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Manual on Low-level Wind Shear

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International Civil Aviation Organization

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AMENDMENTS

The issue of amendments is announced regularly in the *ICAO Journal* and in the monthly *Supplement to the Catalogue of ICAO Publications and Audio-visual Training Aids*, which holders of this publication should consult. The space below is provided to keep a record of such amendments.

RECORD OF AMENDMENTS AND CORRIGENDA

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FOREWORD

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

Lack of adequate operational remote-sensing equipment, the complexity of the subject, the wide range of scale of wind shear and its inherent unpredictability all conspired to hinder a complete solution to the problem which, in turn, limited 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 The latter accident, which occurred at John F. Kennedy (JFK) International Airport, New York, on 24 June 1975, and another at Denver, Colorado, United States, on 7 August 1975, which fortunately resulted in no loss of life and occurred in an area where detailed monitoring of the wind field was possible, marked 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 removed any lingering doubt regarding the real danger of wind shear. The accelerated research effort that followed, culminating in the massive Joint Airport Weather Studies (JAWS) project at Stapleton Airport, Denver, Colorado, United States, in 1982, considerably improved our understanding of the problem, particularly regarding wind shear associated with thunderstorms.

The ICAO Eighth Air Navigation Conference (Montréal, 1974)² recommended the preparation and publication of guidance material to assist all concerned to make the best possible use of the available information on wind shear. In order to assist in the preparation of this guidance material, the Low-level Wind Shear and Turbulence Study Group (WISTSG) 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.

Following the increased research effort, Amendment 64 to Annex 3 — *Meteorological Service for International Air Navigation* was developed and became applicable in November 1983 and included new and revised provisions for the observing and reporting of low-level wind shear. At the same time, the statement of operational requirements was slightly revised (see Appendix 1).

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 those 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

a. When this manual was published, 1983 was the latest complete year for which reports were available in the ICAO accident/incident reporting data bank.

aviation aircraft". In order to accomplish this task, an ad hoc Committee for the Study of Low-Altitude^b Wind Shear and its Hazard to Aviation was formed. The Committee produced an extremely comprehensive report and a series of conclusions and recommendations¹ (see Appendix 2).

Since 1967 the FAA has had a detailed programme directed towards reducing the hazard to aviation of low-level wind shear. Under this programme, action has been taken on the recommendations made by the above-mentioned Committee and also on recommendations made on occasion by the National Transportation Safety Board (NTSB) following accident investigations. In this regard, the FAA developed an "Integrated Wind Shear Programme", which involved close cooperation with a number of government agencies (e.g. the National Aeronautical and Space Administration (NASA), the aerospace industry, pilot associations and ICAO) and included a wind shear training aid that was published in February 1987. The programme's objective was to further develop and refine over the next five to ten years education, training and operational procedures, surface-based and airborne wind shear detection technology and on-board flight guidance systems. In parallel, further explanation of the wind shear hazard was to be provided by continued scientific research. In 1987, with the assistance of the WISTSG, ICAO published Circular 186 on *Wind Shear*, the forerunner of this manual.

At the time the circular on *Wind Shear* (Cir 186) was published in 1987, it was stated in the foreword that "the bulk of the information on wind shear, particularly the operational aspects, is still not sufficiently mature to be translated into regulatory provisions". Subsequent amendments to the relevant Annexes and Procedures for Air Navigation Services (PANS) to take account of the requirement to provide information on wind shear to pilots, and the fact that the original circular has been replaced by this manual, attest to the increased maturity of this subject.

Two main trends are responsible for the progress made in the past sixteen years. Advances in the development of equipment to detect and warn of wind shear, both ground-based and airborne, have occurred since 1987. In particular, there have been major advances in Doppler radar and signal-processing technology, which have led to the development of highly effective, dedicated ground-based wind shear detection/warning systems. Similar advances have also produced forward-looking wind shear detection/warning systems to meet the operational requirements for airborne equipment. The relevant ICAO regulatory documents have been amended in step with these technical developments.

In parallel with the development of wind shear detection/warning equipment, progress has been made in the training of operational personnel concerning the serious effect that wind shear can have on aircraft in flight. Especially important is the training of pilots. Excellent wind shear training aids are available that cover the explanation and recognition of wind shear and its avoidance during landing and take-off. The flying techniques recommended in order for the pilot to recover from an inadvertent encounter with wind shear are also covered. Today all pilot simulator training should include wind shear recognition, avoidance and recovery modules.

There has been a marked reduction in the past decade in the number of aircraft accidents/incidents in which wind shear was cited as a contributory factor. However, it will always be a serious hazard for aviation and a potential killer, and there must be continued vigilance and pilot training on wind shear.

b. In this manual, 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".

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1. Report by the United States National Academy of Sciences Committee on Low-Altitude Wind Shear and its Hazard to Aviation: 1983, National Academy Press, Washington, D.C., Library of Congress No. 83-63100.
 2. ICAO, 1974: Report of the Eighth Air Navigation Conference (Doc 9101), Montréal.
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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 that 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 that produce such air motions are thunderstorms, land/sea breezes, low-level jet streams, mountain waves and frontal systems. In order to understand, in this context, the common denominator linking such varied phenomena, it is necessary to explain the meaning of the term “wind shear”. 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 any physical obstacle to the prevailing wind flow that produces a change in wind speed and/or direction, in effect, causes wind shear.

1.2 Wind shear is always present in the atmosphere and its presence is often visible to an observer. Examples are 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/sandstorms; and trees bending in all directions in response to sudden gusts from a squall line. All 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 effects on flight safety. Although wind shear may be present at all levels of the atmosphere, its occurrence in the lowest level — 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, therefore rendering the aircraft especially susceptible to the adverse effects of wind shear. As will become clear in subsequent chapters, 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 should be pointed out that, considering the high number of aircraft landings and take-offs which take place around the world, only a very small number of aircraft encounter difficulties which result in accidents and, of these accidents, in only a fraction is wind shear a factor. Nevertheless, the fact that wind shear has contributed to aircraft accidents in the past is sufficient reason for everyone engaged in aviation operations to understand 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

2.1.1 The simplest definition of wind is “air motion relative to the earth’s surface”. Wind blows freely in three-dimensional space and, having both speed and direction, must be considered as a vector that can be resolved into three orthogonal components. Relative to the earth, this means components in the north/south, east/west and upwards/downwards direction. 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).

2.1.2 Except in special cases, the vertical component of the wind in the atmosphere is usually small compared with one or both horizontal components. This is especially true near the ground where the wind is constrained to move in the horizontal plane. Because the horizontal components generally predominate, it is assumed that a horizontal wind blows parallel to the earth’s surface, thereby neglecting the vertical component. Special cases, where the vertical component of the wind predominates, are produced by things such as convective cloud (particularly thunderstorms), mountain waves and thermals. The first two phenomena are of particular relevance to wind shear and are discussed in detail in Chapter 3.

2.1.3 Because the aircraft, by suitable choice of runway, generally lands or takes off into wind, the headwind/tailwind or longitudinal component automatically tends to predominate over the crosswind or lateral component. This explains why emphasis is normally placed on changes in the headwind/tailwind (longitudinal) component, except in those special cases already mentioned where the vertical component (updraft/downdraft) predominates. Moreover, calculations of wind shear over the airport must take into account the orientation of the runways, which means resolving all shear vectors to the runway headings, thereby providing shears in the form of headwind/tailwind components.

2.2 SPATIAL VARIATION OF WIND

2.2.1 In the explanation of wind shear given in Chapter 1, the changes in wind speed and/or direction 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, like eddies; while eddies clearly involve wind shear, because they are on a much smaller 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 overall size of the aircraft concerned, is therefore of fundamental importance.

2.2.2 From the foregoing it may also be seen that, while all turbulence involves wind shear, albeit on a very small scale, wind shear, especially large-scale, does not necessarily involve turbulence. Wind shear is not simply some form of clear air turbulence; moreover, wind shear on a scale that affects aircraft performance does not necessarily imply turbulence.¹

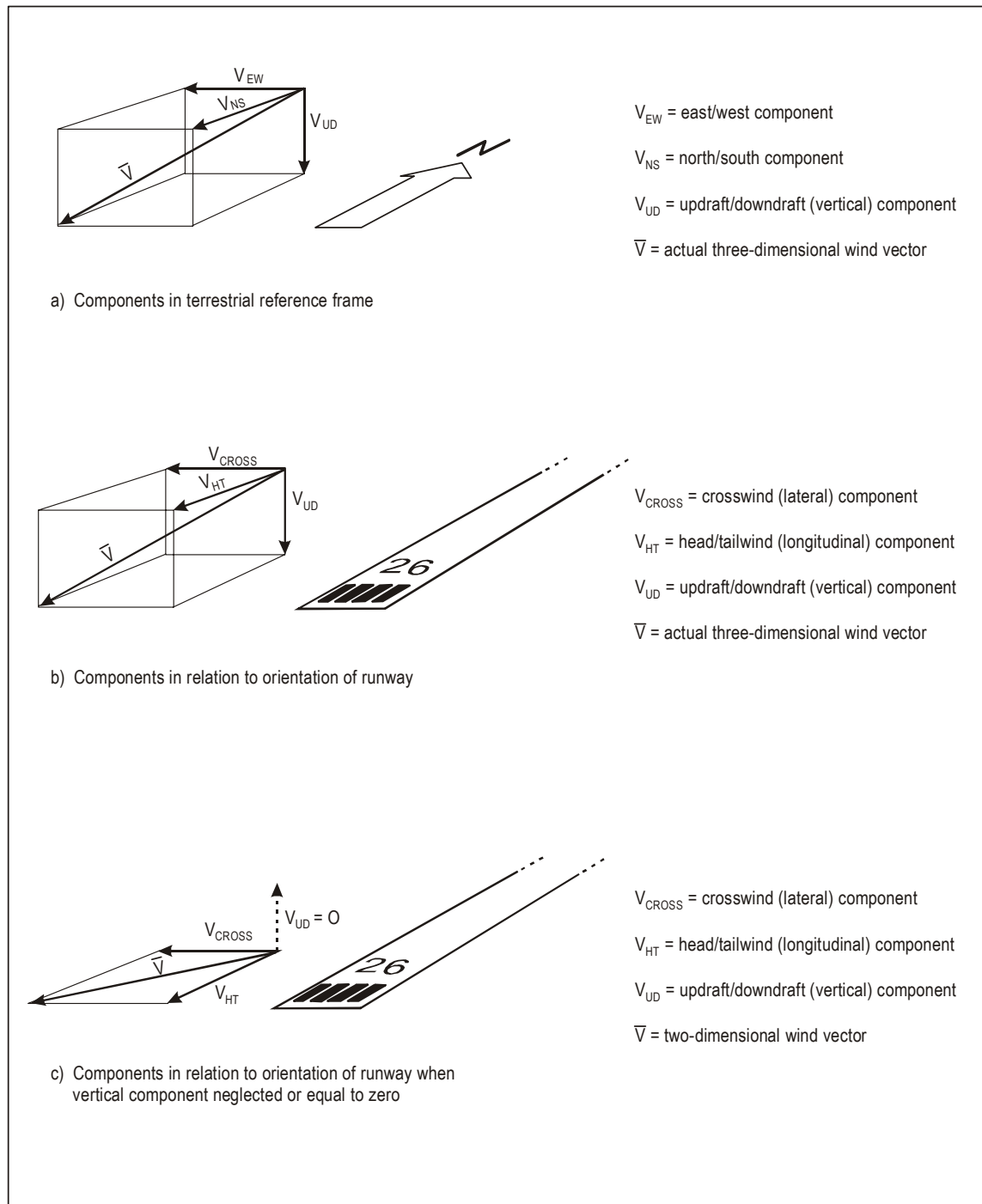


Figure 2-1. Components of the wind in various coordinate systems

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 trigonometry. For example, consider a wind $\vec{V}_1^a$ of 240 degrees/60 km/h (30 kt) at point A 300 m (1 000 ft) above ground level (AGL) changing to a wind $\vec{V}_2$ of 220 degrees/20 km/h (10 kt) at point B 150 m (500 ft) AGL. In Figure 2-2 a) and b), the wind shear vector is calculated graphically by subtraction of the two wind vectors ($\vec{V}_2 - \vec{V}_1$) or ($\vec{V}_1 - \vec{V}_2$); its relationship to the “resultant wind” vector, obtained by the addition of the two wind vectors ($\vec{V}_1 + \vec{V}_2$), is also shown. The resultant can act in only one direction because $(\vec{V}_1 + \vec{V}_2) = (\vec{V}_2 + \vec{V}_1)$, but the vector difference can act in one of two reciprocal directions (with the same speed) depending upon which wind 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 $(\vec{V}_2 - \vec{V}_1) \neq (\vec{V}_1 - \vec{V}_2)$ except in the trivial case $\vec{V}_1 = \vec{V}_2$, 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 important with respect to its effect on aircraft (see Chapter 4 for details). In 2.3.1 it is easy to see that the wind shear vector for landing going from point A to point B would be $(\vec{V}_2 - \vec{V}_1)$, whereas for take-off going from point B to point A, it would be $(\vec{V}_1 - \vec{V}_2)$, i.e. both the same speed but each the reciprocal direction of the other. In Figure 2-2, the vector difference is calculated using components and standard formulae, respectively. In practice, tables are normally precalculated giving wind shear magnitude by insertion of the two wind speeds and the angle between them and resolving these into components along the runway headings (see Figure 2-2 c) and paragraph 2.1.3, respectively).

2.3.3 Paragraph 2.3.2 illustrates wind shear in the vertical as would be measured by an anemometer at 300 m (1 000 ft) and at 150 m (500 ft) AGL. The same calculation could be made for wind shear in the horizontal, i.e. if the same two anemometers were spaced 150 m (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 point A to point B or point B to point A, as in the example in 2.3.2.

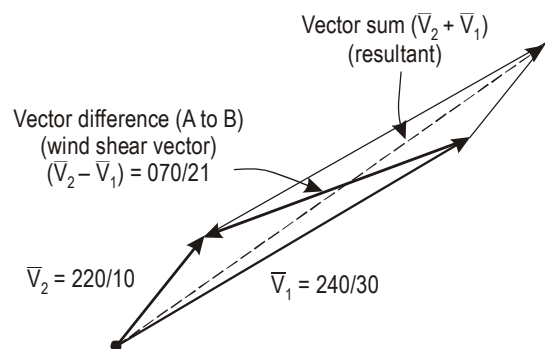
2.3.4 It would be difficult to overemphasize that wind shear is a **vector**, and hence the speed and the direction of the two winds concerned must be taken into account. Wind shear cannot be calculated by simple scalar subtraction of the wind speeds, except in the specific case where the direction of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

2.4 UNITS OF MEASUREMENT FOR WIND SHEAR

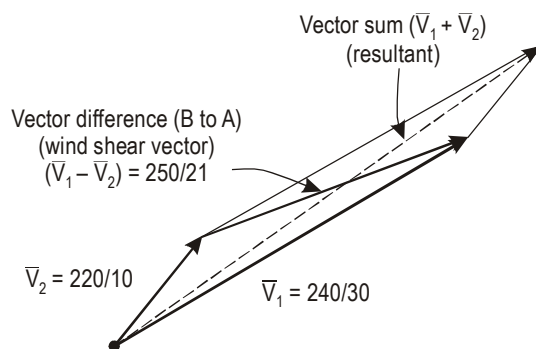
2.4.1 In Figure 2-2, the wind shear between points A and B is 070 degrees/42 km/h (21 kt), and the shear between points B and A is 250 degrees/42 km/h (21 kt). The intensity of the shear in both cases is $21/5 = 8.4$ km/h per 30 m (4.2 kt per 100 ft). It is common practice to give the wind shear intensity in kilometres per hour per 30 m or metres per second per 30 m or in knots per 100 ft because these units are convenient and well understood by aviation personnel. In the case of aircraft landing or taking off where the

a . Vector indicated by $\vec{V}$.

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 ft AGL	Point A, $\bar{V}_1 = 240/30$	+26	+15
500 ft AGL	Point B, $\bar{V}_2 = 220/10$	+6.4	+7.7

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

Vector difference from point A to point B (e.g. in the direction of aircraft landing) = $\bar{V}_2 - \bar{V}_1$.

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 = $\bar{V}_2 - \bar{V}_1 = \sqrt{(-19.6)^2 + (-7.3)^2} = 20.9 = 21 \text{ kt}$.

Direction of vector difference = $\bar{V}_2 - \bar{V}_1 = \tan^{-1} \frac{(-7.3)}{(-19.6)} = 20^\circ$.

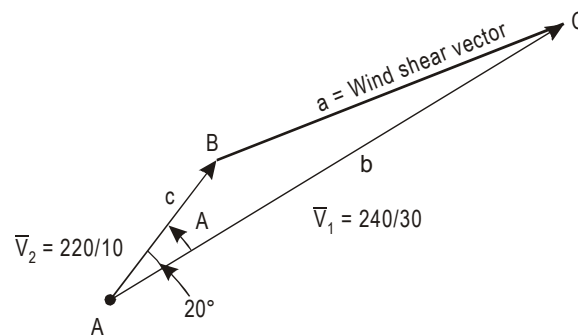
Because both components of the vector difference (shear) are negative, the direction of the wind shear vector is from the north-east quadrant and because the east/west component $\geq$ the north/south component, direction = $(090 - 020) = 070^\circ$.

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

b) 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 $\bar{V}_1$ and $\bar{V}_2 = 240^\circ - 220^\circ$
 $A = 20^\circ$

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)),

$$\begin{aligned} \therefore \text{speed of shear} = "a" \text{ which} &= \sqrt{b^2 + c^2 - 2bc \cos A} \\ &= \sqrt{900 + 100 - 600 \cdot (0.9397)} \\ &= \sqrt{436.2} = 20.9 \\ &= 21 \text{ kt.} \end{aligned}$$

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:

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

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

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

Figure 2-2. cont.

glide path or take-off path is a known fixed angle, e.g. 3-degree glide path, and the ground speed (GS) of the aircraft is known and relatively constant, the wind shear can be converted from kt/100 ft or m/s per 30 m into kt/s or m/s per 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, often used by researchers and encountered in research papers and scientific publications, may be derived by dimensional analysis as follows:

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

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 units are difficult to interpret and in practice are not particularly useful in respect of aircraft operations.

2.4.3 Summarizing the three ways of expressing wind shear intensity discussed in 2.4.1 and 2.4.2 in terms of the example given in Figure 2-2, in the case of a wind changing from $\overline{V}_1$ at point A to $\overline{V}_2$ at point B (e.g. an aircraft landing), the wind shear vector between points A and B is 070 degrees/42 km/h (21 kt) over 150 m (500 ft), therefore:

- a) the intensity in km/h per 30 m = 8.4 km/h per 30 m or in kt/100 ft = 4.2 kt/100 ft;
- b) the same intensity in scientific units = 0.07 m/s; and
- c) the intensity as it might affect a landing aircraft in km/h per s (kt/s) (i.e. acceleration) for a 3-degree glide slope and 300-km/h (150-kt) ground speed (i.e. rate of descent 3.9 m/s (13 ft/s) = 1.09 km/h per s (0.546 kt/s) or 0.025 g, where g = acceleration due to gravity. The actual headwind/tailwind shear components would have to be calculated by resolving the vector difference along the runway headings.

2.4.4 It should be noted that the wind shear discussed so far acts in the free atmosphere and exists whether an aircraft is there or not. In fact such wind shears are used by meteorologists when they plot hodographs or when the thermal wind is 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. $(\overline{V}_1 - \overline{V}_2)$ 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. In particular, as mentioned in 2.4.3 c), the vector shear must be resolved along the runway headings in order to take account of the aircraft flight path during take-off and landing.

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 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 that must also be borne in mind. Calculation of the wind shear from two winds at points separated by a given distance simply gives the overall shear between the two points. No indication is forthcoming on whether the rate of shear is linear or, if not linear, at least gradual between 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 Figure 2-2.

2.5.2 In case 1 of Figure 2-3, the shear between 300 m (1 000 ft) and 150 m (500 ft) is approximately linear, and the overall shear of 42 km/h (21 kt) at a rate of 8.4 km/h per 30 m (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 overall shear is still calculated as 42 km/h (21 kt) or 8.4 km/h per 30 m (4.2 kt/100 ft), this shear is concentrated in 60 m (200 ft) in an unsuspected local wind shear far in excess of 8.4 km/h per 30 m (4.2 kt/100 ft), in the examples given, reaching a maximum of 21 km/h per 30 m (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 3.1.5).

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 interpolation⁴ and, as such, may not indicate the actual wind shear between two particular levels.

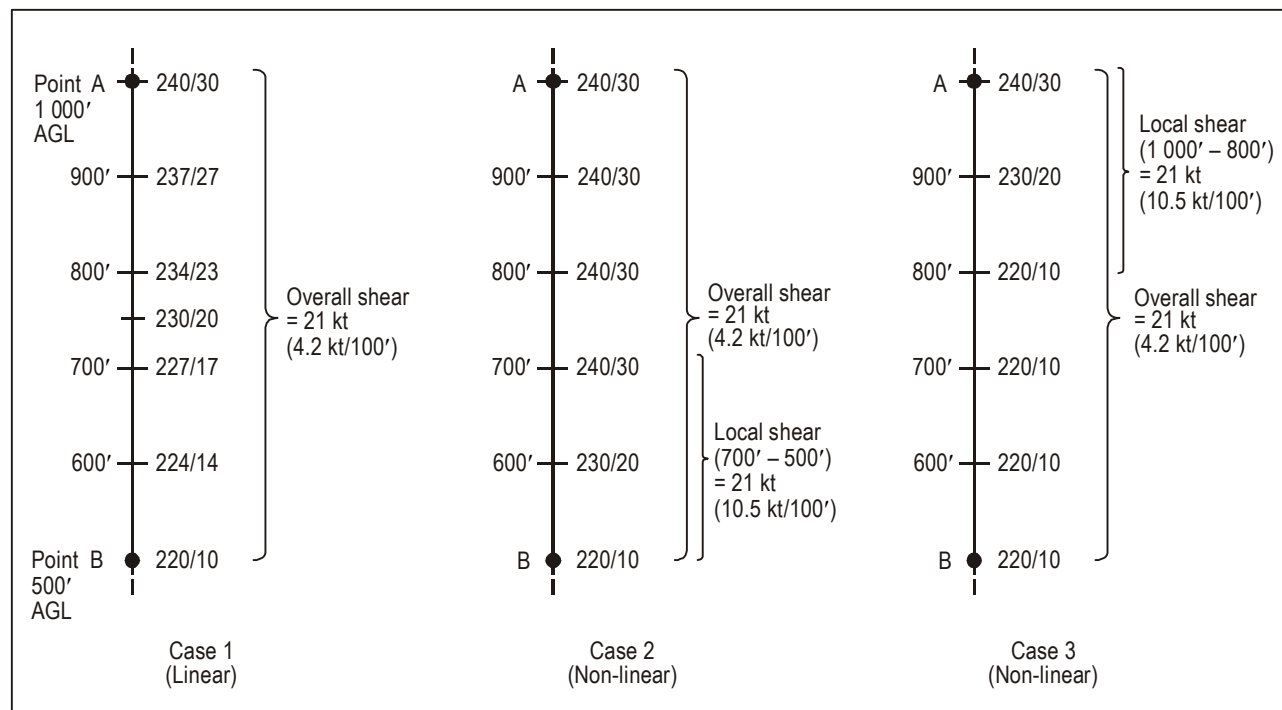


Figure 2-3. Linear and non-linear wind shear

References

1. Melvin, 1975: The dynamic effect of wind shear, *Pilot Safety Exchange Bulletin*, Flight Safety Foundation Inc., Arlington, VA.
 2. Carter, 1977: *Aerospace Safety*.
 3. Jaspersen, 1982: The limiting accuracy of wind profiles obtained by tracking rising balloons, *Journal of Applied Meteorology*.
 4. World Meteorological Organization Compendium of lecture notes, 1971: Determination of upper winds at specified levels, WMO No. 291.
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Chapter 3

METEOROLOGICAL CONDITIONS AND PHENOMENA THAT CAUSE LOW-LEVEL WIND SHEAR

3.1 WIND PROFILE IN THE LOWER LEVELS OF THE ATMOSPHERE

GENERAL

3.1.1 It is a well-known fact that, even outside the influence of specific wind shear-causing meteorological (MET) 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 subdivided 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"^a from about 100 m (330 ft) up to at least 600 m (2 000 ft) in which the effect of friction, while still significant, diminishes progressively with increasing height, and other controlling factors, such as the coriolis force and horizontal pressure gradient force, become increasingly important.

3.1.2 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.

THE SURFACE BOUNDARY LAYER

3.1.3 In the lowest layer of the atmosphere, below about 100 m (330 ft), the wind direction is approximately constant with height while 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

a. V. Walfrid Ekman (1874–1954), Swedish physical oceanographer best known for his studies on ocean currents.

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, 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 = the wind speed at height z ,
- u_* = the “friction velocity”,
- k = von Karman’s constant^b, approximately 0.38,
- z_o = 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”^c and produces the well-known logarithmic wind speed profile.

3.1.4 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 that predicted by the above equation (see Figure 3-1 a)).³

3.1.5 An extreme case of the stable condition, which can involve the entire 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”. Because the maximum speed can exceed 120 km/h (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 and 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 therefore of considerable interest to aviation.

3.1.6 The logarithmic wind law is not simply of academic interest since it also provides a basic wind shear model for use in the simulator certification of automatic landing systems^d and in the training of pilots. It must be stressed, however, that in all cases 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, allowing for such limitations, the model represents well the average conditions that the pilot is most likely to encounter in the lowest levels of the atmosphere below 100 m (330 ft). In the logarithmic profile, wind shear is greatest below 30 m (100 ft) and decreases with height; the shear intensity may

b. Theodore von Karman (1881–1963), Hungarian engineer best known for his application of mathematics and physics to aeronautics.

c. Ludwig Prandtl (1875–1953), German physicist who made fundamental contributions to aerodynamics.

d. See the *Airworthiness Manual* (Doc 9760), Volume II, Part A, Appendix L to Chapter 4.

exceed 10 km/h per 30 m (5 kt/100 ft) in the first 15 m (50 ft) decreasing to less than 2 km/h per 30 m (1 kt/100 ft) above 100 m (330 ft). The question of the development of simulator models based upon more abnormal wind shears is discussed in Chapter 6.

THE EKMAN LAYER

3.1.7 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 (back) with height in the northern (southern) hemisphere.

3.1.8 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 that Ekman derived, when applied to the atmosphere, may be written as follows:⁷

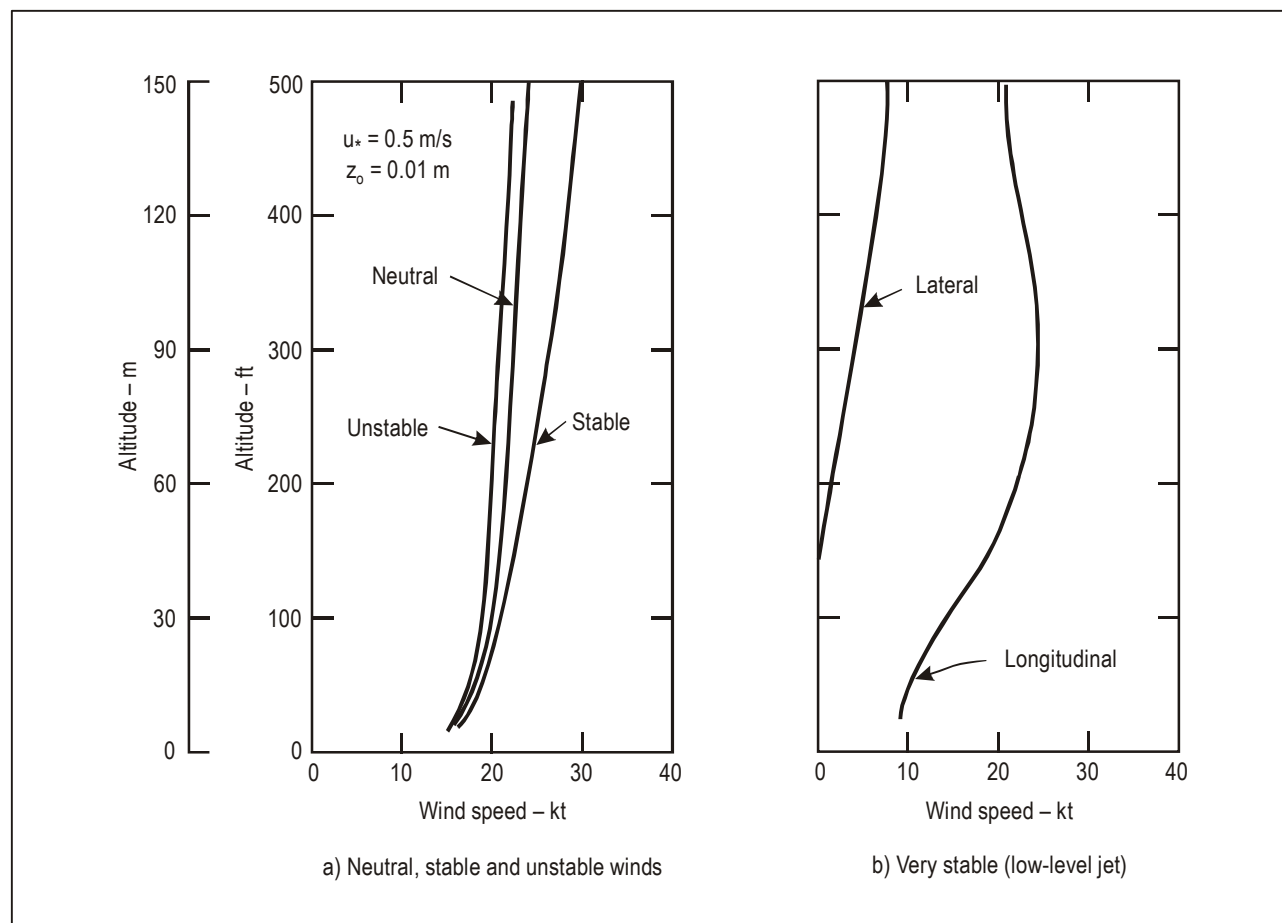


Figure 3-1. Wind profiles from atmospheric boundary layer effects
(from Ellis and Keenan, 1978)

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

and

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

where

- u and v = the horizontal components of the wind at height z ,
- V_g = the geostrophic wind,
- a = the angle between the actual wind at anemometer level and the geostrophic wind (see 3.1.10),
- B = a constant comprising viscosity and coriolis parameters.

3.1.9 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 order 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.

3.1.10 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 degrees at or just above the surface, decreasing exponentially above about 100 m (330 ft) to 0 degrees 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, which is known as the Ekman spiral (see Figure 3-2).

3.1.11 In practice, it is found that the wind speed generally increases with height in the Ekman layer, the wind blows at an angle across the isobars, the angle decreases with height and the wind veers (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 degrees. 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 MET phenomena) from the surface to about 600 m (2 000 ft).

3.1.12 Following recent intensive work on the development of integrated wind-observing systems at aerodromes, such as the integrated terminal weather system (ITWS) described in 5.1.31 *et seq.*, and the wind-profiling system used to support the United States Federal Aviation Administration/National Aeronautics and Space Administration (FAA/NASA) aircraft vortex spacing system (AVOSS) described in 3.8.3, considerable data was assembled on wind profiles in the Ekman layer and the associated wind shear. Low-level jet streams were detected relatively frequently with wind speeds in excess of 400 km/h per 30 m (20 kt per 1 000 ft), and many cases where the winds were in excess of 40 km/h per 600 m (20 kt per 2 000 ft) in the Dallas/Fort Worth area⁸ in the United States.

3.1.13 These wind profiles are of more than academic interest at aerodromes due to the increasing interest of air traffic control (ATC) in using information on the detailed structure of the wind up to 600 m

(2 000 ft) to increase the aerodrome efficiency by allowing better optimization of aerodrome aircraft acceptance rates. Studies⁹ show that landing a few extra aircraft per hour at a capacity-restricted aerodrome can provide very large financial benefits (\$17 million estimated using the terminal winds product at Dallas/Fort Worth Airport and \$27 million at John F. Kennedy (JFK) International Airport, New York). Although severe wind shear was not detected (i.e. non-convective profile shear), the higher profile wind shears require pilots to pay close attention to their approach speeds so as to avoid unnecessary missed approaches, with their attendant costs.

WIND PROFILE MODELS APPLICABLE TO NON-NEUTRALLY STABLE CONDITIONS

3.1.14 Other models were derived empirically that represent atmospheric wind profiles under atmospheric conditions where stability is not neutral.^{10,11,12} The best-known of these is the “power law” that 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 = wind speeds at heights z, z_1 , respectively,

γ = a parameter that 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.

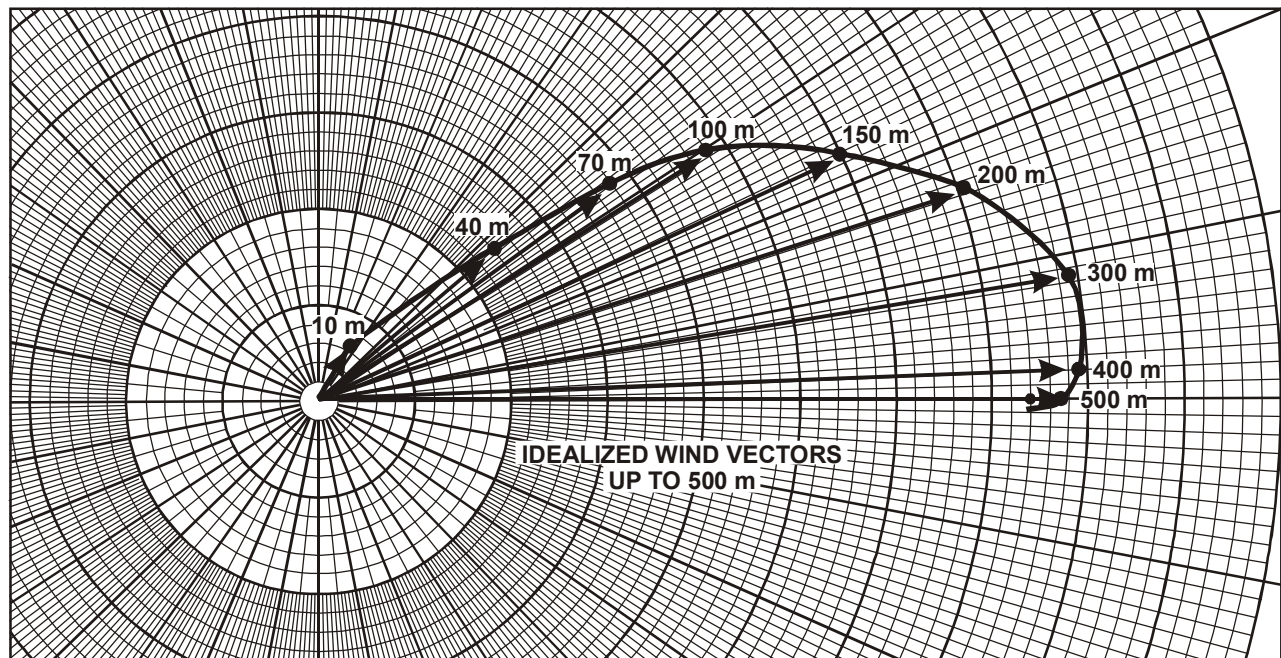


Figure 3-2. Ekman spiral

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 (CAT). The effect that the obstacles have on the prevailing wind flow depends on a number of factors, the most important being 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 while 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 causing the surface wind to vary along the runway (see Figure 3-3 a)). 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.¹³

3.2.3 Airfields sometimes are literally carved out of extensive forests with the result that the runway is effectively situated within a “tunnel” of trees. When the treeline is beyond the runway strip and 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 general interest are runways which, of necessity, were 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 be insufficient 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^e effect that results in an acceleration in the surface wind.¹⁴

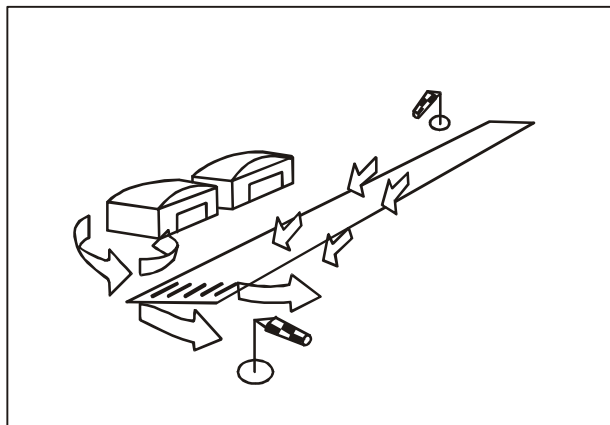
3.2.5 Strong surface winds at aerodromes where there are no substantial obstacles to the wind flow can also cause an increase in wind shear. This is because in the layers of the atmosphere nearest the ground, the strong wind increases mechanical turbulence. This in turn transfers momentum throughout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

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.

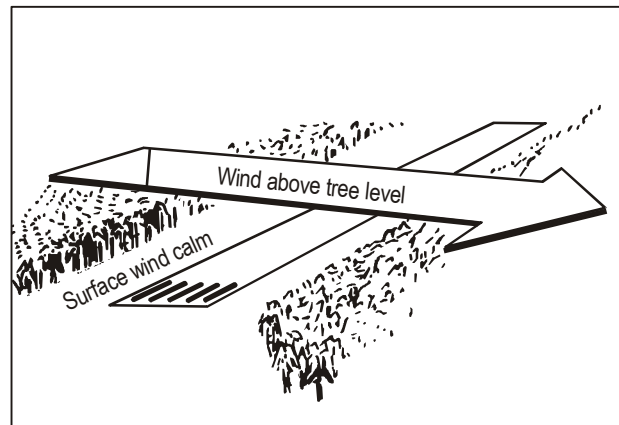
3.2.7 The most common of these conditions, called a katabatic wind, occurs at night over sloping ground when there is no cloud and a weak pressure gradient — especially anticyclonic. The wind is formed

e. Giovanni Venturi (1746–1822), Italian physicist who made contributions in fluid dynamics, including the development of the eponymous “Venturi tube”.

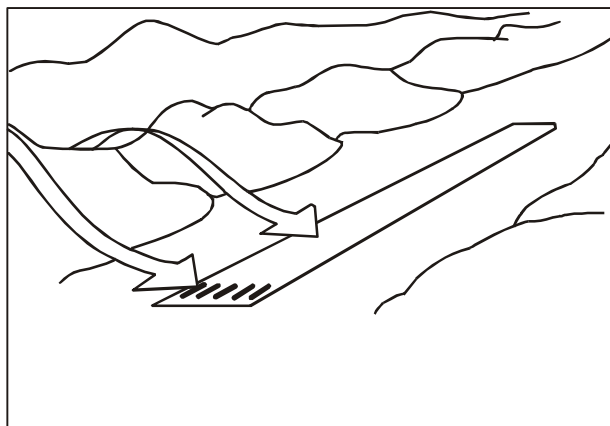
due to the downslope gravitational flow of colder, denser air in contact with the slope below the warmer, less dense air at the same level but some distance away from the surface of the slope. Low-level wind shear and turbulence are present along the leading edge and the top of the colder air as it moves downhill, and on occasion the onset may be sudden, resembling a weak gust front (see 3.5.8 to 3.5.10). 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 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.¹⁵ 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, France, which can accelerate the cold north-westerly downslope wind to 140 km/h (70 kt) or more.



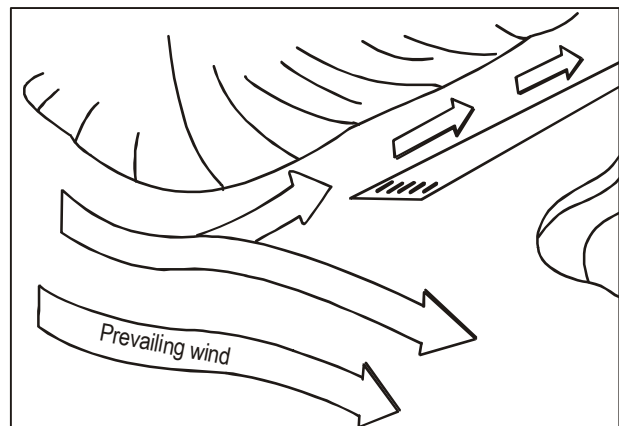
a)



b)



c)



d)

Figure 3-3. Wind flow around obstacles

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. 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 lee side of the mountains.¹⁶ Particular mountain ranges, such as the Rockies in the United States, which have unique features (especially steep lee sides) and favourable MET conditions, are notorious for producing marked lee waves. The MET 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 30 km/h (15 kt) blowing within 30 degrees either side of the line perpendicular to the ridge line;
- c) little or no wind shear direction in the stable layer; and
- d) sea-level pressure differential across the mountain barrier.

3.2.9 If the lee waves that 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 200 km/h (100 kt), e.g. during “wind storms” near Boulder, Colorado.¹⁷ 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 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 that form downwind of the mountain.

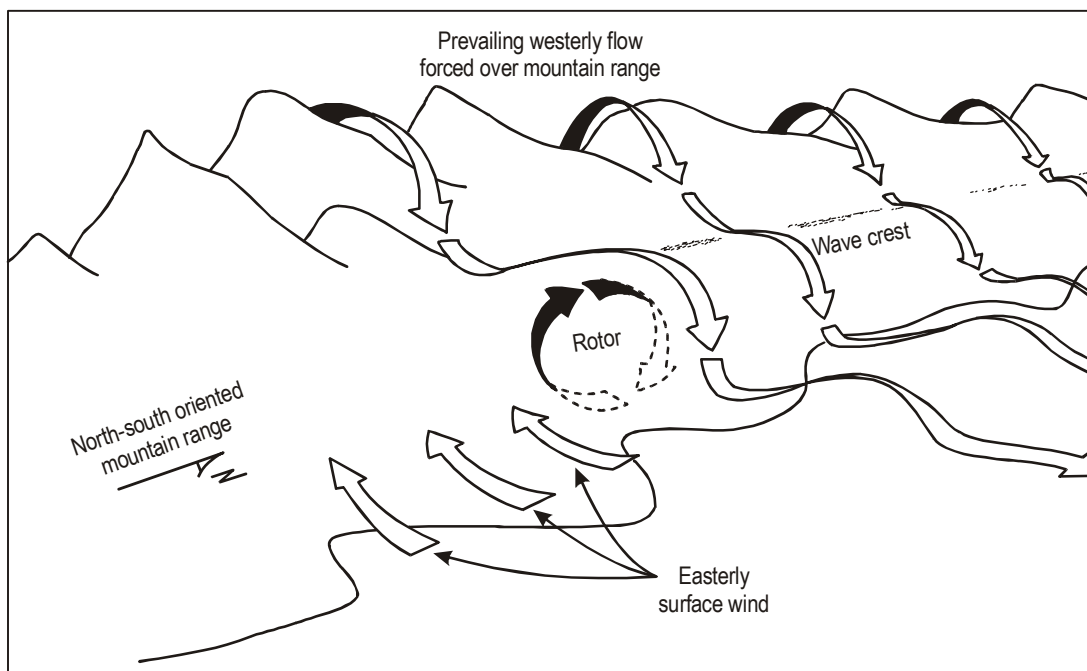


Figure 3-4. Lee waves

3.2.10 Another effect that can be produced when wind flow is forced over a mountain range is “Föhn wind” (e.g. “Chinook” in western Canada and “Santa Ana” in California, United States), which blows down the lee side of the mountains. 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 that occurs as the air moves down the lee side of the mountains is at the dry adiabatic lapse rate. Consequently, the air reaches the ground 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 (330 and 1 600 ft) 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 and 3.2.9.

