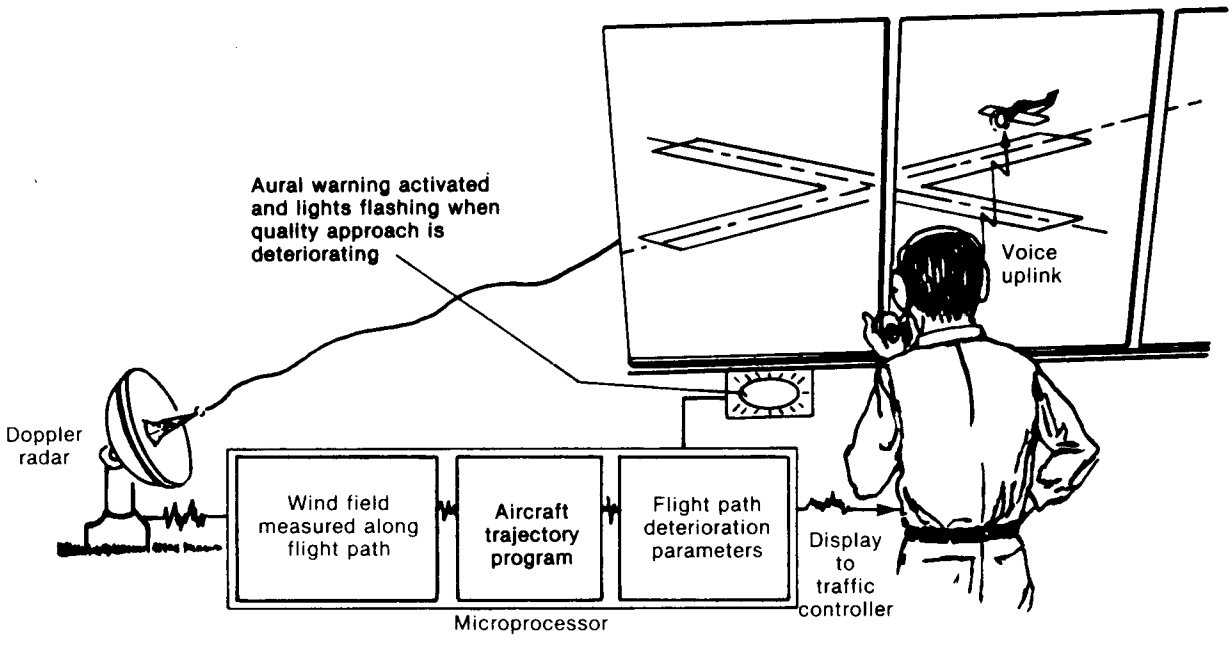


Figure 6-2. Proposed Doppler radar/numerical model low-level wind shear detection and warning system (from Turkel, Kessel and Frost, 1981)

noticeable that aircraft response at the phugoid frequency was not as marked as predicted by theory; the researchers suggest that this is a strong indication that the simulators used were "overdamped" at the phugoid frequency, a situation which they conclude warrants further investigation. Similarly, Frost[14] is of the opinion that a Doppler-based detection and warning system should not attempt to supply the high precision required by an aircraft to thread its way through such shear. Instead, the presence of any strong (horizontal) wind shear should provide sufficient guidance for the aviation system to avoid it.

6.4 Further research

6.4.1 If the JAWS project had access to an impressive array of sensors, etc. (see 3.5.4.2), one is bereft of suitable adjectives to describe the next joint atmospheric experiment to be conducted in the United States. This unique field experiment, sited in northern Alabama, is called the Co-operative Huntsville Meteorological Experiment (COHMEX), and has under its umbrella three distinct but interrelated experiments: the Satellite Precipitation and Cloud Experiment (SPACE), the Microburst and Severe Thunderstorm (MIST) experiment and the FAA Lincoln Laboratories Operational Weather Studies (FLOWS). These experiments are sponsored by NASA, the National Science Foundation and the FAA respectively, with extensive sharing of resources and data.

6.4.2 SPACE will be mainly concerned with atmospheric processes, in particular precipitation, before, during and following the development of convection. The intent is to collect detailed data to permit future modelling of the boundary layer, tropospheric and cloud-scale thermodynamics and the life cycle of small convective systems. It is planned to use no fewer than 10 experimental remote sensing systems, including two high-altitude specially instrumented aircraft, to measure visible, infra-red and microwave radiation for the determination of storm characteristics such as cloud-top structure, cloud microphysics, precipitation, cloud and environmental temperature and moisture soundings and high resolution cloud features.

6.4.3 The MIST experiment is concerned with investigating the three-dimensional structure of microbursts in the "wet" region of the United States. (This will add to the extensive data already collected during the JAWS project (1982) which was conducted in the "dry" region of the United States.) The experiment will employ three Doppler radars, 41 portable automated mesonet (PAM) stations spaced approximately 2 km apart and two research aircraft. One particular feature of this experiment will be the investigation of the structure and development of a microburst with vortex rolls.

6.4.4 The FAA experiment FLOWS will be concerned with the development and testing of automatic algorithms for the detection of wind shear (especially microbursts and gust fronts). The results from FLOWS will be used to develop algorithms for the next generation weather radar (NEXRAD, see 6.2.1.1) and the FAA Terminal Doppler Radar (TDR, see 6.2.2.1). The principal sensor for FLOWS will be an S-band Doppler radar which is functionally equivalent to the NEXRAD system with certain additional features to provide clutter suppression such as might be used in the TDR. The supporting sensors for FLOWS include C-band Doppler radar, two specially instrumented aircraft and 30 FAA mesonet observing stations.

6.4.5 During COHMEX, the NOAA GOES satellite will be operated in dwell-image, dwell-sounding and rapid-scan modes to provide the maximum amount of information. During "SPACE" operational days, high resolution visible infrared spin-scan radiometer (VISSR) atmospheric sounder (VAS) information will be available every three hours and in special cases at intervals of 1½ hours. In addition, the usual information received from polar-orbiting satellites will be incorporated into the COHMEX data sets[15].

CHAPTER 7

TRAINING

7.1 GENERAL

7.1.1 Although wind shear is not a new meteorological phenomenon, and certainly is not the only potential hazard to aviation, the question often arises as to why there seems to be so much emphasis being placed on wind shear. There are at least two reasons. First, although wind shear is as old as the wind itself, there has been a heightened awareness of its hazardous effects on aeroplane performance in recent years with the ever increasing number of large jet transport aircraft. Secondly, there still appears to be widespread confusion and misunderstanding throughout the aviation community regarding the causes of wind shear, what it is and what it does. This may be owing partly to the undoubted complexity of the subject and the uncertainty which surrounds it, and partly to the ephemeral nature of wind shear itself. One of the major difficulties facing the pilot and the meteorologist is predicting accurately the presence of a low level wind shear. This lack of precision is compounded by the fact that even if wind shear is forecast, and actually present in an area, an aircraft flying in that area may not encounter the wind shear because of its localized and transient effects. This is one of the reasons why reporting of an encounter with wind shear (see 7.7) is so important. The only way to counter the confusion and misunderstanding is through training.