3.2.11 There is another type of atmospheric 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. It is most frequently observed in the Gulf of Carpentaria in northern Australia, where it is referred to as a “morning glory”.¹⁸ The name is thought to derive from the spectacular roll cloud or series of roll clouds that accompany the propagating wave. A cross section of relative streamlines associated with a typical morning glory is shown in Figure 3-5.¹⁹ While 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 shifts rapidly (often through 180 degrees) and there are marked downdrafts within the wave itself.²⁰ 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 that 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 to aircraft accidents remains to be confirmed, but some researchers believe that they are implicated.²¹

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 therefore, 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 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 therefore marked wind velocity discontinuities are those most likely to produce wind shear that could affect aircraft.²² 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

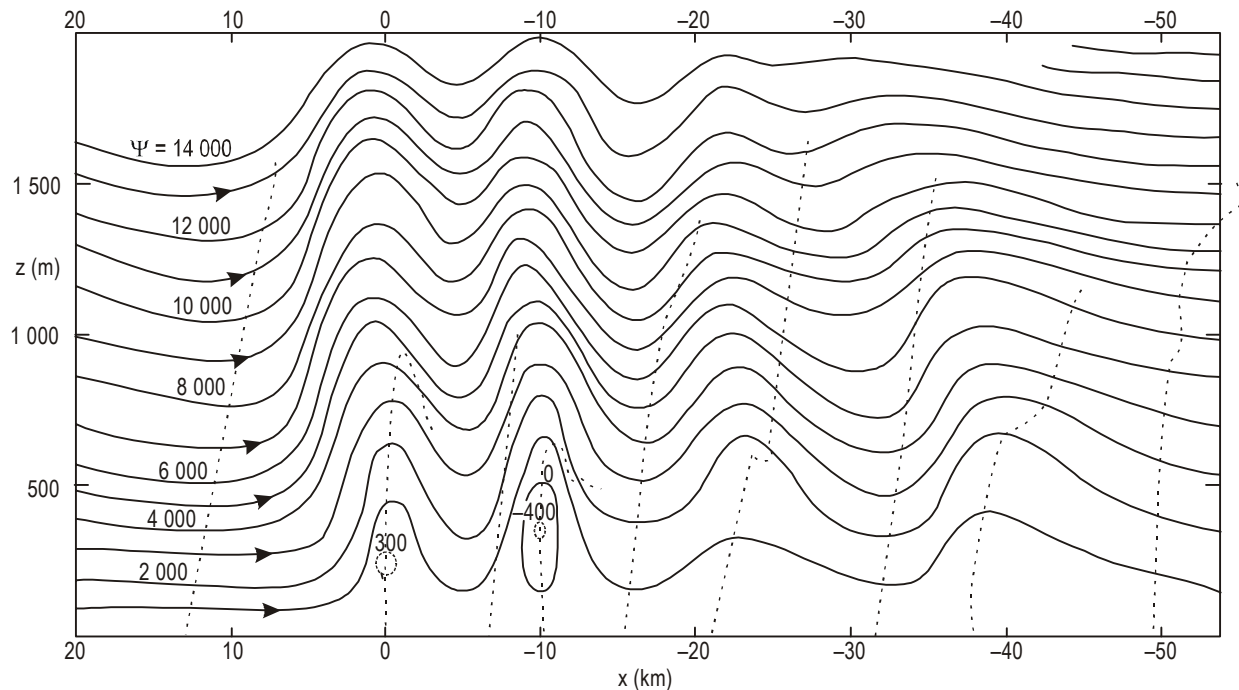


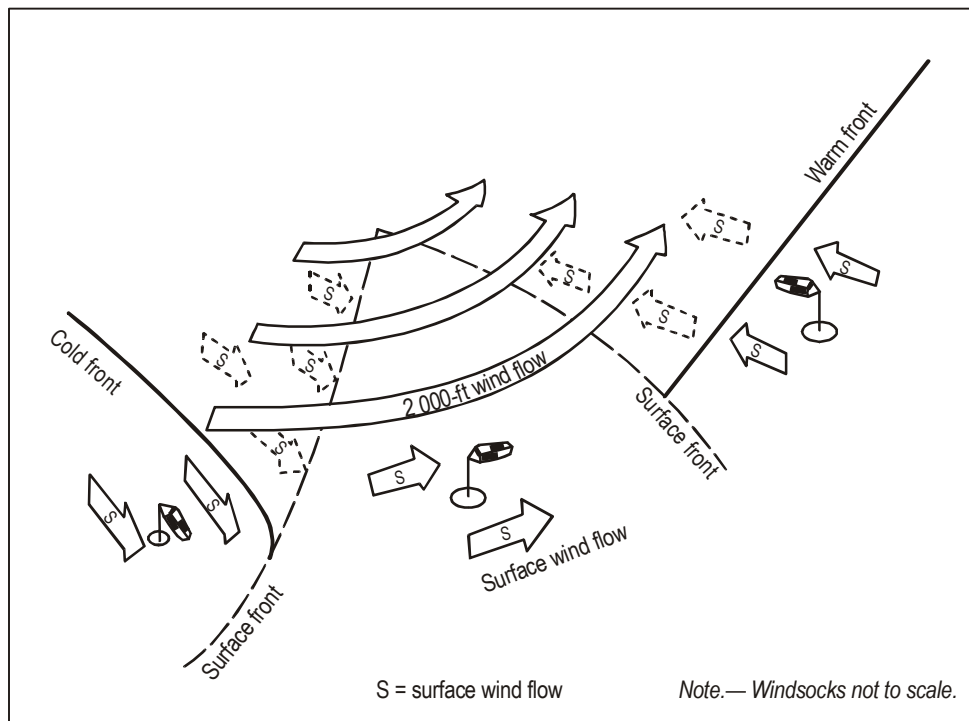
Figure 3-5. Cross section of the relative streamlines normal to the cloud line in the “morning glory” of 4 October 1979 as deduced from double theodolite wind data
(from Smith and Goodfield, 1981, and adapted by ICAO)

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 aforementioned typical slopes 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-degree glide slope ($\sim 1/20$) and much shallower than usual climb-out flight paths.

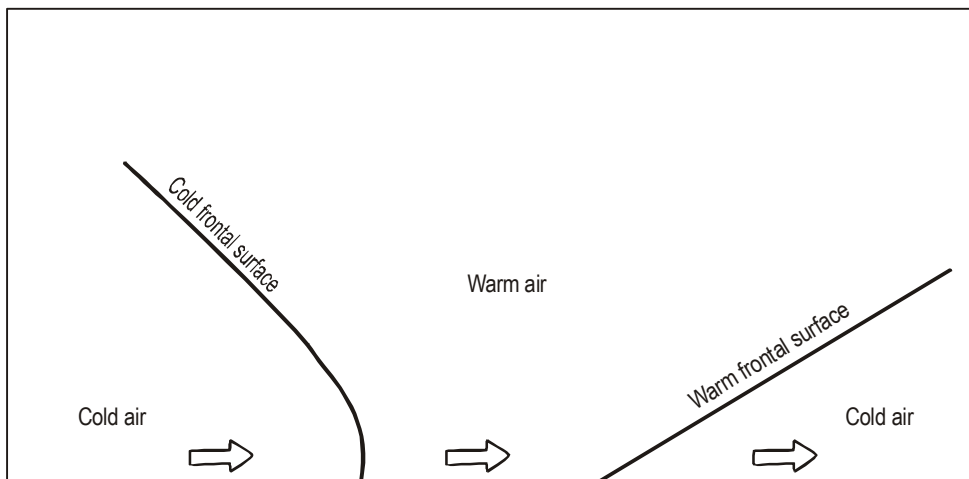
3.3.3 It is clear from the foregoing that the warm front slopes forward in the direction of motion of the front, while the cold front slopes backward in the opposite direction to the motion (see Figure 3-6). The implication this has for an aerodrome through which the fronts are moving is that the vertical 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.

3.3.4 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 may 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. Since 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 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 depends on the width of the



a) Three-dimensional diagrammatic view of wind flow 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

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, 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 inland lakes, there is a well-marked diurnal variation in the surface wind. This effect is due to the temperature gradient that 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, and reverses at night, becoming a land or offshore breeze blowing from the land towards the water (see Figure 3-7). 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 breeze initially is approximately at right angles to the shoreline with speeds of 20 to 30 km/h (10 to 15 kt), although in tropical areas these may exceed 40 km/h (20 kt). The sea breeze is much stronger than the land breeze and may penetrate as far as 48 km (30 NM) inland by mid-afternoon and extend up to 360 m (1 200 ft) above ground level (AGL). 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 a cold front.²³ 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 exists at higher levels. The extent of the sea-breeze effect at any particular location is influenced considerably by the surrounding topography and therefore 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 that in favourable circumstances gives rise to lines of showers or even thunderstorms. A number of subtle effects can be produced by the land or 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.

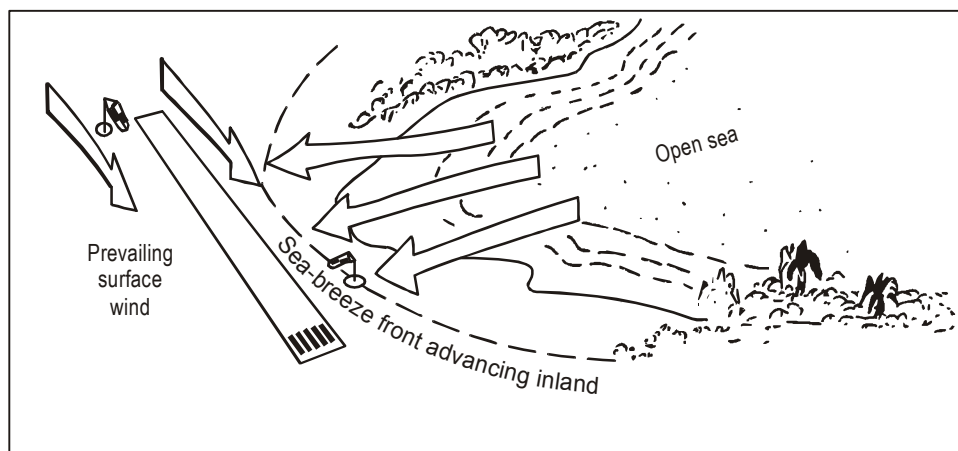


Figure 3-7. Sea-breeze front

3.5 THUNDERSTORMS

GENERAL

3.5.1 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. Thunderstorm is an all-embracing term that includes a number of phenomena produced by mature cumulonimbus clouds, such as thunder and lightning, torrential rain, hail, strong winds and tornadoes. 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 magnitude as a nuclear explosion.

3.5.2 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 is 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.

Air mass or heat thunderstorms 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, while 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.

3.5.3 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 thirty minutes to one hour. These life cycles can be divided naturally into three stages depending on the direction and magnitude of the predominating vertical airflow in the cell (see Figure 3-8) as follows:

- a) cumulus 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.²⁴

3.5.4 The airflow structure in and around a thunderstorm has been generally understood since the 1940s, particularly following the important "Thunderstorm Project" conducted in the United States in 1946–47²⁵ and confirmed by more recent research. In the past decade, the use of multiple Doppler radars to monitor the airflow both in clear air and in cloud, and the computer simulation²⁶ of thunderstorm dynamics has

enabled researchers to analyse the structure of the airflow in extremely fine detail (see 5.1.17 to 5.1.42 and Figure 3-9, respectively). 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 updrafts and downdrafts that intertwine and interact so as to exploit most efficiently the excess energy available from local heat and moisture surpluses. The fact that the airflow within and around mature thunderstorms is concentrated into such strong air currents is of extreme importance to aviation.

3.5.5 The cellular structure and degree of cellular organization exhibited by thunderstorms prove to be features that frequently are identifiable on radar (particularly Doppler radar) and relate in a reasonably systematic way to the severity of the thunderstorm.²⁷ In general, the more organized the cellular structure, the more severe the thunderstorm. This feature provides the basis for a more detailed classification of thunderstorms than has hitherto been possible as shown in Table 3-1. 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 MET 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.²⁸ 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 to 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 that is particularly favourable for the development of supercell storms.^{29,30,31} As indicated in Table 3-1, such storms can cause tremendous damage both directly in the form of extensive hail and indirectly due to the severe downbursts and tornadoes that they spawn (see 3.5.23 to 3.5.27).

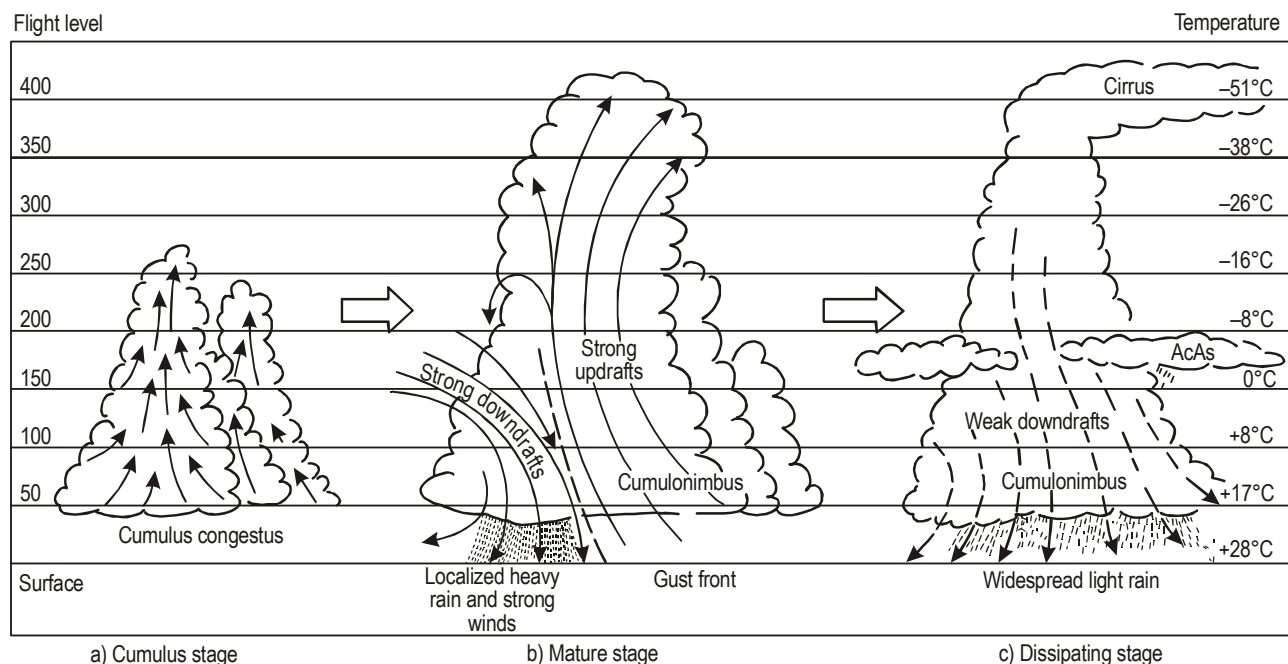


Figure 3-8. Life cycle of a thunderstorm

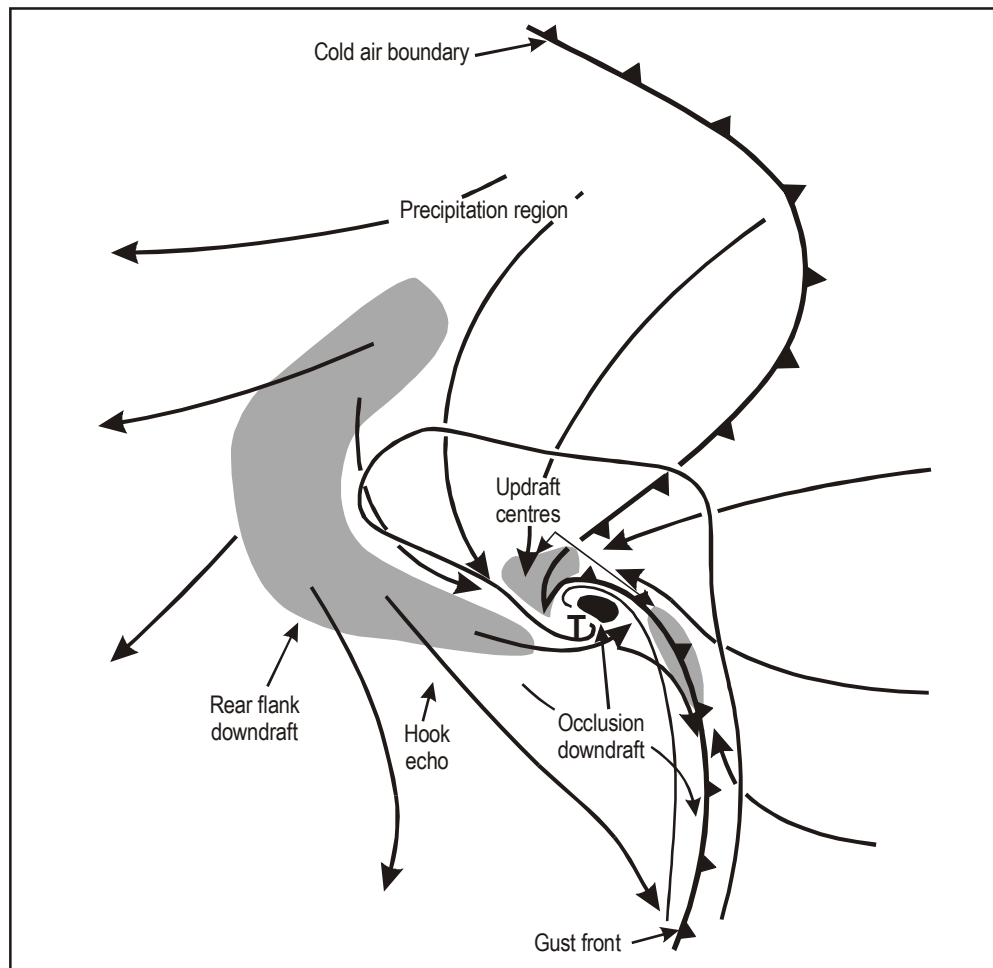


Figure 3-9. Model of tornadic thunderstorm; (T) indicates position of tornado
(from Weisman, 1983)

3.5.6 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 airflow 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 the droplets become so heavy they fall back through the updraft becoming even heavier as they sweep up more ascending water droplets. This is the origin of downdraft currents which at this stage accelerate 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 further accelerating the downdraft current.³²

3.5.7 Those water droplets in the downdraft which do not evaporate completely fall out of the cumulonimbus cloud base as heavy, localized rain accompanied by strong, gusty winds from the descending cold air current. Downdrafts that 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 be accompanied by heavy rain, although they typically are. 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 and are examined in detail in the remainder of the chapter.

THE GUST FRONT

3.5.8 Although the overall 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 its structure is relatively recent.³³ The gust front is the leading edge of the cold, dense air from a thunderstorm downdraft that reaches the ground and spreads out in all directions, undercutting the surrounding warmer, 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 the cold downdraft strikes the ground at an angle instead of vertically, as often happens, therefore 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 because the front may move as far as 20 km (12 NM) 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 degrees and the speed of the gusting winds following passage of the front can exceed 100 km/h (50 kt).

3.5.9 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 (22 NM)) than those generated by individual thunderstorms. Extremely well-organized squall lines are a typical feature of the rainy season throughout West Africa.³⁴ The depth of the cold air in the gust front can reach up to 1 000 m (3 300 ft), and there can be vertical wind shear along the dividing surface between the cold and warm air. As in a cold front, friction tends to slow down the cold air nearest the ground, therefore permitting the cold air at about 200 m (600 ft) AGL 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.

3.5.10 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 roll cloud above the gust front nose which, girding the base of the storm and advancing ahead of the rain belt, always looks turbulent and threatening. In certain regions the downdrafts, and especially the vortices within the gust front nose, cause rising dust or sand that forms into a spectacular travelling wall of sand. These are the well-known “Haboobs” of the Sudan and the “Andhi” of north-west India.³⁵ Gust fronts have 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 observed on satellite pictures. Gust fronts are best detected by Doppler radar, although for it to be effective, automated detection techniques have to be employed.

THE DOWNBURST

3.5.11 The explanation for the development of strong downdrafts in mature thunderstorm cells given in 3.5.6 and 3.5.7 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 because 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 appears no higher than in the usual downdrafts.

3.5.12 The detailed survey of damage caused by winds during a thunderstorm, showing the directions in which trees, corn, wheat, etc., were felled by the wind, was employed in 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 were blown outward. It was suspected that these trees were pushed or felled by strong winds that blew outward from the outburst centre (see Figure 3-12).³⁶ Byers and Fujita (1976) classified this intense downdraft as a “downburst”, defined as “a localized, intense downdraft with vertical currents exceeding a downward speed of 3.6 m/s or 720 ft/min at 90 m (300 ft) above the surface”.³⁶ By 1978, Fujita had generalized the definition as “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, small enough to be missed completely by normal operational observing systems.

Table 3-1. Classification of thunderstorms

	<i>Type of thunderstorm</i>			
	<i>Air mass</i>		<i>Frontal</i>	
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, microbursts, families of tornadoes, extensive hail
Examples	Random air mass development typically over maritime/oceanic area 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 of 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 the 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

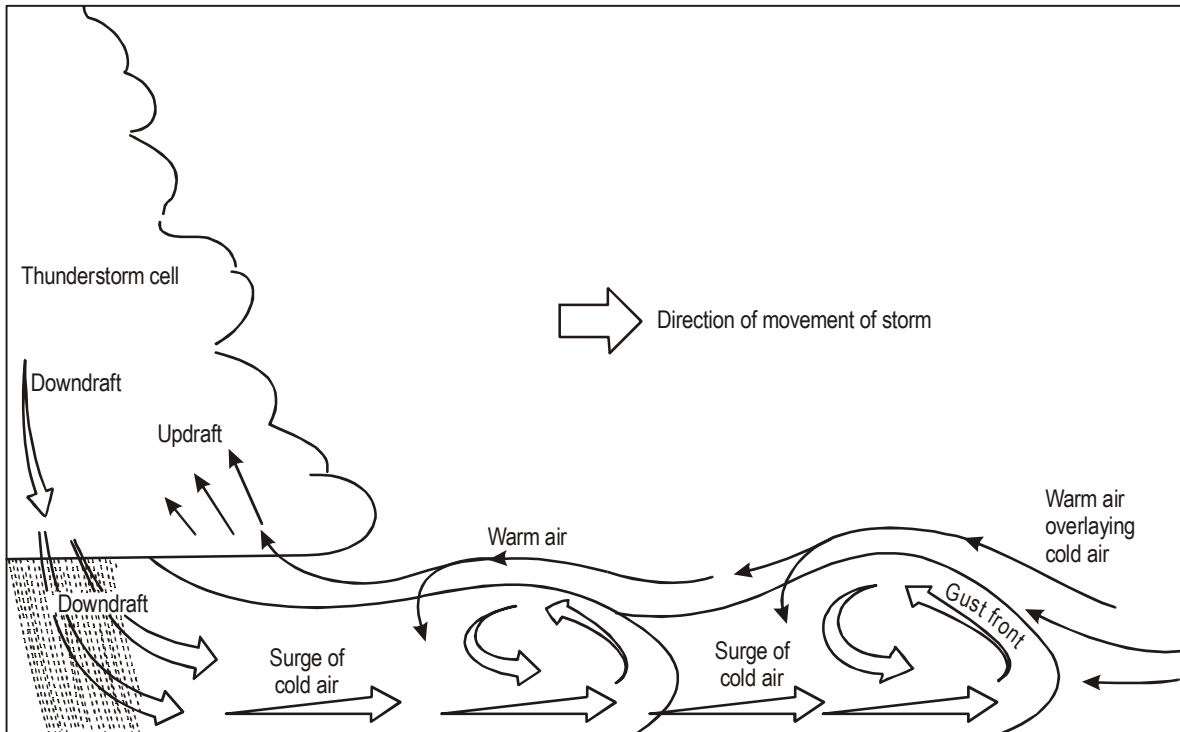


Figure 3-10. Cross section of typical gust front
(after ICAO "Gust Front Turbulence & Wind Shear" Poster P621)

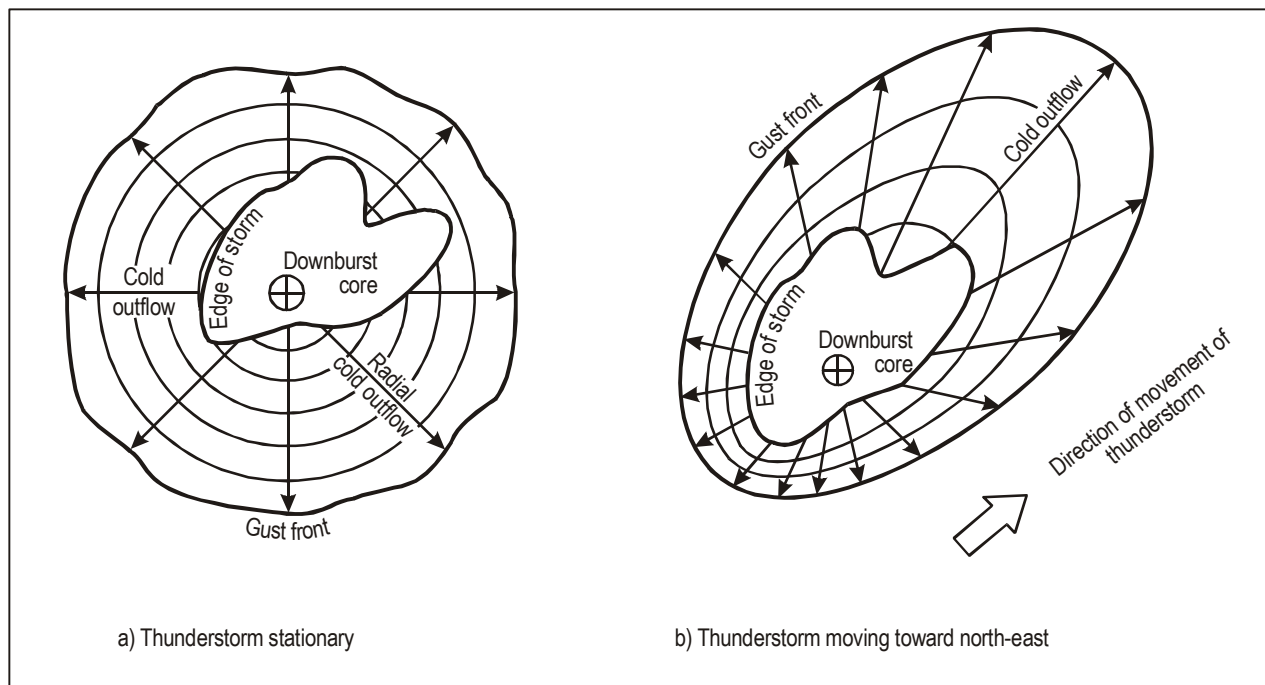


Figure 3-11. Plan views of typical gust fronts

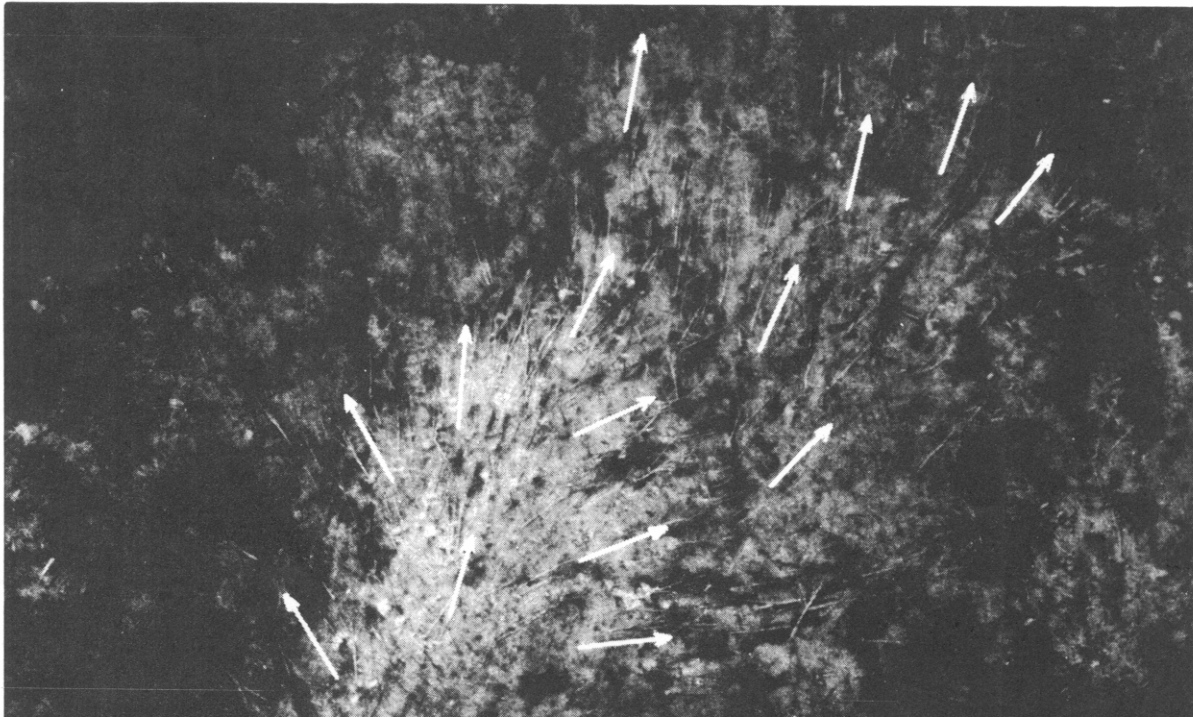


Figure 3-12. Over 300 trees blown over by an intense outburst near Beckley, West Virginia, United States. Similar patterns of trees were photographed by the author at numerous locations along the paths of tornadic thunderstorms of 3 April 1974, the day of the super-outbreak tornadoes (from Fujita, 1976)

3.5.13 A number of explanations have been proposed to account for the marked differences (e.g. downdraft and outflow speeds) between the ordinary thunderstorm downdraft described in 3.5.6 and 3.5.7 and the downburst as postulated, and since conclusively found, by Fujita.^f At one extreme, the downburst is considered to be a “super-downdraft” originating at very high levels in the thunderstorm, while at the other extreme the downburst is said to originate in the middle levels of the atmosphere. The latter explanation appears to agree with the observation and simulation of “supercell storms” (see 3.5.28). An interesting, comparative review of the various explanations is given by Wolfson,³⁷ who concluded that, while all are plausible, none of the mechanisms proposed has so far been demonstrated to be the actual cause of downbursts.

3.5.14 Increased attention was focused on the hazardous nature of downbursts with respect to aviation, following the Eastern Airlines B727, Flight 66, accident at New York’s JFK International Airport in 1975. A detailed analysis of the thunderstorms that occurred over the airport at that time was prepared by Dr. Fujita. He based the scenario on 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

f. A comprehensive review of the state of knowledge on the downburst in 1985 can be found in Fujita’s book “The Downburst” (see bibliography).

likely to be characterized by spearhead (radar) echoes, a definition newly introduced in this paper. About two per cent of the echoes in the New York area, the principal site involved in this research, were spearhead echoes".³⁶

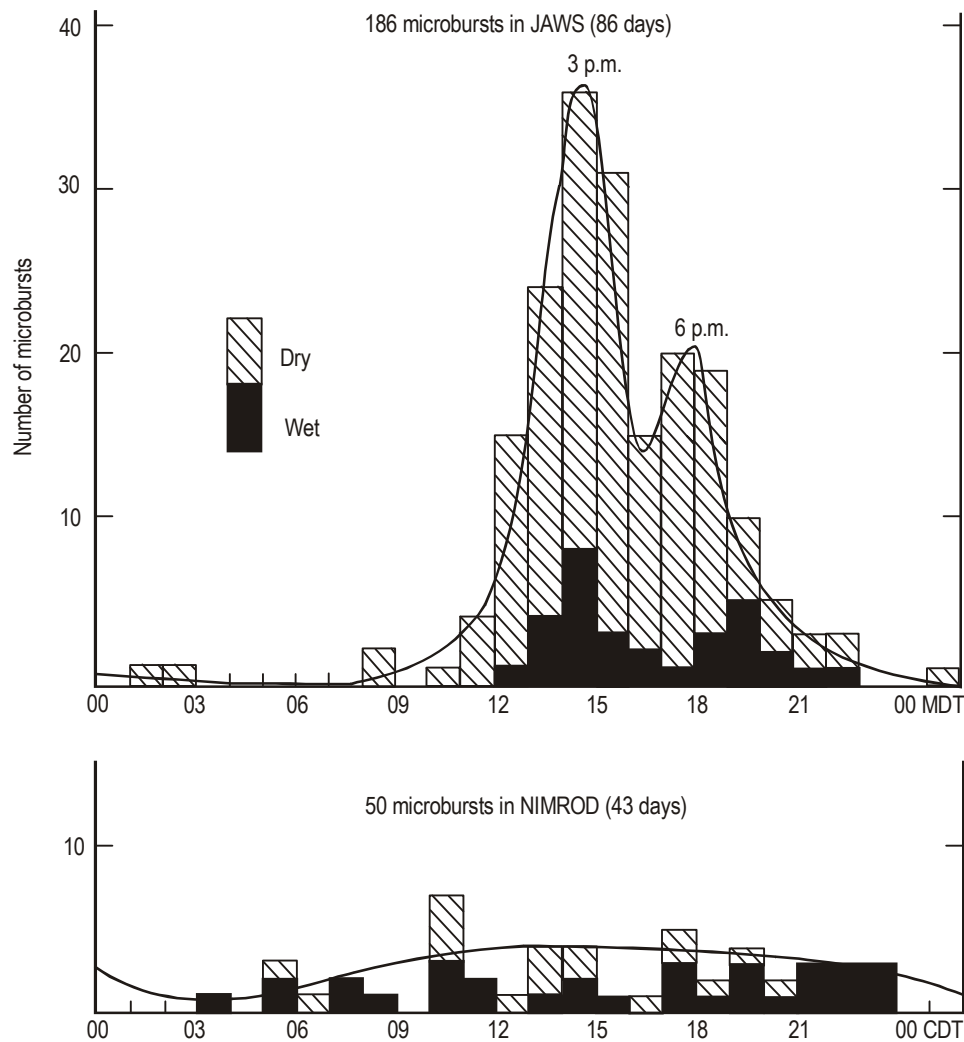
THE MICROBURST

3.5.15 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, more intense downbursts. Fujita named these small, very intense downbursts "microbursts" and defined them 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".³⁸ The small scale of the microburst, both in space and time, renders it almost impossible to observe with present-day observation systems. Unfortunately, this particular scale is the most important from the aviation point of view, 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 frequently associated with severe thunderstorms, can be produced by any convective cloud.

3.5.16 In order to advance this research, a two-year data collection project called NIMROD (northern Illinois meteorological research on downburst)³⁸ 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 airflow within microbursts were obtained by Doppler radar. Due to the spacing of the three radars used, however, only single-Doppler analysis was possible.⁹ 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, United States.³⁹ 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 mesonet (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 the data phase in 1983–84. Although the data will continue to be analysed in increasing detail in future, the results have confirmed the existence and severity of downbursts and microbursts. At the same time, the downburst/microburst is more complex than first thought. For example, there is evidence of even smaller and more intense structures embedded within microbursts. These tend to produce a long and narrow pattern of damage within the overall outflow much like tornado damage. Fujita described these structures as "burst swath".

3.5.17 At least 236 microburst "fish" 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.⁴⁰ The high percentage of dry microbursts was 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-eastern 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 3-15,⁴¹ indicating the possible existence of a vortex ring around the microburst,

g. 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, and adapted by ICAO)

which explains the rapid intensification of the downdraft and accounts for its concentrated and localized nature. It has been suggested that a series of such vortex rings may be formed as shown in Figure 3-16.^{42,43} 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 3-17.⁴⁴

3.5.18 The microburst has a short lifespan and generally reaches maximum intensity within ten minutes. As a direct follow-up and practical application of the results of the JAWS project, the United States National Center for Atmospheric Research (NCAR) and the FAA carried out a research programme 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 (ATS) units with real-time advisory forecasts of wind shear and develop the necessary operational procedures.⁴⁵ During the project (between 2 July and 15 August 1984, from 11 00 to 20 00 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

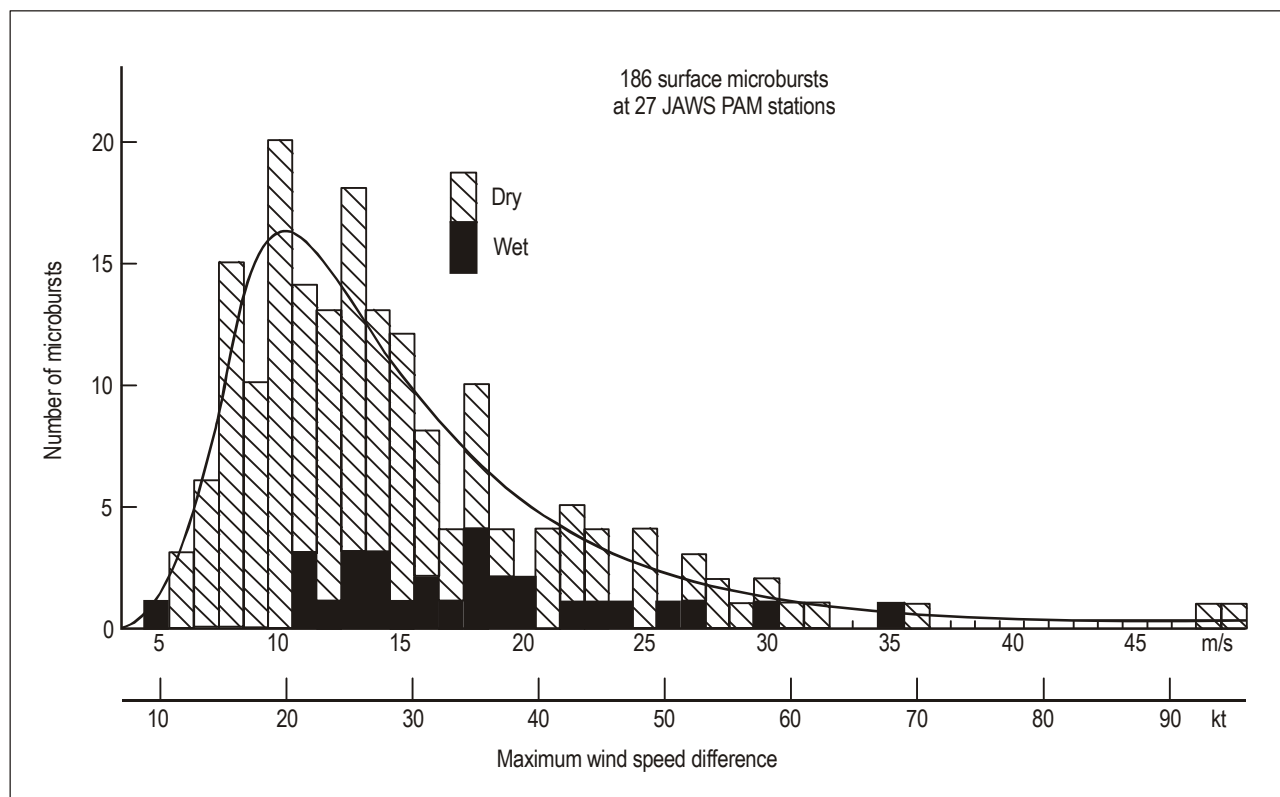


Figure 3-14. Frequency of surface microbursts as a function of the maximum wind speed difference measured at the 27 PAM stations
(from Fujita and Wakimoto, 1983)

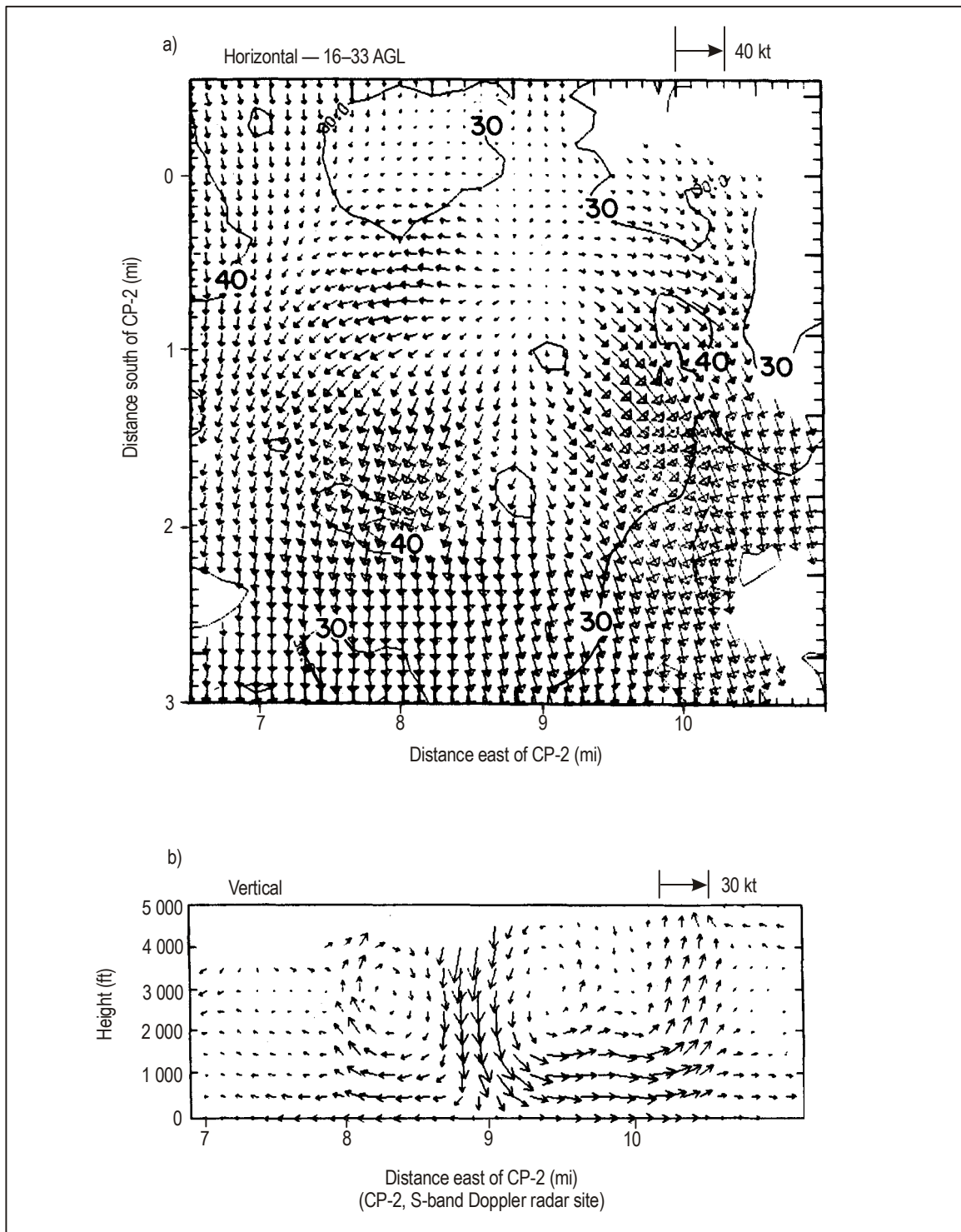
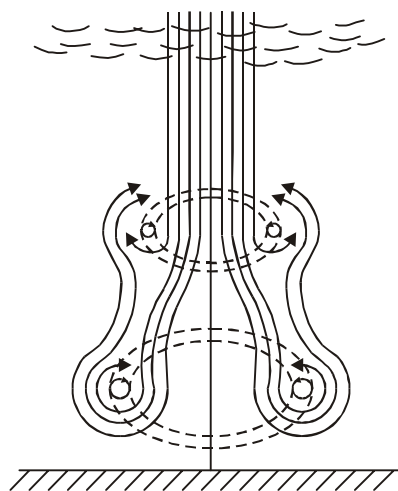


Figure 3-15. Velocity fields with respect to the ground, based on a dual Doppler analysis for a microburst occurring at 1452 MDT on 14 July 1982.
Contours are radar reflectivity factors (dBZ₀)
 (from Wilson and Roberts, 1983, and adapted by ICAO)



a) Thunderstorm downburst — vortex ring flow model
(from Woodfield and Vaughan, 1983 after Caracena)



b) Vortex ring circulation associated with leading edge of a microburst
(from Fujita & Smith, University of Chicago, 1985)

Figure 3-16. Vortex ring

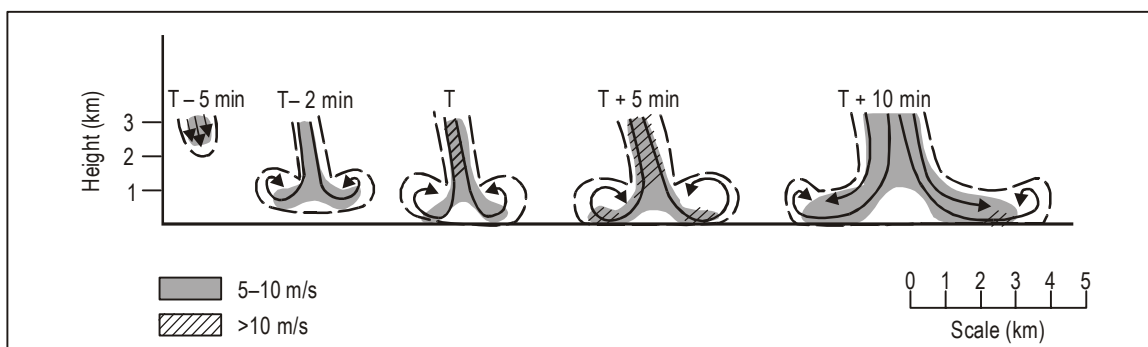


Figure 3-17. Vertical cross section of the evolution of the microburst wind field; T is the time of initial divergence at the surface. The shading denotes the vector wind speeds.
(from Wilson, Roberts, Kessinger and McCarthy, 1984, and adapted by ICAO)

3.5.19 Advice given to ATC concerning wind shifts on the runways assisted controllers in choosing appropriate runways for take-off or landing. The initial project analysis according to McCarthy and Wilson (1985)⁴⁵ 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; and
- c) the area of aviation microburst warnings could be greatly reduced to the immediate region of the aircraft approach/departure operations.