7.1.2 It is impossible to over-emphasize the necessity of developing a training programme to ensure that all those involved with aircraft operations are made aware of the hazardous, indeed potentially lethal, effects of low-level wind shear. The programme for flight crew must begin at an early stage of their training, and be continued throughout their careers. Recurrent training must be provided and should concentrate on improving an understanding of how to recognize, avoid and counter this phenomenon, particularly in the light of continuing technical developments. The training requirements apply to both pilots and flight engineers. In addition, flight operations officers (dispatchers) and air traffic controllers and their assistants need training on the hazards and the recognition of this phenomenon. Meteorologists need their own specialized training in the forecasting of wind shear, with particular emphasis on the effects of wind shear on aircraft operations. Lastly, it is essential that cabin attendants should be made aware of wind shear hazards.

7.1.3 While certain aspects of the subject will require varying degrees of emphasis according to the individual's particular field of work, and the level and scope of training must be appropriate to the responsibilities, all operational personnel need to have an understanding of low-level wind shear, the conditions in which it can occur, and how it can seriously affect aeroplane operations.

7.1.4 At Appendix A, there is a Statement of Operational Requirements. In 4.1 of this statement, which deals with training, the requirement is stated as a need to train pilots to counter the effects of low-level wind shear. Because some of the training is essentially type-specific, much of the required information has to be provided by the aircraft manufacturers, amplified and arranged as necessary by the operators to fit their particular operational and training procedures.

7.2 TRAINING FOR FLIGHT CREW - OBJECTIVES

7.2.1 Pilots and flight engineers should follow the same training programme. It is essential that flight simulator exercises be conducted with a complete flight deck crew so that all flight deck crew members develop the ability to recognize a wind shear encounter and an understanding of the combined crew actions required. The ability to recognize a wind shear encounter and to execute the subsequent actions required will vary considerably with the on-board equipment provided and the severity of the encounter.

7.2.2 The minimum objectives of any flight crew training programme should be:

a) to develop an understanding of the dynamics of wind shear and an appreciation of its effect on aircraft performance;

b) to provide clues to assist in the identification of conditions in which wind shear can occur;

c) to develop the ability to recognize, at an early stage, actual wind shear encounters; and

d) to develop the ability to execute the possibly extreme flight procedures that may be necessary in the event of encountering a wind shear.

7.2.2.1 Of these four objectives, the first two are essentially ground training subjects, while the latter two require the facilities of a flight simulator to enable effective training to be conducted.

7.3 GROUND TRAINING - FLIGHT CREW

7.3.1 The ground training for the initial issue of the private pilot licence and the commercial pilot licence should be directed towards an introduction to the hazards of wind shear and cover the first two objectives a) and b) of the training programme described in 7.2.2.

7.3.1.1 The ICAO Training Manual (Doc 7192) Part B-5, contains details of wind shear training for the commercial pilot licence. Appropriate extracts are at Appendix G of this circular.

7.3.2 As explained in Chapter 4, the size and mass of an aircraft are significant factors in the extent to which wind shear will affect the performance of that particular type of aircraft. This suggests that particular attention must be paid to the training on large aircraft for which the pilots require a type rating. Therefore, besides an extension of the training given on the first two objectives, the ground training provided by operators to the flight crew on a particular type of aircraft MUST introduce the specific characteristics of that type, including details of any airborne wind shear detection equipment which may be carried. This training should also be related to the climatology of the geographical area into which the flight crew will be operating, especially where these areas involve an increased risk of encounter. The following points should be emphasized:

a) that the way to avoid a disaster is to avoid an encounter;

b) that airborne recognition of an actual encounter may come at too late a stage for the action that the pilot may be able to take; and

c) that where special on-board instrumentation is provided it is of paramount importance to take action immediately upon receipt of a warning and to follow the guidance provided and the procedures developed by the operator.

It must be stressed that this ground training must be given to all pilots who apply for type ratings on large aircraft, regardless of the level of the pilot licence held by the applicant.

7.3.3 There are a number of audio-visual training aids available to assist States and operators in the development of wind shear training programmes. Details of these aids are given in Appendix H.

7.4 FLIGHT AND SIMULATOR TRAINING

7.4.1 The second part of the flight crew training programme must cover the in-flight recognition of the presence of wind shear, and the procedures and handling techniques to be followed in the event of a wind shear encounter.

7.4.2 A major obstacle to effective flight training is that the handling procedures which are generally recognized as the most appropriate are, in themselves, too hazardous to be practised in flight. The manoeuvres will be at the extremes of the aircraft performance envelope and there will be little or no room for handling errors. Furthermore, the use of power settings beyond normal engine limits cannot be tolerated except in cases of real emergencies. These factors, combined with the fact that an encounter with a wind shear is fortunately a relatively rare occurrence, make it virtually impossible for realistic airborne flight training. Even if the potential hazards due to incorrect handling could be minimized in some way, it would still be impossible to reproduce the various wind shear conditions on demand. It is thus clear that in-flight training to cope with low level wind shear is not a practicable proposition, and that a suitable flight simulator is essential for effective flight crew training. As simulator training is not normally available for non-airline flight crew, this is all the more reason for such crew members to be able to recognize potential wind shear conditions and make every effort to avoid them.

7.4.3 It is essential that aircraft manufacturers and operators co-operate to develop techniques and procedures appropriate to particular aircraft types and available airborne equipment, and that these procedures are detailed in the operator's operations manual. The flight training programme must be designed to ensure that pilots learn the various techniques, developed and recommended by the manufacturers and operators, for recognizing wind shear and for countering its effect and maintaining or regaining safe control of the aircraft. Where possible, the training should be conducted on a type simulator having the necessary software to reproduce realistic wind shear models. Unfortunately, the development of realistic three-dimensional models of convective wind shear, e.g. downbursts/microbursts which are by far the most hazardous, has only been accomplished in the last few years and consequently, comparatively few flight simulators in current use have this capability.

7.4.4 Under its Advanced Simulation Plan, the FAA in the United States has provided guidelines (see Federal Air Regulations, Part 121, Appendix H) on methods of conducting flight crew training in advanced aircraft simulators. Phase II of this three-phase plan contains a requirement for simulator models to include "representative cross-wind and three-dimensional wind shear dynamics based on aeroplane-related data". Such three-dimensional models permit the reproduction of the rapidly varying headwind, crosswind and downdraft conditions in thunderstorm downbursts/microbursts both on and off the nominal flight path[1,2]. As mentioned in Chapter 4, the introduction into the model of the vertical component (downdraft) is vital if flight crew are to train in conditions where the angle of attack no longer corresponds to pitch attitude/airspeed; a situation which, generally speaking, is totally outside their experience. Representative wind profiles are included in the United States Advisory Circular AC 120-41 "Criteria for operational approval of airborne wind shear alerting and flight guidance systems" (see 5.2.2.6).

7.4.5 Some operators conduct simulator training using full three-dimensional wind shear models, where model wind data points are specified over a range of profiles and flight paths that might be followed during aircraft manoeuvres and in response to various recovery actions taken by the pilot. One such training system includes a three-dimensional model of a microburst (derived from JAWS data, see 3.5.4.2) which may be programmed to have the microburst centre placed along or offset from the flight path. This particular model was developed by the Royal Aircraft Establishment in the United Kingdom, and an illustration of the microburst model used is shown in Figure 3-16 a)[3,4]. Another system simulates the three wind components in space and time, turbulence, temperature, pressure, precipitation (varying rate) and visibility, and to complete the realism correlates this with visual and aural cues and typical airborne weather radar output.[5]

7.4.6 The operating procedures recommended for use in wind shear situations are normally contained in the operating manuals provided by manufacturers for each type of aircraft and in operators' operations manuals. Other sources of information are advisory circulars issued by States' authorities from time to time, such as the FAA Advisory Circular AC 00-50A (1979) (paragraph 7 thereof). Procedures recommended by the manufacturers are discussed in Chapter 4 and, as an example, the "supplementary procedures in adverse weather" recommended for the B737 are given in Appendix E. Whilst all the procedures are based on the same aerodynamic principles, each aircraft type/engine combination, to some extent, can be expected to react differently to wind shear and, depending on each operator's equipment policy, may carry different flight deck instrumentation and equipment.