3.5.20 A report on the operational aspects of the project was produced by the FAA.⁴⁶ It concluded that CLAWS provided the FAA with the opportunity and experience 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. Their usefulness was demonstrated at Stapleton Airport — even in their present, primitive forms. It also provided a pool of operational experience in the use of these products.

3.5.21 In addition to the continued analysis of data collected during the JAWS project, further research on microbursts was conducted under project “MIST” (microburst and severe thunderstorm). This project was conducted jointly by NASA, the University of Chicago and the Marshall Space Flight Centre in the United States. It employed up to five multiple Doppler radars and 55 PAM observing stations, as well as rawinsondes launched hourly during storm days.

3.5.22 The foregoing and other research projects, and the continuing analysis of aircraft accidents/incidents in which wind shear was cited as a factor have confirmed without a doubt the reality of gust fronts, downbursts and microbursts, and the serious hazard they can pose to aircraft in flight. Subsequent efforts in the 1990s, therefore, focused on the detection of wind shear caused by these phenomena using ground-based remote-sensing equipment and airborne wind shear detection/warning equipment and the provision of timely warnings to pilots. The successful results of these efforts are described in Chapter 5.

THE TORNADO

3.5.23 Although microbursts generate strong and dangerous winds, the tornado generates the strongest surface winds of all. In many respects the tornado is the antithesis of the microburst. It results from an extremely concentrated low-pressure system whose vortex literally sucks in the surrounding air, while the microburst is a localized high-pressure system in which the low-level winds diverge from its centre. The generalized structure and scale of the various pressure systems that produce damaging surface winds, their classification in commonly accepted planetary scales and the expected maximum wind speeds proposed by Fujita (1981) are shown in Figure 3-18.⁴⁷ 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 (70–124 km/h (35–62 kt)) through F5 (454–552 km/h (227–276 kt)).

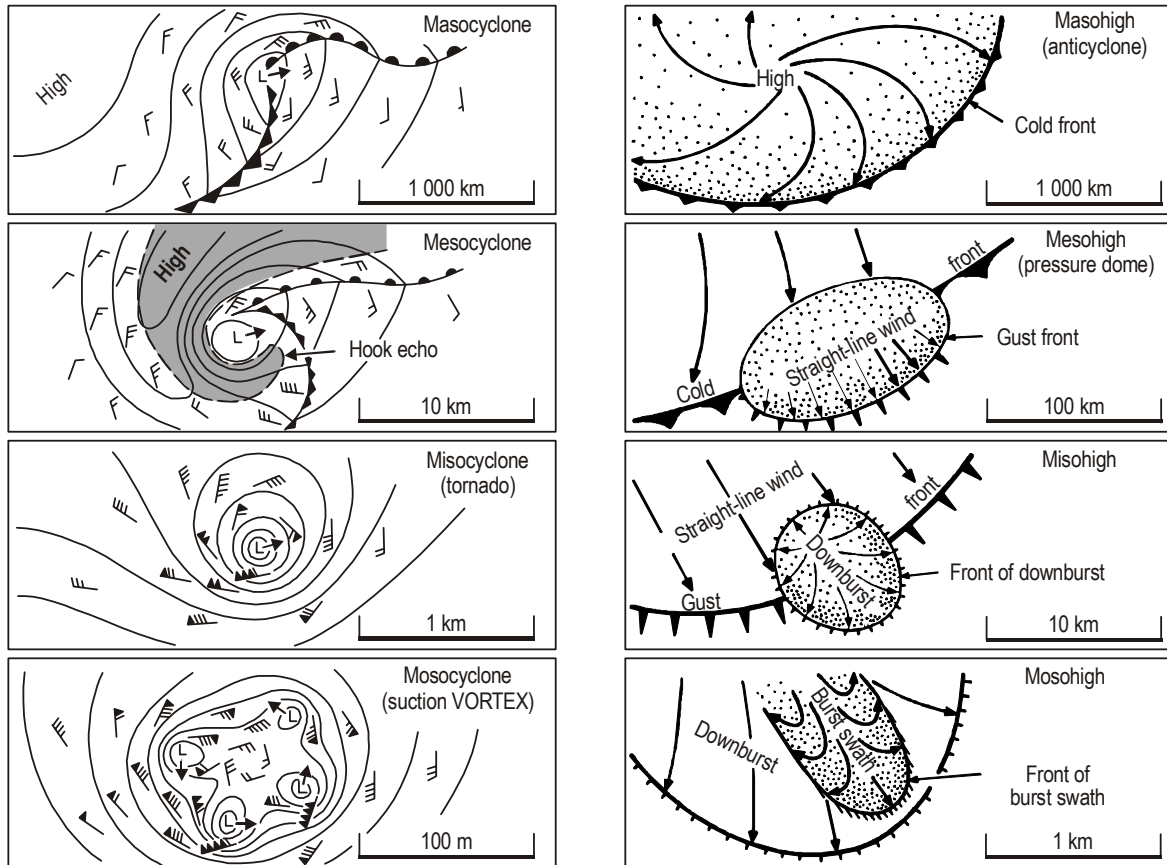
3.5.24 Tornadoes are produced in the concentrated and persistent updrafts of severe thunderstorms. Such severe thunderstorms are generally of the same type as those that produce microbursts, with tornadoes forming in the updrafts, and microbursts and gust fronts forming in the downdrafts. There is, of course, considerably more to it than this because tornadoes do not necessarily develop in all severe thunderstorms. One of the most important questions facing research meteorologists continues to be why some severe thunderstorms generate tornadoes while others do not. A good description of a tornado given by Snow⁴⁸ 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 (3 300 ft). Winds in a tornado are almost always cyclonic.” The sheer destructive power of a tornado results from a proportion of the vast amount of energy available in a severe thunderstorm concentrated in an area usually no more than several hundred metres in diameter. The highest wind speed measured in a tornado was 270 km/h (135 kt);⁴⁷ however, the analysis of tornado damage to engineered structures where 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 indicate that maximum wind speeds approach or exceed 400 km/h (200 kt).^{49,50}

3.5.25 Most tornadoes (and all strong ones) form within “mesocyclones”^h, which frequently are also associated with reports of heavy hail and damaging downburst winds (see Figure 3-18 a)).³⁰ Because all mesocyclones do not produce tornadoes, the presence of a mesocyclone is clearly necessary but not sufficient for tornado development.

3.5.26 There is evidence from the analysis of tornado wind damage that there are intense, organized “suction vortices” within the parent tornado (their scale is indicated in Figure 3-18 a)). A model of such a tornado proposed by Fujita⁴⁷ is shown in Figure 3-19. 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”ⁱ, which have a far wider distribution throughout the world than tornadoes over land.⁵¹

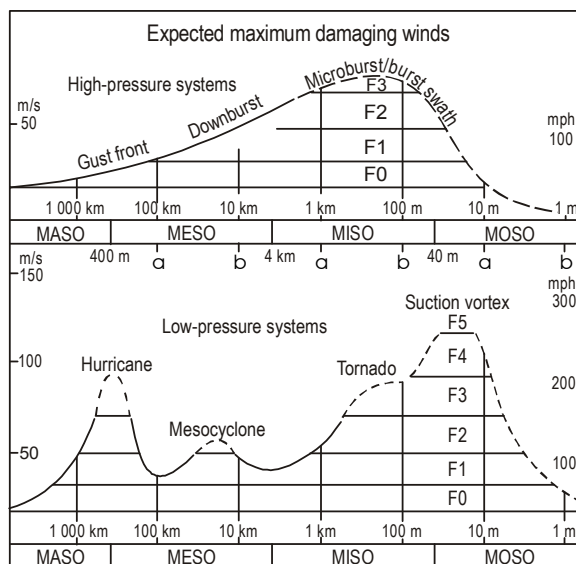
h. A mesocyclone is a mesoscale cyclonic vortex with core diameter between 3 and 9 km which frequently produces a recognizable radar “signature”.

i. 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.



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.

b) Maso-, meso-, miso- and moso-highs in the context of generalized planetary scales.



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.

Figure 3-18. Generalized planetary scales
(from Fujita, 1981, and adapted by ICAO)

3.5.27 It is obvious that tornadoes represent an extreme case of wind shear and a hazard to aircraft landing and taking off. 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.

The danger that tornadoes pose to aviation cannot be taken too lightly 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.

THE SUPERCELL STORM

3.5.28 Paragraph 3.5.5 and Table 3-1 mention “supercell” storms. The main features that 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;
- d) a tendency to move to the right of the mean wind flow; and
- e) the phenomenal damage that can result from the associated hail and, in certain regions of the world, from the families of tornadoes and microbursts.⁵²

Browning coined the term “supercell” in 1962 in connection with a very severe hailstorm that caused extensive damage near Wokingham, England, in July 1959. The typical structure of a supercell storm, developed in some detail since the advent of multiple Doppler radar observation of such storms and computer simulation,²⁹ is shown diagrammatically in Figure 3-20.⁵³

3.5.29 Perhaps the 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 are estimated as being in excess of 40 m/s (or nearly 8 000 ft/min), 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.

3.5.30 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, therefore sustaining the updraft.

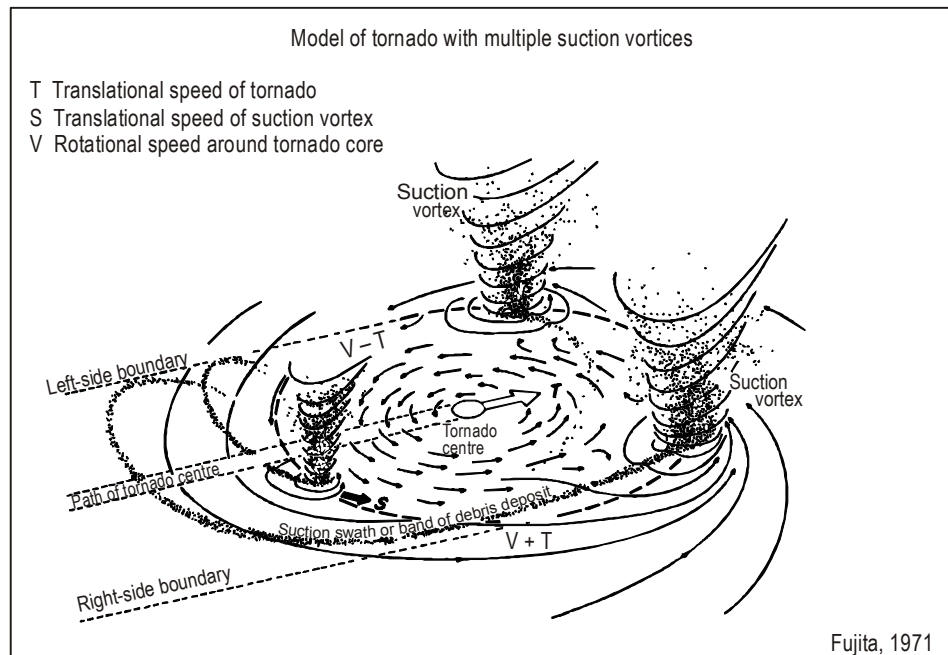


Figure 3-19. A model of a tornado with multiple suction vortices
(from Fujita, 1971, and adapted by ICAO)

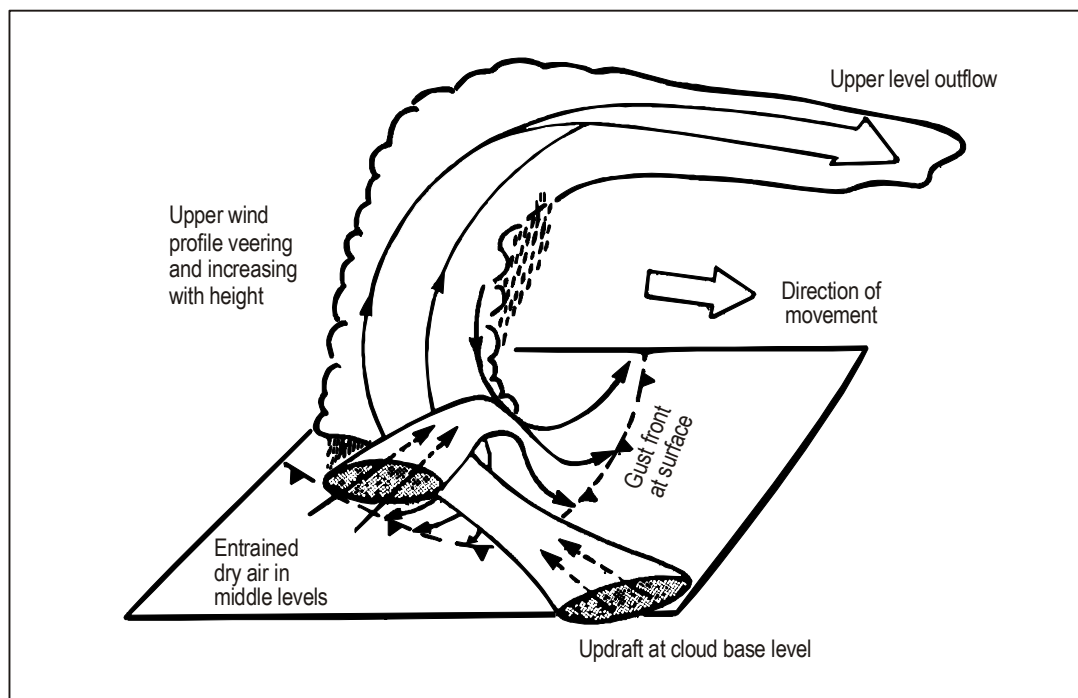


Figure 3-20. Diagrammatic structure of a “supercell” thunderstorm
(after A.J. Thorpe, 1981)

3.5.31 The atmospheric prerequisites for the development of supercell thunderstorms given sufficiently unstable conditions are, as mentioned in 3.5.5, the wind veering (northern hemisphere) and increasing with height (shear $\geq 0.001 \text{ s}^{-1}$) and reasonably strong winds at all levels. Very dry air aloft is conducive to the formation of severe hail. Fortunately supercell storms are not widespread or frequent because the hail, microbursts and tornadoes associated with them present extreme danger to aircraft landing and taking off.

3.5.32 Recent research into incidents in which aircraft have encountered severe 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. While 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. It is also believed that vortices or waves can develop for some distance downwind of thunderstorm tops.⁵⁴ 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, whereas those crossing or travelling with the airstream would have no such warning. NASA Ames Research Centre in California is attempting to develop a model for use on flight simulators that reproduces the effects on different types of aircraft.

3.6 CLIMATOLOGY OF CONVECTIVE WIND SHEAR

3.6.1 The annual frequency distribution of thunderstorms throughout the world is shown in Figure 3-21,⁵⁵ and distribution over the United States is shown in Figure 3-22.⁵⁶ The thunderstorm regions of the United States and their associated diurnal and seasonal variation of thunderstorm activity are shown in Table 3-2.⁵⁷ The world distribution of accidents/incidents where microbursts were confirmed or suspected to have been a factor is shown in Figure 3-23⁵⁸, and the paths of confirmed violent tornadoes reported over the United States during the period 1880–1982 are shown in Figure 3-24.⁵⁹

3.6.2 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 wider distribution, most tornadoes occur in the central and south-eastern parts of the United States. The worldwide distribution of microbursts is not known since they are generally not visible directly and their effects, such as forest or crop damage, are unlikely to be recognized as due to a microburst unless detailed aerial damage surveys are made.

3.6.3 Microbursts have only achieved notoriety in about the past ten years, 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 ensure 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 amount of worldwide data on low-level wind shear in the vicinity of aerodromes was derived from the airborne integrated data systems (AIDS) on-board British Airways (BA)⁶⁰ and Royal

Dutch Airlines (KLM)^{61,62} wide-bodied jet aircraft (BA B747s, KLM B747s and DC-10s). Up to 1984, the database comprised 10 000 landings by KLM aircraft of which 8 573 have been analysed^{j,63} so far and selected data published, and 9 136 landings by BA aircraft all of which have been analysed and the results published. In Germany, airborne integrated data systems (AIDS) data were collected from Deutsche Lufthansa Airbus A300 aircraft for one year, stored and then analysed.⁶⁴

3.7.2 The data from the BA landings were analysed by the Royal Aircraft Establishment (RAE), United Kingdom, using discrete gust methods. The statistics on the 1 in 1 000 probability of encountering wind shears with particular patterns of headwind speed changes calculated from over 9 000 BA landings are shown in Table 3-3.⁶⁰ Regarding the KLM data, detailed analysis pertaining to 1 909 landings at Schiphol Airport, Netherlands, and an analysis of worldwide “worst-case airports” were published. From this data various probability statistics were calculated: Figure 3-25 shows the probability density distribution of along-track wind change per 30 m (100 ft) height, and Figure 3-26 shows probabilities of exceeding given wind shear values, all of which are applicable to Schiphol Airport.⁶¹

3.7.3 One reason 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, they provide invaluable data on the types and intensity of wind shear at many aerodromes throughout the world.^k The Woodfield and Woods paper discusses the variation of wind shear at different aerodromes as follows:

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 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 31. 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 overall selection of airports is representative of a wide variety of conditions around the world, the overall distributions are believed to be representative of most international route systems.

Haverding⁶² lists the “worst-case” airport sequence (based on 300 landings or more), from highest to lowest fraction of wind shear landings, as JFK (New York), Houston, Montréal, Schiphol (Amsterdam), Dubai, Singapore and Bangkok.

j. 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.

k. Readers interested in wind shear at specific aerodromes are advised to consult the original papers by Woodfield and Woods (1984)⁶⁰ and by Haverdings (1981)⁶².

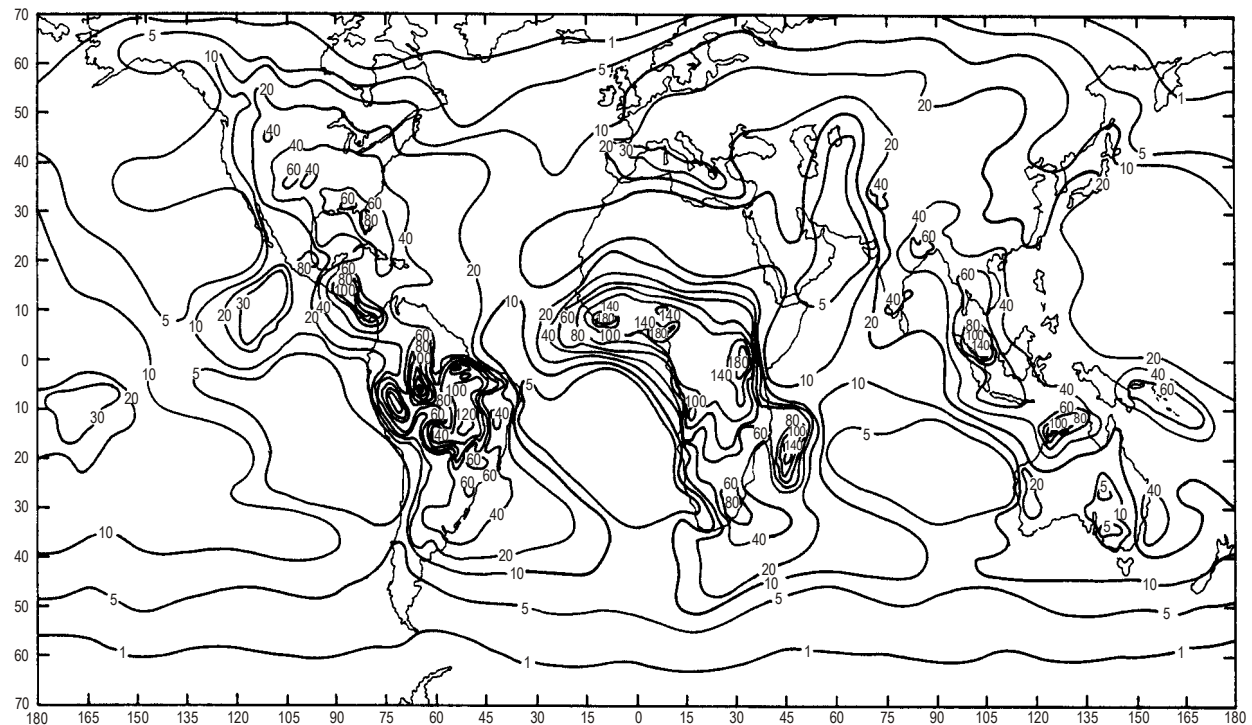


Figure 3-21. Average annual worldwide thunderstorm days
(from WMO Publication No. 21 TP21, 1953)

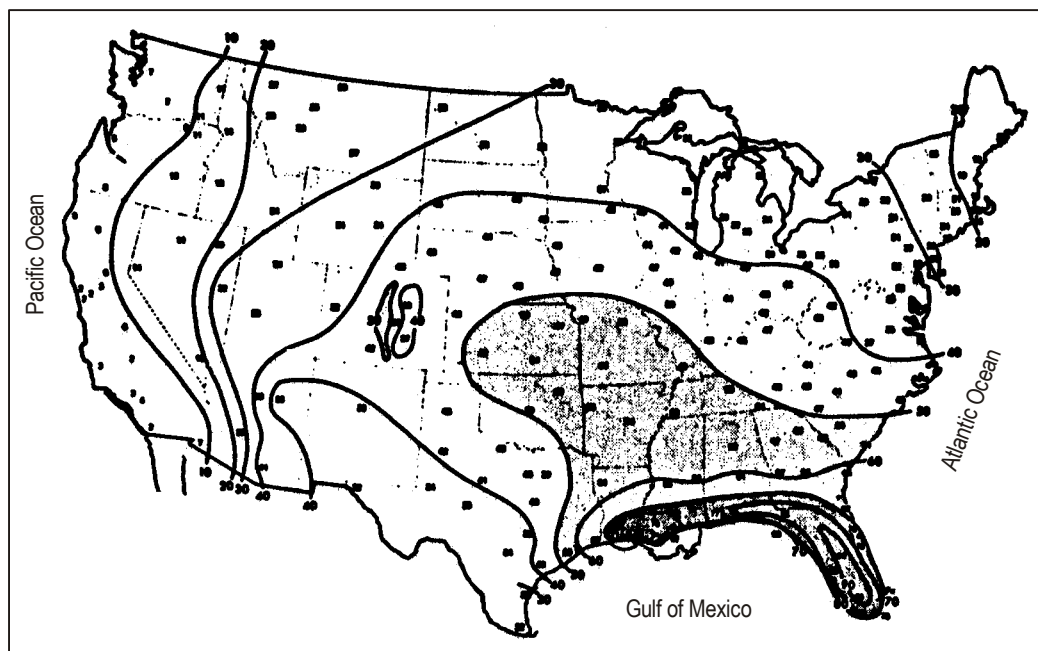


Figure 3-22. Mean number of days per year with thunderstorms in the United States, 1951–1975
(from Court and Griffiths, 1982)

Table 3-2. Thunderstorm regions of the United States
(from Easterling and Robinson, 1985)

Region	Spring		Summer		Fall		Winter	
	<i>t</i>	<i>a</i>	<i>t</i>	<i>a</i>	<i>t</i>	<i>a</i>	<i>t</i>	<i>a</i>
West Coast	A	H	–	–	A/N	L/M	A/N	M
Inter-Montane	A	H	A/N	H	A	H	–	–
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
North-east	A	M	A	M	A	M	–	–
South-east	A	L/M	A	H	A	H	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 = amplitude: L = low (≤ 0.5)
 A = afternoon M = medium (0.5–1.0)
 N = night H = high (≥ 1.0)

**Table 3-3. Single-ramp wind shears with a
1 in 1 000 landings probability — worldwide data**
(from Woodfield and Woods, 1984)

Nominal ramp length <i>m</i>	Ramp lengths for 1 000 landings	Speed change (ramp length) ^{1/3} (m/s)/m ^{1/3}	Ramp length <i>m</i>	Speed change <i>kt</i>	Gradient <i>kt/100 m</i>
305	30 000	–1.04	200	–11.8	–5.9
			300	–13.5	–4.5
			400	–14.9	–3.7
609	15 000	–0.85	400	–12.2	–3.0
			600	–13.9	–2.3
			800	–15.3	–1.9
1 218	7 500	–0.78	800	–14.1	–1.8
			1 200	–16.1	–1.3
			1 600	–17.7	–1.1

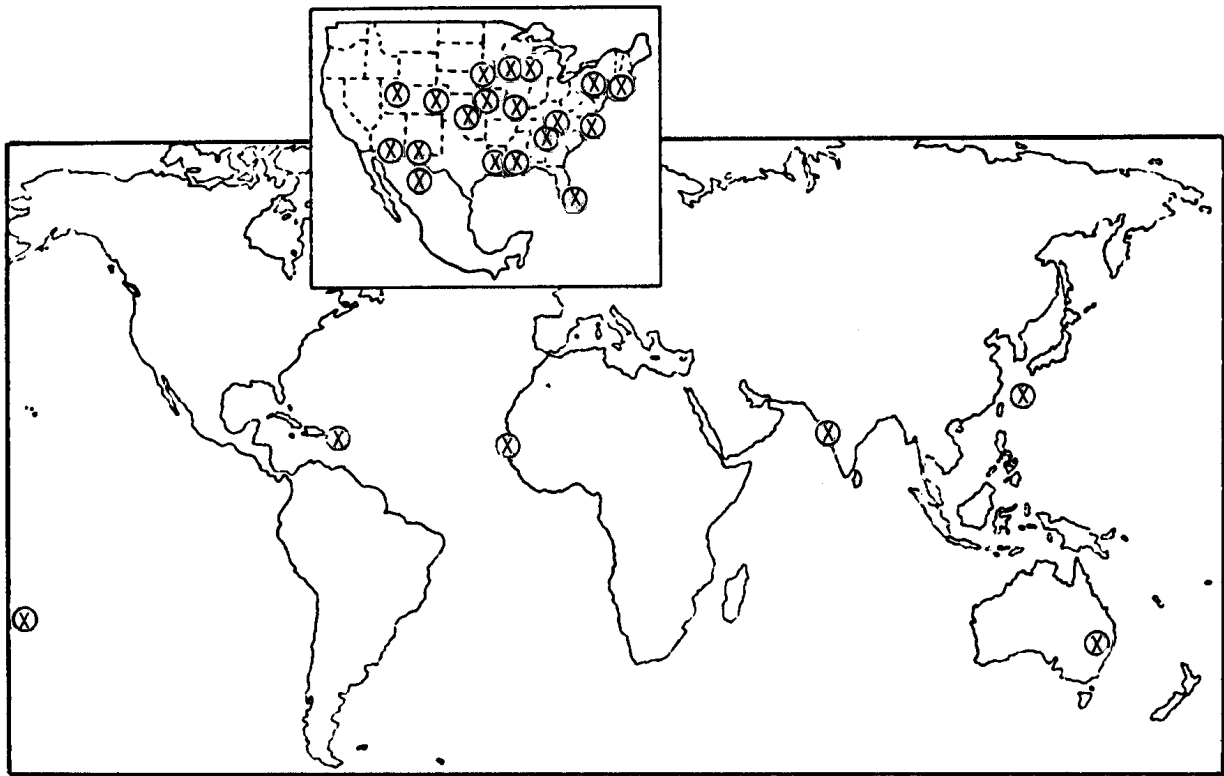


Figure 3-23. World distribution of accidents/incidents in which microbursts have been confirmed or suspected
(from McCarthy and Wilson, 1984, and adapted by ICAO)

3.7.4 The Netherlands' National Aerospace Laboratory (NLR) has also analysed the worldwide 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 database is likely to comprise over 20 000 landings worldwide 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 5.2.5 to 5.2.14).

3.8 WAKE VORTICES

3.8.1 Wind shear is generated behind every aircraft in flight, mainly as wing tip vortices forming two counter-rotating cylindrical vortex tubes trailing behind the wing tips. Such vortices are severe when generated by large, wide-bodied jet aircraft. 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 their effect 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 the *Procedures for Air Navigation Services — Air Traffic Management* (Doc 4444), Chapters 6 and 7.

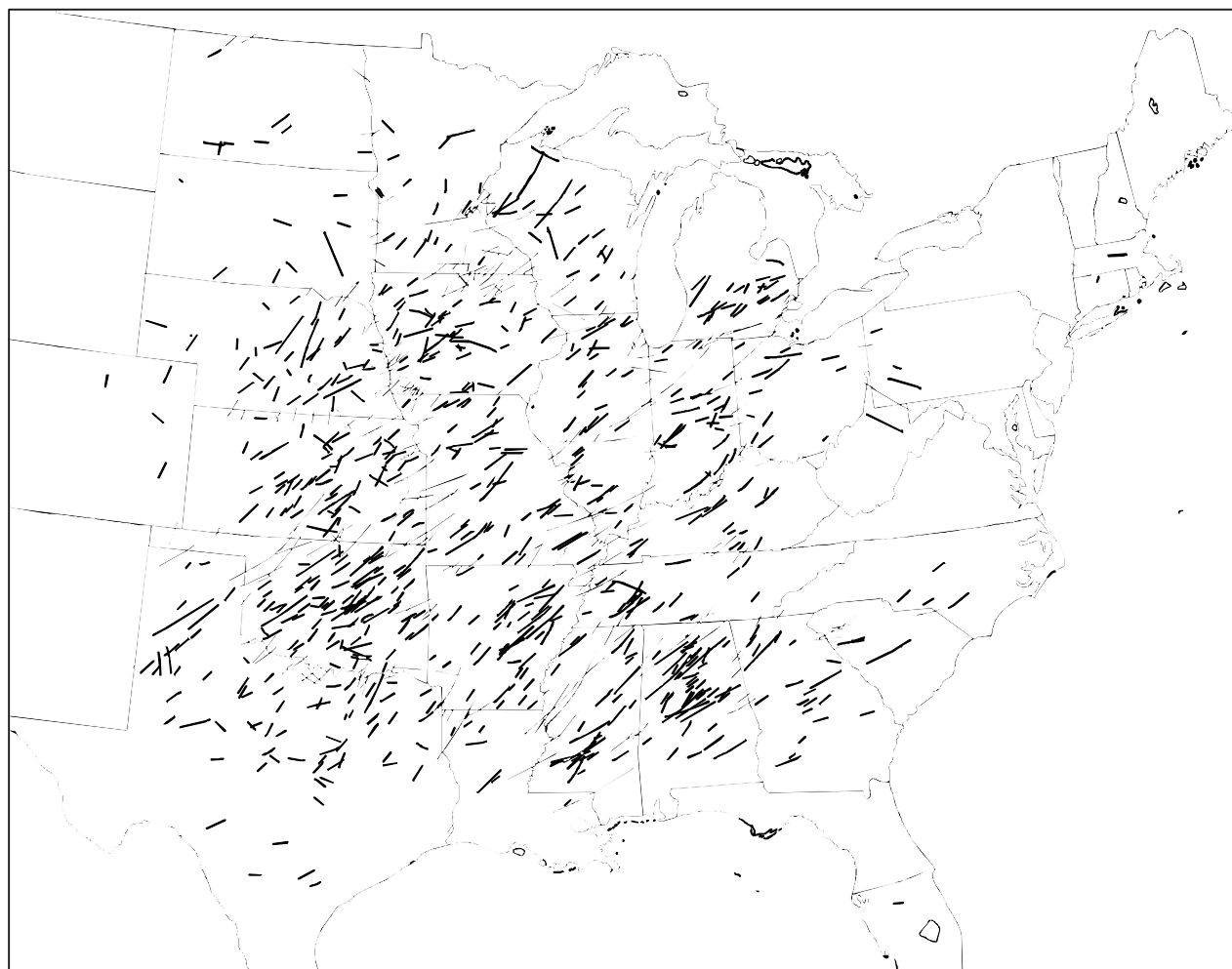


Figure 3-24. Paths of 972 confirmable violent (F4/5) tornadoes over the United States, 1880–1982
(from Grazulis and Abbey, 1983)

3.8.2 Research is being conducted in a number of States (e.g. Germany, Netherlands, United Kingdom and United States) on the development of a “wake vortex avoidance system” which, based upon relevant real-time MET information, would permit air traffic controllers (ATCOs) 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 air traffic increases.^{65,66} It should be noted, however, that while such experiments tend to confirm the technical feasibility of such a system, for practical reasons it has been difficult to establish it operationally. However, as fully integrated weather observing systems that provide a four-dimensional picture of the wind field over the airport become available at the busiest, capacity-restricted airports (see 5.1.10), the inclusion of wake vortex forecasts may become cost-effective and operationally feasible to contribute to increasing runway and terminal airspace capacity.

3.8.3 Development work on wake vortex systems in the United States takes full advantage of the various wind sensor systems already installed at many busy aerodromes as part of the ITWS (see 5.1.31 *et*

seq.). Specific algorithms were developed to merge this data, such as the Doppler profiling algorithm, which was the prototype AVOSS wind analysis system (AWAS). These have demonstrated that accurate wind profiles with 50-metre vertical resolution can be generated from terminal Doppler weather radar (TDWR) data⁶⁷ (see 5.1.17 to 5.1.42). The next step is to design an algorithm to format a suitable message for ATC and pilots to warn of profile shears that are strong enough to affect their approach and landing at the aerodrome.

3.9 AERODYNAMIC PENALTIES OF HEAVY RAIN

3.9.1 Some researchers⁶⁸ have postulated that in a number of aircraft accidents where wind shear was cited as being involved (e.g. the Eastern Airlines accident at JFK International Airport in 1975), much of the deterioration in aircraft performance that occurred may be accounted for by the aerodynamic penalties due to heavy rain. 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;

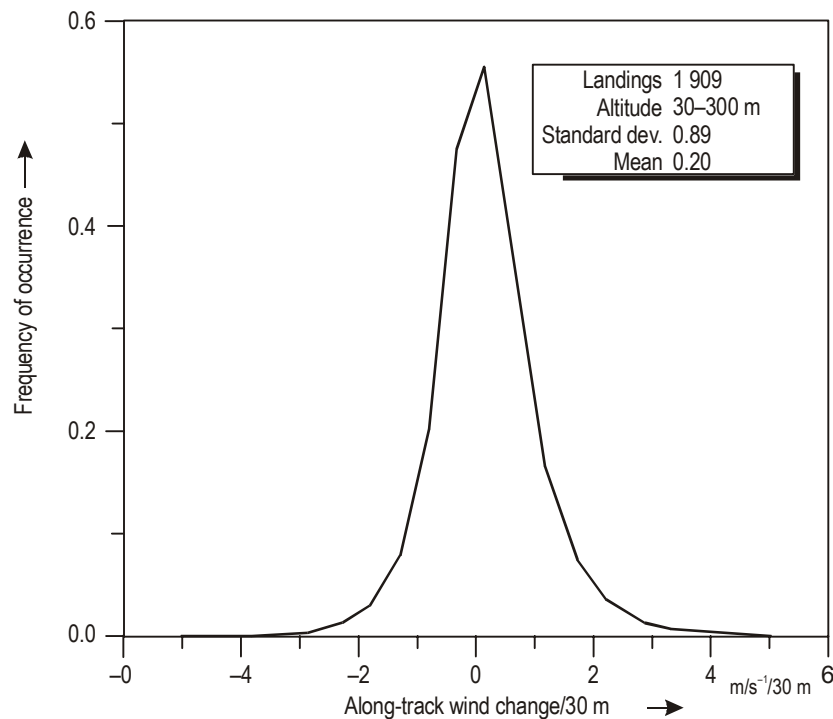


Figure 3-25. Probability density distribution of along-track wind change per 30 m for Schiphol Airport, for a height range of 30 to 300 m, based on AIDS data of November 1977–1978 (from Haverdings, 1980, and adapted by ICAO)

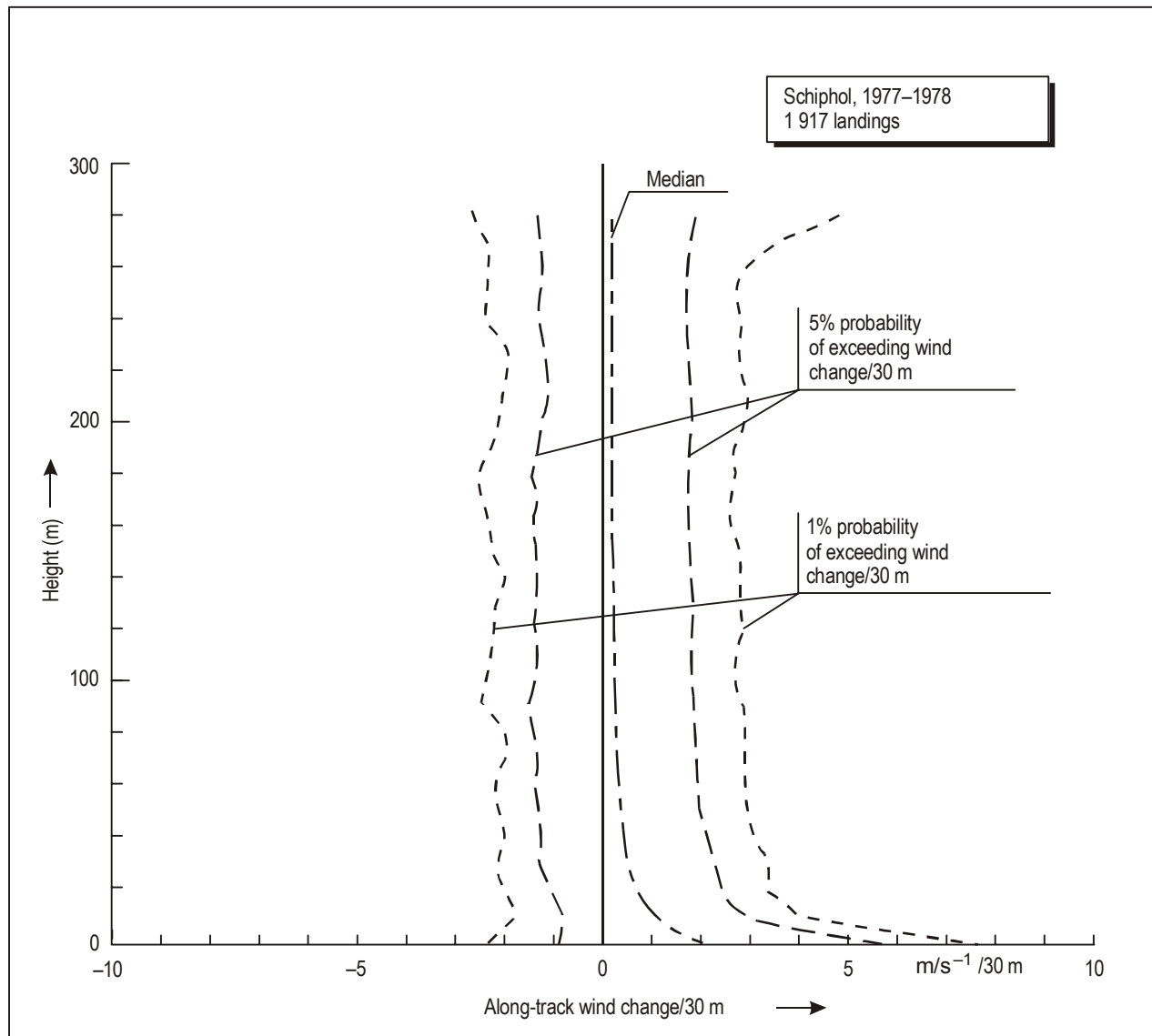


Figure 3-26. 50%, 5% and 1% probabilities of exceeding along-track wind change/30 m per landing, versus height
(from Haverdings, 1980, and adapted by ICAO)

- c) this film of water can be “roughened” by subsequent drop impact and surface stresses that 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); and
- b) lift/drag penalties could be very significant for rainfall rates exceeding 100 mm/h (heavy rain).