7.5 FAA INTEGRATED WIND SHEAR PROGRAMME (TRAINING)

7.5.1 There is concern in the aviation industry that the existence of many different wind shear training programmes could prove counter-productive and contribute to the confusion among operational personnel. The FAA training programme became available in early 1987; its objective was the development, with the assistance of aircraft manufacturers and operators, of a definitive "wind shear training aid" which would include pilot handouts, a sample wind shear training programme, and a management overview, all derived from documented substantiating data. In addition to written material, considerable attention was paid to the production of video training aids.

7.6 TRAINING FOR ATC PERSONNEL

7.6.1 The air traffic controller is normally the vital communications link between meteorologist and pilot, and between pilot and pilot, for the reporting of wind shear. As such, it is essential that a training programme be available for all controllers. Emphasis should be mainly directed to those employed in aerodrome and approach control, since take-off, approach and landing are the most critical phases of flight for an encounter with a low-level wind shear.

7.6.2 To assist in the development of a suitable training programme, training of air traffic controllers is the subject of Part D-2 of the ICAO Training Manual (Doc 7192), with a suggested curriculum published separately in Part A-3 of the manual. In particular, the subject of aeronautical meteorology includes at Item 10.4.5 the following:

> "Surface wind, gusts, low-level wind shear and turbulence, effect on landing and take-off operations, weather situations associated with wind shear and methods of recognition".

The recommended level of required knowledge is described as "... a knowledge of the subject and the ability, where applicable, to apply it practically."

7.6.3 The objectives for the wind shear training programme for air traffic controllers should be:

a) to provide an understanding of wind shear, and the probable effects on aircraft performance;

b) to assist in identifying the conditions in which wind shear can occur; and

c) to develop a knowledge of the procedures for reporting wind shear, and to practise these procedures (see 7.8).

7.6.3.1 Items a) and b) above cover much the same ground as that dealt with on the flight crew ground training programme. As such, the material available for flight crew is of use for the training of controllers. In addition, it would be beneficial to give the controller an opportunity, when possible, to attend as an observer the flight simulator training sessions for pilots when wind shear procedures are being reviewed.

7.7 TRAINING FOR METEOROLOGISTS

7.7.1 In accordance with the working arrangements agreed between ICAO and the World Meteorological Organization (WMO) (see ICAO Doc 7475), "While WMO will be responsible for specifying the requirements for meteorological knowledge of meteorological personnel engaged in the provision of meteorological service for international civil aviation, the definition of the requirements for non-meteorological knowledge that should be met by such personnel will be undertaken by ICAO and will be transmitted to WMO in the form of recommendations." As a consequence of the foregoing arrangement, guidelines for the education and training of personnel in aeronautical meteorology have been developed and are contained in WMO publication WMO-No. 258, Chapter 11[6].

7.7.2 In the WMO training publication, the recommended syllabi for specialization in aeronautical meteorology for Meteorologist Class I, II, III and IV are given in detail. The syllabi for Meteorologist Class I and II in respect of aeronautical meteorological knowledge are the same, and contain specific reference to wind shear both non-convective and convective (thunderstorms) and its effect on aircraft in the approach and landing phases of flight. Although a "grading system" for level of knowledge required is not used in WMO training publications, as far as aeronautical meteorology is concerned the level or standard of training should be the same as for pilot licences. Of course training for Class I and II meteorologists would also include extensive general forecasting training, which would cover forecasting specific phenomena which are known to produce low-level wind shear (low-level jets, air mass fronts, thunderstorms and especially severe thunderstorms, etc.).

7.7.3 For Class III and IV meteorologists, the aeronautical meteorological knowledge recommended is less than for Class I and II and the recommended syllabi for specialization do not specifically mention low-level wind shear and its effect on aircraft. However, general information on wind shear and phenomena which produce it would be included under "Fundamental Meteorological Education" in Chapters 6 and 7 of the WMO training publication[6].

7.7.4 A compendium of lecture notes for training meteorologists is also published by WMO for all classes of meteorologist (WMO-No. 364); Volume II, Part 2 of this publication is devoted to aeronautical meteorology for Class I and II personnel. Low-level wind shear is treated in the appropriate places throughout this publication.

7.8 TRAINING ASPECTS OF REPORTING WIND SHEAR

7.8.1 Aside from a breakthrough in the development of operational remote-sensing equipment to detect wind shear, the single most important advance towards a solution of the wind shear problem which could be made at this time is the application by States of standardized terminology and reporting procedures for wind shear. Inclusion in relevant training programmes of reporting procedures and terminology based upon those given in this circular would be a major step forward towards standardization world-wide. These procedures are a compromise, given the unavoidable fact that, so far, there is no operational equipment capable of detecting and measuring wind shear in the approach and take-off paths. When such equipment becomes available commercially, the procedures will need to be amplified to take account of the equipment's capabilities. It should always be borne in mind, however, that even when such equipment becomes available, due to the

intrinsically capricious nature of wind shear, training must still emphasize the need for pilots to continue to exercise vigilance, especially when flying near thunderstorms, or in other areas where wind shear is forecast.

7.9 SUMMARY

7.9.1 Wind shear has always been there, even if we have not been aware of it. In recent years we have become increasingly aware of its potentially lethal characteristics. At the same time our knowledge of the effects of wind shear is increasing, and the means at our disposal to forecast it and counter it are improving. Training is of paramount importance in flight safety, and an effective programme of training in all aspects of wind shear is essential for all operators.

7.9.2 From all the knowledge and experience gained to date, the following key factors emerge:

1. AVOID areas of known wind shear.
2. Evaluate the weather and environmental conditions.
3. Use, and follow, standard operating procedures (SOPs).
4. Be alert, and take the necessary precautions whenever there is a high probability of wind shear.
5. Never hesitate to apply recovery procedures if wind shear is inadvertently encountered.
6. If in doubt, delay your take-off or, if wind shear is indicated, do not hesitate to initiate a missed approach or hold until conditions improve. As a last resort, divert to a suitable alternate.

Appendix A

Statement of Operational Requirements

1. Information to the pilot

1.1 There is an operational requirement for information on low-level wind shear and turbulence (from any cause) to be provided to the pilot in such a manner as to enable the pilot to counter their effects and to maintain safe control of the aircraft.

1.2 Pending the further development of reliable operational airborne and ground equipment, this information should be based on reports from aircraft and/or ground-based meteorological observations or assessment of the current weather situation.

2. Ground-based equipment

2.1 There is an operational requirement for ground-based equipment from which to derive the following information which shall be provided to the pilot prior to take-off or the commencement of the initial approach:

a) significant changes in surface wind along the runway; and

b) significant changes in the wind along the take-off and final approach paths extended to 500 m (1 600 ft) above runway level with particular emphasis on the layer between runway level and a height of 150 m (500 ft);

Note: 500 m (1 600 ft) should not be considered restrictive where local conditions require increases above this height.