3.9.3 Aircraft landing simulations indicate that a 400 mm/h rainfall rate encountered on the approach may produce an aircraft performance deterioration equivalent to a wind shear of 18 km/h per 30 m (9 kt/100 ft). In addition, 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 recommends that investigations continue (see Appendix 2).

3.9.4 Aside from the ongoing debate regarding the aerodynamic penalties of heavy rain, 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 that crashed in 1977 while making an emergency landing after losing all-engine power in flight; the United States National Transport Safety Board (NTSB) 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.⁶⁹ 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 degrees from the horizontal.

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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 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 engines, 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 has to 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 $\sin \gamma \approx \gamma$ and equation (1) becomes:

$$T = D + W\gamma$$

and so

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

Therefore, the angle of climb depends directly on the excess of thrust over drag and inversely on the weight. In 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 All this information is relevant to wind shear as is seen by examining what each of the four main forces acting on an aircraft comprises. The weight is simply $W = mg$ (mass of the aircraft $\times$ acceleration due to gravity); the thrust (T) is the direct force produced by the engines; 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:

$$L = \frac{1}{2} C_L \rho S V^2$$

and

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

depend on, among other things, the angle of attack (α) of the wing. These equations show that lift and drag depend on the angle of attack (through C_L) and the square of the airspeed, and that wind shear can affect both angle of attack and airspeed, which in turn affect lift and drag, which ultimately disturb the equilibrium of the aircraft (see Appendix 3).

EFFECT OF WIND SHEAR ON AIRSPEED

4.1.5 The statement “wind affects airspeed” seems to contradict the rule stressed in basic pilot training which is “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:

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

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 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 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:

$$\begin{aligned} &140 \text{ kt ground speed and no wind} \\ &140 \text{ kt (GS)} = 140 \text{ kt (TAS)} - 0 \text{ (WIND)} \end{aligned}$$

$$\begin{aligned} &\text{a gradual change to a 20-kt headwind becomes} \\ &120 \text{ kt (GS)} = 140 \text{ kt (TAS)} - 20 \text{ kt (WIND)} \end{aligned}$$

Note.— In the above example, the non-SI alternative unit “knot” is used for speed. In accordance with Annex 5, the corresponding primary unit “kilometre per hour” may be used instead.

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

$$\begin{aligned} &140 \text{ kt ground speed and no wind} \\ &140 \text{ kt (GS)} = 140 \text{ kt (TAS)} - 0 \text{ (WIND)} \end{aligned}$$

a rapid shear to 20-kt headwind temporarily becomes

$$140 \text{ kt (GS)} = 160 \text{ kt (TAS)} - 20 \text{ kt (WIND)}$$

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

$$120 \text{ kt (GS)} = 140 \text{ kt (TAS)} - 20 \text{ kt (WIND)}$$

as in the previous example.

The way in which the aircraft restores equilibrium by virtue of its longitudinal stability is covered in 4.1.11 to 4.1.13.

4.1.6 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:

$$F = ma \text{ (mass} \times \text{acceleration)} \text{ or } F = \frac{W}{g} a$$

Under the transient effect of wind shear when the equilibrium is disturbed, equations (1) to (6) would be rewritten:³

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

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

The aircraft accelerates in the direction **in which the disturbing (resultant) force acts** until equilibrium is again attained. The bold text emphasizes that, although equilibrium is 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 that 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 it to return to the intended flight path, the pilot has 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.

Note.— At this point, as far as the transient wind shear effect on airspeed is concerned, a decreasing headwind has exactly the same transient effect on airspeed (a decrease) as an increasing tailwind. Similarly, an increasing headwind has exactly the same transient effect on airspeed (an increase) as a decreasing tailwind. Additional considerations apply once equilibrium is re-established particularly for landing aircraft as discussed in 4.2.6.

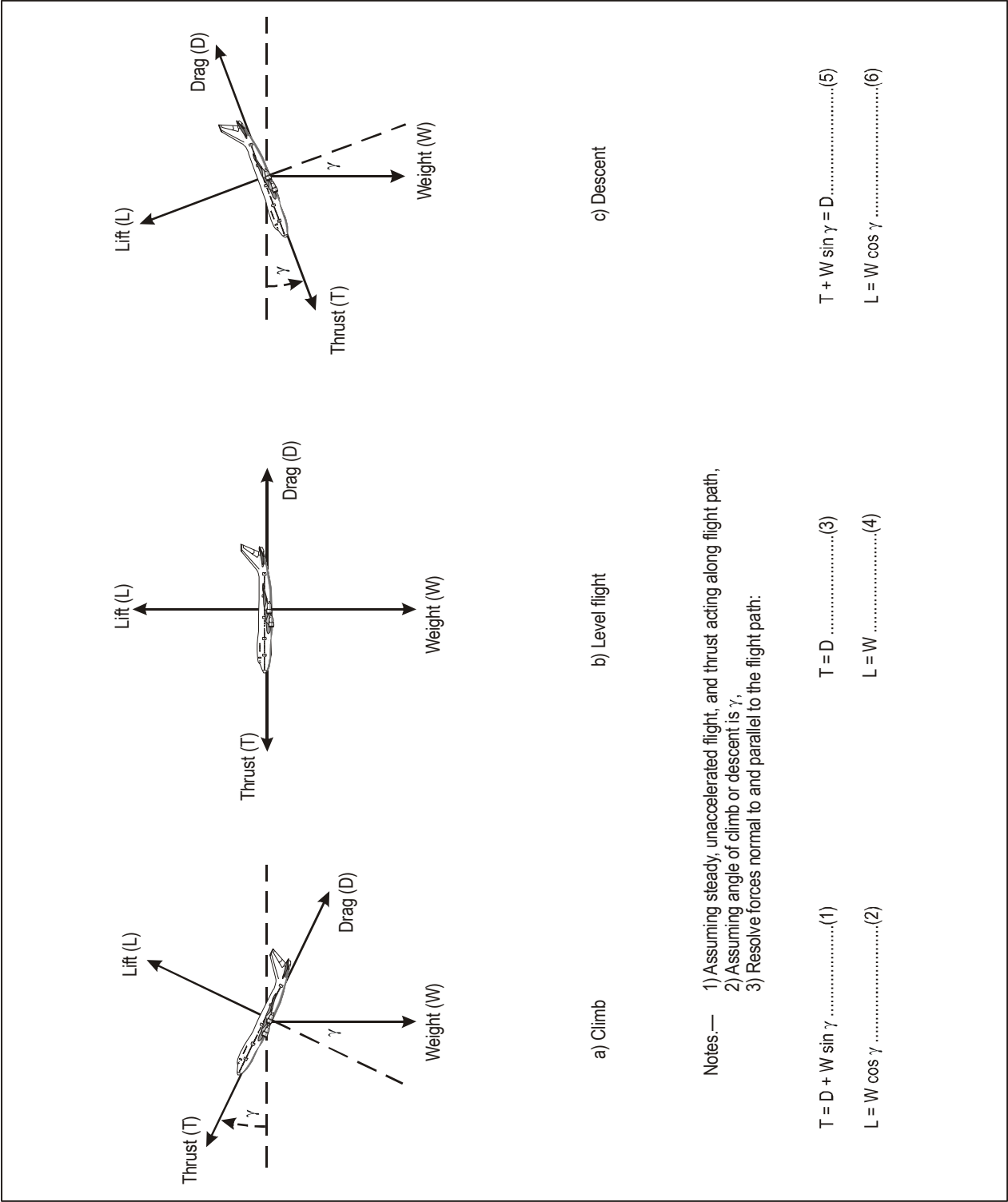


Figure 4-1. Forces acting on an aircraft in flight

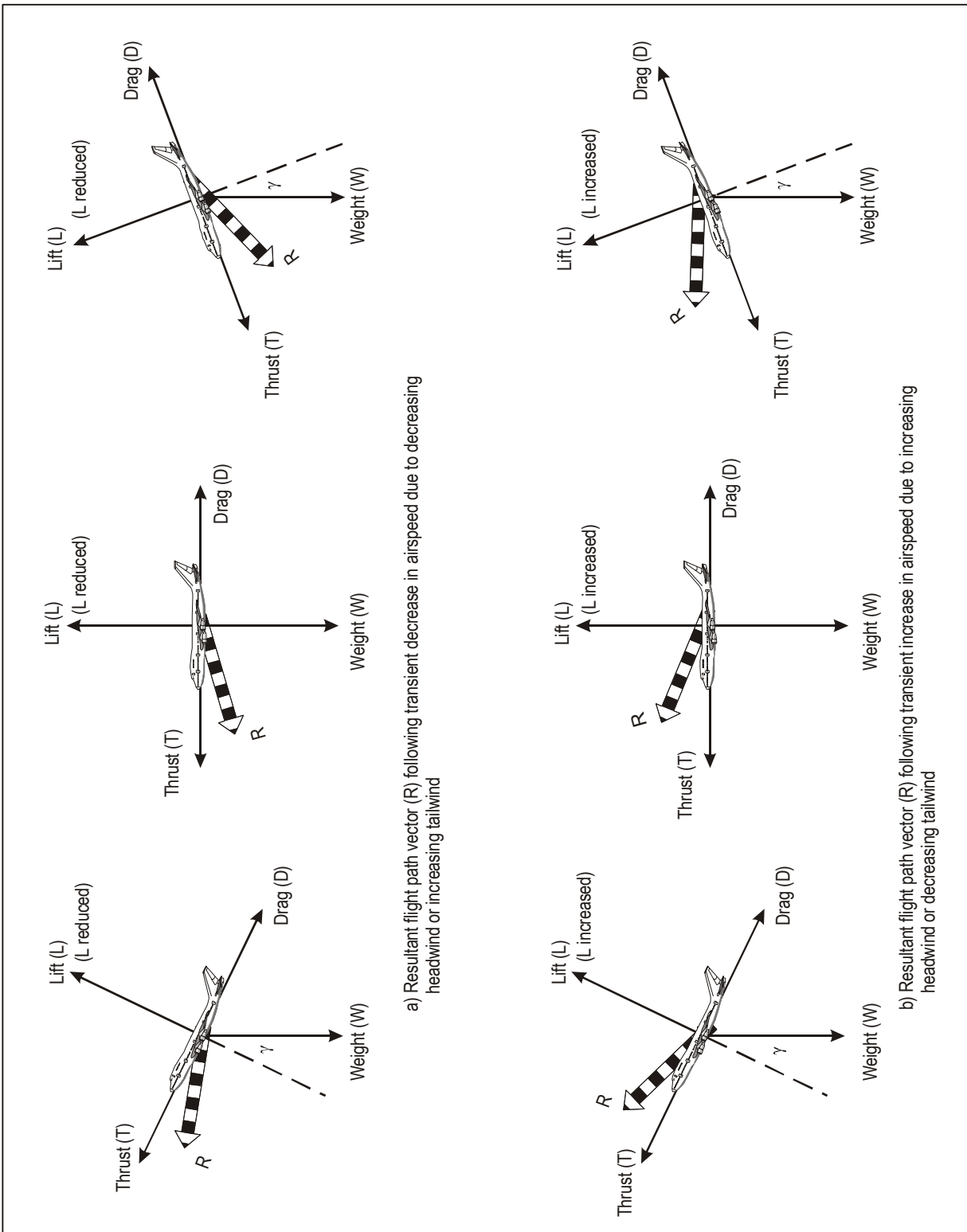


Figure 4-2. Resultant flight path vector due to shear in the horizontal wind

EFFECT OF WIND SHEAR ON ANGLE OF ATTACK

4.1.7 In 4.1.4 it states that wind shear can affect the angle of attack. Paragraph 2.1.1 discusses special cases in the atmosphere where the vertical component of the wind is not zero (or very small) and may even predominate over the headwind/tailwind and crosswind components. Such cases include mountain waves and especially downbursts associated with convective clouds (see 3.2.8 and 3.5.11 to 3.5.14, respectively). Paragraphs 4.1.8 and 4.1.9 concentrate on the wind shear effect of downbursts because 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.

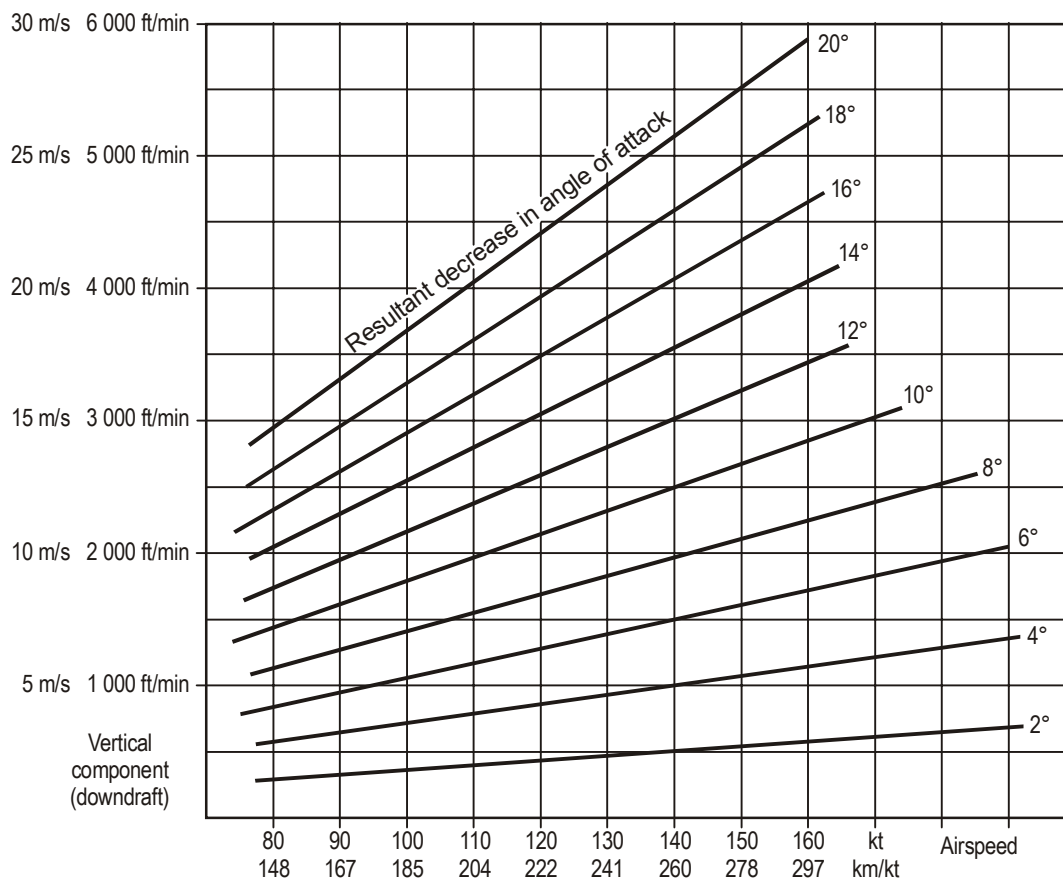
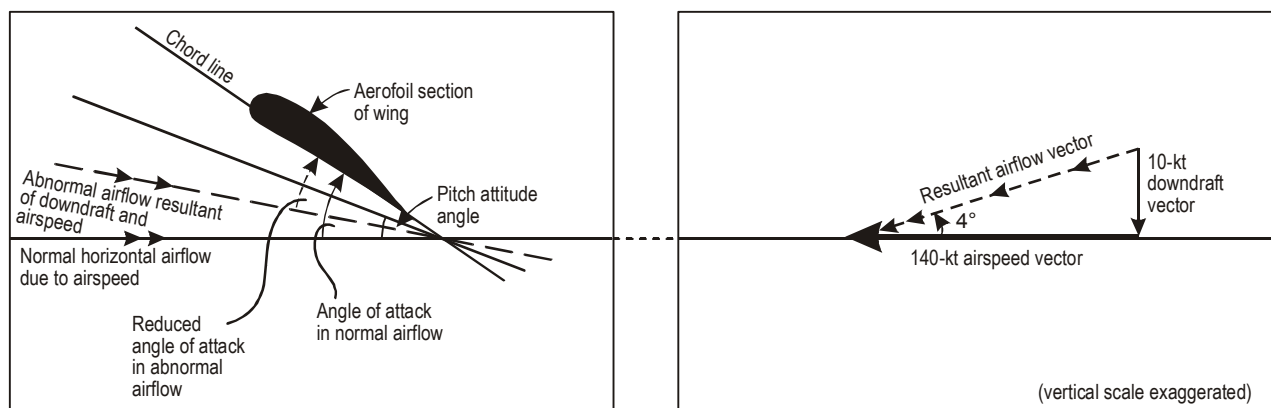
4.1.8 In level (non-turning) flight, an aircraft is flown at a pitch attitude that provides for an angle of attack (α) of the wing appropriate to the airspeed. The relationship between the angle of attack and the airspeed assumes that the air is striking the leading edge of the wing horizontally (i.e. negligible upward or downward component) and usually 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 Figure 4-3 shows how the angle of attack is reduced by a downdraft while the pitch attitude angle remains unchanged. The example given is a downdraft of 5 m/s (1 000 ft/min) and an aircraft with an airspeed of 280 km/h (140 kt) reducing the angle of attack by approximately 4 degrees with no change in pitch attitude.

Note.— While downdraft speeds of 5 m/s (1 000 ft/min) are probably fairly typical of most downdrafts, peak downdraft speeds in excess of 25 m/s (5 000 ft/min) have been measured in severe thunderstorms.

4.1.9 As in the case of a change in airspeed due to wind shear dealt with in 4.1.5, 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 that 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 therefore has the same initial effect on an aircraft as a decreasing headwind or increasing tailwind, and an updraft has 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 while 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 as seen in 4.2.6.

EFFECT OF CROSSWIND SHEAR

4.1.10 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 mentioned in 2.1.3, because runways are oriented, as far as practicable, in the direction of the least crosswind component, the 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 that there is no crosswind component shear or that it has no effect on the aircraft. In fact there is nearly always some crosswind component shear involved, but generally 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 which are discussed in 4.2.8.



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 a ttrack due to sharp-edged downdraft

RESTORATION OF EQUILIBRIUM DUE TO LONGITUDINAL STABILITY

4.1.11 It is necessary to consider how the aircraft restores equilibrium conditions after a disturbance that might be caused by wind shear. The restoring effect is referred to as the stability of the aircraft, which is its ability to return to a given condition of flight after having been slightly disturbed from that condition. The aircraft is designed to be stable in all three axes (pitch, roll and yaw). In a disturbance due to wind shear, the stability about the pitch axis or the longitudinal stability is of particular interest. 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.⁵ (The detailed analysis of these forces is a very complex matter and will not be dealt with here.) As far as longitudinal stability is concerned, the restoring forces are mainly due to the tailplane or horizontal stabilizer. For the particular flight conditions of concern (straight and 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).

4.1.12 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^a with an oscillation period of about 40 seconds. 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 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, produce a well-damped oscillation in pitch of about five seconds, usually referred to as the short-period oscillation (see Figure 4-3).

4.1.13 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.

4.2 AIRCRAFT PERFORMANCE IN PARTICULAR WIND SHEAR CONDITIONS

GENERAL

4.2.1 In this and the following sections, the MET 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. The conclusion which emerges is that an encounter with wind shear should be avoided as far as possible. Much time is spent analysing in detail the phenomenon and its effect on aircraft in order to assist aeronautical meteorologists and provide a

a. The unusual term “phugoid” was coined by the British aerodynamicist, Frederick Lanchester, at the beginning of the twentieth century. He derived the term from two Greek words meaning literally “flight-like”; however, unfortunately he used the Greek word for “flight” in the sense of “fugitive” instead of “flight of a bird” as intended.

firm basis for assisting pilots in recognizing and thus avoiding potential wind shear situations. Knowing the range of wind shear types and intensity that have been recorded gives 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, however, that pilots are not encouraged to attempt to fly in known or suspected wind shear conditions; on the contrary, the overwhelming advice is AVOID AVOID AVOID.

HEADWIND/TAILWIND WIND SHEAR

4.2.2 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, is dealt with in 4.2.9 to 4.2.13 since 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. A frontal surface may be considered a special case of a wind profile, 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 knots) from the top of the layer to the bottom. In general, wind shear is only a problem when both of these characteristics are significant.

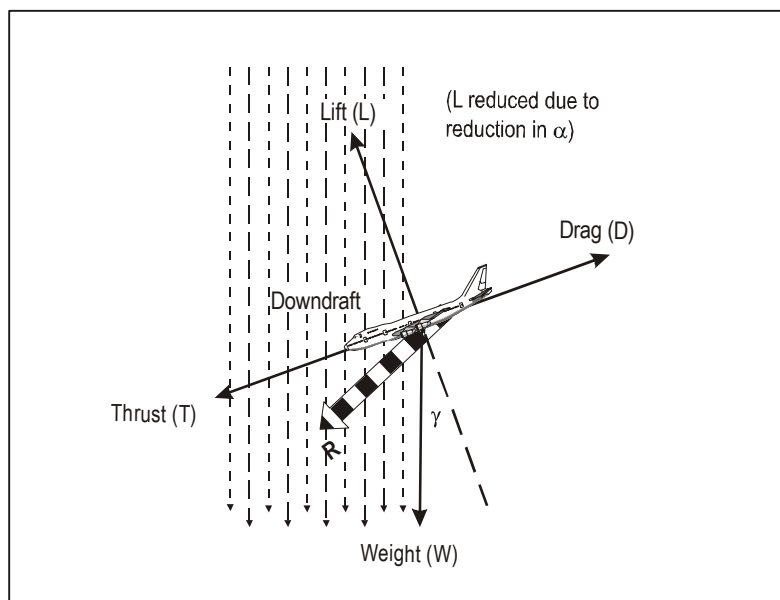


Figure 4-4. Resultant flight path vector due to shear in the vertical component of the wind (downdraft) — hypothetical sharp-edged steady downdraft

Note.— Both 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 independent of an aircraft. Both characteristics have an effect on aircraft landing or taking off, but the effect also depends on how fast the aircraft transits the shear layer, i.e. the rate of encounter measured, for example, in knots per second.⁶

4.2.3 In the example given in 2.4.3, the wind shear intensity is 8.4 km/h per 30 m (4.2 kt/100 ft), and the rate of descent of the aircraft is 3.9 m/s (13 ft/s); hence the wind encountered by this aircraft will decelerate by $\frac{4.2 \times 13}{100} = 0.546$ kt every second.⁷ The approximate airspeed changes in different wind shear

intensities and aircraft rates of descent on a 3-degree glide slope are shown in Figure 4-5. The total wind shear over the layer in this example from 300 m (1 000 ft) AGL to 150 m (500 ft) AGL is 42 km/h (21 kt), and assuming 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 42 km/h (21 kt) at a rate of 1.09 km/h per s (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 (see 2.3.2).

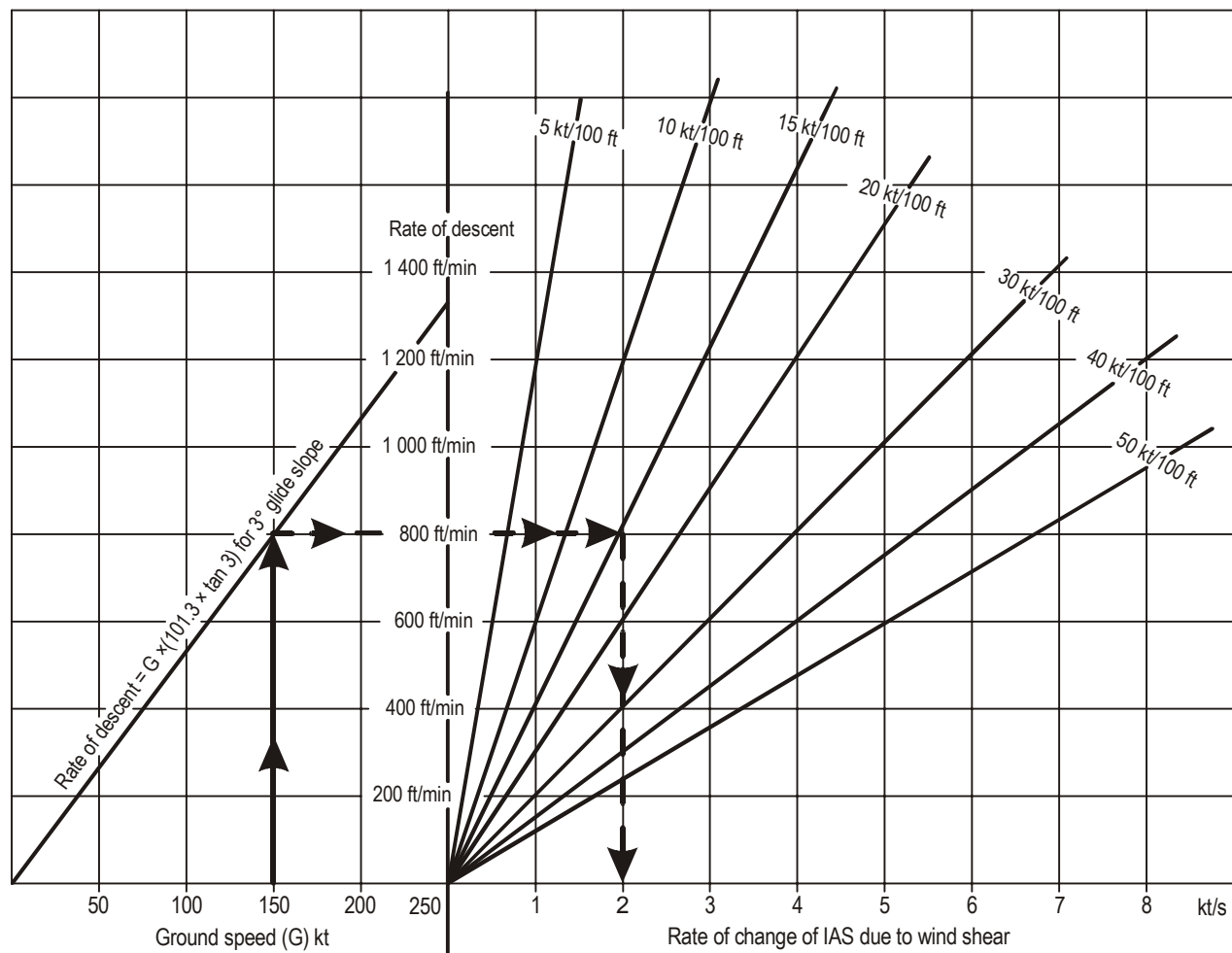


Figure 4-5. Rate of change of IAS due to wind shear and aircraft rate of descent
(after Lord, 1978, and adapted by ICAO)

4.2.4 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 to fly 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).

4.2.5 From the pilot’s point of view, the actual sequence of events that might be observed from the flight deck instruments depends largely 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. However, the sequence of events is relatively straightforward if the aircraft’s response 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’s 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 that is critical so near the ground and obstacles, not the airspeed, as long as the latter remains sufficiently above the stall speed.

4.2.6 The techniques recommended for use by pilots to control the flight path are dealt with in 4.3; however, first it is necessary to look at the reasoning behind the techniques used in particular wind shear situations. The pilot uses elevator (pitch attitude, hence angle of attack) and thrust controls to vary the aircraft’s speed and altitude and, consequently, rate of climb/descent. These are also 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. As explained in 4.2.2 and 4.2.3, 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, shear can be compensated for. A typical acceleration capability for a jet transport aircraft in the landing configuration with all engines operating is 6 km/h per s (3 kt/s) (0.1375 g), which means that it could maintain level flight at constant airspeed in a 6 km/h per s (3 kt/s) decreasing performance wind shear. However, it should be noted that wind shear intensity can exceed this capability. 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 land 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 shows that when landing into a headwind or tailwind, the angle of attack and the speed of the relative wind are changed compared to 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

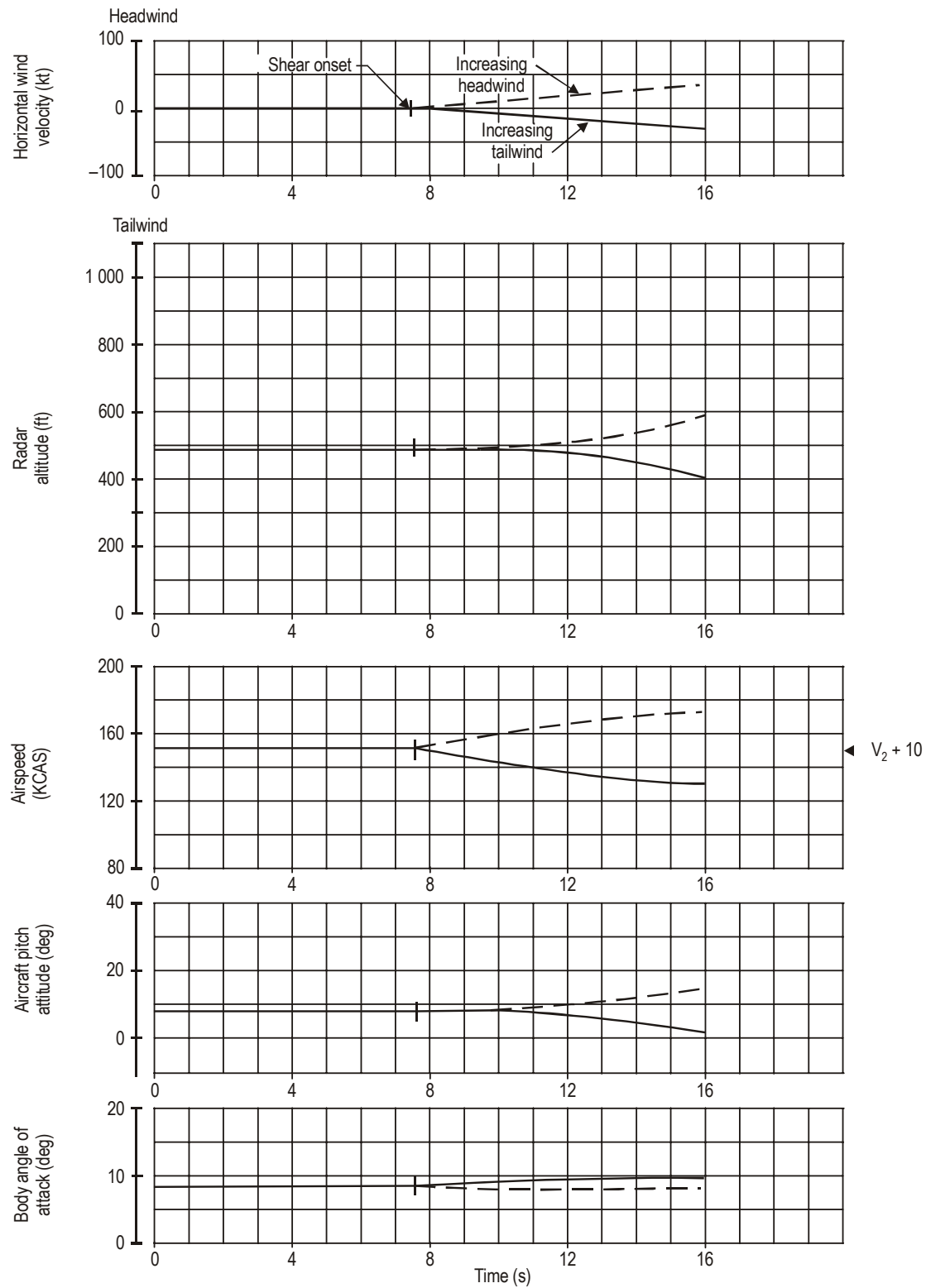


Figure 4-6. Initial aircraft fixed control response to headwind/tailwind shear components
(from FAA Wind Shear Training Aid, 1987, and adapted by ICAO)

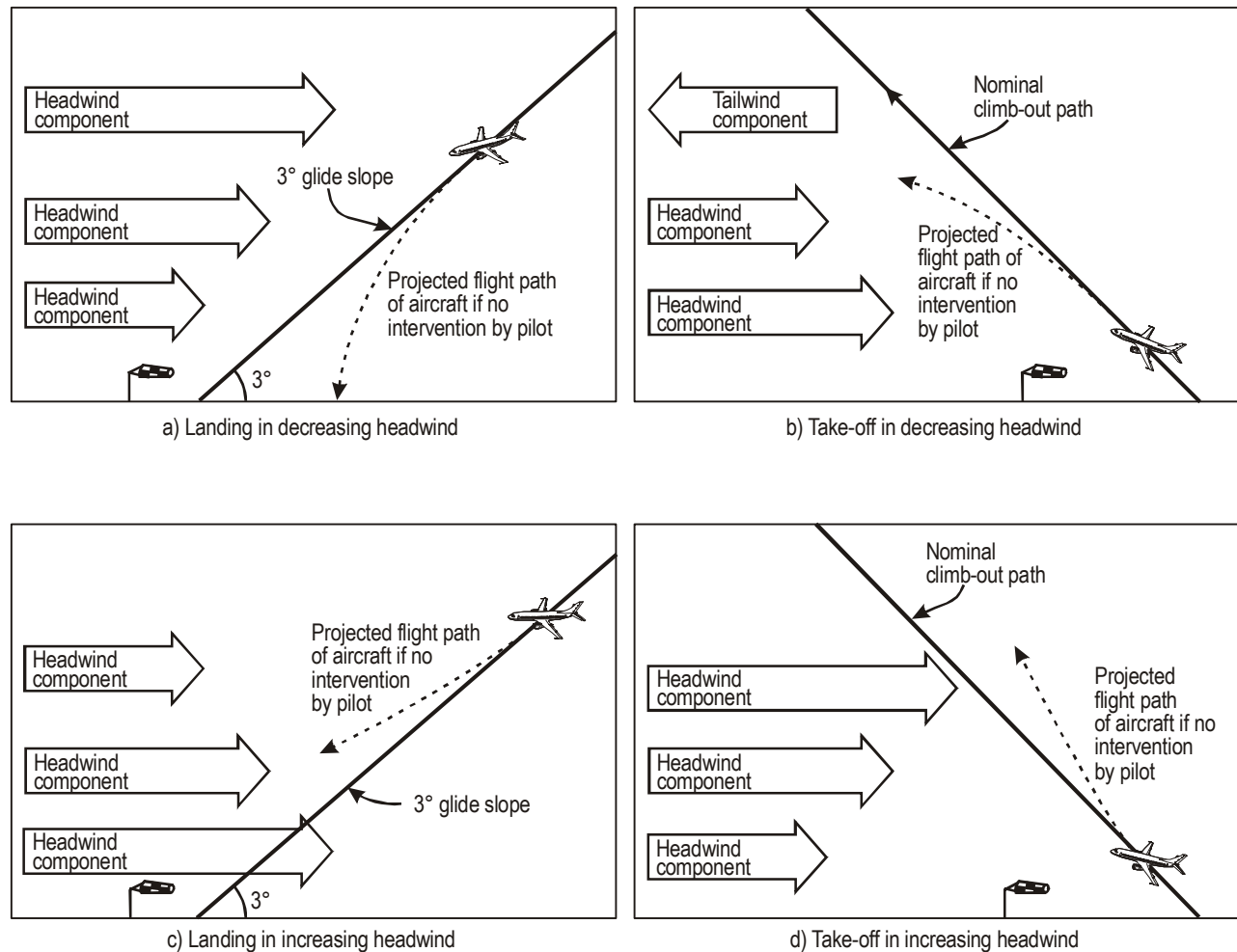


Figure 4-7. Effect of head (tail) wind shear on aircraft, assuming no intervention by pilot

4.2.7 In addition to using thrust to control the flight path, the pilot can 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 done only once since the aircraft at any one time possesses a finite amount of energy comprising potential (depending on its altitude) plus kinetic energy (depending on its speed). Trading one for the other does not change the total energy. An increase or decrease in thrust, however, changes 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 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 reverts to the second characteristic of wind shear important to aircraft referred to in 4.2.2 and 4.2.3, namely, the total wind speed change across the shear layer. The 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 50 km/h (25 kt) for a jet transport aircraft). The techniques recommended in 4.3 employ both thrust and pitch attitude adjustments to maintain control of the flight path. It should be pointed out that while most profile shears may 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 4.3.42 to 4.3.71, a go-around is executed.

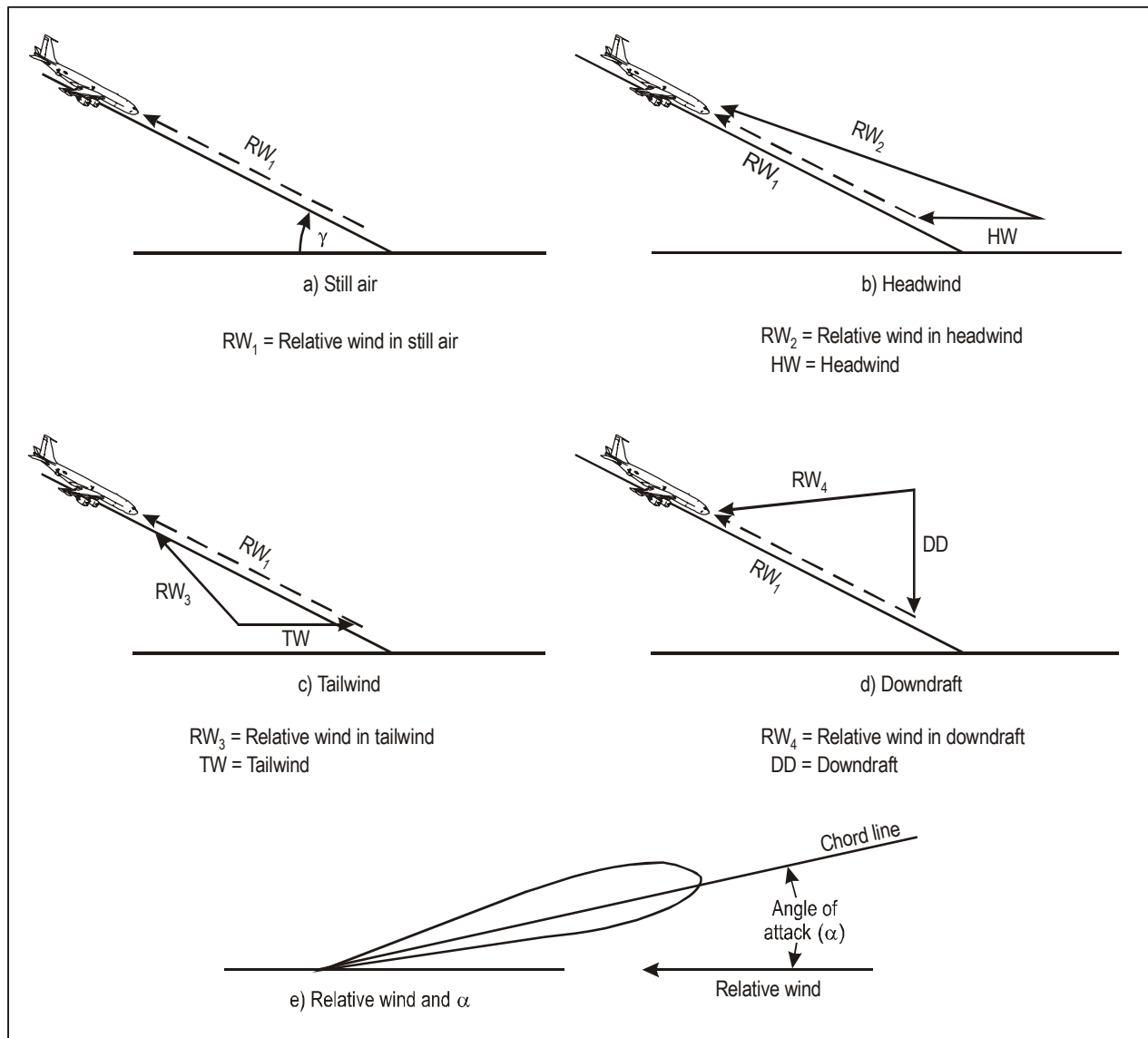


Figure 4-8. Relative wind experienced by an aircraft landing in various steady wind conditions

4.2.8 The effect on an aircraft of a shear in the crosswind component is referred to in 4.1.10. A crosswind shear has a direct initial effect on drift and side-slip 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 yaw and roll flying techniques are sufficient to counter the effects of crosswind shear. Of course it may be necessary to initiate a go-around due to severe crosswind shear, but again the techniques that apply for strong but steady crosswinds will also apply to severe crosswind shear. Changing crosswind components occurring together with headwind/tailwind shears add considerably to pilot workload in an already highly dynamic and difficult situation.

Note.— Winds indicated by an inertial navigation system are in degrees true, while 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.⁸

SHEAR IN VERTICAL WIND COMPONENTS (UPDRAFTS/DOWNDRAFTS)

4.2.9 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 4.1.7 to 4.1.9, where it is shown that downbursts/microbursts associated with convective cloud are the main causes. In a downburst (a microburst being simply a concentrated form of a downburst) as described in 3.5.11 to 3.5.22, 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.

4.2.10 The first case to consider is an aircraft penetrating a downburst that 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. Therefore, 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. Although the pilot can counter this and regain the intended flight path by decreasing thrust, if the pilot suspects that the headwind increase is due to a downburst (as discussed in 4.2.11), decreasing thrust is not advisable, and instead it is recommended that a go-around be initiated immediately. As the aircraft progresses through the downburst, the vertical component becomes increasingly predominant until the centre (or centre line) of the downburst is passed. 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 and continues to decrease further for as long as the speed of the downdraft increases⁹ (see Figure 4-8 d)). 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 that 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 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 is made by the pilot, and the initial aircraft fixed control response to the downdraft and tailwind shears are shown in Figures 4-11 and 4-12, respectively.

4.2.11 If the downburst is offset to either side of the flight path, the immediate effect on the aircraft, though still potentially serious, will not normally be as severe as when the aircraft passes more or less directly under the downburst (Figure 4-10 b) and c)). This is because in these cases there will be less vertical component but more crosswind component to contend with. However, since 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 could all be encountered in as little as 30 seconds, presenting 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 does not matter exactly where the downburst hits on the runway since all cases cause serious problems for the pilot. If the downburst hits the runway 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 since at take-off the aircraft is operating close to or at maximum thrust levels and probably 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 enough for take-off on the runway length available. These and other problems, and measures which pilots can take to deal with them are discussed in detail in 4.3.

4.2.12 In 3.5.8 to 3.5.10, 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 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 are as an increasing headwind and hence increasing performance shear mainly because the aircraft is normally operating into wind. However, there are 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.

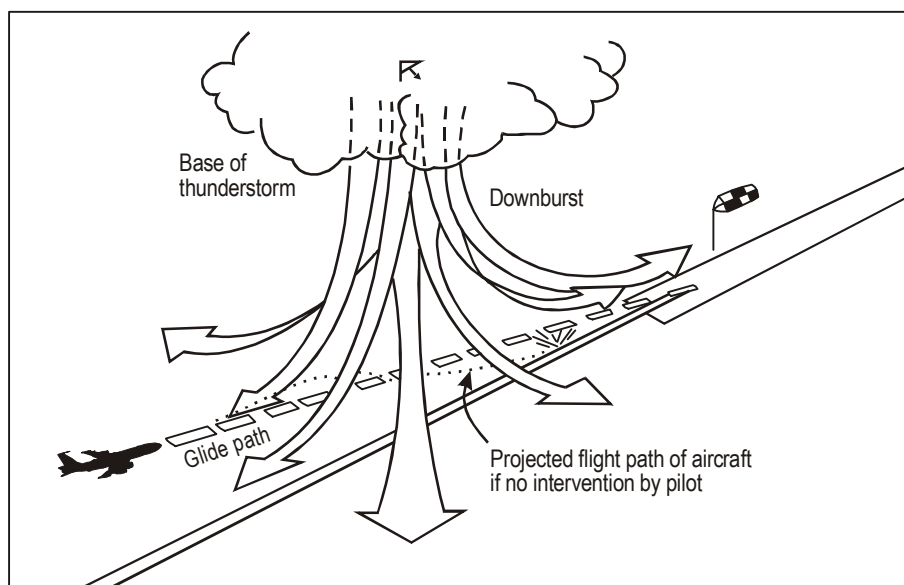


Figure 4-11. Landing through a downburst results in a change in flight path
(after Melvin, 1977)

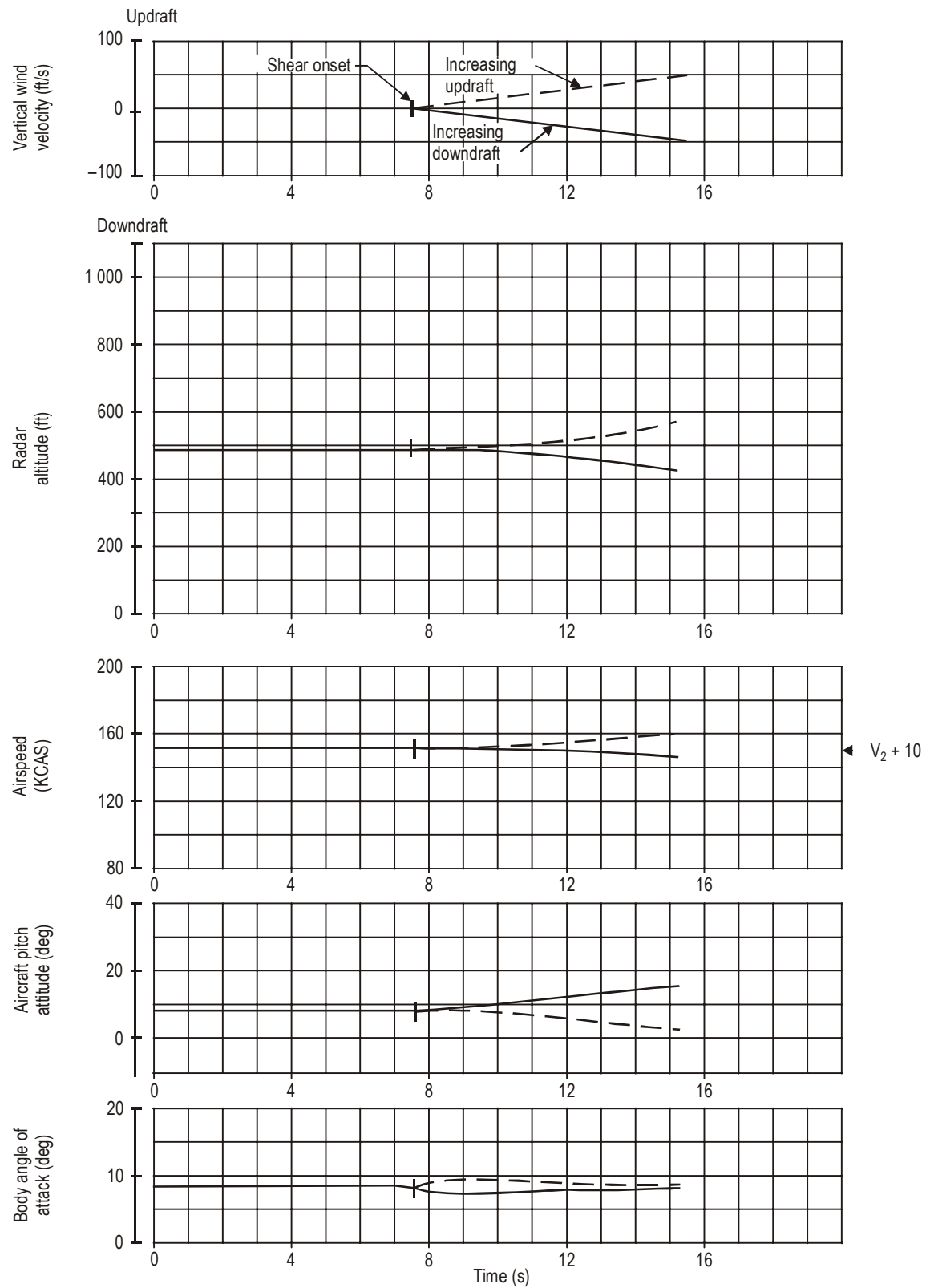


Figure 4-12. Initial aircraft fixed control response to vertical (updraft/downdraft) components
(from FAA Wind Shear Training Aid, 1987, and adapted by ICAO)

4.2.13 Paragraph 3.5.27 mentions the possible consequences to an aircraft passing through a tornado or the wake of a tornado. A particular case of this, documented by Roach and Findlater (1983),¹⁰ concerns the loss of a Fokker F-28 aircraft that took off from Rotterdam at 1604 UTC in October 1981 bound for Eindhoven, Netherlands. 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 west of Moerdijk a few minutes before the crash, and a police launch managed to take photographs of it and, less than one minute later, the smoke from the crash. 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

GENERAL

4.3.1 Before a pilot can apply the recovery techniques described in 4.3.42 to 4.3.71, the pilot 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, applying the appropriate recovery techniques and the aircraft responding accordingly. Reducing the time lag to a minimum means early recognition of the wind shear condition by the pilot and the unhesitating application of the recommended wind shear recovery techniques.

4.3.2 Recognition and reaction times are largely a function of training, by giving the pilot the knowledge to quickly spot 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 it. 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 MET clues. Moreover, whether and how quickly the pilot recognizes the instrument and MET signs for wind shear depends on 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 6)).

RECOGNITION OF WIND SHEAR

External MET clues

4.3.3 Recognition of external MET 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 close attention to the progress of the landing or take-off by reference to the flight deck instruments. External clues that may be directly visible to the pilot include the following:

- a) 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);
- b) lenticular cloud (smooth lens-shaped altocumulus) indicating the presence of standing waves, usually downwind from a mountain (see 3.2.8 and 3.2.9);
- c) virga, i.e. precipitation falling from the base of a cloud but evaporating before reaching the ground (especially under convective cloud) because downdrafts may still exist and reach the ground even though the precipitation itself has evaporated (see 3.5.6 and 3.5.7);

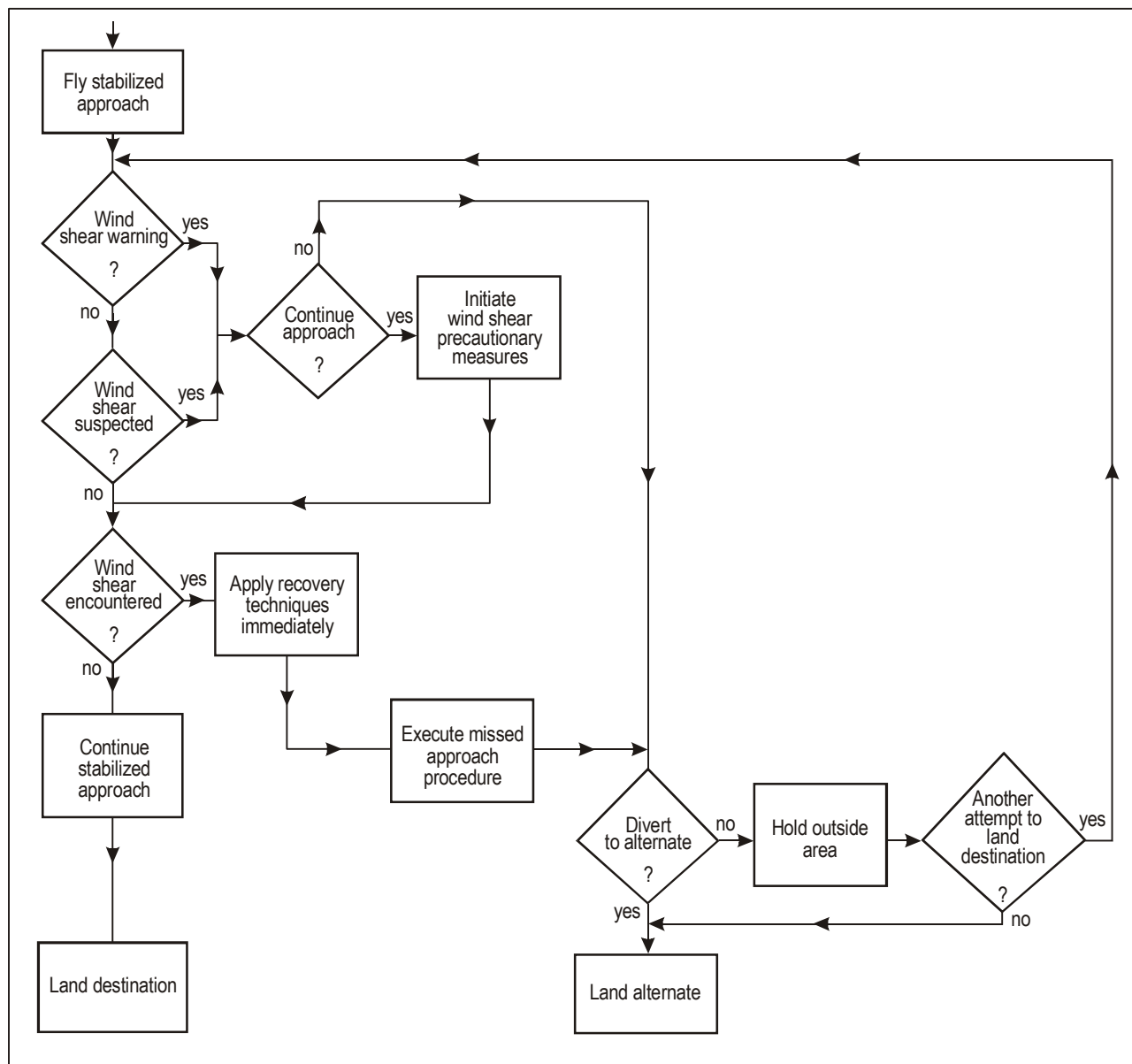


Figure 4-13. Flow chart sequence of pilot decisions and actions with respect to wind shear

- d) roll cloud girding the base of a thunderstorm and advancing ahead of the rain belt, indicating the presence of a gust front (see 3.5.10);
- e) areas of dust raised by wind, particularly when in the form of a ring below convective clouds, indicating the presence of a downburst (see 5.1.2 and Figure 3-16);
- f) wind socks responding to different winds;
- g) smoke plumes sheared, with upper and lower sections moving in different directions; and
- h) 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.

4.3.4 The wind shear warnings that 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. At those airports not equipped with remote-sensing wind shear detection systems, which will continue to be the majority, these warnings are likely to be based largely on air-reports. 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.

Indications from flight deck instrumentation and/or airborne equipment

4.3.5 Concerning flight deck clues, these may be derived from the behaviour of flight deck instruments and, in aircraft so equipped, from 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 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 quickly recognizing any abnormal deviations in these parameters. A stabilized approach 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 that could save valuable seconds in a wind shear encounter and should be encouraged from *ab initio* training.

4.3.6 The indications of wind shear that 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. The foregoing alerting clues are 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 pilot will be largely dependent on external indications of wind shear and, based on these, will

have to decide whether or not to delay the take-off. The presence of wind shear may also be detected by the abnormal build-up of airspeed during the take-off roll. If it is detected during the early stage of the take-off roll, it may be advisable to abandon the take-off.

4.3.7 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 were developed as part of the FAA Wind Shear Training Aid (see Table 4-1). The probabilities are classified as follows:

HIGH PROBABILITY:	Critical attention needs to 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.

4.3.8 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, an air-report 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).

4.3.9 The guidelines in Table 4-1 apply to operations in the airport vicinity (within 3 m (10 ft) of take-off or landing along the intended flight path below 300 m (1 000 ft) AGL). Although encountering the weather conditions described in Table 4-1 above 300 m (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. Using Table 4-1 should not replace sound judgement in making avoidance decisions.

PRECAUTIONARY MEASURES

4.3.10 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 since experience has shown that this is not the case. An example of such measures is given in Appendix 11 in the abstract from the B737 operations manual 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 that 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)¹¹ and are reproduced with the permission of the FAA. 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 Table 4-2). The training aid contains the following disclaimer and indemnity 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, 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. 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.”

4.3.11 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.

4.3.12 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.

Table 4-1. Microburst wind shear probability guidelines

<i>Observation</i>	<i>Probability of wind shear</i>
Presence of convective weather near intended flight path:	High
— 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)	Medium
— 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
<i>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.</i> 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.	

Take-off precautions

Thrust setting

4.3.13 Maximum rated take-off thrust should be used for take-off. This shortens the take-off roll and reduces overrun 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 workload.

Runway selection

4.3.14 Use the longest suitable runway that avoids suspected areas of wind shear. 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

4.3.15 The choice of take-off flap setting is dependent on the aircraft type. The flap settings in Table 4-2 should be considered unless limited by obstacle clearance and/or climb gradient.

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 in Table 4-2 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

4.3.16 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 workload.

4.3.17 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 600 m (2 000 ft) from the end of the usable runway surface reduces the probability of overrun and maximizes the available energy after lift-off.

Table 4-2. Aircraft type and take-off flap setting

<i>Aircraft type</i>	<i>Take-off flap setting</i>
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

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

- a) 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.
- b) Determine field length limit maximum mass and corresponding V_R for selected runway.
- c) If field length limit V_R is greater than actual gross mass V_R , use the higher V_R (up to 40 km/h (20 kt) in excess of actual gross mass V_R) for take-off. Airspeed bugs should not be reset to the higher speeds.
- d) 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 600 m (2 000 ft) from the end of the usable runway surface (see 4.3.42 to 4.3.71, recovery techniques).

4.3.19 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

4.3.20 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).

4.3.21 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. Table 4-3 provides a summary of take-off precautions.

Table 4-3. Summary of 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
-

Approach precautions

Stabilized approach

4.3.22 A stabilized approach should be established no later than 300 m (1 000 ft) AGL to improve wind shear recognition capability.

Thrust management

4.3.23 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

4.3.24 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

4.3.25 The choice of landing flap setting is dependent on aircraft type. The flap settings in Table 4-4 should be considered. Studies of wind shear encounters using all available landing flap settings have shown that the flap settings recommended in Table 4-4 provided the best overall recovery performance for a wide range of wind shears.

Table 4-4. Aircraft type and landing flap setting

<i>Aircraft type</i>	<i>Landing flap setting</i>
B727	30
B737	5 to 30
B747	25 to 30
B757	30
B767	30
DC-9-10	*
MD-80	28
DC-10	35
L-1011	33

* Minimum flap setting for particular model

Increased airspeed

4.3.26 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.

4.3.27 If available landing field length permits, airspeed may be increased by up to a maximum of 40 km/h (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.

4.3.28 As many variables are involved, it is not practical to provide exact guidance on the effect of 40 km/h (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.

4.3.29 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 40 km/h (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 40 km/h (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

4.3.30 During approach it is desirable to utilize the flight director, autopilot and auto-throttles to the maximum extent practicable. These systems may relieve pilot workload, 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. Table 4-5 provides a summary of approach precautions.

Table 4-5. Summary of approach precautions

-
- Stabilize approach no later than 300 m (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
-

Follow established standard operating techniques

4.3.31 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 coordination.

4.3.32 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.

4.3.33 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 coordination are vital for timely wind shear recognition, particularly at night or in marginal weather conditions.

Crew awareness

4.3.34 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.

4.3.35 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 build-up. 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.

4.3.36 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 build-up is low during rotation and lift-off. Vertical flight path displays should be used to cross-check flight director commands.

4.3.37 During take-off while at relatively low altitude (below 300 m (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.

4.3.38 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 300 m (1 000 ft) AGL.

4.3.39 High workload 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.

4.3.40 Crews should be prepared to execute the recommended recovery procedure immediately if deviations from target conditions in excess of those shown in Table 4-6 occur. 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 pilot flying (PF) is responsible for assessing the situation and using sound judgement to determine the safest course of action.

Crew coordination

4.3.41 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."

Table 4-7 provides a summary of SOTs.

Table 4-6. Target conditions

<i>Take-off/approach</i>	<i>Approach</i>
1) ± 15 kt indicated airspeed	1) ± 1 dot glide slope displacement
2) ± 500 FPM vertical speed	2) unusual throttle position for a significant period of time
3) $\pm 5^\circ$ pitch attitude	

Table 4-7. Standard operating techniques summary

<i>Take-off</i>	<i>Approach</i>
— Know normal attitudes, climb rates, airspeed buildup	— Know normal attitudes, descent rates, airspeeds, throttle position
— Know/use all-engine initial climb attitude	— Cross-check flight director commands
— Make continuous rotation at normal rate	— Avoid large thrust reductions
— Cross-check flight director commands	— Monitor vertical flight path instruments, call-out deviations (PNF)
— Minimize pitch attitude reductions	— Know recovery decision guidelines
— Monitor vertical flight path instruments, call-out deviations (PNF)	
— Know recovery decision guidelines	

WIND SHEAR RECOVERY TECHNIQUE

General

4.3.42 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.

4.3.43 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.

4.3.44 Extensive analysis and pilot evaluations have been conducted. Although a range of recovery attitudes (including 15 degrees and the range of all-engine initial climb attitudes) provides good recovery capability for a wide variety of wind shears, 15 degrees was chosen as the initial target pitch attitude for both take-off and approach. Additional advantages of 15-degree 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 degrees,
approach = 15 degrees.*

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.

4.3.45 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.

4.3.46 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.

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

4.3.47 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 300 m (1 000 ft) AGL on take-off or approach. The guidelines for unacceptable flight path degradation are repeated in Table 4-8.

4.3.48 Again, these should be considered as guidelines, since exact criteria cannot be established. In every case, it is the responsibility of the PF 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.

4.3.49 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

4.3.50 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

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

- a) At normal pitch rate, increase or decrease pitch attitude as necessary toward an initial target attitude of 15 degrees. 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.
- b) Always respect stick shaker. Use intermittent stick shaker as the upper pitch limit. In a severe shear, stick shaker may occur below 15-degree pitch attitude.
- c) If attitude has been limited to less than 15 degrees to stop stick shaker, increase attitude toward 15 degrees as soon as stick shaker stops.
- d) If vertical flight path or altitude loss is still unacceptable after reaching 15 degrees, further increase pitch attitude smoothly in small increments.
- e) Control pitch in a smooth, steady manner (in approximately 2-degree increments) to avoid excessive overshoot/undershoot of desired attitude.
- f) Once the aircraft is climbing and ground contact is no longer an immediate concern, airspeed should be increased by cautious reductions in pitch attitude.

Table 4-8. Guidelines for unacceptable flight path degradation

<i>Take-off/approach</i>	<i>Approach</i>
1) ± 15 kt indicated airspeed	1) ± 1 dot glide slope displacement
2) ± 500 ft/min vertical speed	2) unusual throttle position for a significant period of time
3) $\pm 5^\circ$ pitch attitude	

Configuration

4.3.52 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:

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

4.3.53 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.

4.3.54 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.

4.3.55 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.

4.3.56 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.

4.3.57 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.

4.3.58 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.

4.3.59 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. Table 4-9 provides a summary of after lift-off/on approach wind shear recovery technique.

Encounter during take-off on runway

4.3.60 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 build-up may be indications of a wind shear encounter.

4.3.61 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.

Prior to V_1

4.3.62 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

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

Thrust

4.3.64 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.

**Table 4-9. Summary of
after lift-off/on approach
wind shear recovery technique**

Thrust

- apply necessary thrust

Pitch

- adjust toward 15 degrees
- increase beyond 15 degrees if required to ensure acceptable flight path
- always respect stick shaker

Configuration

- maintain existing configuration
-

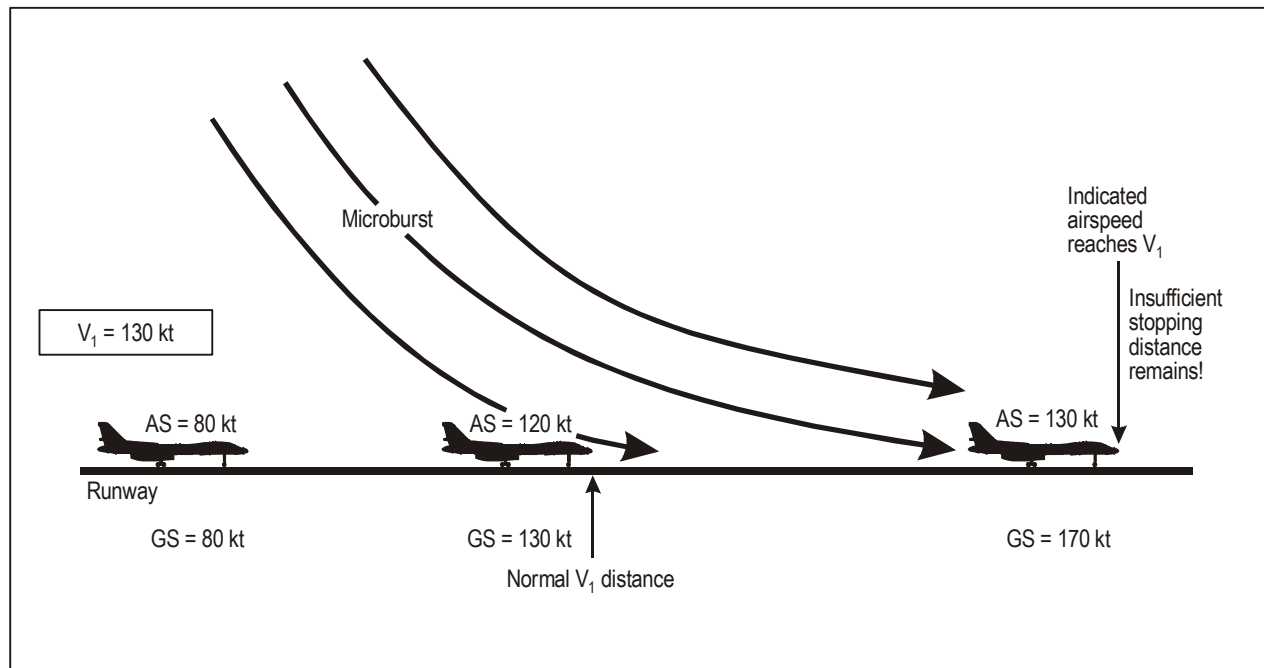


Figure 4-14. Wind shear effects on go/no-go decision point. V_1 decision speed may not be attained until insufficient runway remains to abort take-off
(from FAA Wind Shear Training Aid, 1987)

Pitch

4.3.65 When V_R is reached, rotate at normal rate toward 15-degree 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 600 m (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).

4.3.66 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. See Table 4-10 for summary of take-off (on runway) recovery technique. Once airborne, follow the “after lift-off recovery technique” discussed earlier.

4.3.67 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 900 m (3 000 ft) of runway remaining (i.e. 300 m (1 000 ft) until rotation must be initiated). As take-off continues, the 600-m (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 150-m (500-ft) intervals from the departure end threshold.

Table 4-10. Take-off (on runway) recovery technique**Thrust**

- apply necessary thrust

Pitch

- rotate toward 15° (no later than 600 m (2 000 ft) remaining)
- increase beyond 15° if required to lift off

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

4.3.68 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 600 m (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 900 m (3 000 ft) from the end of the runway (300 m (1 000 ft) until rotation must take place). From 900 m (3 000 ft) to the 300-m (1 000-ft) remaining point the centre line lights alternate white and red. The centre line lights are all red for the last 300 m (1 000 ft) of runway. A line of red lights perpendicular to the runway indicates the end of usable runway surface.

4.3.69 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 300 m (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 600-m (2 000-ft) remaining point.

4.3.70 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 150 m (500 ft) starting from the runway threshold. Fixed distance markers may also be present approximately 300 m (1 000 ft) 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 600 m (2 000 ft) of the runway.

Non-recommended recovery techniques

4.3.71 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.

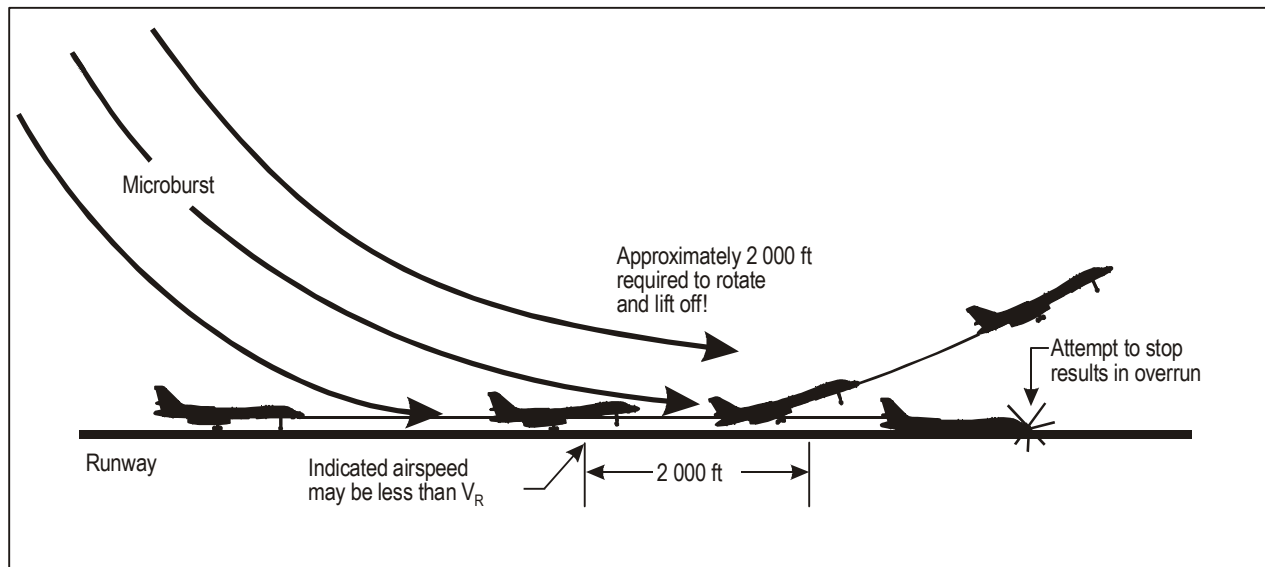


Figure 4-15. Wind shear effects on rotation decision.
 Wind shear effects may force rotation at speeds below V_R . Rotation should begin no later than 2 000 ft from runway departure
 (from FAA Wind Shear Training Aid, 1987)

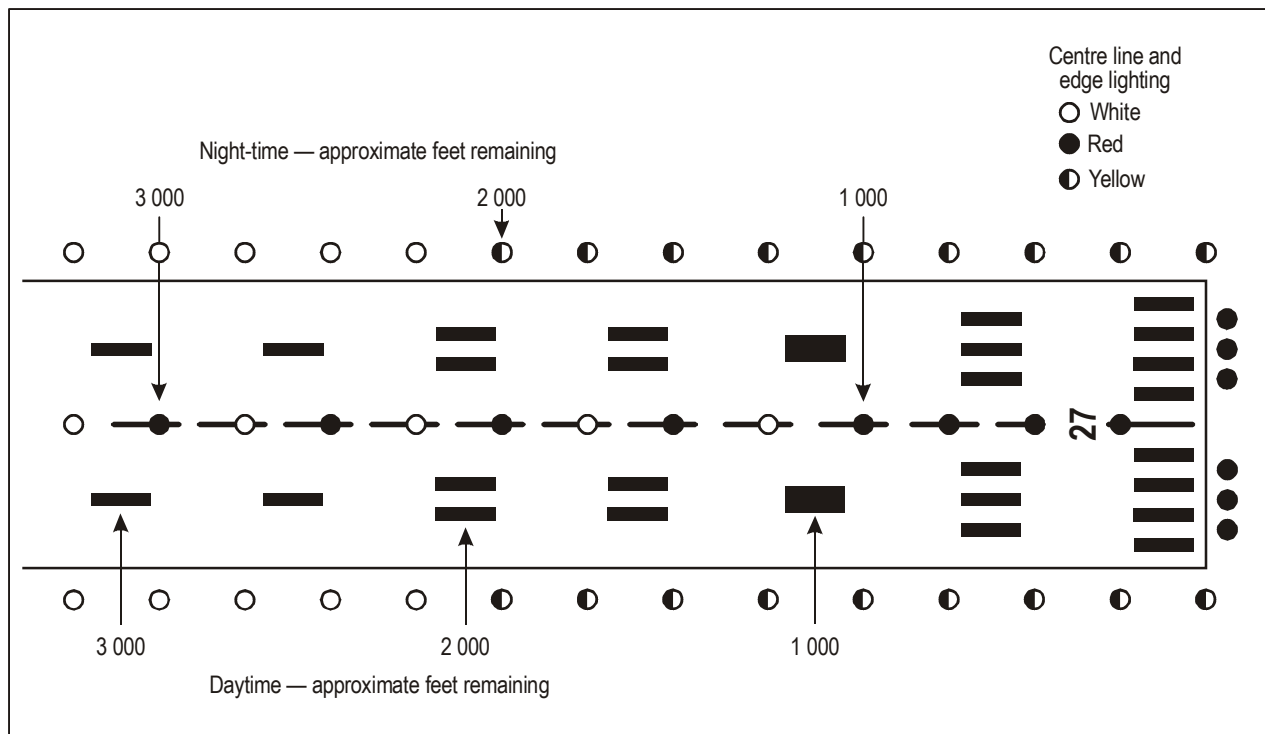


Figure 4-16. ICAO/FAA precision approach runway markings and lighting
 (from FAA Wind Shear Training Aid, 1987, and adapted by ICAO)

- d) Refracting 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.
- e) 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.
- f) 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.

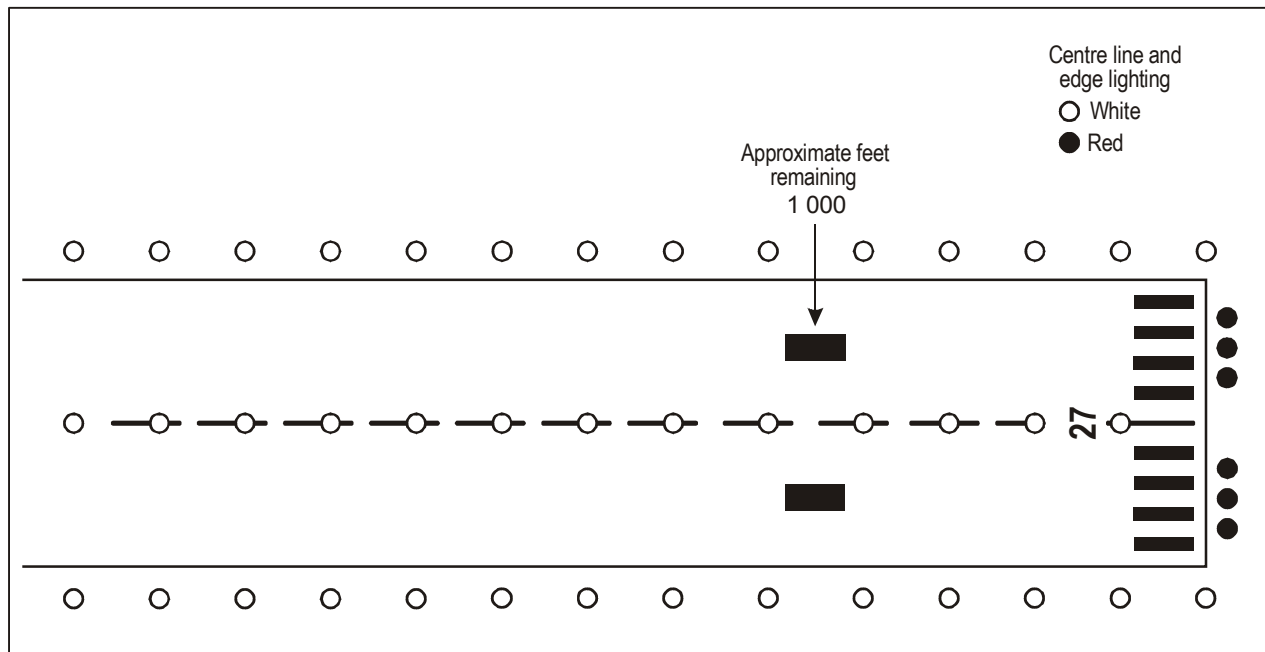


Figure 4-17. FAA non-precision approach runway markings and lighting
(from FAA Wind Shear Training Aid, 1987, and adapted by ICAO)

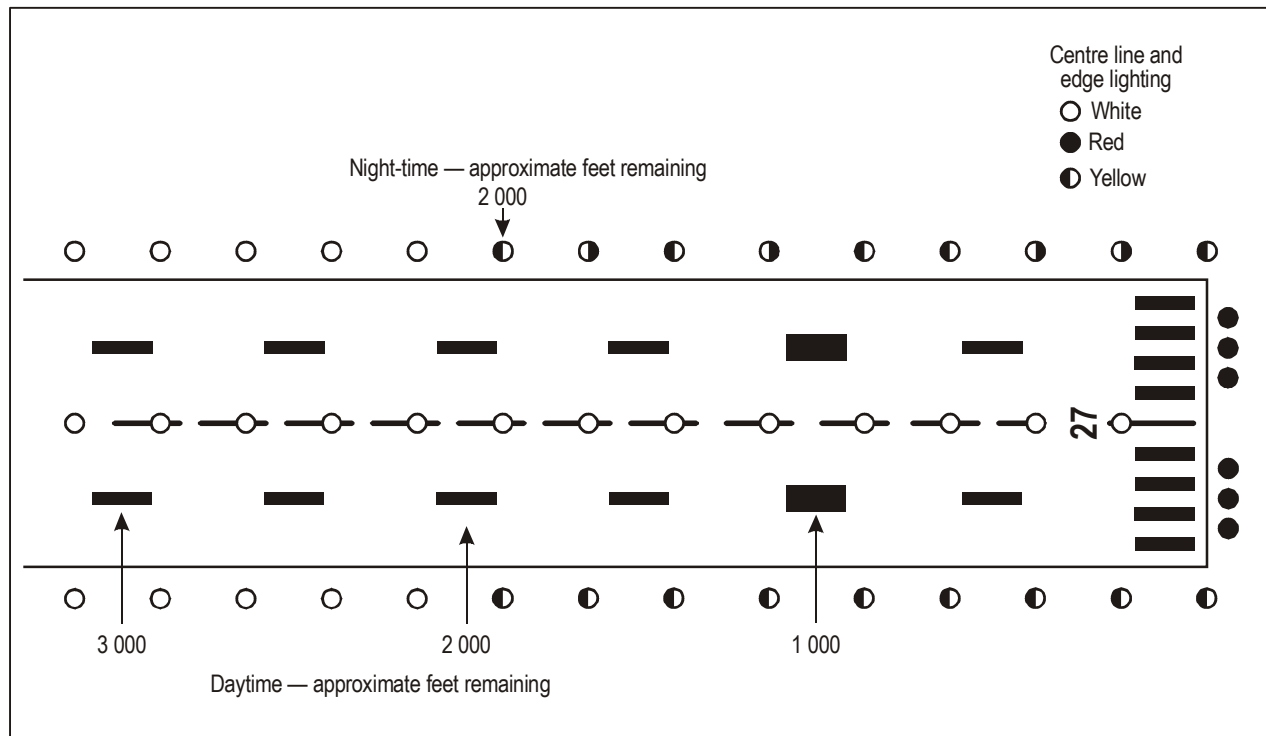


Figure 4-18. ICAO non-precision approach runway markings and lighting
(from FAA Wind Shear Training Aid, 1987, and adapted by ICAO)

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Chapter 5

OBSERVING, FORECASTING AND REPORTING OF LOW-LEVEL WIND SHEAR

5.1 OBSERVING WIND SHEAR — GROUND-BASED AND AIRBORNE OBSERVATIONS

GENERAL

5.1.1 The statement of operational requirements calls for information on low-level wind shear to be provided to the pilot (see Appendix 1). The source of this information may be observation (from the ground or in the air) or forecasting. The successful development and deployment of TDWR and the significant improvements made to anemometer-based wind shear detection/warning systems means that the real-time operational detection and observation of low-level wind shear from ground-based equipment has been achieved. However, such sophisticated equipment is costly to purchase and maintain and, therefore, is likely to be restricted to very busy airports that are also known to be affected by wind shear and especially microbursts. At most airports, recourse will continue to be made to a variety of different methods of observation, mostly indirect, to detect the presence and, where possible, the intensity of wind shear.

GROUND-BASED OBSERVATIONS

Visual observation of wind shear

5.1.2 Wind shear itself cannot be seen but very often its effects can. Section 4.3 mentions some ways in which evidence of the existence of wind shear may be deduced from other MET information. The list of clues includes:

- a) adjacent cloud layers moving in different directions;
- b) smoke plumes sheared and moving in different directions;
- c) roll cloud ahead of an approaching squall line;
- d) strong, gusty surface winds affecting trees, flags, etc.;
- e) windsocks around an aerodrome responding to different winds;
- f) dust^{a,1} (especially in the form of a ring) raised by downdrafts beneath convective cloud;

a. 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

- g) dust raised in gust front ahead of squall line;
- h) virga, especially when associated with convective cloud;
- i) lenticular cloud indicating standing waves, etc.;
- j) funnel clouds;
- k) waterspouts;
- l) 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 based on 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.

Observation of wind shear using standard meteorological (MET) instruments

5.1.3 *Anemometers.* The use of anemometers to observe and measure wind shear in the horizontal plane (e.g. along a runway) is referred to in Chapter 2. At many aerodromes, in order to provide surface wind information that represents 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 led to the development of a dedicated wind shear warning system, i.e. the low-level wind shear alert system (LLWAS)^b, (see 5.1.7 to 5.1.14 for details). Some 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 5.3.25). In Hong Kong, China,² anemometers were installed on hills near the approach path to Kai Tak Airport (replaced by Hong Kong International Airport in 1998) to provide information for wind shear warnings.

5.1.4 *Balloon soundings.* Another obvious source of wind shear information is from rawinsonde and pilot balloon ascents. However, as mentioned in 2.5.3, 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 3.1.5 regarding low-level jet streams). While wind data from balloon soundings would be most useful to indicate profile wind shear (vertical), these data are unlikely to be of much assistance in detecting wind shear associated with convective clouds (gust fronts, downbursts, microbursts, etc.). However, while sounding data may be of limited use operationally for observing wind shear, they are of considerable assistance in forecasting conditions favourable for the development of wind shear (see 5.2).

5.1.5 *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 and also on 3-cm radars) as a thin but very distinct arc or line. This 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 caused by strong temperature or moisture gradients causing relatively abrupt changes in the refractive index of the air.

b. The first “S” in the acronym LLWSAS has now been dropped when used to describe current systems.

The arc or line echoes caused by gust fronts mark the leading edge of the cold downdraft air and 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 angles because their formation seems to depend on a comparatively rare combination of atmospheric and radar-reflective variables. Moreover, at ranges beyond about 50 km (31 NM), 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 able to forecast how and when the gust front will affect the aerodrome concerned (see 5.2.37 to 5.2.40). A number of radar-processing techniques are available that enable the meteorologist to assess the severity of thunderstorm echoes and 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 the radar reflectivity factor (dBZ).^c One such technique, used in the United States, called the radar echo-contouring system, employs an automatic video integrator and processor (VIP). The six contour levels produced are commonly referred to as VIP levels (dBZ). These methods are discussed in more detail in 5.2.39. The radar scan may be made in the horizontal plane (plan position indicator (PPI)) or in the vertical plane (range height indicator (RHI)).

5.1.6 *MET 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, especially in gust fronts formed from squall lines (see 3.5.10). A good example of such a picture is the extensive arc of cloud moving radially outwards from a cluster of cumulonimbus clouds shown in Figure 5-1.³ This picture poses a problem because, while arc section L'L is indeed roll cloud (stratus) associated with the gust front, from comparison of the infrared and visual pictures, that part of the arc of cloud labelled L'U seems to be cirrus cloud.

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

Low-level wind shear alert system (LLWAS)

5.1.7 The original LLWAS system⁴ comprises five surface wind sensors located at strategic points around the perimeter of the aerodrome, a centre-field surface wind sensor and microprocessor, and display units that 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.

5.1.8 Displays are located in ATC units that 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 audio-visual alarm is triggered. The controller can select for display any or all of the perimeter winds at any time.

5.1.9 The LLWAS system was designed and installed following several aircraft accidents during the mid-1970s and was eventually installed at over 100 aerodromes in the United States. It was originally intended to detect gust fronts as they crossed the aerodrome perimeter, and in this respect the system worked reasonably well, although there were problems with the level of false alarms (over-warning). Following further research into low-level wind shear associated with convective cloud, it became apparent that gust fronts were only part of the problem — the main problem was the precursors of the gust front that develop above ground level, i.e. downbursts and microbursts, rather than the front itself. In this respect,

c. dBZ is decibels relative power.

LLWAS 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 original temporal and spatial resolution of the system, microbursts could easily occur between two perimeter sensors without affecting either of them.

5.1.10 In order to address these concerns, the LLWAS underwent three major enhancements which markedly improved its operational efficacy, rate of false alarms and maintainability. The improvement in observational efficacy focused on extending system coverage out to 5.5 km (3 NM) around critical areas, such as runway approaches and take-off corridors, and providing increased capability to detect microbursts. Extending the coverage automatically meant an increase in the number of sensors, from the original five up to as many as 32 at Denver International Airport. Improving microburst detection involved the development of a new algorithm that calculated divergence in triangles of three sensors and on triangle edges between the sensors. These results are resolved into components along the runway headings and headwind/tailwind gain/loss estimates (see 2.1.3). The calculation of divergence patterns across the whole system permitted the detection of positive divergence generated by microbursts as they reach ground level and the negative divergence (convergence) along and ahead of gust fronts crossing the aerodrome. This information is converted into the wind shear warnings issued to pilots. The pilot does not care about the divergence, so the warnings give the estimated headwind gain/loss. These shears are calculated over 4-km flight paths, with headwind loss above 30 km/h (15 kt) but equal to, or less than, 60 km/h (30 kt) indicated as “wind shear with loss”. A headwind loss of more than 60 km/h (30 kt) over 4 km is indicated as a microburst. Shears over distances greater than the nominal 4 km are considered of reduced risk because the shears are less abrupt. A headwind gain of 30 km/h (15 kt) or more over 4 km is indicated as “wind shear with gain”, representing areas of convergence (negative divergence) normally ahead of and along a gust front.