3. Airborne equipment

3.1 There is an operational requirement for airborne equipment which can detect the presence of significant low-level wind shear and turbulence (from any cause) and will:

a) provide the pilot with a timely warning and the information necessary to maintain safely the desired flight path or to take avoiding action; and

b) indicate that the limits specified for certification of automatic landing equipment are being approached, when this is in use.

4. Training

4.1 There is an operational requirement for pilots to be trained to counter the effects of low level wind shear and turbulence. All relevant information on the subject, together with recommended flight techniques, flight profile data and performance information relevant to the particular type of aircraft should be given.

Appendix B

Terms and Explanations

1. Explanation of wind shear terms

Term	Explanation
Cross-wind effect*	An effect caused by wind shear which requires a rapid change of aircraft heading to maintain a desired track. Note: The flight path of the aircraft should always be specified when describing the effects of wind shear. This is to distinguish between different wind shear effects which will occur for different runway directions, and between different wind shear effects on take-off and on landing.
Downburst	A strong downdraft which induces an outflow of damaging winds on or near the ground.
Gust front	The leading edge of the cold air from a convective cloud downdraft which reaches ground level and spreads outwards, undercutting the surrounding warmer air.
Horizontal wind shear	Change of horizontal wind direction and/or speed with horizontal distance, as would be determined by two or more anemometers mounted at the same height along a runway.
Low-level wind shear	Wind shear along the final approach path or along the runway and the take-off and initial climb-out flight path.
Microburst	A strong localized downdraft which induces a sudden outflow of damaging winds on or near the ground with a horizontal extent between 0.4 and 4 km.
Overshoot effect*	An effect caused by a wind shear which results in an aircraft flying above the desired flight path and/or an increase in indicated airspeed. Note: Overshoot effect may result from flying into an increasing headwind, a decreasing tailwind or an updraft.

* Term used in air-ground communications.

Turbulence*	Eddy motions in the atmosphere which are functions of both time and space.
Undershoot effect*	An effect caused by wind shear which results in an aircraft flying below the desired flight path and/or a decrease in indicated airspeed. Note: Undershoot effect may result from flying into a decreasing headwind, an increasing tailwind or a downdraft.
Updraft/downdraft*	Vertical component of the wind. Note: The most hazardous updrafts and downdrafts are usually those associated with thunderstorms.
Vertical wind shear	Change of horizontal wind direction and/or speed with height, as would be determined by means of two or more anemometers mounted at different heights on a single mast.
Wind shear*	A change in wind direction and/or speed in space, including updrafts and downdrafts.
Wind shear reversal effect	An effect caused by wind shear which results in the initial effect on the aircraft being reversed as the aircraft proceeds further along the flight path. Note: Where wind shear reversal effect occurs, it should be described as overshoot effect followed by undershoot effect, or undershoot effect followed by overshoot effect, as appropriate.

2. Explanation of other terms not directly related to wind shear

Coriolis force	An "apparent" force which acts on moving particles in a non-inertial coordinate reference system. In meteorology this applies to air moving in relation to the rotating earth. In the northern (southern) hemisphere the apparent force acts to the right (left) when viewed along the motion. In order to account for the deflection due to the earth's rotation an "apparent" force has to be introduced. The force is named after Gustave-Gaspard Coriolis, a French mathematician who first described the effect in 1835.

* Term used in air-ground communications

Geostrophic wind	The horizontal wind velocity for which the horizontal component of the coriolis force exactly balances the horizontal pressure gradient force (see below) so that the wind blows parallel to the isobars.
Gravity wave	A wave disturbance in a fluid in which the controlling forces are buoyancy and gravity.
Horizontal pressure gradient force	The horizontal component of the force which acts on air particles due to the variation in pressure in space. The force acts perpendicular to the isobars from high to low pressure.
Isentropic analysis	A system of analysis based upon charts showing meteorological variables such as pressure, moisture and wind, etc., plotted on a surface of constant potential temperature.
Mesoscale	Most of the phenomena which produce low-level wind shear of significance to aviation occur in the mesoscale. Historically this scale referred to dimensions the order of from 10 to 100 km. Fujita (see reference 40 under Chapter 3) has proposed that in order to fit in with a consistent set of scales based upon the dimensions of the earth, this scale should be broadened to refer to dimensions of from 0.4 km to 400 km.
Nowcast	A description of current weather and a forecast for up to two hours ahead.
Spectral analysis	A particular aspect of time series analysis which seeks to split up a time series, e.g. a wave form, into its component frequencies or frequency spectrum.

Appendix C

Recommendations of the United States National Academy of Sciences Committee on Low-Altitude Wind Shear and its Hazard to Aviation (1983)

The committee's recommendations are listed under four broad categories: general, detection and prediction, aircraft performance and operations, and research. The numbering of the recommendations does not signify any priority. The broad spectrum of specific recommendations reflects the complexities of the low-altitude wind shear problem.

1. GENERAL

1.1 Need for an integrated wind shear programme

1.1.1 To provide for the safety of the flying public, the FAA and the aviation industry should address the many facets of the low-altitude wind shear problem as a whole. The FAA should develop and implement a coherent and sustained programme for coping with the educational, meteorological, technological, and operational aspects of low altitude wind shear hazards.

1.2 Wind shear education programme

1.2.1 The FAA and the industry should prepare and disseminate as widely as possible updated and authoritative information on wind shear. Informational materials should stress avoidance of wind shear and should describe flight control techniques for recovery from encounters. The information should encompass all types of aircraft, with appropriate guidance for each class. It should include recommendations on the most effective means of training pilots.

1.2.2 The FAA should revise and update its 1979 Advisory Circular (AC 00-50A) on wind shear and the Airman's Information Manual (AIM) to present the latest information, including detection techniques, alerting and warning procedures, effects of wind shear on aircraft performance, and procedures for recovery from wind shear encounters.

1.3 Pilot/controller communications

1.3.1 The FAA should promote the use of standardized terminology and improved communications between flight crews and control towers. A standardized system of pilot reports (PIREPs) should be developed for reporting low-altitude wind shear encounters. PIREPs should be mandatory and should include a report of the location, severity, and nature of the shear encountered - in consistent, standardized terminology. Controllers should communicate such reports to all flight crews in the vicinity. In addition, techniques for the direct broadcast to pilots of wind shear data from low-level wind shear alert system (LLWSAS) or other sensors should be investigated.

1.4 Wind shear detection system development

1.4.1 The FAA should select a site to test direct and remote-sensing techniques in a complete system for detecting low-altitude wind shear and for providing information to pilots and controllers and to test the use of the information in the air traffic control system. The test site should be at a major airport where wind shear conditions are relatively frequent.

2. DETECTION AND PREDICTION

2.1 The low-level wind shear alert system (LLWSAS)

2.1.1 LLWSAS is the only system currently available in the near term for detecting low-altitude wind shear on an operational basis and every effort should be made to assess and improve its performance. Opportunities include, but are not limited to, better signal processing, reduced spacing between and increased number of sensors, improved sensor response and improved wind-display techniques and criteria for issuing wind shear warnings, and the possible use of ground-based pressure sensors to augment LLWSAS information. An improved LLWSAS system is being developed for installation at New Orleans International Airport. This upgraded system, to be operationally tested in early 1984, should provide the basis for modification of current LLWSAS installations and for improved system performance for future installations. Depending on the New Orleans test results, the FAA should modify existing LLWSAS systems and install improved systems at all high-traffic density airports with terminal automation systems (153 airports) where there is likelihood of the occurrence of dangerous wind shears.

2.2 Record and analyse LLWSAS data

2.2.1 LLWSAS wind measurements should be recorded and analysed to evaluate the system's performance and to learn more about the climatic properties of low-altitude wind shear. This should be done at all airports equipped with LLWSAS.

2.3 Use of available radar data

2.3.1 The existing network of weather radars, operated by the NWS, should be used more effectively to judge the likelihood of wind shear conditions. These radars detect rain showers, thunderstorms, and phenomena often associated with wind shear. Information from weather radars should be made available to air traffic controllers in a timely and easily understandable fashion.

2.4 Next generation weather radar (NEXRAD)

2.4.1 The next generation Doppler weather radar system (NEXRAD) should be developed and installed with all possible speed. This long-range radar system will serve many national needs related to severe weather detection, forecasting, and warning. For aviation, the NEXRAD system can be used to detect and monitor weather situations along flight routes and, if located at or near some airports, to detect low-altitude wind shear or its precursors. Moreover, the Doppler radar will advance the rate of development of radar techniques for the detection of low-altitude wind shear and the development of dedicated Doppler terminal radars.

2.5 Airport terminal weather radar

2.5.1 The FAA should take immediate action to develop a pulsed Doppler radar system that can be used to observe weather conditions at and around airport terminals. This terminal radar system should be able to operate with a high degree of automation and to provide information on low-altitude wind shear, turbulence and rainfall intensity. Such a radar must be capable of supplying information updated each minute and must have such features as ground-clutter cancellation and adequate spatial resolution.

2.6 Use of airport terminal weather radar observations

2.6.1 For terminal Doppler radar to be most useful to traffic controllers and pilots, a concerted effort should be devoted to developing procedures for analysing, displaying, and using its observations.

2.7 Airborne remote sensors

2.7.1 Research should continue on the use of airborne Doppler lidars and microwave Doppler radar as a means for detecting low-altitude wind shear.

3. AIRCRAFT PERFORMANCE AND OPERATIONS

3.1 Wind shear effects on flight characteristics

3.1.1 The FAA should sponsor analytical and simulator investigations to determine:

a) the wind shear penetration and recovery capabilities of transport aircraft, based on various on-board detection, guidance and control systems; and

b) the effects of wind shear on various typical categories of general aviation aircraft and helicopters so that authoritative information on their response characteristics and piloting techniques in wind shear can be provided.

3.2 Aircraft operating procedures

3.2.1 The FAA should ensure that air carriers and other commercial operators instruct flight crews on what to do if they inadvertently encounter a low-altitude wind shear during take-off or landing. In addition, the FAA should encourage operators of jet aircraft to incorporate in their manuals the operating procedures recommended in its advisory circular on wind shear. Aircraft manufacturers should recommend configuration-change sequences (gear, flaps, power, spoilers, etc.) that provide the highest probability for recovery from a wind shear encounter. Pilots should be taught to exceed the normal maximum thrust limits and to go to emergency thrust when necessary.

3.3 Guidance and control aids

3.3.1 On-board sensors and guidance aids should be evaluated in a systematic manner to determine their merits for future development and for possible retrofit in existing aircraft. These include flight director modifications, ground speed/airspeed

flight management systems, vertical-acceleration sensors, and energy-rate sensors. Angle-of-attack indicators should be added to the cockpit instrumentation of transport aircraft for use in manoeuvring through wind shears. Angle of attack should be provided either as a separate variable or as an input to other command displays. Sensors should provide flight crews with a voice warning of a hazardous wind shear.

3.4 Standardization of wind shear models

3.4.1 The FAA should sponsor a programme to develop and define standardized models of wind shear based on the latest meteorological data. These models are required for design and certification of aircraft sub-systems and for use in training simulators. The FAA should include other government agencies, aircraft manufacturers, commercial operators, and any other interested parties in the programme.

3.5 Certification of on-board systems

3.5.1 The FAA should update its certification requirements for airborne wind shear alerting, flight guidance and automatic control systems.

3.6 Wind shear simulation training

3.6.1 The FAA and the industry should co-operate to investigate new and innovative ways to make available the best possible simulation training for wind shear to the largest possible number of pilots, including general aviation pilots.

4. RESEARCH

4.1 Effects of heavy rain

4.1.1 Investigations should continue on how heavy rain affects the low speed aerodynamic characteristics of aircraft. Particular attention should be paid to the possible adverse effects of heavy rain on aircraft lift, performance, and controllability, including its effects on wind shear detection and flight sensor systems.

4.2 Research on the nature of low-altitude wind shear

4.2.1 More must be learned about the various kinds of wind shear and the meteorological conditions that cause or are associated with them. This knowledge is needed to reduce the hazards represented by low-altitude wind shear. Research should include additional field observations and the construction of theoretical models over the relevant scales - from about 1 000 ft to 10 to 20 miles and from minutes to hours.

4.2.2 The existing body of data obtained by various research programmes should be re-examined and augmented, at an appropriate time, by a field programme in the humid southeastern United States. Analyses of the data obtained from the JAWS project should be used to plan any new field investigation. Basic research into the origins of strong thunderstorm downdrafts and possible forecast methods should be an important component of any new programme.

Appendix D

Mathematical analysis of the effect of wind shear on lift, reproduced by kind permission of Dr. T.T. Fujita, University of Chicago, from his book "The Downburst", published by the Satellite and Mesometeorological Research Project (SMRP) Department of the Geophysical Sciences, University of Chicago

The flow of air which affects aircraft operations is grossly divided into "turbulence" and "wind shear". An aircraft in turbulent flow exhibits irregular and random motions while, more or less, maintaining its intended flight path. Wind shear, with or without turbulence, alters the lift force acting on an aircraft, resulting in a significant sinking or rising motion.

In meteorology, wind shear is the local variation of wind velocity in a given direction. The three components of wind shear can be described by expressing the wind velocity W by:

$$W = iu + jv + kw \tag{1}$$

where i, j, k are unit vectors pointing toward the x, y, z directions and u, v, w are the x, y, z components of the wind vector.

Wind shear, in aviation, is the time variation of wind velocity along the path of a given aircraft, which can be written as:

$$\frac{\Delta W}{\Delta t} = G\frac{\partial W}{\partial L} + \frac{\partial W}{\partial t} \tag{2}$$

where L is the distance measured along the flight path. The second term on the right side of this equation denotes the local variation of the winds caused by the formation or the development of a wind system penetrated by an aircraft. That is to say, the second term may not exist prior to the penetration. Whereas, the first term denotes the change of the winds as an aircraft flies into an existing wind shear system.