5.1.11 The LLWAS algorithms have generally performed well (the latest major upgrade being the wind shear and microburst detection (WSMD) algorithm⁵), although it is considered that there is still scope for improvement, particularly in the detection of gust fronts. The performance of the algorithms largely depends on the threshold shears selected and also on the quality of the sensor input. In the latter, false alarms are of critical importance, especially when they prompt the issuance of a microburst warning which, in turn, prompts important operational decisions by the pilot. A high level of false alarms also erodes confidence in the system among pilots and air traffic controllers. The question of false alarms is rather complicated and, to an extent, is dependent on each particular aerodrome. The false alarms can be caused by gusty wind conditions, by less than ideal anemometer siting, e.g. shielding from certain directions (which may be known but re-siting is impossible), by anemometers under/over-reading or even going unserviceable but still inserting erroneous data into the system. All of these factors are under scrutiny,⁶ for example, with unserviceable sensors being flagged by the software and related warnings being suppressed, and original sensors being replaced by improved anemometers (see below).

5.1.12 The siting of the anemometers in the LLWAS network at an aerodrome received serious consideration from the start, as seen in the siting guidelines in FAA Order 6560.21A.⁷ These guidelines involved detailed site surveys and reference to relevant climatological/environmental, logistical and operational factors at each aerodrome. Siting faced numerous constraints, including access to the land, power and ownership of the aerodrome, etc., and sometimes the ideal site could not be used. Originally, five or six anemometers at each aerodrome were involved, but the latest enhancement programme will increase this number to cover 5.5 km (3 NM) beyond the runways, which is a major logistical task. In addition to installing additional anemometers, the enhancement programme will review the siting and anemometer height of those from the earlier phase and relocate or raise them as necessary. It is estimated that enhancement of the LLWAS at all the aerodromes concerned requires 200 anemometer masts to be relocated, replaced or added. Earlier, the enhanced system was referred to as the LLWAS relocation and sustainment (LLWAS-RS),⁸ although LLWAS-NE is since being used in the literature to denote “network expansion”. Initially, the full enhancements will be applied to eight major United States aerodromes where TDWRs are installed (see below).

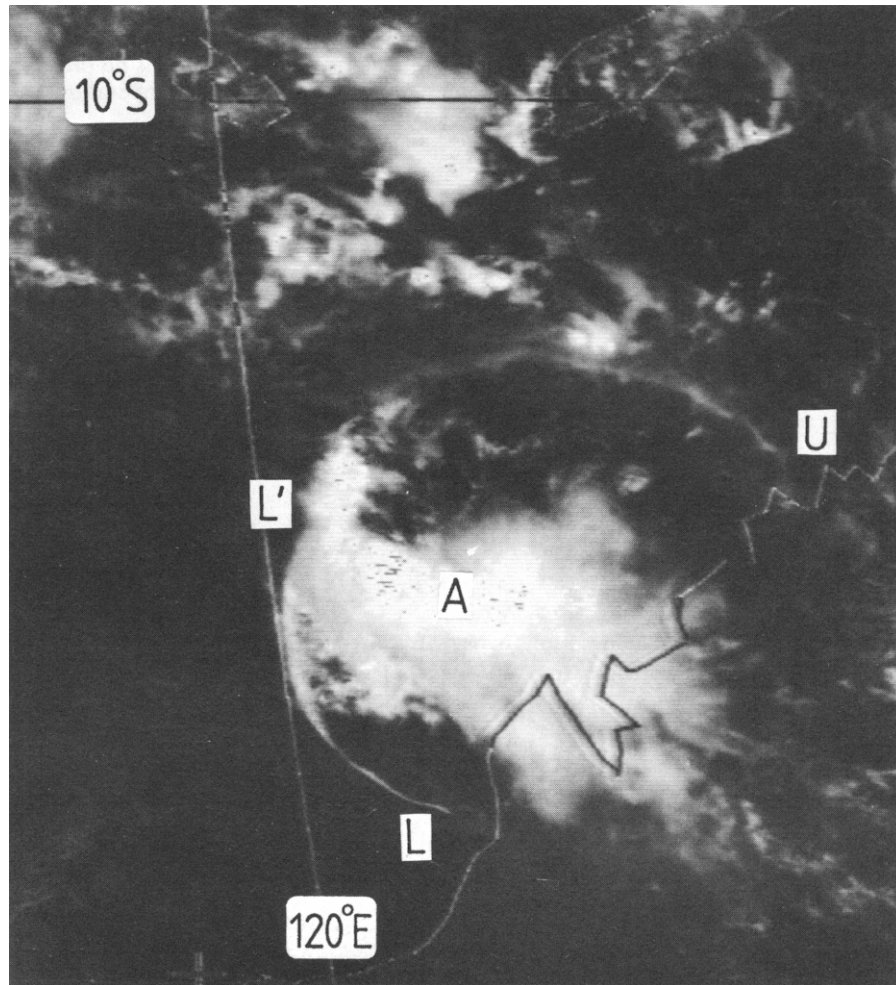


Figure 5-1. Weather satellite picture of arc cloud
(from Kingswell, 1984)

5.1.13 The enhancement will not be restricted to the siting or addition of anemometers. As mentioned above, new technology such as sonic anemometers will replace the customary vane anemometers. These new sensors have a much better reliability and maintainability as being solid-state instruments. The output displays in ATC units are also being upgraded to ribbon display terminals, which permit the replacement of earlier sector alerts by runway-orientated wind shear and microburst alerts (MBAs). Furthermore, the additional sensor sites can be accommodated in the ATC displays at Denver International Airport, which can display output from 32 sensors. The LLWAS-RS will use off-the-shelf components wherever possible; 40 operational systems and 3 support systems will be installed. Where both LLWAS-RS and TDWR are installed, their output will be integrated for the issuance of warnings. This important development is detailed in 5.1.43.

5.1.14 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 may eventually be used to augment the LLWAS system.

Sound wave detection and ranging (SODAR)

5.1.15 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 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 since 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 too long for the provision of timely convective wind shear warnings. Recent developments are expected to reduce this to below 5 minutes. In addition, the use of three-axis SODAR has enabled measurement of the vertical component of the wind.

5.1.16 Current SODAR equipment is restricted to sensing the atmosphere directly above the observing site, although the SODAR sound beam is being developed to be pointed at an angle which, if successful, could lead to continuous monitoring of all three components of the wind profile along the climb-out and approach paths at aerodromes.⁹ 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.¹⁰ SODAR is used operationally at aerodromes in several locations, including Canada; Denmark; France; Hong Kong, China; and Sweden. Turesson and Dahlquist have reported using multiple SODAR installations to observe and measure, with a data integration time of 20 minutes, a downburst that occurred at Copenhagen Airport; the resulting wind shear is shown in Figure 5-2.¹¹

Doppler radar

5.1.17 Conventional weather radars compute and display on 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 and from the radar has hitherto been only of incidental interest. However, this phenomenon, known as the “Doppler shift”, permits the elimination of obscuring stationary targets (permanent echoes such as hills) from ATC radar by means of moving target indicator (MTI) circuits. In the past 20 years, 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 where the direct analysis of thunderstorm clouds is possible by detecting and tracking cloud droplets and rain/hail/snow, and also tracers in “clear air”.¹² 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, which are of prime concern to aviation.¹³

5.1.18 In order to detect targets of MET 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 produces a frequency shift of 62 Hz, 36 Hz and 20 Hz for radar wavelengths of 3.2, 5.5 and 10 cm, respectively. Paragraph 5.1.5 mentions 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 was found that frequency-modulated, continuous-wave (FM-CW) 10-cm radars are particularly well suited for detecting radar angels and can be used to detect clear air turbulence (CAT).

5.1.19 Concerning 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 (AGL) along the approach and climb-out paths. As mentioned in 3.5.16, 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 useful in detecting wind shear where the wind field is unlikely to be uniform; but it was 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). Algorithms that are capable of detecting divergence patterns (+ve and –ve) caused by wind shear phenomena have been developed with good reliability from single Doppler radar radial flow field data. One such set of algorithms is used in the TDWR. This is a C-band Doppler radar developed specifically to detect gust fronts and microbursts. The TDWR was the outcome of an intense prototyping process in the United States aimed at fielding an operational system as quickly as possible at the main airports threatened by gust fronts and microbursts. This process ran in parallel with continuing research on detection algorithms and output products and benefited from input and feedback from all user groups concerned.¹⁴ Moreover, when observing the lowest levels of the atmosphere, the Doppler radar signal is still subject to considerable degradation due to ground clutter. The technical characteristics of the TDWR¹⁵ are as follows:

- a) C-band with 1.1 μ s 250 kW pulses at Doppler mode pulse repetition frequencies (PRF) from 1 066–1 930 Hz;
- b) pencil beam antenna with 0.5 degree beamwidth and side lobes less than –27 dB;
- c) PPI volume scans over airport every 2.5 minutes, with surface scans every minute;
- d) clutter suppression by high-pass filters as well as point target and ground clutter residue editing;
- e) PRF selection to minimize data contamination near airport by out-of-trip echoes and editing of data contaminated by out-of-trip weather using low PRF (325 Hz) scan data;
- f) velocity folding using dual scans at different PRFs and two-dimensional continuity of velocity fields;
- g) extensive use of site adaptation parameters in microburst and gust front algorithms to facilitate performance optimization in a variety of environments; and
- h) alphanumeric wind shear warning messages on ribbon display for local tower ATCOs and colour situation displays for terminal area planning by ATC supervisors.

5.1.20 The TDWR MET algorithms were developed by researchers at NCAR. The TDWR microburst algorithm employs radial velocity data from the lowest elevation scanned. It detects segments of increasing radial velocity along the radar beam and groups these together in “clusters”. The clusters are assumed to be associated with microbursts, the rough shape of which is constructed from the outer envelope of the clusters. A headwind loss is then estimated for each shape, and depending on the estimated headwind loss and location of the shape in relation to the runway approaches and take-off corridors, a “microburst” or a “wind shear with loss” alert is issued, as described in 5.1.10. The detection of gust fronts uses a similar technique by identifying regions of radial convergence, which are fitted by a polynomial curve to represent the gust front. The headwind gain across the gust front is estimated and, depending on the gain (30 km/h (15 kt) or more) and whether the front affects the runway approaches or take-off corridors, a “wind shear with gain” alert is issued.¹⁶

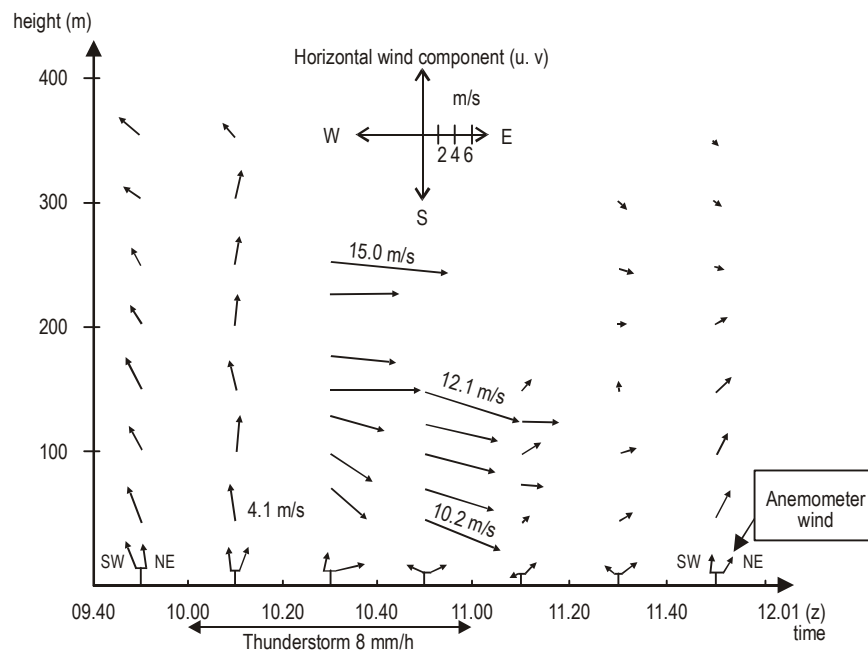
5.1.21 One of the main problems with Doppler radar concerns the unavoidable contamination by return signals from ground clutter, which have been and to an extent continue to be a source of false alarms. This effect is countered by using clutter maps and polygons to subtract significant stationary ground target signals within the radar range. Fine-tuning such maps is difficult and varies from airport to airport. Initially, removal of ground clutter from the TDWR signal degraded the overall signal input and the performance of the wind shear detection algorithms, thus missing some genuine warnings.¹⁷ The clutter removal had to be relaxed until a reasonable balance between clutter removal and degradation of the signal was achieved. Research continues to further improve this situation.¹⁸ The TDWR microburst algorithm has demonstrated a probability of detection of over 90 per cent and a false alarm rate of approximately 6 per cent. The TDWR microburst algorithm requires confirmation of a reflectivity signature signifying convective cloud before it validates a microburst detection. The majority of TDWR false alarms are in the 30–50 km/h (15–25 kt) category (i.e. wind shear with loss). In this regard, the latest version of the TDWR gust front algorithm (machine intelligent gust front algorithm (MIGFA)) has a probability of detection of 85–95 per cent for shears of 40 km/h (20 kt) or more, but for shears in the 30–40 km/h (15–20 kt) category, the false alarm rate can approach 20 per cent. While these are in the lighter category of shears, the warnings that they prompt can, nevertheless, persist at an airport for a considerable length of time, which is annoying, costly and contributes to the erosion of confidence in the system. MIGFA does not require the presence of a reflectivity signature aloft before it validates the gust front detection, and introducing such a validation poses a difficult dilemma because gust fronts can travel some distance from the parent cumulonimbus cloud (see 3.5.8); therefore, the absence of a reflectivity signature need not preclude the presence of a gust front. Further research is being carried out to see if the false alarm rate for shears below 50 km/h (25 kt) can be reduced.¹⁹

5.1.22 The TDWR, a C-band radar, also provides good information on the type of precipitation at the airport. This permits the provision of some useful products for ATC and pilots in addition to wind shear warnings (or alerts, the term used in the United States), such as freezing rain/drizzle and snow. However, this also means that the TDWR is very susceptible to attenuation due to rain, more so than S-band radars such as the NEXRAD (all-purpose Doppler weather radar) and the ATC radar (ASR-9) weather channel. Furthermore, TDWR is particularly susceptible to signal degradation due to rain on the TDWR radome. Normal rain attenuation from the return signal (from radar antenna to target and back) is flagged by the TDWR software, but even larger signal losses are experienced from rain on the radome itself (up to 20 dB), and research is determining the optimum way for the software to flag this occurrence and automatically lower certain thresholds based on the TDWR reflectivity values.²⁰

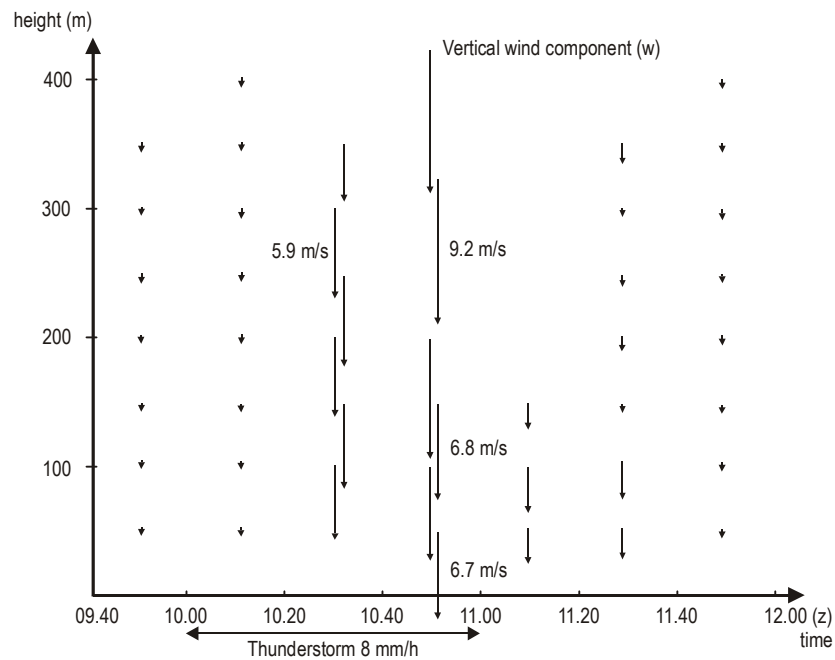
5.1.23 Section 3.3 states that wind shear can be associated with frontal surfaces. The low-level convergence due to cold front wind shear has been detected by the TDWR algorithms, even without the presence of convective cloud. However, there have been few cases where warm front shear has been detected, especially where the warm frontal surface is aloft.¹⁶ Warm front shear also cannot normally be detected by the LLWAS system which, given the inherent constraints on an anemometer network, is not surprising.

5.1.24 It is clear from the foregoing that the LLWAS and the TDWR have their own strengths and weaknesses. Moreover, as mentioned above, their issuance of false warnings largely tends to be in different wind shear categories so that one can be used to check the other. There are additional advantages and disadvantages of the TDWR and LLWAS as shown in Table 5-1.

5.1.25 For these reasons, the LLWAS-NE systems were installed first at the eight airports that had TDWR. This way, in theory, each system could support the other to the overall benefit of the airport wind shear warning systems. However, although there are advantages in having the mutual support each system provides for the other, it was operationally impractical to have those systems give potentially different wind shear warnings at the same airport. While it was feasible to switch off the system having the lowest overall performance, the support each system provided for the other's deficiencies dictated otherwise. This meant that the output from the two systems had to be integrated, which led to the development of sophisticated integration algorithms.



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, Denmark
(from Turesson and Dahlquist, 1985, and adapted by ICAO)

Table 5-1. Comparison of TDWR and LLWAS data and products¹⁶

<i>Category</i>	<i>TDWR</i>	<i>LLWAS</i>
Spatial resolution	High	Low
Temporal resolution	Low	High
Velocity data measurements	Radial, 3-D	2-D
Reflectivity information	Yes	No
Above-surface information	Yes	No
Areal coverage	Large	Small
Potential for microburst prediction	Yes	No

5.1.26 There were three options for integrating the information from the TDWR and LLWAS. In increasing order of complexity these were message level, product level and data level; the attributes of each level are as follows:

Message level. The TDWR and LLWAS systems would produce wind shear warnings independently for each operational runway. These warnings would be combined to generate a single warning for each runway based on worst-case logic. This option is the simplest and could be quickly and easily implemented. However, although it would retain the best probability of detection of the two systems, the false alarm rate would tend to be higher because it is not easy to take advantage of the potential cross-validation between TDWR and LLWAS, which as indicated is significant.

Product level. This option would combine intermediate and final algorithm outputs or “products” to generate wind shear warnings. It could be viewed as an “expert” system with one cross-validating the other. The advantages include the ability to simultaneously maximize accurate detection and minimize inaccurate and/or false detections. However, the extra system-to-system interdependency requires care in preventing the cancellation of correct warnings and in dealing with failure modes. Furthermore, the comparison of information between two stand-alone systems would introduce more algorithmic and statistical assumptions, with the associated potential for introducing case-specific problems.

Data level. Integration at the raw data level would be a major, expensive task. Moreover, the reality of any potential for improvement over the previous two options, though plausible, remained to be proven. The best means to synthesize such very different two- and three-dimensional data, both spatially and temporally, was not obvious.

5.1.27 It was decided to develop and test integration algorithms based on the “message” level and the “product” level; the data level integration was not pursued at this stage.²¹ Three algorithms were tested, two integrating at the product level and one at the message level. The first product level algorithm, developed at NCAR, was termed the “prototype product level” algorithm, which attempted to reduce the number of false wind shear-with-loss warnings by suppressing weak wind shear LLWAS detections not near additional indications of hazardous weather, i.e. strong TDWR or LLWAS detections, or TDWR features detected aloft. Following this assessment, the algorithm issues a warning based on the strongest detection indicated by either the TDWR or the LLWAS for each operational runway. This prototype algorithm was installed and tested operationally at Stapleton International Airport, Denver, from 1988 to 1992.¹⁴ The second product level integration algorithm, developed at Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL), was similar to the first but used streamlined processing. It attempted to reduce false warnings from both the

TDWR and the LLWAS systems and false microburst warnings by suppressing weak detections that were not independently confirmed by their proximity to hazardous weather. Following this assessment, the strongest warnings generated by either the TDWR or the LLWAS are issued for each operational runway. The message level integration algorithm was also developed at MIT/LL.²² It attempted to reduce false wind shear-type warnings and microburst warnings from both the TDWR and the LLWAS in much the same way as the MIT/LL product-level algorithm. Because this algorithm operates at the message level, the only indications of hazardous weather are from the warning messages themselves. Weak wind shear-level warnings given by only one system are suppressed, and weak microburst warnings given by only one system are reduced to wind shear-level warnings. Unlike the product-level algorithms, when both systems issue a wind shear with loss warning, the integrated headwind loss estimate is derived from an averaging technique in order to sharpen the estimated headwind loss.

5.1.28 The comparison of the three algorithms was based on data collected at MIT/LL test-bed site at Orlando International Airport. The LLWAS data was collected from three anemometer networks: a six-sensor LLWAS, a nine-sensor LLWAS and a fifteen-sensor mesonet. The two LLWAS networks were phase II standard, but the sensors were relocated and heightened as necessary. The asynchronous data from the three networks over ten days were merged into ten-second synchronous archival records by re-sampling, with each record containing the sensor winds at all thirty sensors for a ten-second period. This parallels the recording scheme used in the operational LLWAS-NE (or phase III as it is now known). The MIT/LL TDWR test-bed radar was used to generate the TDWR warnings, and a dual-Doppler wind field was generated using additional data from the University of North Dakota's Doppler radar. A dual-Doppler wind shear detection algorithm was developed, and the warnings it generated were compared with those of the three test integration algorithms. There was a fundamental difference between the NCAR product-level algorithm and the two MIT/LL algorithms in that NCAR did not use flight path shear integration, whereas the MIT/LL algorithms did. Although all three algorithms performed well, based on the extensive review, evaluation, methodology and test results, NCAR and MIT/LL issued a joint recommendation to the FAA that the MIT/LL message-level integration algorithm should be selected as the production TDWR/LLWAS integration algorithm. This recommendation was accepted and the TDWR contractor (Raytheon) incorporated it into "build 5" of the TDWR software. Subsequent operational demonstrations were conducted at Orlando and Stapleton Airports by MIT and NCAR,²³ respectively, and these indicated that the benefits of TDWR/LLWAS integration were much greater at Stapleton Airport.

5.1.29 These developments were not isolated since they developed in the past 15 years, when airport and airspace congestion, and arrival/departure delays began to exercise considerable constraints on the aviation systems around the world, especially in North America and Europe. Consequently, all aspects of the aviation system had to be re-examined to identify prospective areas for improvement, with each small incremental improvement considered important since it added to the overall improvement in the efficiency of the aviation system. It is well known that adverse weather and the quality of weather observations and forecasts in general had an important bearing on aircraft delays, rerouting and the resulting congestion. Given this situation, at the busy hub airports in the United States seriously affected by wind shear, such individual MET hazards could no longer be viewed separately but as part of an airport integrated weather system.

5.1.30 The first step involved ensuring that pilots in the terminal area had access via data link to the same warning information being provided to ATC from the TDWR, including information on thunderstorms and wind shear. This service was designated terminal weather information for pilots (TWIP). TWIP software specification was drawn up by MIT/LL in 1995; the software package was built by Raytheon and accepted by the FAA in 1997, and the associated network and communications upgrades completed by the FAA and Aeronautical Radio, Inc. (ARINC) in 1997.¹⁹ TWIP is scheduled to be installed at 45 airports in the United States. Its use is a decision for each airline. There are two ways in which TWIP may be used: request/reply and send/cancel. TWIP messages are issued every minute in bad weather and every 10 minutes otherwise. Pilots using the request/reply method receive the latest message; therefore, in the absence of a request, no message updates when significant changes in the weather occur. Pilots using the send/cancel service

receive all TWIP messages, including messages warning of a significant change. This service uses the airline's own distribution software, obtaining the messages from a central database. The drawback to receiving all TWIP messages is that they trigger aural and visual cues in the cockpit prompting the pilot to retrieve and read the messages. If the messages are frequent, this can be a nuisance particularly during heavy crew workload periods, when the aircraft may be some distance from the airport. Furthermore, this problem is exacerbated by false warnings. Some airlines go further by restricting the reception of TWIP messages to aircraft within 40 minutes of estimated arrival time and during taxiing and take-off. At least one airline stores all TWIP messages so they are accessible to the dispatchers and meteorologists, but it does not uplink to its aircraft messages indicating "no storms within 24 km (15 NM)" and warnings of wind shear of less than 60 km/h (30 kt).

5.1.31 TWIP service took the initial step to assist pilots' decision making by providing them with virtually the same MET information in the terminal area that was available to ATC. The next step was to enhance the overall level and quality of MET information in the terminal area by integrating all available data and providing it in a user-friendly format to ATC and pilots. In the terminal area, ATC requires accurate forecasts and warnings of MET phenomena affecting safety, short-term ATC planning and runway capacity optimization. It has to be provided quickly, reliably and in a simplified form that ideally eliminates or minimizes any interpretation by ATC. In order to achieve this, the FAA initiated ITWS. Planning of ITWS began in 1991,²⁴ full-scale development in 1995, with operational deployment in the 2000 to 2004 time frame.²⁰

5.1.32 Wind shear is only one of the important MET phenomena included in ITWS. A brief overview of ITWS with emphasis on wind shear and wind shear-related aspects and what the system is intended to achieve is as follows:

- a) real-time, fully automatic integration of weather data from sensors operated by the FAA, national weather service and airlines;
- b) product distribution to ATC towers, approach (radar units) and en-route ATC centres, with products for terminal areas and en route available to all users; and
- c) real-time displays in airline offices (flight dispatch and central operational control), with the same capability as FAA displays, to facilitate coordination between the FAA air traffic management units and airline flight dispatchers to improve efficiency and safety.

5.1.33 The real-time data fusion from these multiple sensors would provide the following:

- a) predictions of wind shear and thunderstorm movement;
- b) gridded upper-wind information to provide time of flight estimates for traffic merging and sequencing;
- c) information on thunderstorm severity (e.g. lightning, hail and mesocyclones); and
- d) robust handling of individual sensor deficiencies (e.g. attenuation, false alarms, limited coverage, limitations associated with radial velocity data).

The estimated benefits that could accrue from the successful implementation of ITWS are given in Table 5-2.

5.1.34 The most severe wind shear is associated with severe thunderstorms. The objective of ITWS is to provide products to ATC forecasting the development, movement and decay of thunderstorms in the terminal area.²⁵ In this regard, the terminal convective weather forecast (TCWF)²⁰ was developed and was well received by users in the United States. The key attributes of TCWF include frequent updates (every

six minutes), high spatial resolution (1–2 km), high resolution in forecast times (every ten minutes) and self-scoring to provide the user with a quantitative measure of its accuracy. The prototype display of the TCWF products is shown in Figure 5-3. TCWF was demonstrated at four airports in 1999–2000 and was well received by users. It is considered very effective in assisting ATC units to:

- a) pre-plan severe weather avoidance procedures and avoid ground delays during coordination period;
- b) return aircraft to normal routes sooner, avoiding unnecessary re-routes;
- c) avoid premature reaction to the beginning of closures so that more aircraft avoid airborne holds/diversions;
- d) position airborne holds more appropriately in relation to adverse weather so that optimal approach and landing sequences can take place upon clearance of such conditions;
- e) re-route arrivals further from terminal airspace, avoiding airborne holds/deviations at lower altitudes; and
- f) increase the ITWS benefits shown in Table 5-2.

5.1.35 The actions described in 5.1.34 a) to f) identify a number of potential improvements that could be made to the wind shear detection algorithms. One improvement already made to the original microburst algorithm introduced the validation of a microburst detection using reflectivity aloft, specifically, the vertically integrated liquid (VIL) water content, to reduce false alarms. However, situations exist where very dry subcloud environments can still produce microbursts with very low reflectivity aloft (see Figure 3-13). In such cases a valid microburst detection could be invalidated by the VIL threshold test. Simply reducing the VIL threshold only increases the false alarm rate in many cases. The preferred approach is to reduce the VIL threshold *selectively*.²⁶ A number of main airports in the United States have more than one Doppler radar in or near the terminal area. There could be substantial improvements in forecasting wind shifts due to gust fronts, for example, at these airports if the data from all the Doppler radars in a terminal area could be combined and provided to ATC as a mosaic.

**Table 5-2. United States national implementation benefits
from improved ATC decision making using ITWS initial products**
(from Evans and Wolfson, 2000)

<i>User-identified pay-off</i>	<i>Benefit (\$ million per year)</i>
Higher effective airport capacity during thunderstorms	18
Anticipated arrival and departure areas closure/re-opening	134
Anticipated runway impacts and shifts	94
Better terminal area traffic pattern	10
Optimizing traffic flow	125
Improved merging and sequencing using terminal winds	71
TOTAL	452

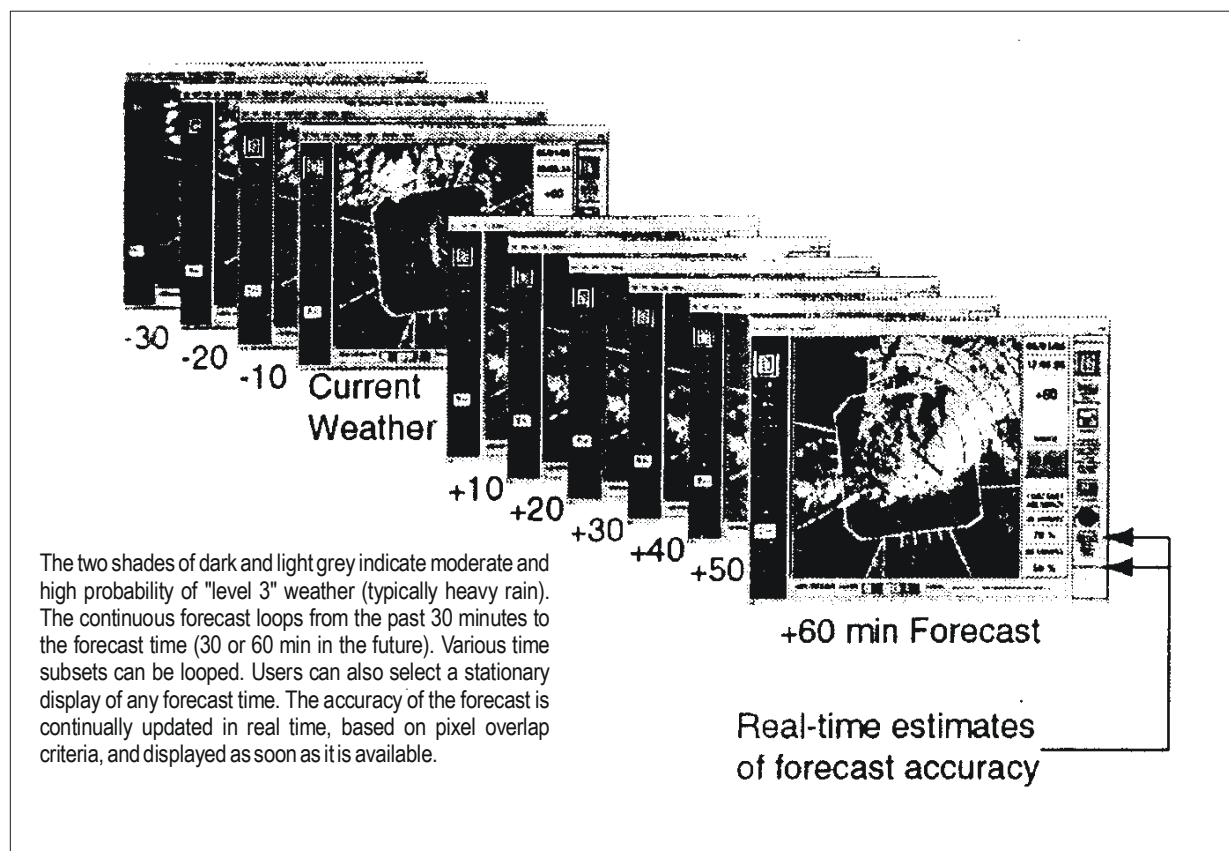


Figure 5-3. Prototype display concept for Terminal Convective Weather Forecast
(Reprinted with permission of MIT Lincoln Laboratory, Lexington, Massachusetts.)

5.1.36 The next challenge that would bring substantial improvements to safety and efficiency involved development of an algorithm for the automated, accurate and timely forecasting of the development of gust fronts and microbursts in the terminal area. This was a major part of ITWS, including specific gust front and microburst prediction output products suitable for use by ATC. The ITWS microburst prediction algorithm, developed by MIT/LL, was based on the fundamental physical principles of thunderstorm evolution and downdraft development. Three-dimensional gridded reflectivity data are used, together with the ambient temperature structure (height of freezing level and lower level lapse rate), thunderstorm location and movement, and total lightning flash rate, etc.²⁷ The ITWS microburst prediction algorithm provides a two- to three-minute warning of a microburst event, before the TDWR warning is available. The list of prototype ITWS products is given in Table 5-3.

5.1.37 The ITWS microburst detection/prediction algorithms use TDWR precipitation data and temperature data from surface and upper air observations and commercial aircraft. Graphical warnings are displayed on the situation in the ATC tower and radar approach. Text messages are transmitted verbally to the pilot by ATC. The algorithm also provides the rate and magnitude of wind speed change.

5.1.38 The ITWS gust front and wind shift combined output product provides ATC with the location and strength of detected gust fronts, and forecasts of gust front movement and associated surface wind shifts across the runways. The algorithm²⁸ uses radar reflectivity, Doppler velocity data and reference wind input, together with thin lines analysis of the reflectivity pattern and analysis of any lines of convergence detected

from the Doppler velocity map. Each gust front is tracked and, based on estimated speed and direction, future positions are forecast. This information is updated approximately every five minutes. When a gust front crosses an active runway and the wind shear is greater than 15 kt, ATC transmits a warning to pilots. The typical ITWS output as displayed to ATC is shown in Figure 5-4.

5.1.39 The foregoing paragraphs describe the development and deployment of automated TDWR in the United States, where the system was initially developed. A TDWR system has also been installed at the new Hong Kong International Airport (HKIA) at Chek Lap Kok to provide wind shear and turbulence warnings. The terminal area around the Kai Tak International Airport, replaced by HKIA in July 1998, had a wind shear and turbulence problem that was addressed using an anemometer network located on the surrounding hills. During planning for the new HKIA, MET analysis of the airport's location indicated that it would be susceptible to convective cloud wind shear and terrain-induced wind shear and turbulence.²⁹ Therefore, in 1993, the Government of Hong Kong, China, contracted the development of an operational wind shear warning system (OWWS) with the necessary algorithms. The OWWS was installed in 1997 and has been successfully operating since then (see Appendix 4).

5.1.40 Integrated systems similar to the ITWS have also been developed in other States, including France, Germany, Japan, Sweden and the United Kingdom, but they do not have a primary role in wind shear detection at airports. These systems are more appropriately described as integrated "nowcasting" systems that merge MET data from many diverse sources to provide short-term forecasts and warnings. They use data from various combinations of Doppler radars, wind profilers, satellite-based scanning multi-channel microwave radiometers, weather satellites, mesoscale surface observing systems and upper air observations, etc.

5.1.41 These systems combine, into a composite picture, digitized radar data from an organized radar network (conventional or Doppler) and superimpose these data on the current atmospheric state as derived from weather satellites, rawinsondes and mesoscale observation networks, etc. The combined data is available for visual presentation to the analyst in real time and in virtually any desired configuration. The analyst is able to intervene interactively through the display keyboard to produce nowcasts. An example of current nowcast products developed by Météo-France for the ATCO's use is in Figure 5-5. From the aspect of wind shear, these systems 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.

Table 5-3. Current ITWS prototype products³⁰
(from Nierow, Showalter and Sanders, 1999)

<i>Wind shear</i>	<i>Precipitation</i>	<i>General</i>
Microburst detection/forecast	Thunderstorm	Tornado detection
Gust front detection/forecast	Thunderstorm motion	Lightning
Surface wind shift estimate	Extrapolated position	LLWAS winds
Timers	Thunderstorm cell information	Terminal climb/descent winds
Thunderstorm location and severity		Pilot text/character graphics message

5.1.42 In addition to Doppler radar and the various integrated systems based on it, different Doppler radar strategies have been pursued by several private MET equipment manufacturers. For example, the infrared Doppler radar avoids much of the problem of ground clutter and side-lobe problems and is particularly suitable for detecting dry microbursts (i.e. presence of few “tracers” in the atmosphere). These “radars” operate at wavelengths closer to the visual spectrum and are more often referred to as Doppler LIDAR (light detection and ranging). Considerable progress has been made in several States in the development of ground-based continuous-wave infrared Doppler LIDARs capable of measuring three-dimensional winds up to a height of 6 to 8 km (20 000 to 26 500 ft). 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 Germany, such a system was developed and 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.³¹ Whichever strategy is selected, it is always a compromise, with each set of radar frequencies and wavelengths having inherent advantages and disadvantages.

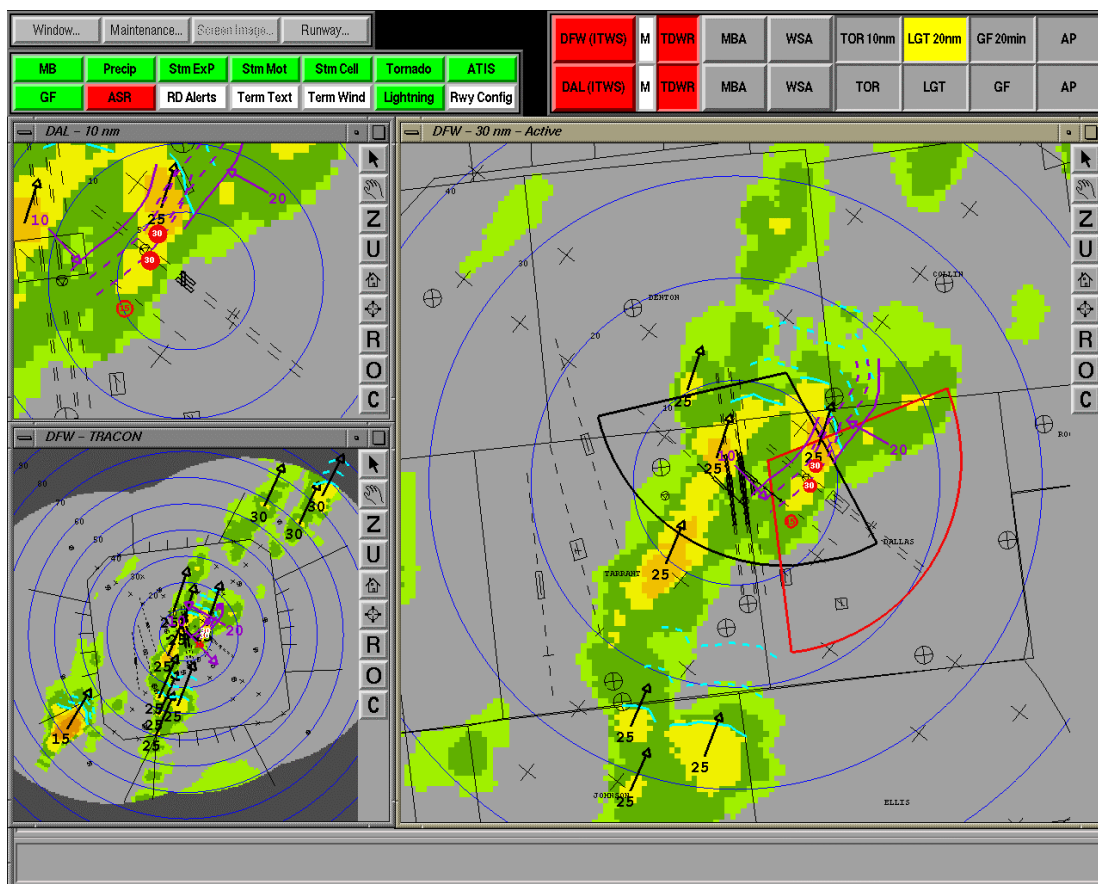
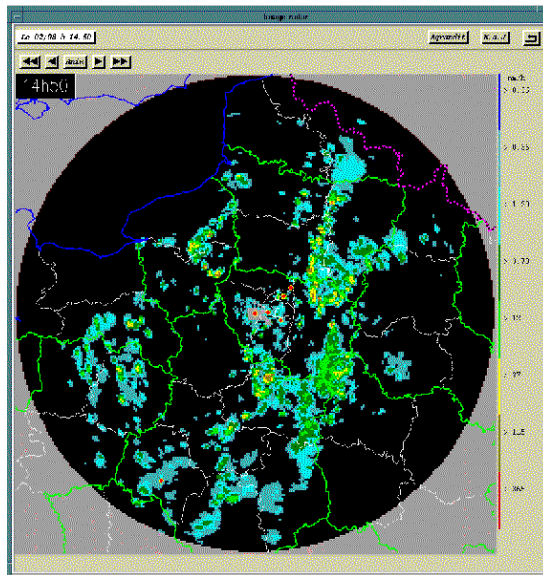


Figure 5-4. Integrated Terminal Weather System Examples
(from the “Role of ITWS in the Modernization of the National Aerospace System”,
Eighth Conference on Aviation, Range, and Aerospace Meteorology)

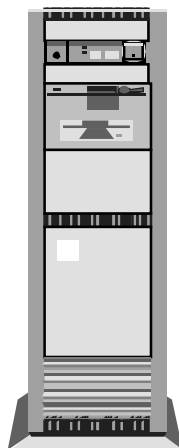


Thunderstorm and convective areas alert and nowcasting for air traffic controllers



Weather radar data

Lightning data

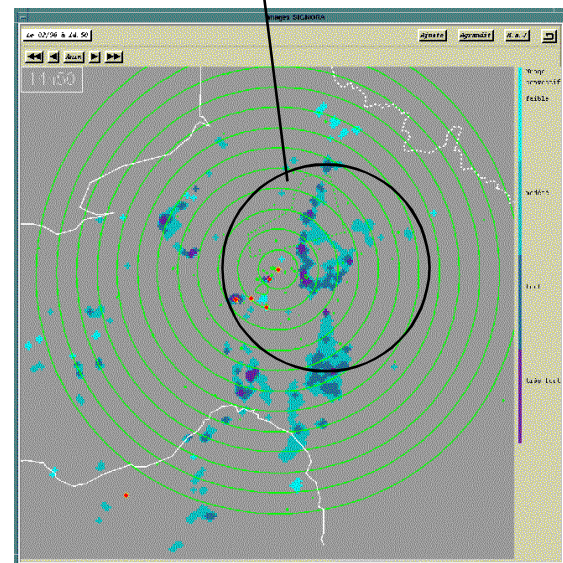
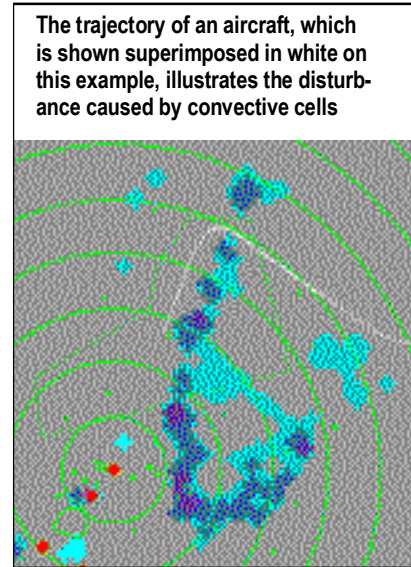


Data fusion

Identification of convective cells

Nowcasting algorithm

Adaptations to controller's visualization needs



Example of final product used by air traffic controllers in the en-route centre of Paris

Figure 5-5. Thunderstorm and convective areas alert and nowcasting for air traffic controllers
(from Météo-France)

Wind profilers

5.1.43 Continuous measurement of winds (all three components) up to the tropopause may be made using vertically pointing VHF and UHF Doppler radars.³² Of the two types, the UHF Doppler radar profiler is better suited to measuring winds in the boundary layer in near real time and provides hourly profiles of wind in the vicinity of the aerodrome. Profilers are of considerable research interest because their potential to augment and possibly replace the existing rawin network at a reduced recurrent cost, while also producing more frequent and higher resolution wind profiles, could revolutionize mesoscale forecasting. Profilers are useful for detecting and monitoring non-transitory wind shear such as that associated with low-level jet streams and terrain-induced wind shear. However, aside from providing additional data for forecasting severe thunderstorms, etc., they are not 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 are very encouraging. In addition, a wind profiler forms an integral part of the OWWs at HKIA at Chek Lap Kok, which is described in 5.1.39 and Appendix 4. France also has in operation a VHF wind profiler at Nice Côte d'Azur Airport, which is highly useful for the appropriate ATC units. Information about the raw data and the visualization is provided in Appendix 5, Table A5-1.