Noting that the flight path is included in the x-z plane in Figure D-1, we define the shear of the three component winds u, v, w by:

$$\frac{\Delta u}{\Delta t} = \text{Headwind shear, + headwind; - tailwind} \tag{3}$$

$$\frac{\Delta v}{\Delta t} = \text{Cross-wind shear, + from right; - from left} \tag{4}$$

$$\frac{\Delta w}{\Delta t} = \text{Vertical wind shear, + upward; - downward} \tag{5}$$

Effects of wind shear upon lift force

An aircraft with true airspeed A, flying inside a three-dimensional wind W, moves with the ground-relative velocity G. The lift force acting on the aircraft is

perpendicular to vector A, and the drag force points opposite to vector A. Using the symbols in Figure D-1, the lift force can be expressed by:

$$F = \frac{1}{2} \rho A^2 C_L S \tag{6}$$

where ρ is the density of air, C_L the lift coefficient, and S the cross-sectional area of the lift force acting on the aircraft. Since β is small and both Θ and G do not vary with time as fast as the winds do, we are able to approximate the ground speed and the angle of attack as:

$$G \cong A + u \text{ or } 0 = \frac{\Delta A}{\Delta u} + 1 \tag{7}$$

$$\alpha = \theta - \gamma + \frac{w}{G} \text{ or } \frac{\partial \alpha}{\partial w} = 0 - 0 + \frac{1}{G} \tag{8}$$

The increment of the lift force due to the variation of u and w is computed by differentiating Equation 6 as:

$$\Delta F_L = \frac{1}{2} \rho C_L A^2 S \left(\frac{2}{A} \frac{\partial A}{\partial u} \Delta u + \frac{1}{C_L} \frac{\partial C_L}{\partial \alpha} \frac{\partial \alpha}{\partial w} \Delta w \right) \tag{9}$$

Using Equations 7 and 8, we simplify Equation 9 into

$$\frac{\Delta F_L}{F_L} = - \frac{2}{A} \Delta u + \frac{k}{G} \Delta w \tag{10}$$

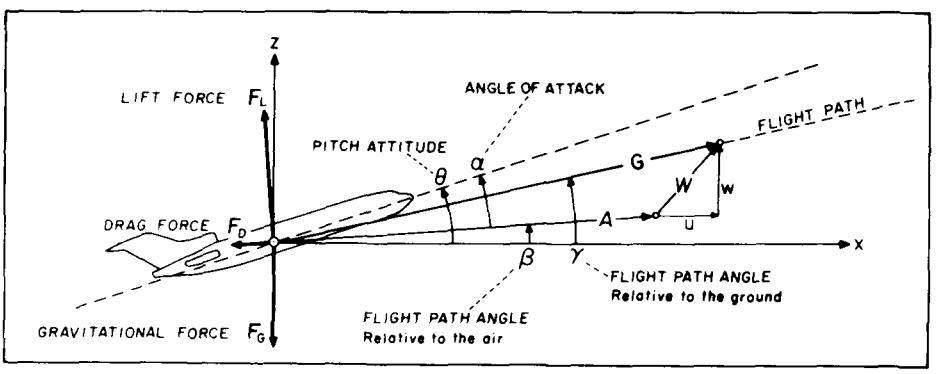


Figure D-1. Definition of the quantities used in this chapter. F_L = lift force; F_G = gravitational force; F_D = drag force; α = angle of attack; β = flight path angle relative to the air; γ = flight path angle relative to the ground; θ = pitch attitude; W = wind vector, u, v, w being the x, y, z components of wind vector; A = true airspeed; and G = ground speed

where $$k = \frac{1}{C_L}\frac{\partial C_L}{\partial \alpha}\ (\text{radians}) = \frac{180}{\pi C_L}\frac{\partial C_L}{\partial \alpha}\ (\text{degrees}) \qquad (11)$$

is determined by the characteristics of the lift coefficient during a wind shear penetration. This equation states that the loss of lift is not only caused by the loss of airspeed but also by the loss of angle of attack which, in turn, reduces the lift coefficient.

A representative curve of a lift coefficient for swept-wind aircraft during a flap-down take-off configuration is shown in Figure D-2. Values in Table D-1, computed from the figure, reveal that the loss of lift due to a tailwind is constant, irrespective of the angle of attack at which an aircraft flies. On the other hand, the loss of lift increases appreciably with decreasing angle of attack. Equation 10 suggests that the lowering of the pitch angle, selected for gaining airspeed in a tailwind/downflow wind shear, could result in a loss of lift and a subsequent heavy sink.

Table D-1. Fractional(%) loss of lift force due to a one knot increase of the tailwind or one knot increase of the downflow. For simplification, A = G = 150 kts was assumed.

	Angle of attack 0°	5°	10°	15°	20°
Loss of lift by tail wind	1.3	1.3	1.3	1.3	1.3% per knot
Loss of lift by downflow	13.2	4.5	2.5	1.3	0.5% per knot

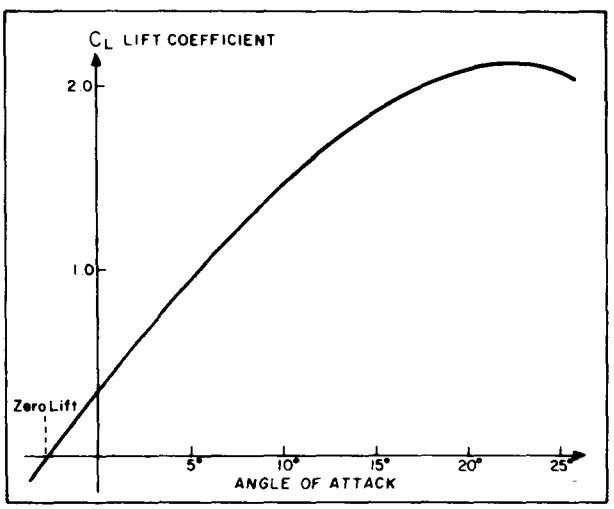


Figure D-2. Lift coefficient of swept-wing aircraft with a 15° flap setting and gear-up configuration. The angle of attack is fuselage-relative. The wind-relative angle of attack is approximately 2° larger than the fuselage-relative angle of attack

Appendix E

B737 Supplementary Procedures - Adverse Weather
Abstracted from B737 Operations Manual (1985)

WIND SHEAR

General

Wind shear is a change of wind speed and/or direction over a short distance along the flight path. Severe wind shear is that which produces airspeed changes greater than 15 kt or vertical speed changes greater than 500 ft per minute.

Avoidance

The flight crew should search for any clues to the presence of wind shear along the intended flight path. Stay clear of thunderstorm cells and heavy precipitation and areas of known wind shear. If severe wind shear is indicated, delay take-off or do not continue an approach.

The presence of wind shear may be indicated by:

- thunderstorm activity;
- virga (rain that evaporates before reaching the ground);
- PIREPS; and
- low-level wind shear alerting system (LLWAS) warnings.

Prevention

If wind shear is suspected, be especially alert to any of the danger signals and be prepared for the possibility of an inadvertent encounter.

The following preventative actions are recommended if wind shear is suspected:

Take-off

- Use maximum take-off thrust instead of reduced thrust.
- Use the longest suitable runway.
- Do not use the flight director for take-off.
- Be alert for any airspeed fluctuations during take-off and initial climb. Such fluctuations may be the first indication of wind shear.

- Know the all-engine initial climb pitch attitude. Rotate at the normal rate to this attitude for all non-engine failure take-offs. Minimize reductions from the initial climb pitch attitude until terrain and obstruction clearance is assured, unless stick shaker activates.

- Crew co-ordination and awareness are very important. Develop an awareness of normal values of airspeed, attitude, vertical speed, and airspeed build-up. Closely monitor vertical flight path instruments such as vertical speed and altimeters. The pilot not flying should be especially aware of vertical flight path instruments and call out any deviations from normal.

- Should airspeed fall below the trim airspeed, unusual control column forces may be required to maintain the desired pitch attitude. Stick shaker must be respected at all times.

- If wind shear should be encountered near VR, and airspeed suddenly decreases, there may not be sufficient runway left to accelerate back to the normal VR. If there is insufficient runway left to stop, initiate a normal rotation at least 2 000 ft before the end of the runway even if airspeed is low. Higher than normal attitudes may be required to lift-off in the remaining runway.

Approach and landing

- Select the minimum landing flap position consistent with field length.

- Add an appropriate airspeed correction (correction applied in the same manner as gust), up to a maximum of 20 kt.

- Avoid large thrust reductions or trim changes in response to sudden airspeed increases as these may be followed by airspeed decreases.

- Check flight director commands using vertical flight path instruments.

- Crew co-ordination and awareness are very important, particularly at night or in marginal weather conditions. Closely monitor the vertical flight path instruments such as vertical speed, altimeters, and glide slope displacement. The pilot not flying should call out any deviations from normal. Use of the autopilot and autothrottle for the approach may provide more monitor and recognition time.

Recovery

Pull up/terrain avoidance

This procedure is immediately accomplished by recall whenever the threat of ground contact exists. The following conditions are regarded as presenting a potential for ground contact:

- activitation of the "pull up" warning;

- below 500 ft AGL, inadvertent wind shear encounter - or other situations - which result in uncontrolled changes from normal steady state flight conditions in excess of any of the following:

  - 15 kt indicated airspeed;
  - 500 FPM vertical speed;
  - 5 degrees pitch attitude;
  - 1 dot displacement from the glide slope.

Note.- If a "pull up" warning occurs when flying under daylight VFR conditions, and positive visual verification is made that no hazard exists, the approach may be continued.

Recovery manoeuvre

Simultaneously: Apply maximum thrust, disengage autopilot and autothrottle (if installed), and increase pitch attitude to avoid terrain.

Increase pitch attitude, smoothly and at a normal rate, initially toward 15 degrees. Do not use flight director commands.

Pitch attitudes in excess of 15 degrees may be required to silence the pull up warning and/or avoid terrain.

Note.- In all cases, the pitch attitude that results in intermittent stick shaker or initial buffet is the upper pitch attitude limit (this may be less than 15 degrees in a severe wind shear encounter).

Large thrust increases may result in a nose-up pitching tendency requiring forward column pressure and trim.

Monitor vertical speed and altitude. Do not attempt to change flap or gear position or regain lost airspeed until ground contact is no longer a factor.

Appendix F

1. Forecasting Rules of Thumb Used by the United Kingdom Meteorological Office in 1977 Wind Shear Forecasting Trial Which May Give Useful Pointers to Other Offices Considering Such Trials

WIND SHEAR WARNING SERVICE

Meteorological criteria

Notation: $\underset{\sim}{V}_{10}$ = Surface (10-metre) wind (vector)

$V_{10} = |\underset{\sim}{V}_{10}|$ = Surface wind speed (scalar)

$\underset{\sim}{V}_G$ = Gradient (600 m or 2 000 ft) wind (vector)

$V_G = |\underset{\sim}{V}_G|$ = Gradient wind speed (scalar)

(a) Winter trial

A warning should be issued if any of the following criteria are satisfied:

1) $V_{10} \geq 30$ kt

2) $V_{10} \geq 10$ kt and $V_G - 2V_{10} \geq 25$ kt

3) $V_{10} < 10$ kt and $|\underset{\sim}{V}_G - \underset{\sim}{V}_{10}| \geq 40$ kt

4) $V_{10} < 10$ kt and $|\underset{\sim}{V}_G - \underset{\sim}{V}_{10}| \geq 30$ kt,

and an isothermal or inversion layer is present below 600 m

5) THUNDERSTORM(S) within 20 km and/or CUMULONIMBUS within 10 km of the approach/climbout

6) FRONTAL ZONE below 600 m on the approach/climbout, with

   a) vector wind change across it of at least 10 kt magnitude (noted either locally or at a neighbouring station during passage of the front)

   or b) temperature difference across it of at least 5 degrees C

   or c) speed of at least 30 kt.

7) Significant LOW-LEVEL JET suspected below 600 m (separate rules at Appendix C)

8) AIRCRAFT REPORT(S) of low-level wind shear received during the previous hour

(b) Summer trial

A warning should be issued if any of the following criteria are satisfied:

1) $V_{10} > 30$ kt

2) Winter trial criterion not used in summer trial

3) $|\underset{\sim}{V_G} - \underset{\sim}{V_{10}}| > 40$ kt

4) $|\underset{\sim}{V_G} - \underset{\sim}{V_{10}}| > 30$ kt and an inversion or isothermal layer is present below 600 m

5) there are

   a) THUNDERSTORM(S) within 10 km
   b) CUMULONIMBUS cloud(s) within 5 km

   } having a component of motion towards the station

6) there is, on the approach/climbout a FRONTAL SURFACE or other DISCONTINUITY below 600 m with

   a) vector wind change across it of at least 10 kt magnitude - noted either locally or from its passage through a nearby station

   or b) temperature difference across it of at least 5 degrees C

   or c) speed of at least 30 kt

7) a significant LOW-LEVEL JET is suspected at or below 600 m (criteria for this are unchanged from the winter trial)

8) AIRCRAFT REPORT of significant low-level wind shear received during the previous hour

Notes

1) The form of a warning issued under Rules 1-7 is to be:
"Wind shear expected below 2 000 ft."

2) The form of a warning issued under Rule 8 is to be:
"Wind shear reported and expected below 2 000 ft."

(c) Low level jet criteria

Criteria to be tested at observation times 2100, 0000, 0300 and 0600 GMT.

A low level (nocturnal) jet should be suspected if all the following criteria are satisfied:

1) Time is in the range (sunset + 3 hours) to (sunrise + 1 hour)

2) A ground-based inversion or isothermal layer is present, and has been present for at least the preceding three observations, and

$$T_aT_a(max) - T_aT_a \geq 10\ C$$

3) $V_{10} \leq 10$ kt and V_{10} (max) ≥ 10 kt

4) $V_G \geq 10$ kt and V_G (sunset) ≥ 10 kt

5) No surface front has passed through since 1200 GMT.

Notes

1) $V_{10}(max)$ and $T_aT_a(max)$ are the maximum reported values of V_{10} and T_aT_a from 1300 to 1800 GMT inclusive (previous afternoon). (T_aT_a is the surface (screen) temperature.)

2) If all the criteria are satisfied, then a low-level jet should be suspected for the current hour and the succeeding two hours, and the warnings will be issued throughout the three-hour period.

2. Current (1986) London/Heathrow and Belfast/Aldergrove Wind Shear Alerting Service (HWAS) - Abstract from the United Kingdom AIP MET-07

6.8.2.1 Forecasters at LONDON/Heathrow and Belfast/Aldergrove meteorological offices review the weather conditions on an hourly basis and monitor any aircraft reports of wind shear experienced on the approach or climb-out. Where a potential low-level wind shear condition exists an alert is issued, based on one or more of the following criteria:

a) mean surface wind speed at least 20 knots;

b) the magnitude of the vector difference between the mean surface wind and the gradient wind (an estimate of the 2 000 ft wind) at least 40 knots; and

c) thunderstorm(s) or heavy shower(s) within approximately 5 NM of the airport.

Note.- Alerts are also issued based on recent pilot reports of wind shear on the approach or climb-out.

6.8.2.2 The alert message is given in the arrival and departure ATIS broadcasts at Heathrow and by R/T to arriving and departing aircraft at Aldergrove in one of three formats:

a) "WIND SHEAR FORECAST".- When the meteorological conditions indicate that low-level wind shear on the approach or climb-out (below 2 000 ft) might be encountered.

b) "WIND SHEAR FORECAST AND REPORTED".- As above, supported by a report from at least one aircraft of wind shear on the approach or climb-out within the last hour.

c) "WIND SHEAR REPORTED".- When an aircraft has reported wind shear on the approach or climb-out within the last hour, but insufficient meteorological evidence exists for the issue of a forecast of wind shear.