OBSERVING WIND SHEAR FROM THE AIR

Use of standard flight deck instruments

5.1.44 The use of standard flight deck instruments to observe wind shear was dealt with in detail in Chapter 4 in connection 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 airspeed 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 inertial navigation system (INS) ground speed and wind speed and direction read-out.

Airborne wind shear warning equipment

Wind shear warning systems based on the monitoring of aircraft performance

5.1.45 One of the earliest effective systems 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/s or (in a downdraft) a decrease in angle of attack of 0.15 radians (8.6 degrees) or any combination of the two that provides the equivalent signal level (deceleration of 0.15 g).

5.1.46 Another system, available commercially since 1986, provided a wind shear detection and warning capability as part of a performance management system. This system was developed in two phases, with phase I providing detection and alerting components and phase II providing guidance to the pilot. 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.

5.1.47 Both systems mentioned in 5.1.45 and 5.1.46 are referred to as “reactive” wind shear detection/avoidance equipment because they are only able to warn the pilot of the presence of wind shear when the aircraft actually enters the wind shear. Nevertheless, even with this limitation, they are able to detect and warn of wind shear a vital few seconds before the pilot would normally recognize the situation. In parallel with the development of the equipment, in the early 1980s, the FAA began development of airworthiness criteria for the approval of airborne wind shear warning systems in transport category aircraft, and criteria for their operational approval which, ultimately, were published as advisory circulars in 1987.³³ The circulars provided guidance for airworthiness certification of both “warning only” and “warning with escape guidance” reactive-type airborne wind shear warning equipment.

5.1.48 In order to fully characterize the impact of wind shear on aircraft performance in terms of kinetic and potential energy in real time, a non-dimensional index quantifying the wind shear threat in comparison with aircraft performance data available from existing on-board sensors/computers was developed based on work done by Bowles.³⁴ After testing by NASA and the FAA, this index was adopted as the basis for certification of airborne wind shear warning systems. It was derived from the equations of flight described in Figure 4-1 and the customary equation of energy (kinetic plus potential). The aircraft total specific energy (E_T) is defined as follows:

$$E_T = z + \frac{1}{2} \frac{V_a^2}{g}$$

where V_a is the airspeed, g is the gravitational acceleration, and z is the altitude above ground. This equation^d uses air mass kinetic energy, since airspeed (not ground speed) describes an aircraft’s ability to climb and maintain altitude. In the case of potential energy, the altitude above ground can be traded for airspeed and vice versa (see 4.2.7). The time rate of change of E_T , or the potential rate of climb of the aircraft, is the differential and can be equated to the aircraft energy input from thrust and drag (see Figure 4-1), as follows:

$$\dot{E}_T = \dot{z} + \frac{V_a}{g} \dot{V}_a = V_a \frac{(T-D)}{W}$$

The above equation applies only to a uniform air mass. If account is taken of the wind flow, and second-order terms are neglected, the relationship may be written^d as:

$$E_T = V_a \frac{(T-D)}{W} - \frac{\dot{U}_x}{g} + \frac{w}{V_a} = V_a \frac{(T-D)}{W} - F, \text{ where } F = \frac{\dot{U}_x}{g} + \frac{w}{V_a}$$

F is a dimensionless index that combines $\dot{U}_x$, the horizontal component of the wind along the flight path, hence $\dot{U}_x$ is the rate of change of the horizontal component of the wind or the wind shear term, and “ w ” is the vertical component of the wind (updraft/downdraft within the air mass). The F -factor or index, a parameter defined by Bowles, represents the wind field terms of concern to an aircraft’s response to wind

d. The notation $\dot{z}$ is equivalent to $\frac{dz}{dt}$ and, similarly, $\dot{E}_T$ and $\dot{U}_x$ are equivalent to $\frac{dE_T}{dt}$ and $\frac{dU_x}{dt}$, respectively.

shear and is used to define the threshold hazardous wind shear values in airborne wind shear warning equipment. From the foregoing equations, it is seen that a +ve F-factor decreases the energy state of the aircraft, this occurs for a descending air mass (w is -ve), and for an increasing tailwind or decreasing headwind (i.e. $\dot{U}_x$ is +ve). As described in Chapter 4, in performance decreasing wind shear where F is +ve, the pilot can maintain or gain altitude by adding thrust and/or pitching up (thereby trading airspeed for altitude or trading kinetic energy for potential energy).

5.1.49 The equations discussed in 5.1.48 describe the instantaneous effect of shear on an aircraft and must, therefore, be integrated over an appropriate scale length in order to fully characterize the wind shear hazard. For example, very large F-factor values may occur over a small-scale length and are more akin to turbulence. The scale length over which the wind shear operates is, therefore, critical and the subject of much research³⁵ (see 2.5.2). Based on this research, the FAA adopted the 1-km scale length and an average F-factor of 0.13 or greater for the alert threshold. For the certification of airborne wind shear warning equipment, the FAA considers wind shear potentially hazardous at F-factors above 0.1, and a warning (alert in the United States) is required at F-factor 0.13.³⁶ To illustrate typical F-factors in wind shear-producing phenomena, low-level jet streams are unlikely to produce values above the 0.1 threshold; notwithstanding, an unsuspecting pilot could still experience difficulty, and forewarned, the pilot should normally be able to cope with such situations by adding thrust. In microbursts, the 0.1 threshold is exceeded in about half of the well-documented cases, with the centres of intense microbursts producing values ranging between 0.25 and 0.36, which for most jet transport aircraft is considered unflyable.

5.1.50 Certification of airborne wind shear warning equipment involves verifying that the equipment concerned is capable, inter alia, of producing the required alerts at the correct threshold values, reliably and within the accepted level of false alarms and failure modes, etc. In order to do this, the FAA developed a set of wind shear models based on the JAWS data and wind fields derived from wind shear aircraft accident data (see 3.5.17 to 3.5.20). The wind shear warning equipment manufacturer has to demonstrate that the equipment is capable of functioning as claimed when flown in a simulator against the FAA wind shear models.

5.1.51 In the FAA Advisory Circulars referred to in 5.1.47, the following policy is stated:

The application of this [reactive-type] technology inherently requires the entry of the airplane into some level of wind shear with a resulting loss or gain of potential climb gradient. Nevertheless, these systems provide a valuable service in the detection, timely annunciation, and confirmation of a potentially hazardous wind shear condition generally in advance of human pilot recognition time. For systems that provide command guidance features, the available energy of the airplane is efficiently managed to enhance flight path control during the escape maneuver. Ideally, the development of a sensor located on a moving platform, capable of detecting the movement of clear air ahead of the airplane against the background of the earth's surface, would have all the advantages of a look-ahead system. The FAA has identified a requirement to define the systems requirements for these devices and requested NASA to take the technical leadership in this area as extensive research and testing are required.

The operational requirements approved by the ICAO Air Navigation Commission in 1982 and reproduced in Appendix 1 could only be fully met by airborne forward-looking wind shear warning equipment. The successful development of airborne forward-looking wind shear warning equipment is described in the following paragraphs.

Forward-looking wind shear warning systems

5.1.52 In 1990, the FAA amended FAR 121.358 — “Low-altitude wind shear system requirements” to include airborne forward-looking (predictive) wind shear detection and avoidance systems as a recognized

alternative to the “reactive-type” systems. As indicated in the previous paragraph, the ICAO operational requirements can be met only by forward-looking systems. From 1990, the FAA permitted use of forward-looking systems, as soon as these systems could be developed, made available and certified.³⁷ As a result of this FAR extension, four major United States airlines applied to the FAA for an extension to the compliance date stated in FAR 121.358 in order to complete an evaluation and certification of forward-looking systems. These four airlines submitted a comprehensive plan stating their objectives for the evaluation and a time schedule for completion. The FAA subsequently approved the four applications in an exemption granting a two-year extension of compliance. In order to facilitate the rapid development of the required technology, the FAA, NASA, wind shear equipment manufacturers, and the four airlines granted extension of compliance were organized into a “Forward-looking Wind Shear Detection System Working Group”. This working group developed a “road map to certification”, which ultimately led to the development of the general certification methodology and system level requirements referenced above.

5.1.53 Although some of the criteria and basic methods already employed in the certification of reactive-type systems could also be used for the forward-looking systems, the simulations could not, since the reactive-type systems experience the shear in real time, whereas the forward-looking systems have to detect hazardous shear ahead of the aircraft and estimate a predicted performance loss along the flight path. In particular, the atmospheric data set used for the simulation would have to include, in addition to the wind field, the MET conditions present during the wind shear events to be used that could affect the detection capability of the systems. Models of severe ground clutter environments at representative major airports having significant moving ground traffic in the vicinity also had to be obtained by flight tests, and this data merged with the simulated wind shear detection dynamic range capabilities of the system being certified. The FAA certification methodology, system requirements and alerting, annunciating and display requirements for airborne forward-looking wind shear warning systems are given in Appendix 6.

5.1.54 A number of different technologies were tested as part of the FAA airborne forward-looking wind shear warning systems development and certification programme, as follows:

- a) passive infrared;
- b) Doppler radar;
- c) millimetre-wave radar;
- d) LIDAR.

The passive infrared technology was based on the detection of the temperature difference (colder) occurring in microbursts compared to the surrounding atmosphere and correlating this with the vertical velocity (intensity) of the downdraft. The radiometer sensors were multi-spectral scanning instruments operating in the 10–14 μm atmospheric window. Such instruments have also been tested for use in the detection of CAT and volcanic ash, the latter case is described in the *Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds* (Doc 9691). The elimination of signal noise due to, inter alia, turbulence and/or precipitation between the sensor and the target is a difficult, although not necessarily insuperable, problem for all passive infrared sensor technology. Moreover, unless the sensors were to be combined with other infrared sensors, such as for turbulence/volcanic ash, which might become mandatory equipment in the future, it would be necessary to install a separate dedicated infrared sensor to detect wind shear. The installation of completely new equipment on the already “crowded” flight deck tends to meet considerable resistance from the manufacturers and airlines for a variety of reasons; hence, efforts will normally be focused on developing existing flight deck equipment, where feasible.

5.1.55 This latter consideration applied nicely to the weather radars already available and installed on all jet transport aircraft. The latest generation of weather radars available from several airborne weather radar manufacturers already used Doppler signal processing techniques to detect areas of turbulence in the storms, and they had suitable antennas and solid state, coherent transmitters operating in the X-band that

could be modified. It was possible, therefore, that, with the modification of some modules and the design of additional microburst detection/warning algorithms, these radars could be used to detect wind shear, perhaps including the retro-modification of existing installed late-model weather radars.³⁸ Nevertheless, the development of airborne Doppler radar to detect wind shear still presented a number of challenges. The perennial “false alarm” problem, which is of relevance to all sensors, had to be addressed. Then there was the problem of noise due to ground clutter in both the transmitter main and side lobes, which was especially acute for look-down radars on approach and landing, due to urban/airport buildings and moving ground vehicles, etc. After all, these weather radars were already used intentionally by pilots in a look-down mapping mode, in which the return signals from ground features/topography were the required input. It was clear, therefore, that a separate wind shear detection mode would be required in which the ground clutter was subtracted from the return signals. This would mean three operational modes: a weather and map mode, a turbulence detection mode and a wind shear detection mode.

5.1.56 Initial research on airborne Doppler radar was undertaken in the 1980s by NASA using various instrumented research aircraft. The data obtained from these flight tests defined the scope of the problem and pointed to various potential solutions that were worth pursuing further by industry.³⁹ The NASA research programme also produced a baseline set of wind shear parameters, including wet and dry microbursts, that could be used for simulation of the hazard, inter alia, for testing airborne forward-looking wind shear warning equipment.⁴⁰ As the development process continued, the interested airborne radar manufacturers undertook their own flight tests and also teamed with the four airlines that sought and received a two-year extension of compliance with the installation of airborne wind shear warning equipment. The F-factor, described in 5.1.48, was also used as the determining wind shear hazard level in the algorithms developed for the airborne forward-looking wind shear warning systems. The requirement for the probability of detection and false alarms was refined. It was also noted that great care had to be taken over the maintenance of the radome. By the mid-1990s, a number of airborne radar manufacturers had successfully developed and certified effective airborne forward-looking wind shear warning systems as modifications of their “late-model” airborne weather radars. In view of the importance of these systems in combatting wind shear, a detailed description of a typical airborne forward-looking wind shear warning mode on a commercially available airborne weather radar is given in Appendix 6.

5.1.57 In parallel with the successful development and certification of the airborne forward-looking wind shear warning systems, in 1998 ICAO amended the relevant regulatory document (Annex 6 — *Operation of Aircraft*, Part I — *International Commercial Air Transport — Aeroplanes*) to recommend the installation of these systems on turbo-jet engine aircraft of a take-off mass of more than 5 700 kg. These amendments were based on the Statement of Operational Requirements given in Appendix 1 to this manual. In developing the amendment proposal, States and interested international organizations were specifically asked their opinion on whether or not the requirement to install airborne forward-looking wind shear warning equipment should also apply to turbo-propeller aircraft. In this regard, it was considered that turbo-propeller aircraft were not normally as susceptible to the effects of wind shear as turbo-jet engine aircraft. This was mainly because the application of full power by the pilot in a turbo-propeller aircraft produces an almost immediate increase in airflow (propeller slipstream) over the wings and increased airspeed and lift. In the case of a turbo-jet engine-powered aircraft, following the application of full power by the pilot, the whole aircraft mass has to be accelerated before it is translated into increased airspeed and lift, and this, unavoidably, takes a vital few seconds. It was decided that, for the time being, the recommendation should be restricted to all turbo-jet aeroplanes of maximum certificated take-off mass in excess of 5 700 kg or authorized to carry more than nine passengers.

5.1.58 In the case of millimetre-wave radar, most research efforts have focused on developing a system that could be used for instrument landings in virtually zero visibility, enabling the pilot to see the runway on a head-up display (HUD) even when landing in rain and fog. If successful, it is expected that a forward-looking wind shear warning mode could be added to the system. Results are promising and research continues, but so far such a system has not been submitted for certification.

5.1.59 The possible use of airborne LIDAR to detect wind shear has been the subject of research in a number of States over the past two decades. The United Kingdom RAE at Bedford and NASA have been studying the use of Doppler LIDAR for airborne measurement of wind speed and direction.^{41,42,43} Doppler LIDAR operates on exactly the same principle as Doppler radar but employs coherent infrared light produced by a CO₂ infrared laser (see 5.1.17 to 5.1.42). In the RAE system, called the laser true airspeed system (LATAS), the laser beam was focused 500–600 m ahead of the aircraft and measured the motion of the air at this point relative to the moving transmitter. In this way the system was able to advise the pilot of likely airspeed changes due to wind shear about four seconds ahead of the aircraft. The instrument was measuring the motion of aerosol particles in the air relative to the aircraft and along the flight path (headwind/tailwind) so it was incapable, 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 HS-125 aircraft on which the system was installed also took part in the JAWS project (see 3.5.16). The system was reportedly rugged, reliable and lightweight, required minimal maintenance, adjustment and calibration and could measure “airspeed” up to 800 m ahead of an aircraft in clear air or in cloud. The performance was considerably better below 6 km (20 000 ft) where aerosols are normally plentiful, and although the signal return decreases above this level, wind measurements were made up to the operating ceiling of the HS-125 (13 km (43 000 ft)).

5.1.60 In the United States, Doppler LIDAR has been under research and development for several years, both for the measurement of wind velocities^{44,45} and for the detection of CAT. Although these systems are capable of measuring wind velocities ahead of the aircraft, so far none of them have been submitted for certification as forward-looking wind shear warning systems. In the case of CAT, however, this may lead to the certification of a LIDAR system that could perhaps serve a dual purpose for the detection/warning of wind shear and CAT. This latter MET phenomenon has assumed increasing importance over the past decade due to a number of aircraft incidents causing serious injuries to numerous people and aircrew and fatality as a result of severe CAT at cruise level. Some of the most recent work in this field⁴⁶ shows excellent promise, and it will be interesting to see if airborne forward-looking CAT detection/warning systems become “required” equipment on jet transport aircraft in the future. Research indicates that even moderate CAT could be detected at ranges of 5–8 km and up to 100 s ahead of an aircraft. Such an advance warning would permit an altitude change and/or a check to ensure that all passengers and aircrew are properly and securely seated. Recent research on turbulence to be reported by aircraft in flight shows the parameter called “eddy dissipation rate (EDR)”, which is a viable measure of turbulence and a reasonable predictor of increased variation in the vertical acceleration. An example of the comparison between the vertical acceleration and the EDR during the flight tests is shown in Figure 5-6. The EDR is of particular interest because in the ICAO requirements it already forms the basis for the automated reporting of turbulence from aircraft. Since the EDR can be ingested as a variable into the atmospheric numerical weather prediction models, its potential future use in airborne detection/warning systems would neatly complete the loop, whereby the observing/warning/automated reporting of turbulence and the World Area Forecast System (WAFS) forecasting of turbulence in significant weather (SIGWX) forecasts for flight documentation would be based on the same parameter.

5.1.61 HUDs have been regular equipment on fighter aircraft for many years and have also been installed on commercial aircraft by some airlines but not specifically for the purpose of wind shear warning. HUD is a system for presenting to the pilot essential guidance and control information 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; however, 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 several States on providing specific flight path indicators

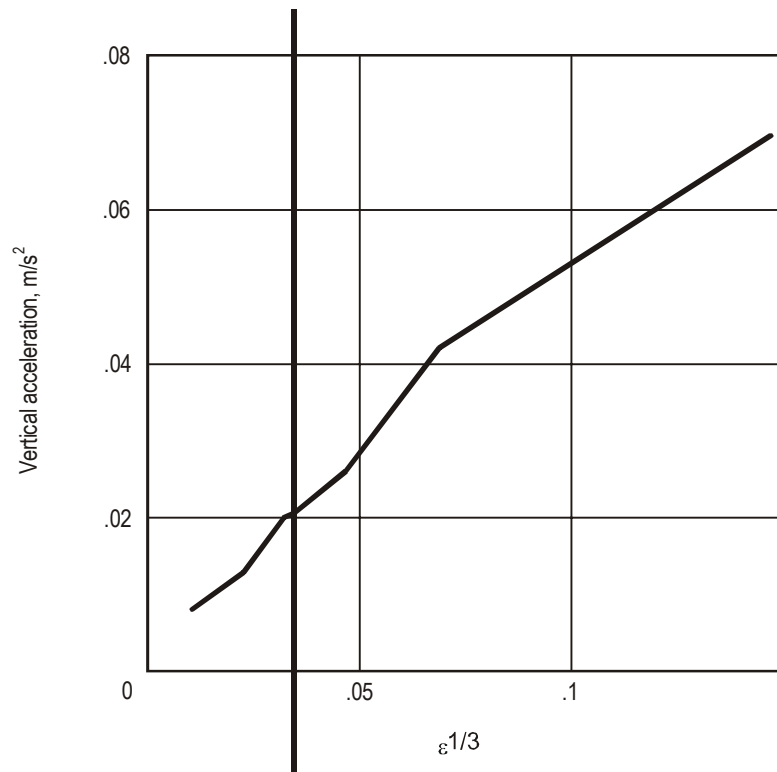


Figure 5-6. Variation in the vertical acceleration and the cube root of eddy dissipation rate
(from Soreide, Bogue, Ehernberger, Hannon and Bowdle, 2000)

(FPIs), for example, an FPI symbol representing the touchdown point on the runway projected from the existing flight path and a “potential flight path (PFP)” symbol that indicates acceleration or deceleration of the aircraft (assuming the FPI is maintained on the aiming point, e.g. by elevator adjustment). When the two symbols are superimposed, the aircraft is neither accelerating nor decelerating, and wind shear is indicated when the symbols separate on the display.⁴⁷ Most pilots taking part in HUD tests indicated that the tests assisted considerably in coping with the simulated wind shear conditions.

WIND SHEAR AND TURBULENCE MODELS

5.1.62 This section covers wind shear and turbulence models and their use in the certification of airborne wind shear warning systems and flight training simulators. The development of wind models progressed quickly in the United States, primarily as an integral part of the FAA wind shear and turbulence programme in the mid to late 1980s. In this context, the models were designed to serve multiple purposes, and there were a number of options available relative merits of which had to be adjudicated upon prior to their selection for operational use. Models of many different levels of complexity have been developed, with those used for research purposes being the most complex (three- and four-dimensional), while those used in flight simulators for daily pilot training, for obvious reasons, are probably the least complex (mostly two-dimensional). The wind data used as the basis of the first wind shear models for research were obtained from two main sources: the JAWS project and subsequent wind data sets from related projects, and recreated winds from aircraft accidents where wind shear was cited as a factor⁴⁸ (see 3.5.16 *et seq.*).

However, wind shear and turbulence models were also urgently required for the development of ground-based and airborne detection/warning systems, for the certification of airborne detection/warning systems using simulation and for flight simulators used for pilot training.

5.1.63 Initially, the models, referred to as phase I models, selected by the FAA for the certification of the “reactive-type” airborne wind shear systems and for use in flight training simulators were based on information provided by the flight data recorders involved in actual wind shear-related aircraft accidents. This approach focused the models on known “hazardous” wind shear and provided sufficient aircraft parameters recorded during these encounters, such as aircraft airspeed, heading, altitude and acceleration, to enable the development of model wind fields or profiles that exhibited hazardous wind shear.

Note.— At that time the majority of aircraft had four-channel flight data recorders, although more recent flight data recorders are required to record even more data.

The phase I models were relatively simple, using data from two wind shear accidents (the Eastern Airlines B727 at New York and the Iberian DC-10 at Boston). These models were found unsatisfactory for use in flight training simulators. Consequently, the FAA contracted with SRI International to assemble a team of experts from relevant disciplines, such as meteorology, fluid dynamics and simulator technology, to revise the models without losing the important linkage with real-life wind shear accidents on which they were based. This combined effort produced a wind field better representative of hazardous wind shear that was included as an example in the 1983 FAA Advisory Circular 120-41 — *Criteria for Operational Approval of Airborne Wind Shear Alerting and Flight Guidance Systems*.

5.1.64 Since the issuance of the initial SRI model wind field data, the wind shear models used by the FAA for airborne systems certification, ground-based systems validation and pilot training, etc., have been continuously revised and improved. A reasonably stable set of models is now available the relative complexity of which is appropriate for their intended particular purpose. In this regard, a detailed data set of the wind fields known as the NASA TASS (terminal area simulation system) is used for the certification of airborne wind shear warning systems. The use and content of these data sets for simulation purposes and the certification scenarios employed are shown in Table A7-1 of Appendix 7. Table A7-1 shows that the models comprise a mix of recreated accident data, aerodrome sounding and derived sounding data illustrating particular wind shear situations and flight data.

5.1.65 The wind field models in flight simulators used in pilot training, for logistical and economic reasons, cannot and normally need not be as sophisticated and extensive as the TASS wind field data set used for airborne systems certification. The pilot training simulator wind fields recommended by the FAA are mainly two-dimensional profiles, but each data point contains u , v and w components along the three-degree glide path and climb-out paths derived from accident data, although some operators use three-dimensional models of a microburst. Pilot training is a major part of the FAA wind shear training aid, which contains a volume of substantiating data, *inter alia*, including a set of recommended wind shear wind profiles. (See Chapter 6 for pilot training.)

5.2 FORECASTING WIND SHEAR

GENERAL

5.2.1 At aerodromes affected by wind shear but lacking the operational equipment to observe or detect and measure wind shear (referred to in 5.1), it is extremely difficult to forecast wind shear. Generally, the only viable approach is to attempt to forecast the occurrence of the MET phenomena known to produce wind shear, understanding that significant wind shear may or may not occur, and if it does, 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.

5.2.2 Concentrated research efforts have been expended during the past few years, and progress is 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 worldwide database of wind shear encountered during landing and take-off derived from AIDS installed on most large jet transport aircraft (see 3.7). These efforts provide a clearer understanding of wind shear and, in particular, permit focus on the specific types of wind shear that appear to be the most dangerous for aircraft.

5.2.3 In the meantime, most aerodromes have to resort to various forecasting “rules of thumb” that were developed on the basis of MET theory and extensive knowledge of the area concerned. An example is the set of rules employed by the MET office in the United Kingdom during wind shear forecasting trials in 1977. The current rules derived from those trials, used operationally since 1985, is given in Appendix 8. A similar set of rules, modified as necessary for different conditions, are currently used by the United States National Weather Service.⁴⁹

5.2.4 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 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. However, 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 wind shear, the many problems associated with classifying wind shear in terms of intensity should be examined.

WIND SHEAR INTENSITY

5.2.5 In Chapter 2, various methods for calculating wind shear are discussed, and the different units currently used are 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. kt per 100 ft or m/s per 30 m. At first glance it seems that the classification of wind shear intensity in terms of a number of classes, bounded by empirically derived values in kt/100 ft or m/s per 30 m, is a straightforward matter. This approach was followed at the Fifth Air Navigation Conference (Montréal, 1967), where the interim criteria for wind shear intensity given in Table 5-4 were recommended. This original table gave wind shear intensities in four classes from light to severe in terms of kt 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.

5.2.6 At that time 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, which 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:

- a) the same wind shear intensity, as proposed in Table 5-4, can affect each aircraft type differently; what might be considered severe for one aircraft type 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 the distance over which the wind shear operates and hence time of exposure to the shear;

Table 5-4. Interim criteria for wind shear intensity recommended by the Fifth Air Navigation Conference (Montréal, 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)

- c) information on wind shear intensity given in units of speed and distance is not of direct assistance to the pilot flying a three-degree glide slope because a pilot does not think in such units, which do not relate to any of the usual flight deck instruments. A pilot thinks in terms of airspeed, and therefore changes in airspeed are accelerations or decelerations in kt/s or g units;
- d) the most hazardous wind shear is that associated with thunderstorms, i.e. 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 5-4 (*excluding* downdrafts) do not seem to have been substantiated following the analysis by the RAE of AIDS data from over 9 000 landings worldwide of British Airways B747 aircraft. In this context, the aircraft encountered wind shear conditions classed as severe in accordance with the criteria in Table 5-4, but which evidently presented little or no problem for the pilot in landing the aircraft.⁵⁰

5.2.7 The fact that there are a number of unresolved problems associated with the interim criteria for wind shear intensity has two main effects. First, it is impossible for now to use the qualifying terms “light”, “moderate”, “strong” and “severe” in relation to wind shear in the provisions covering wind shear in 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 Annex 3, Appendix 6, 6.2.4, Note 2, 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, and such qualifications have to be included unchanged in the report.” Second, although a number of proposals were made for improving the interim criteria, the tendency seems to be to avoid the issue 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 (see 5.2.8 to 5.2.14 for details).

5.2.8 One proposal to improve the wind shear intensity criteria was made by Woodfield and Woods in their analysis of worldwide wind shear data derived from over 9 000 landings of BA B747 aircraft.⁵⁰ 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 6 km/h per s (3 kt/s) 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 50 to 60 km/h (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 is illustrated by considering two extremes: at one extreme an aircraft can cope with a 200-km/h (100-kt) wind speed change if the rate of change is only 0.2 km/h per s (0.1 kt/s); similarly, at the other extreme, with only a 10-km/h (5-kt) wind speed change, a rate as high as 20 km/h per s (10 kt/s) also presents no problem.

5.2.9 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 dominates 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. Researchers 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),

V_{app} = normal approach speed.

The primary parameter is $\frac{\Delta V}{R^{1/3}}$ or the "normalized" wind shear. Suggested forms of intensity boundaries are shown in Figure 5-7.⁵⁰ Researchers recommend that such intensity criteria be tested in the appropriate flight simulators.

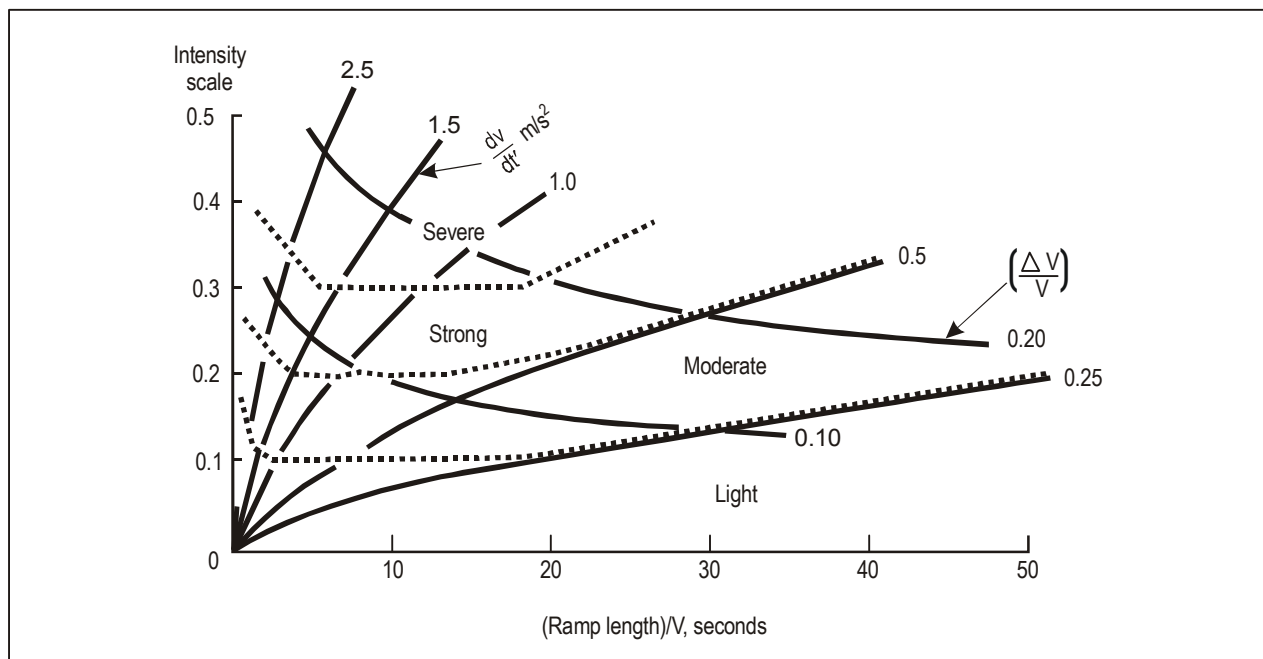


Figure 5-7. Suggested form of intensity boundaries
(from Woodfield and Woods, 1984)

5.2.10 A different approach to the problem of wind shear intensity was suggested by Swolinsky⁵¹ who points out that the intensity factor proposed by Woodfield and Woods⁵⁰ does not take into account changes in the vertical component of the wind (see 5.2.9). Swolinsky's proposal is based upon energy considerations (potential and kinetic) for approach/landing, termed the "energy height error" (ΔH_E), as follows:

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

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

5.2.11 The derivation of the F-factor and its increasing usefulness to define the wind shear hazard for airborne wind shear warning systems and flight simulators is described in 5.1.48 and Appendix 5.

5.2.12 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 followed this course of action when it issued Advisory Circular (AC) 120-41, dated July 1983, *Criteria for Operational Approval of Airborne Wind Shear Alerting and Flight Guidance Systems*.⁵² The circular contained 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, MET data and other sources against which an airborne detection system may be flown on the simulator. For this procedure, severe wind shear was 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 or 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)."

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 implied that there was another class of wind shear intensity beyond "severe" that cannot be safely transited even with the use of airborne wind shear detection systems. At the time, the advisory circular applied to "reactive-type" airborne wind shear warning systems.

5.2.13 Although not strictly a measure of wind shear intensity per se, as discussed in 5.1.48, the F-factor proved to be a very useful index of wind shear intensity in the changing energy state of an aircraft caused by the wind shear. This index is situation-specific and is primarily being used in the certification of airborne wind shear warning systems and thus in the system's algorithms that determine warning status and in flight simulators. However, because the F-factor is comparatively weakly dependent on the airspeed in these instances, nominal airspeeds are selected for landing and take-off, for example, 240-, 300- and

400-km/h (120-, 150- and 200-kt) airspeeds, which roughly bracket the typical airspeeds for landing and take-off for most jet transport aircraft. For the most part, it seems that use of the F-factor is likely to be most suitable for use in automated equipment, such as airborne wind shear warning systems and flight simulators. Otherwise, in warnings (especially those derived manually) wind shear “intensity” will continue to be stated in airspeed (kt) loss/gain over a suitable scale length such as 1 km and in the case of strong vertical components, simply as “microburst”.

5.2.14 With the advent of the development of airborne forward-looking wind shear warning systems, the FAA issued Technical Standing Order (TSO) C117 — *Airborne Wind Shear Warning and Escape Guidance Systems for Transport Airplanes*, dated 1990.⁵³ In the TSO the definition of “severe” wind shear for the purpose of certification was modified slightly as follows:

“*Severe Wind Shear.* A wind shear of such intensity and duration which would exceed the performance capability of a particular aircraft type, and likely cause inadvertent loss of control or ground contact if the pilot did not have information available from an airborne wind shear warning and escape guidance system which meets the criteria of this TSO.”

As discussed in 5.1.53, many of the certification criteria already used successfully for “reactive-type” systems could be used for “forward-looking” systems. However, by 1990 the F-factor had been proposed by Bowles, and henceforth this factor defined the “severity” of the wind shear detected by both reactive and forward-looking systems, as described in 5.1.48 and 5.1.49, respectively.

TRANSITORY AND NON-TRANSITORY WIND SHEAR

5.2.15 From the forecasting standpoint, low-level wind shear may be conveniently classified into two types, either transitory or non-transitory. While 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 5-5). Non-transitory wind shear, which might be associated with, for example, marked low-level temperature inversions, mountain waves or airflow around obstacles, tends to affect a particular area and persist for relatively long periods (measured in hours). It 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.

FORECASTING NON-TRANSITORY WIND SHEAR

Forecasting wind shear associated with air mass fronts

5.2.16 Forecasting the development and movement of frontal surfaces is based on mature techniques that 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 that has 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 the description it is evident that, concerning 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.

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

<i>Wind shear type</i>	
<i>Transitory</i>	<i>Non-transitory</i>
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

5.2.17 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, synoptic analysis has been considerably augmented by using information from polar-orbiting and geostationary weather satellites. The former provides information relevant to a particular location every 6 hours while the latter provides quasi-continuous observation. The geostationary operational environmental satellites (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 approximate 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 using radar to monitor the development, intensity and movement of precipitation areas (both convective and non-convective) associated with the fronts.

5.2.18 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) AGL. The simplest method of doing this is to locate the surface position of the front on the surface chart at a particular time and at the same time determine from rawinsonde/satellite data the height above ground of the frontal surface ahead of a surface warm front or behind a surface cold front. More detailed analysis may be necessary using cross-sections (especially isentropic^e) through the frontal surface. Isentropic analyses in the past were notoriously labour-intensive, but recently the preparation of such analyses, in real time, by computer has become relatively straightforward. Given the speed of movement and the slope, an 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 5-8.⁴⁹ Only two typical speeds and a selection of typical slopes are shown for each front, but it is straightforward to derive information for other speeds and slopes using proportion and interpolation, respectively.

5.2.19 The question arises whether all fronts need to be treated in such detail or if there are 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 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 degrees Celsius per 90 km (50 NM) was suggested and used successfully in this regard.⁴⁹ 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 front's speed of movement. In this context, a vector wind difference of magnitude 40 km/h per 90 km (20 kt per 50 NM) was suggested and simple nomograms to calculate the magnitude of

e. Such cross-section analysis is dealt with in detail by Saucier in *Principles of Meteorological Analysis*, 1955.

the vector difference directly from two winds using the relationship discussed in Figure 2-2 c), 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 two aspects to be considered with respect to criteria based upon speed of frontal movement. While fronts moving at speeds of 30 kt or more (usually steeply sloped cold fronts) 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 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 overall on aircraft operations (e.g. numerous missed approaches) than the intense, fast-moving cold fronts.

5.2.20 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 is situated at an appropriate location in relation to the frontal surface, the wind shear may be calculated directly as shown in Chapter 2, taking note 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 was 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 a cold front, the geostrophic wind in the cold air behind the front is more representative of the wind below the frontal surface than the surface winds (this provides an estimate of 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 resolved⁴⁹ (see 5.1.10). 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.

5.2.21 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.⁵⁴

Forecasting wind shear associated with sea-breeze fronts

5.2.22 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 5.2.19 may be used to analyse sea-breeze fronts. There are, however, a number of additional considerations: mainly that the sea breeze is not advected steadily across a synoptic chart as with air mass fronts, and its formation must be forecast every 24 hours. The formation of the sea breeze is not automatic and is subject largely to the overall synoptic situation and 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 dense 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 the local knowledge and experience of the forecaster.

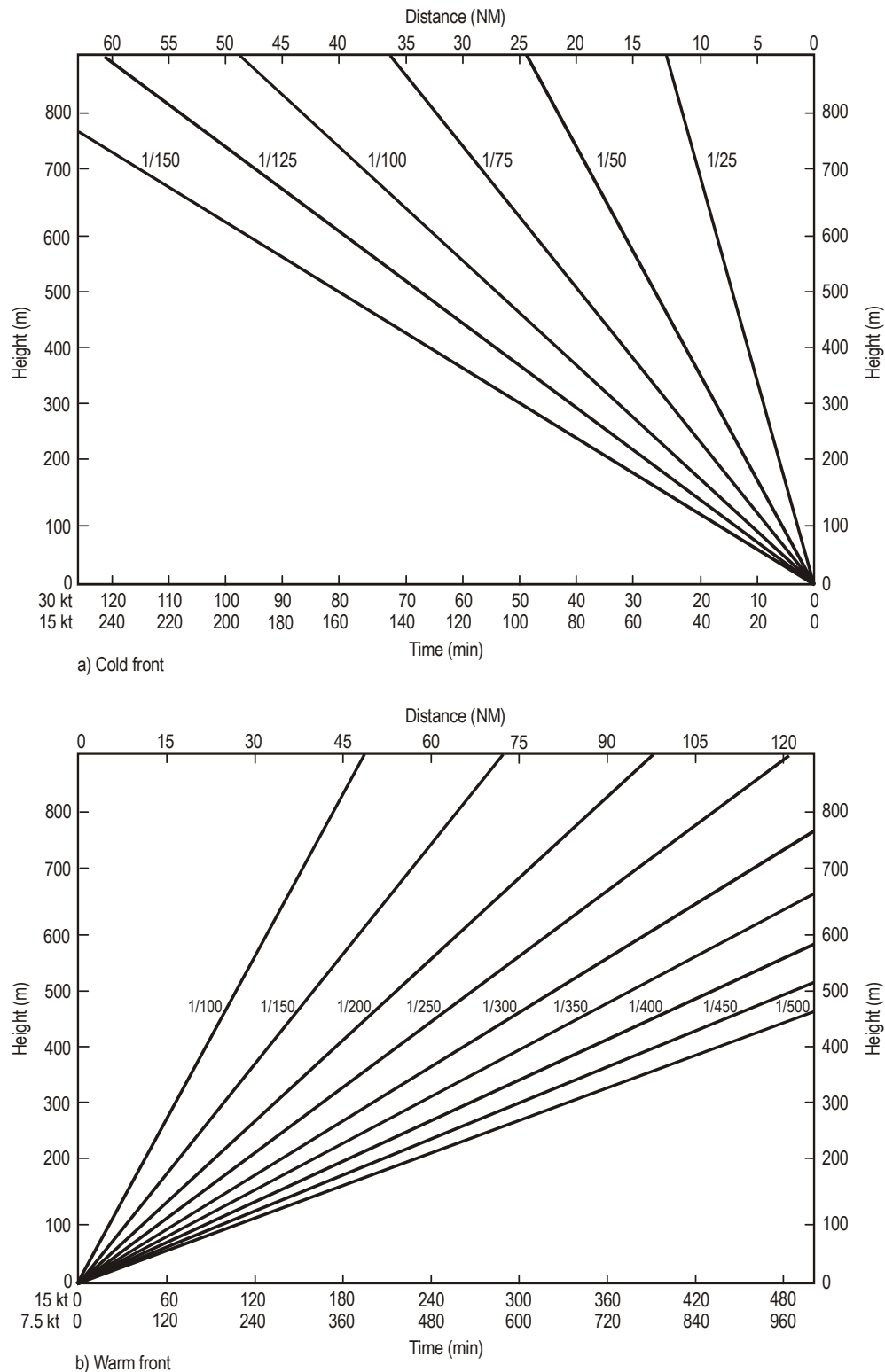


Figure 5-8. Height of warm and cold fronts versus distance/time from airport for various slopes
(from Badner, 1979, and adapted by ICAO)

5.2.23 A particularly good example of an actual case of a sea-breeze front near Boston is shown in Figure 5-9.^{3,12} 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 perhaps would have been slightly stronger than the 30 kt at the surface. The surface wind at Boston (BOS) is taken as typical of the wind below the frontal surface. The magnitude of the vector difference (wind shear) between them is at least 40 kt. The surface temperatures (degrees Fahrenheit) are also plotted alongside the station circle in Figure 5-9. 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 noted that intense sea-breeze fronts are capable of penetrating up to 50 km inland under suitable conditions.

Forecasting wind shear due to wind flow around obstacles

5.2.24 Although terrain-induced wind shear is notorious for its variability in intensity and therefore is usually accompanied by CAT, from the forecasting standpoint, it is best considered as non-transitory because, given certain favourable MET 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 MET 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),⁵⁵
- d) soliciting low-level wind and wind shear/CAT 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^f is warranted (e.g. Rock of Gibraltar), hydrodynamic tests can be run on scale models or computer simulations made.