6.8.2.3 Pilot reports of wind shear experienced on the approach or climb-out can greatly enhance the operational efficiency of this service. In addition, they also serve in the continuous evaluation of the criteria upon which alerts are forecast. Thus pilots who experience conditions of moderate to severe wind shear on the approach or climb-out are requested to report the occurrence to ATC, as soon as it is operationally possible to do so. Wind shear reporting criteria are shown below.

Wind shear

Pilots using navigation systems providing a direct wind velocity readout should report the wind and altitude/height above and below the shear layer, and its location. Other pilots should report the loss or gain of airspeed and/or the presence of up-or-down draughts or a significant change in crosswind effect, the altitude/height and location, their phase of flight and aircraft type. Pilots not able to report wind shear in these specific terms should do so in terms of its effect on the aircraft, the altitude/height and location and aircraft type, for example, "Abrupt wind shear at 500 ft QFE on finals, maximum thrust required, B707". Pilots encountering wind shear are requested to make a report even if wind shear has previously been forecast or reported.

Appendix G

Extract from ICAO Training Manual, Part B-5, Volume 2, Instructor Briefing Sheets

Part B-5 of the ICAO Training Manual series, Doc 7192, provides details of an integrated course of flight and ground training. The aim of this training course is to produce pilots who are capable of serving as airline co-pilots, or as pilots-in-command or co-pilots for other commercial operations, after appropriate additional crew training and type rating. The course has been designed as a straight-through ab initio programme for students with no previous flying experience. On graduation, the student will be qualified, in accordance with the requirements of Annex 1 to the Convention on International Civil Aviation, for the issue of:

a) a commercial pilot licence (CPL) - aeroplane;

b) an instrument rating; and

c) a multi-engine class rating - land (MEL).

During the course, the problems associated with low-level wind shear and turbulence are introduced in such a way as to provide the student with a basic understanding and appreciation of the causes, indications and effects of the phenomena. The following are extracts from the relevant parts of the training manual.

Group Briefing (GRB) 15

Operational safety of light aeroplanes

* Wind shear

  - circumstances under which wind shear can be expected
  - effect of sudden change in wind speed/direction on aircraft speed/flight path
  - risk in vicinity of thunderstorms
  - gust fronts

Meteorology (ME) 12

THUNDERSTORMS

Take-off and landing hazards

* Wind shear

* Strong gusts and rapid change of wind direction

* Up and down draughts and vertical wind shear

* Heavy precipitation

* Gust fronts

Meteorology (ME) 20

LOW-LEVEL WIND SHEAR

Causes and indications

* Frontal shear

  - fast moving fronts
  - shear in direction and speed
  - duration usually less than two hours

* Thunderstorms, gust fronts

  - downdrafts strike ground and spread out
  - gust fronts can extend as much as 20 km in advance of a thunderstorm
  - wind velocity increases up to 50 per cent from surface to 1500 ft AGL
  - directional shear of 90° to 180° is not uncommon

* Terrain effects

  - funnelling effect as large amounts of air are channelled through a narrow space such as a canyon
  - air accelerates to high velocities and can lead to strong speed shear

* Indications

  - the usual indications of frontal passage such as rapid temperature change, wind shift, rapid pressure change
  - fluctuations in aircraft instrument readings such as airspeed, vertical velocity
  - presence of thunderstorms, dust clouds
  - need for abnormal power settings during approach

Critical conditions

* Wind shear during take-off and initial climb

* Wind shear during approach and landing

Effect of rapidly changing wind components

* Rapid decrease in headwind component

* Rapid increase in headwind component

* Sudden shift to a tailwind condition

Appendix H

Audio Visual Aids Available from ICAO

In order to assist States and operators in developing their various training programmes, ICAO has a large number of audio-visual training aids which may be purchased. These include posters, slides and films, some of which have been produced by ICAO and others made available to ICAO by Contracting States who have granted printing rights to the Organization through the acquired rights programme. As far as wind shear is concerned, there is one poster available dealing with the subject (P621). It draws attention to the particular hazards of gust fronts associated with thunderstorms. A second poster dealing with the downburst/microburst is currently under preparation. Thunderstorms are covered in a two-part film (F64 and F67), and there are two films on wind shear entitled "The Probable Cause" (F645) and "The Wind Shear Factor" (F647). These audio-visual aids are especially suitable for those undergoing training. It should be noted that all films are available in a video format. Full details of all films, posters and audio-slide presentations are contained in the ICAO Catalogue of Audio-Visual Training Aids. Requests for copies of this catalogue, or orders for any AVA training aid, should be addressed to:

International Civil Aviation Organization
(Attention: Document Sales Unit)
1000 Sherbrooke Street West
Montreal, Quebec
H3A 2R2

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ICAO TECHNICAL PUBLICATIONS

The following summary gives the status, and also describes in general terms the contents of the various series of technical publications issued by the International Civil Aviation Organization. It does not include specialized publications that do not fall specifically within one of the series, such as the Aeronautical Chart Catalogue *or the* Meteorological Tables for International Air Navigation.

International Standards and Recommended Practices are adopted by the Council in accordance with Articles 54, 37 and 90 of the Convention on International Civil Aviation and are designated, for convenience, as Annexes to the Convention. The uniform application by Contracting States of the specifications contained in the International Standards is recognized as necessary for the safety or regularity of international air navigation while the uniform application of the specifications in the Recommended Practices is regarded as desirable in the interest of safety, regularity or efficiency of international air navigation. Knowledge of any differences between the national regulations or practices of a State and those established by an International Standard is essential to the safety or regularity of international air navigation. In the event of non-compliance with an International Standard, a State has, in fact, an obligation, under Article 38 of the Convention, to notify the Council of any differences. Knowledge of differences from Recommended Practices may also be important for the safety of air navigation and, although the Convention does not impose any obligation with regard thereto, the Council has invited Contracting States to notify such differences in addition to those relating to International Standards.

Procedures for Air Navigation Services (PANS) are approved by the Council for world-wide application. They contain, for the most part, operating procedures regarded as not yet having attained a sufficient degree of maturity for adoption as International Standards and Recommended Practices, as well as material of a more permanent character which is considered too detailed for incorporation in an Annex, or is susceptible to frequent amendment, for which the processes of the Convention would be too cumbersome.

Regional Supplementary Procedures (SUPPS) have a status similar to that of PANS in that they are approved by the Council, but only for application in the respective regions. They are prepared in consolidated form, since certain of the procedures apply to overlapping regions or are common to two or more regions.

The following publications are prepared by authority of the Secretary General in accordance with the principles and policies approved by the Council.

Technical Manuals provide guidance and information in amplification of the International Standards, Recommended Practices and PANS, the implementation of which they are designed to facilitate.

Air Navigation Plans detail requirements for facilities and services for international air navigation in the respective ICAO Air Navigation Regions. They are prepared on the authority of the Secretary General on the basis of recommendations of regional air navigation meetings and of the Council action thereon. The plans are amended periodically to reflect changes in requirements and in the status of implementation of the recommended facilities and services.

ICAO Circulars make available specialized information of interest to Contracting States. This includes studies on technical subjects.

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