5.2.25 There are numerous ways in which the climatological 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). The simplest way is to calculate the mean and standard deviation of the ratio of gust speed to mean speed, monthly or annually. An example of this analysis (annual) is shown in Figure 5-10 for Seychelles International Airport.⁵⁶ In this example it is immediately evident that south-westerly winds are very gusty. This agrees well with the fact that there is high ground in relatively close proximity to the west of the anemometer site.

f. While such experiments are normally expensive, this is not always the case; see, for example, reference 22 for the analysis of wind flow over Cyprus.

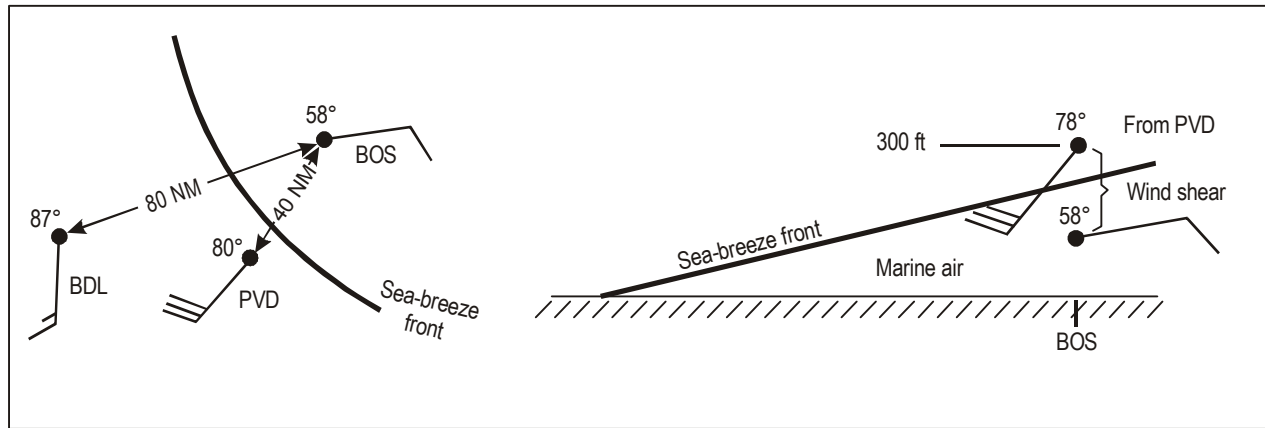


Figure 5-9. Wind shear associated with a sea breeze
(from Badner, 1979)

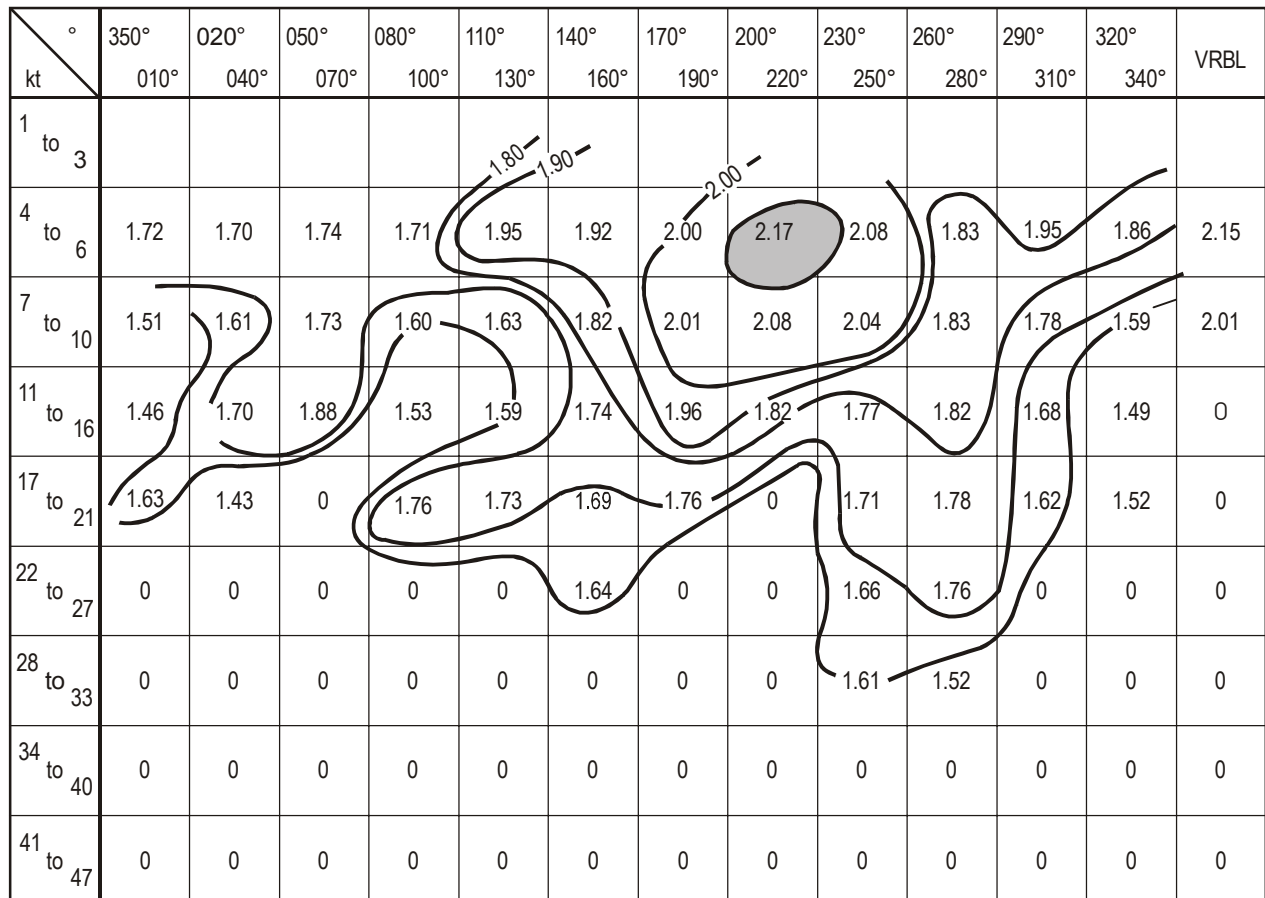


Figure 5-10. Mean gust factor for various classes of wind speed (kt) and direction, Seychelles International Airport
(from *Climate of the Seychelles*, 1979)

5.2.26 Once the nature, prevalence and, where possible, the average intensity of terrain- or building-induced wind shear in the vicinity of an aerodrome are known, and the particular MET conditions that 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 (AIP).

Forecasting wind shear associated with mountain waves

5.2.27 Wind shear associated with mountain waves is a special case of wind flow around or over obstacles (see 3.2.8 to 3.2.10 for details). In general, it is of concern only to aerodromes situated on the lee side of high and long mountain ranges that 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 the largest amplitude wave that reinforces the usual Föhn wind effect (see 3.2.10). This can result in the sudden onset of very strong, gusty and noticeably warm, dry surface winds. Such gusts have exceeded 200 km/h (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 extended down to ground level and reverse the usual surface wind (see Figures 3-4 and 5-11). Intense rotor flows may contain downdrafts/updrafts as strong as 25 m/s (5 000 ft/min).⁵⁷

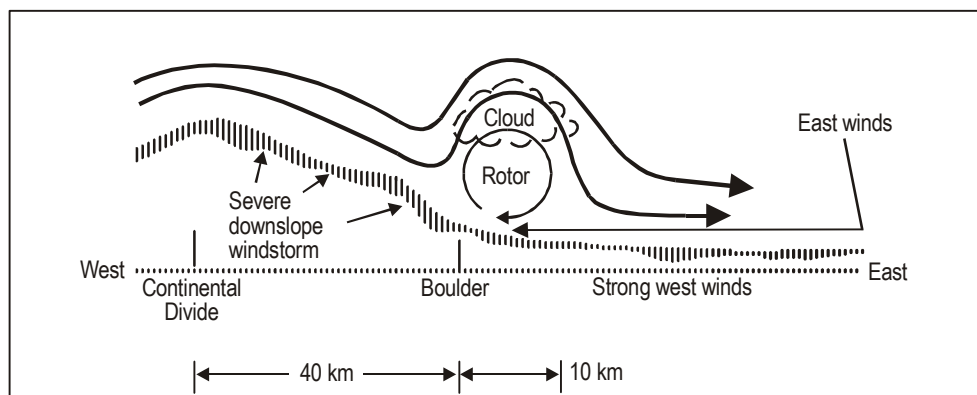


Figure 5-11. For 24 January 1982, schematic vertical cross section through Boulder, Colorado, United States, believed representative of the mean flow field from about 0900–1800 MST. While winds from a general easterly direction prevailed in a zone around Boulder, strong west winds were observed 2–3 km above ground level in the stratocumulus clouds, which systematically formed just west of Boulder.
(from Zipser and Bedard, 1982, and adapted by ICAO)

5.2.28 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.^{58,59} 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 is based on two of these factors — sea level pressure difference across the mountain range against wind speed normal to the mountain range.^{60,61} With north-south orientated mountain ranges, marked mountain waves can be triggered by a passing cold front.

5.2.29 The forecasting of wind shear associated with mountain waves would in most circumstances be translated into a SIGMET and/or AIRMET message. The requirements for the issuance of these messages are given in Annex 3, Chapter 7. In this context Annex 3, Appendix 6 — Technical Specifications Related to SIGMET and AIRMET Information, Aerodrome Warnings and Wind Shear Warnings, 4.2.8, also defines the severity of mountain waves as follows:

“A mountain wave (MTW) should be considered:

- a) severe whenever an accompanying downdraft of 3.0 m/s (600 ft/min) or more and/or severe turbulence is observed or forecast; and
- b) moderate whenever an accompanying downdraft of 1.75–3.0 m/s (350–600 ft/min) and/or moderate turbulence is observed or forecast.”

Forecasting wind shear associated with katabatic winds

5.2.30 This type of wind flow is of particular concern to aerodromes situated in a valley. The MET situation favouring its development includes calm, clear nights under anticyclonic conditions (see 3.2.7). 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, the katabatic wind itself does not normally constitute a problem at most aerodromes, except in extreme cases. 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 200 km/h (100 kt) (e.g. the “Bora” of the Adriatic).

5.2.31 Significant local wind shear above ground level due to the normal downslope katabatic winds is only likely to occur if the surface inversion that develops at night is sufficiently strong to prevent mixing in the lowest levels of the atmosphere.⁶² 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, therefore 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) AGL).⁶³ 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.

Forecasting wind shear associated with the low-level jet stream

5.2.32 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 3.1.5, the axis of the low-level jet stream is generally found below 500 m (1 600 ft), although the axis tends 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,⁶⁴ 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 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 (see 5.1.18).

5.2.33 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, fairly detailed rules may be developed. Otherwise the following general rules proposed by Badner⁴⁹ 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 ≥ 40 km/h (≥ 20 kt). The pressure gradient should not relax below the spacing sufficient to produce the maximum 40-km/h (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, $\frac{30 \text{ kt}}{350 \text{ m}} = 30 \times \frac{30}{350} = 30 \times .086 = 26 \text{ kt/30 m}$. 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).

FORECASTING TRANSITORY WIND SHEAR

Forecasting wind shear associated with convective clouds

General

5.2.34 Forecasting low-level wind shear associated with convective clouds, especially mature thunderstorms, is critical to aviation but extremely difficult. Furthermore, forecasting convective cloud, particularly thunderstorms, in the area of interest is necessary, but as far as low-level wind shear is concerned, it is not sufficient. The different types of low-level wind shear of concern to aviation that may be associated with thunderstorms are described in detail in 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 produces it.

5.2.35 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, which should be understood 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 that are 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 few decades, mainly due to the threat to life and the horrendous 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 the detailed knowledge of the minute-by-minute state of the atmosphere at a given location. The forecast that results may, at the extreme, constitute no more than a critical few minutes' warning. These techniques have come to be known as "nowcasting", a term explained by Browning⁶⁵ 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 (WMO)⁶⁶ 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 forecast” as provided in Annex 3, Chapter 6, which renders nowcasts especially suitable for aviation purposes.

5.2.36 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 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.⁶⁷

Forecasting gusts, gust fronts, downbursts/microbursts and tornadoes

5.2.37 Without exception, all thunderstorms may 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. The Fawbush and Miller method 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 0 degrees Celsius (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 is then subtracted from the observed surface temperature or forecast temperature prior to the onset of the thunderstorm. The difference is proportional to the maximum gust according to the graph shown in Figure 5-12.^{g,68} 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.⁶⁹ Having forecast the probable maximum gust, there is no guarantee that such a gust will affect any particular area in the thunderstorm’s path, such as an aerodrome.

g. Sometimes referred to as the Delta-T Index.

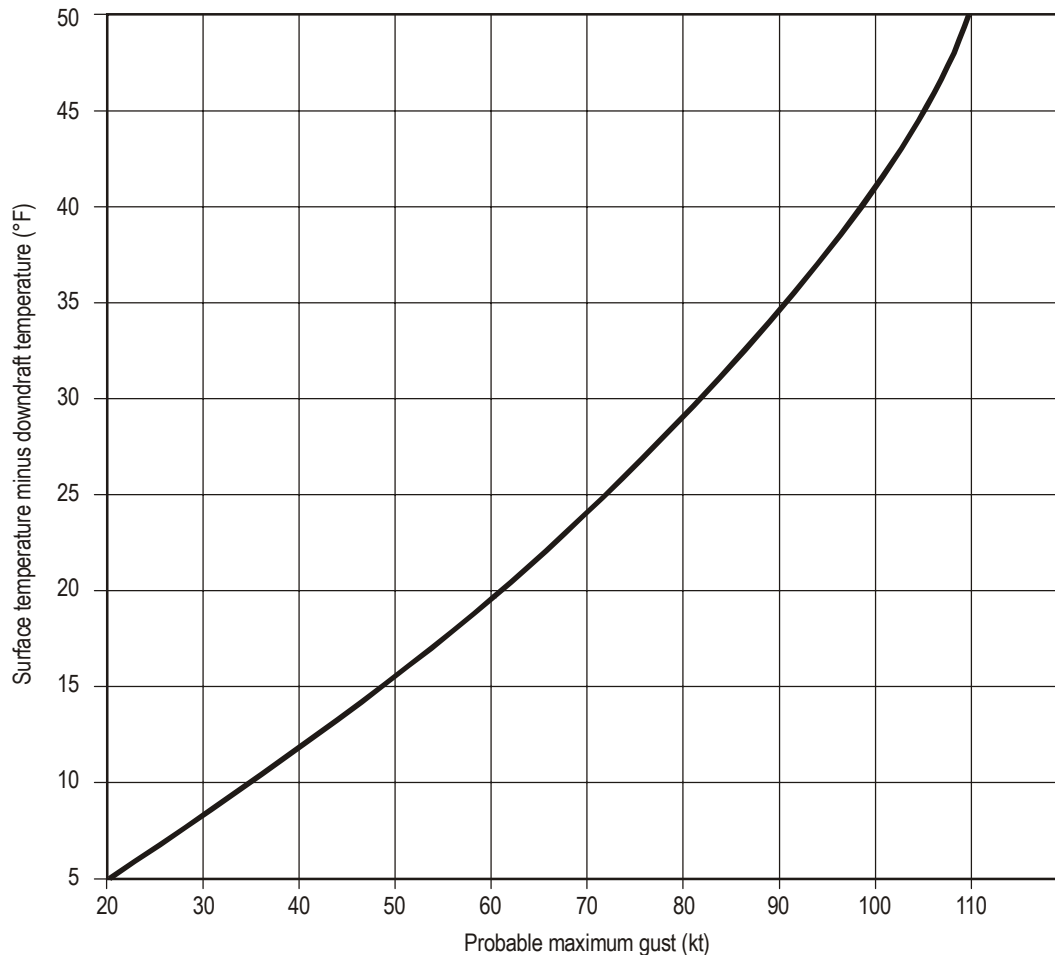


Figure 5-12. Empirical forecasts of probable maximum gusts
(after George, 1960)

5.2.38 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 more organized and propagating system of gusts known as a “gust front”, which can produce much higher gust speeds sometimes travelling as far as 35 km (19.5 NM) ahead of the parent storm or squall line (see 3.5.2). Gusts due to thunderstorms originate from the cold downdraft currents that penetrate the base of the cloud with or without accompanying heavy rain. The gust front originates from particularly strong downdrafts that 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 gust speed due to a gust front is difficult, but if its speed and orientation can be established from 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.⁷⁰ Techniques for forecasting the development of downbursts dealt with in 5.2.39 may also be applied since 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 3.5.10 and 5.1.5,

occasionally the gust front shows on dBZ conventional weather radar, especially on 10-cm radar configured to receive weaker than usual returns (down to ≤ 10). 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 5.1.6 and Figure 5-11), although rare, can also provide the basis for an accurate forecast. The use of an array of wind sensors around the perimeter of an aerodrome to detect gust fronts, such as in the LLWAS installed at many United States aerodromes, is described in detail in 5.1.7 to 5.1.14. This system was originally designed to provide short-term warning of gust fronts and microbursts crossing the aerodrome perimeter, and works well for this purpose.

5.2.39 Generally available “nowcasting” techniques for forecasting thunderstorms likely to produce downbursts (and hence gust fronts), microbursts and tornadoes depend largely on the interpretation of conventional, i.e. non-Doppler, radar echo characteristics and cloud top pictures from geostationary weather satellite infrared 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 diagrammatically⁷⁰ in Figure 5-13 a), and the typical evolution of radar echoes through various stages and the location of downbursts are shown in Figure 5-13 b). The spearhead echo concept was introduced by Fujita and Byers in their analysis (1976) of the MET aspects of the Eastern Airlines accident at New York’s JFK International Airport in 1975. The plan and elevation views of a spearhead echo are shown diagrammatically in Figure 5-14;⁷¹ comparison should also be made with Figure 3-11. The plan and elevation views of typical cloud tops seen from infrared imagery of thunderstorms that produced downbursts are shown in Figure 5-15⁷⁰. The identification of such radar echo patterns is not always simple, and their absence does not preclude the development of severe thunderstorms. For details on the interpretation and forecasting of severe storms using these techniques, see references 49, 70 and 74 at the end of this chapter.

5.2.40 As described in 5.1.32, the ITWS comprises a variety of products, most of which would be classed as nowcasts. Browning’s paper published in 1983⁶⁵ regarding the status and future progress of nowcasting has to a large extent been realized in the ITWS and other integrated MET observing/forecasting/warning systems.

5.3 REPORTING WIND SHEAR

GENERAL

5.3.1 The first two paragraphs of the statement of operational requirements given in Appendix 1 deal with the need to provide pilots with information on low-level wind shear and turbulence. At first the mechanics of providing available wind shear information to pilots would not seem to be very 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.

5.3.2 At present, information on low-level wind shear at aerodromes 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 MET 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 5-16. Essentially, the flow of information would also be applicable to other hazardous low-level weather phenomena reported by and to pilots.

5.3.3 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, of 40 microbursts examined by Doppler radar, 50 per cent reached their maximum intensity within 5 minutes of first detection, while 95 per cent did so within 10 minutes of the time the diverging outflow reached the ground (see 3.5.16 and Figure 3-16). Some dissipated within 5 to 10 minutes, with maximum wind speed differential across the microburst increasing from 50 to 100 km/h (25 to 50 kt) during this time. They are small-scale events, 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, an air-report of wind shear and wind shear warnings must be passed to aircraft with the minimum possible delay.

5.3.4 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 that are directly understandable by a pilot in terms of the performance of the aircraft type concerned. For example, advising a pilot of 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, while it at least alerts the pilot, also raises a series of consequential questions in the pilot's mind, e.g. What type? What intensity? What height? These are not trivial questions because the course of action the pilot should take depends upon these questions being answered.

5.3.5 Two examples of difficulties in terminology will 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). It would be simple, direct and informative to refer to such types of wind shear as "positive wind shear" and "negative wind shear", respectively. From the theoretical standpoint it is attractive and appropriate, and from the pilots' standpoint it relates immediately to potential performance applicable to all aircraft. Unfortunately, "negative wind shear" in English can also be understood to mean "*no* wind shear", which could have disastrous results. Inserting an additional word such as "type" (hence "negative-type wind shear") to alleviate this difficulty would not be foolproof because "type" could be missed in transmission or even deliberately dropped due to the natural human temptation to shorten radiotelephony phrases. Alternative terms, which have been proposed by the ICAO Low-Level Wind Shear and Turbulence Study Group (WISTSG), are "overshoot effect" and "undershoot effect". These are longer terms but are understood directly by pilots. Originally there was difficulty associated with these terms — if the word "overshoot" were heard by a pilot, it might have been taken to be an ATC instruction to overshoot. This potential source of confusion has been eliminated by the introduction by ICAO of the terms "missed approach procedure" and "go around".

5.3.6 The difficulty in resolving wind shear intensity classification problems dealt with in 5.2.5 to 5.2.14 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 recommended by the Fifth Air Navigation Conference (Montréal, 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 worldwide wind shear data by RAE indicates that the interim criteria, with respect to shear in the horizontal wind components, are probably on the conservative side⁷² (see Table 5-4 and 5.2.6 e), respectively).

AIRCRAFT REPORTS OF WIND SHEAR

5.3.7 In view of the lack of remote-sensing equipment capable of detecting and measuring low-level wind shear, information on wind shear at most aerodromes is largely based upon air-reports, a situation acknowledged in Annex 3, Chapters 4 and 7. Such air-reports are to be made in accordance with Chapter 5, 5.6, of Annex 3. Because it may be the only source of information, the reporting of wind shear by pilots is of vital importance in helping to safeguard other aircraft. Ideally, pilots should give the maximum amount of relevant information to help other pilots assess the likely effect of 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 time, and to expect pilots to report in detail in all circumstances is therefore unrealistic.

5.3.8 Guidance for pilots to assist them in formatting 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 formatting 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 conditions, air-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 Annex 3, Chapter 5;
- c) height or height band at which wind shear was encountered;
- d) phase of flight, if not obvious; and
- e) appropriate detailed MET 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.

5.3.9 Guidance on the wind shear terms recommended for use in air/ground communications has also been developed with the assistance of the WIST Study Group. Example reports based on the foregoing guidance are as follows:

- a) minimum reports where time and/or information is not available to give further details:

“[call sign] WIND SHEAR B737 ON APPROACH (RWY36)”; or

“[call sign] STRONG WIND SHEAR B737 ON APPROACH (RWY36)”; or

“[call sign] WIND SHEAR A340 ON APPROACH (RWY28)”; or simply

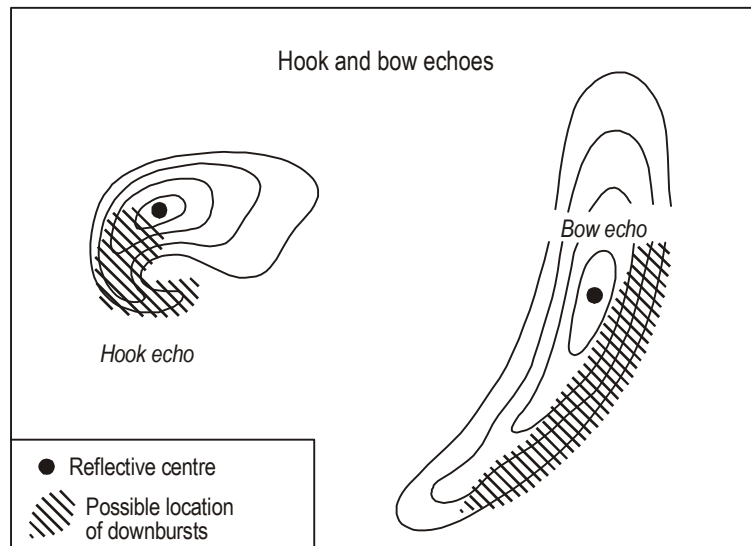
“[call sign] WIND SHEAR”; and

- b) further amplified reports where sufficient time and information are available:

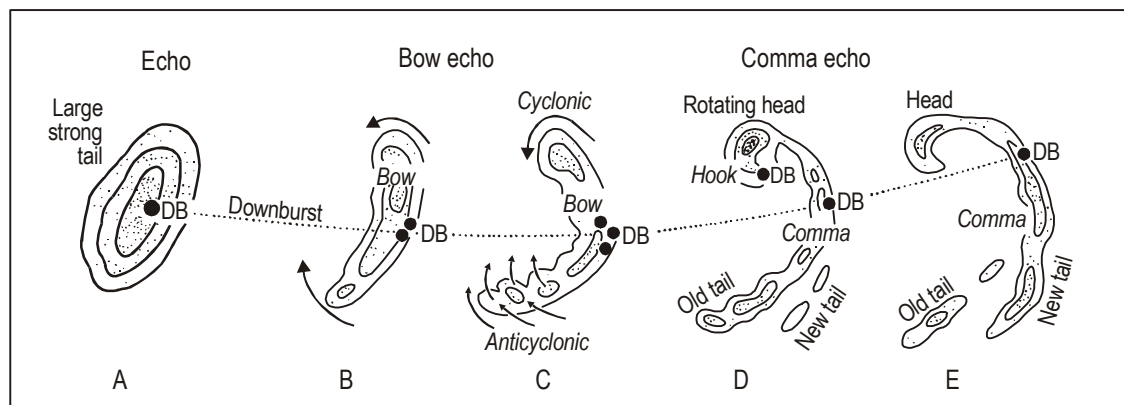
“[call sign] MODERATE WIND SHEAR B747 AT 150 FT ON APPROACH (RWY36) LOST 10 KT (AIRSPEED)”; or

“[call sign] STRONG WIND SHEAR B747 UNDERSHOOT EFFECT BETWEEN 300 FT AND 600 FT TEMPORARILY UNABLE MAINTAIN CLIMB ON DEPARTURE (RWY13)”; or

“[call sign] STRONG WIND SHEAR A320 ON APPROACH (RWY26) WIND 350 DEGREES 45 KT AT 500 FT BECOMING 230 DEGREES 10 KT AT 200 FT”.



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 downbursts).

Figure 5-13. Characteristics of radar echoes that produce downbursts
(from Fujita, 1978, and adapted by ICAO)

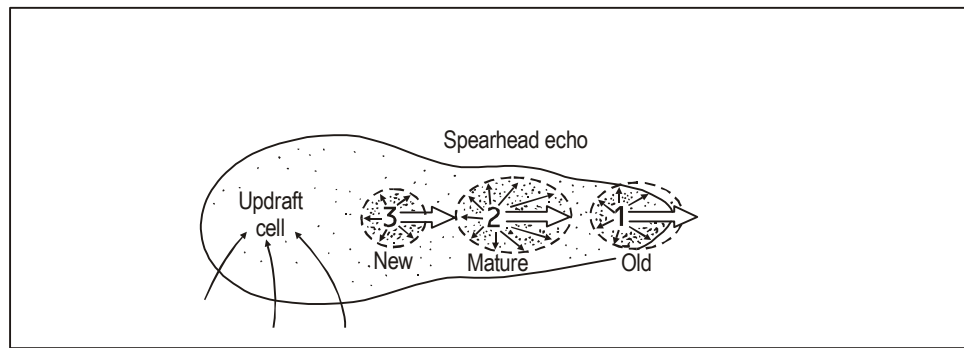


Figure 5-14. Plan view of the Fujita-Byers model of a spearhead echo
(from Fujita, 1976)

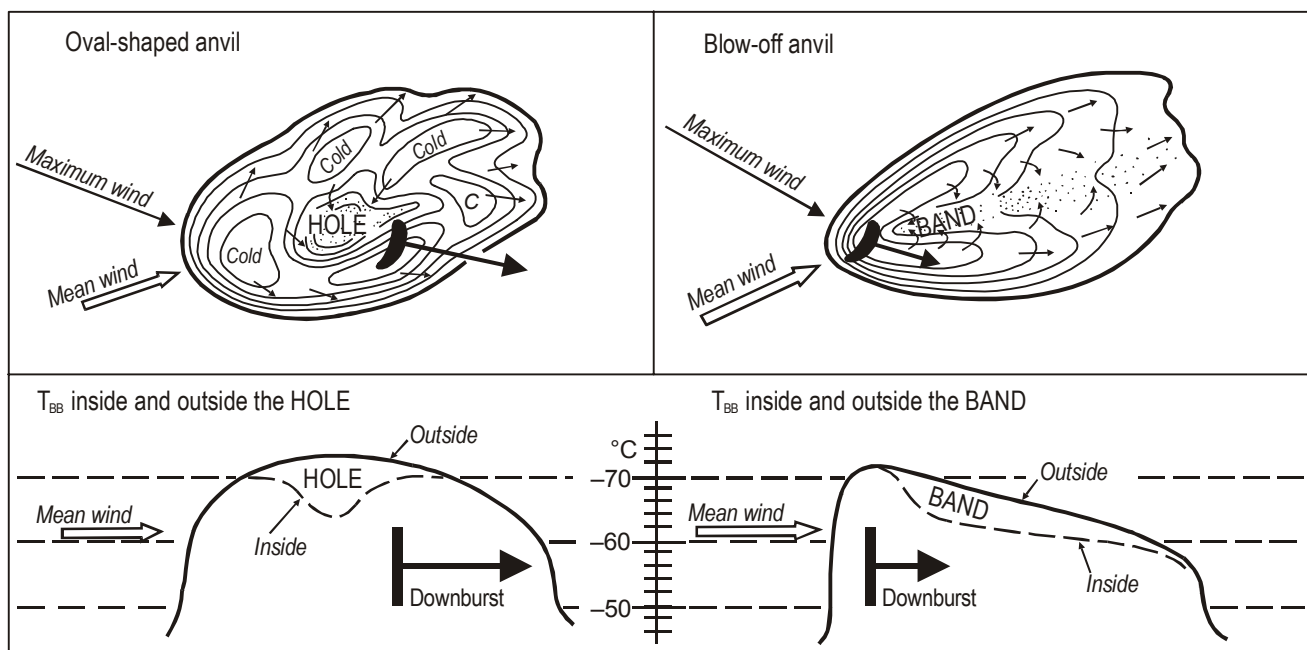


Figure 5-15. Schematic diagrams showing patterns and profiles of cloud-top temperature (T_{BB}).
Mean wind denotes the mean layer wind 0 to 3 km or 3 to 6 km below the height of the maximum
wind near anvil level. Based on the analyses of infrared imagery for four downburst cases.
(from Fujita, 1978, and adapted by ICAO)

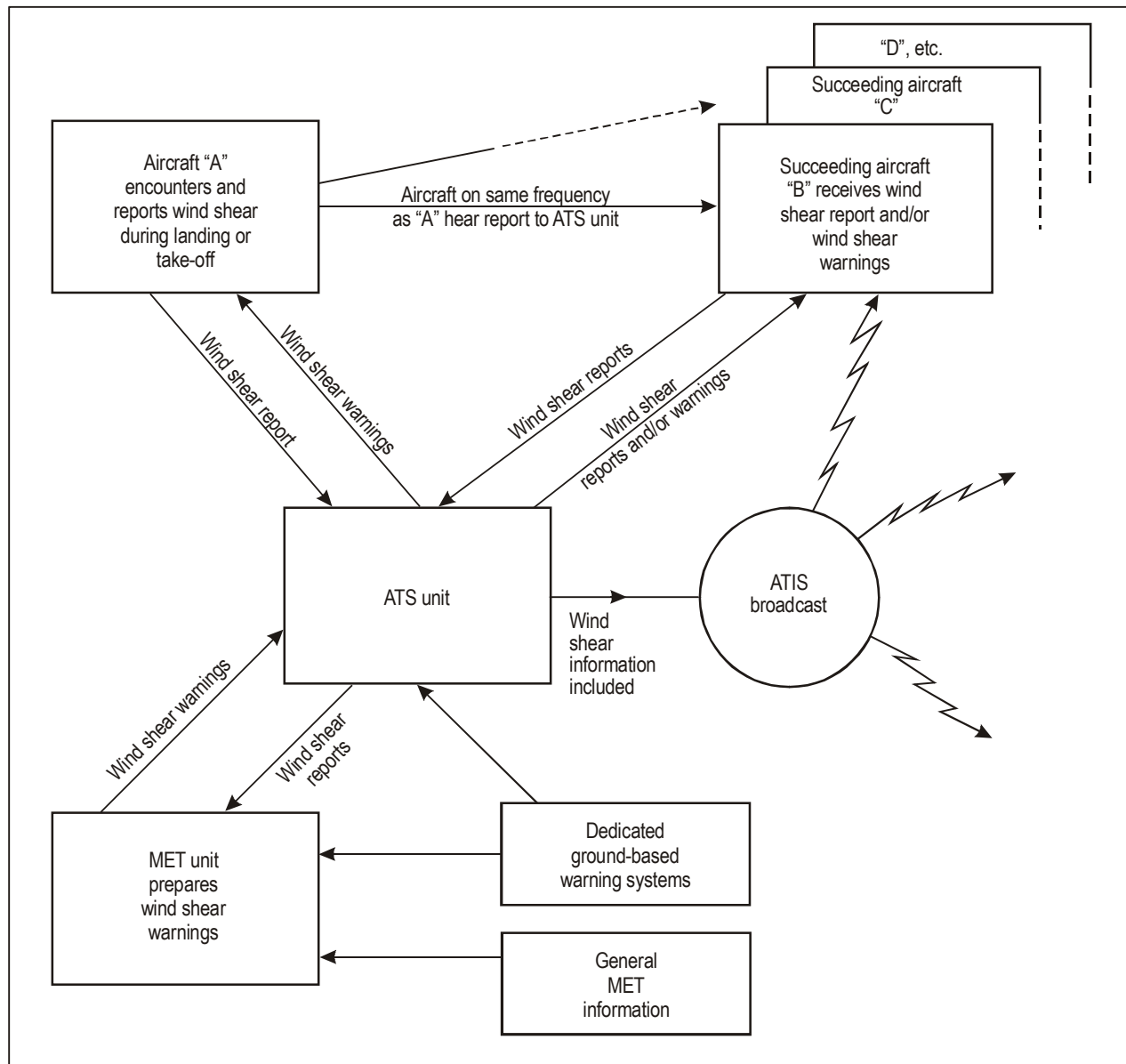


Figure 5-16. Flow of wind shear information between MET, ATS and pilots

AIR TRAFFIC SERVICES (ATS) REPORTING OF WIND SHEAR

5.3.10 As shown in Figure 5-16, ATS units are the critical communications interface between aircraft, and between aircraft and MET units. On receipt of an air-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.

5.3.11 The relay of air-reports of wind shear to other aircraft and the provision of wind shear information to pilots in general are covered in the *Procedures for Air Navigation Services — Air Traffic Management* (Doc 4444, PANS-ATM), 6.4.1, 6.6 and 7.3.1.2.2. The air-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). The reports should be relayed using the following standard sequence, the contents depending upon the details of the original report:

- a) wind shear — identifier;
- b) aircraft type — added if not included in the original report;
- c) description of event — no change to the report as received from the pilot;
- d) height wind shear encountered — no change to the report as received from the pilot;
- e) phase of flight — no change to the report as received from the pilot;
- f) runway — added if not included in the original report;
- g) time of encounter — no change to the report as received from the pilot; and
- h) MET/operational information — no change to the report as received from the pilot.

An example of such a report is as follows:

“WIND SHEAR B747 REPORTED STRONG WIND SHEAR AT 300 FT ON APPROACH RWY27 AT 0937 MAX THRUST REQUIRED”.

5.3.12 The inclusion in the ATIS broadcast of available information on significant MET phenomena (i.e. including wind shear) in the approach, take-off and climb-out areas is covered in Annex 11, Chapter 4.

5.3.13 The relaying of air-reports of wind shear by ATS units to the associated MET office is covered in 4.12.6 of the PANS-ATM. These reports form the basis for wind shear warnings prepared by the MET office (see 5.3.4).

5.3.14 The statement of operational requirements in Appendix 1, 2.1 a), refers to the need for pilots to be provided with information on changes in the surface wind along the runway. The occurrence of horizontal wind shear along the runway, indicated by a highly variable surface wind or significantly different surface winds from multiple anemometers, may be caused by wind flow around buildings, air-mass fronts, sea-breeze fronts, gust fronts and microbursts, etc., and can cause difficulty for pilots at touchdown and roll-out

and during the take-off run (see Chapter 4). At aerodromes where this is a problem, Annex 3, Appendix 3, 4.1.1.2, recommends the installation of multiple sensors. In accordance with the PANS-ATM, information on surface wind and significant changes and variations thereto should be:

- a) passed by approach control service to aircraft on first contact and at the commencement of final approach (Chapter 6);
- b) passed by aerodrome control to aircraft prior to their entering the traffic circuit (Chapter 7);
- c) passed by aerodrome control to aircraft prior to taxiing and prior to take-off (Chapter 7); and
- d) available at appropriate area control centres or flight information centres for transmission to supersonic aircraft (Chapter 9).

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 20 KNOTS GUSTING TO BETWEEN 10 AND 30 KNOTS”.

5.3.15 At some aerodromes, notably in the United States, an LLWAS has been installed (see 5.1.7 to 5.1.14). 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 (≥ 30 km/h (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”.

5.3.16 ATS units should continue to transmit information on wind shear conditions until it is confirmed, either by subsequent aircraft reports or by advice from the associated MET office, that conditions are no longer significant for operations at the aerodrome. The cancellation of wind shear warnings by the MET office is covered in Annex 3, Chapter 7, and is discussed in more detail in 5.3.23. The ATS unit should continue to relay air-reports of wind shear to other aircraft concerned until such time as the reports have been incorporated into a wind shear warning by the associated MET office. Thereafter, the wind shear warning will be transmitted to all aircraft concerned until cancelled by the MET office.

5.3.17 At those aerodromes having automated anemometer arrays, TDWR or other remote-sensing systems, warnings should be transmitted in accordance with the format examples given in Annex 3, Chapter 7. The basis for these messages is given in 5.1.20.

MET SERVICES' RESPONSIBILITIES FOR REPORTING WIND SHEAR

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

- a) in wind shear warnings (Annex 3, Chapter 7 and Appendix 6, Table A6-3); and
- b) in the supplementary information section of the routine and special MET reports (Annex 3, Chapter 4).

5.3.19 Wind shear warnings may be based upon aircraft reports received through an ATS unit (see 5.3.13), direct observations from conventional MET equipment (e.g. anemometer), forecasts of MET 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 in accordance with the template in Annex 3, Appendix 6, Table A6-3, and should be identified as "WS WRNG", for example:

"YUDO WS WRNG 01 211230 VALID 211245/211330 WS APCH RWY12 FCST SFC WIND: 320/10 KT
60 M-WIND: 360/25 KT"
[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:

"YUCC WS WRNG 02 201500 VALID TL 201545 MOD WS IN APCH REP AT 1455 B747 30 KT
ASPEEDL 2 NM FNA RWY13".

5.3.20 With respect to wind shear warnings based upon forecasts of relevant MET 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, meaning that only qualitative statements can be made. Under such circumstances there is a temptation to include information that is not strictly relevant. This should be avoided, and the warning should always be made as concise as possible and in conformity with the template in Annex 3, Appendix 6, Table A6-3. It should clearly indicate its "forecast" status by use of the abbreviation FCST.

5.3.21 Convective wind shear and non-convective wind shear must also be considered and may have to be treated separately. While 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. microbursts. Such a warning might be formulated as follows:

"YUDO WS WRNG 231530 VALID 231600/231605 MBST CLIMBOUT RWY26 FCST".

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.

5.3.22 In the case of non-convective wind shear (e.g. low-level jet), the possibility of forecasting the MET phenomena concerned is much higher. An example of such a warning might be as follows:

"YUDO WS WRNG 01 240600 VALID 240700/240900 WS IN APCH FCST SFC WIND: 270/10 KMH
600 M-WIND: 360/100 KMH".

Where non-transitory wind shear is a regular feature of the aerodrome climatology under well-known and recurring MET conditions, such as local terrain-induced wind shear, 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.

5.3.23 In accordance with Annex 3, Chapter 7, 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 coordination in this regard cannot be overemphasized. These matters are dealt with in more detail in the *Manual on Coordination between Air Traffic Services, Aeronautical Information Services and Aeronautical Meteorological Services* (Doc 9377).

5.3.24 The inclusion of information on wind shear in the supplementary information section of the routine and special MET reports has been a Recommended Practice in Annex 3, Chapter 4, for many years. Observers are therefore familiar with the procedure, and little specific advice is required here. It might be pointed out, however, 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 that 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. An example of such supplementary information in abbreviated plain language is as follows:

"SPECIAL YUDO 151115 Z WIND 050/25 KT MAX 37 MNM 10 VIS 2500 M TSRA CLD BKN CB 500 FT T25/DP22 QNH 1008 HPA WS IN CLIMBOUT".

FAA INTEGRATED WIND SHEAR PROGRAMME (TERMINAL INFORMATION)

5.3.25 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 systems such as weather radar, LLWAS and TDWR (see 5.1.5, 5.1.7 to 5.1.14 and 5.1.19, respectively).

TYPICAL BASIC WIND SHEAR WARNING SYSTEM

5.3.26 A final look at a typical basic "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 the specific problem⁷³ of non-transitory wind shear. An example of a more sophisticated system to deal with the problem of transitory wind shear is given in Appendix 4.

5.3.27 In Finland, Scandinavia and 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 headwind/tailwind components, is a serious concern to the authorities. In order to deal with the problem, wind, temperature and humidity sensors were installed at selected levels on an existing 300-m (1 000-ft) high television transmitter mast 20 km (12 NM) south-west of the airport. The data from these sensors is transmitted to the airport and analysed in real time by computer.

The wind data from the television mast are correlated with the INS data reported from aircraft landing and taking off and both sets of data correlated +0.85 for speed and +0.99 for direction. Warnings are issued for wind shear and for significant inversions ($\geq 10^{\circ}\text{C}$ as per the provisional requirement (Recommendation 3/5) formulated by the Eighth Air Navigation Conference (Montréal, 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”.

A wind shear/inversion warning that 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 is considered very useful. Similar systems are in operation elsewhere, e.g. in Denmark; Hong Kong, China; Sweden; and the Russian Federation. In the case of Hong Kong, China, the anemometers are located on hills that are situated at strategic points along the approach path.⁷⁴

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Chapter 6

TRAINING

6.1 GENERAL

6.1.1 Although wind shear is not a new MET phenomenon, and certainly not the only potential MET hazard to aviation, there are at least two reasons why there is so much emphasis being placed on it. First, 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 and a series of fatal aircraft accidents in the 1970s and 1980s. Second, there still appears to be 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 that surrounds it, and partly to its short-lived nature. It is true that the successful development in the 1990s of effective ground-based and airborne wind shear warning systems served to tilt the balance in favour of the pilot. At the same time, however, no system can be totally foolproof and, in any case, few States can afford to install and maintain sophisticated ground-based wind shear warning equipment such as TDWR. Whatever warning equipment is available, surviving an encounter with severe wind shear always requires fast reactions and skill by the pilot. The major difficulty still facing the pilot and the meteorologist is accurately predicting 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 present in an area, an aircraft flying in that area may not encounter it because of its localized and transient effects. This is one reason why reporting an encounter with wind shear is so important (see 6.8). The only way to counter the confusion and misunderstanding and provide a basis for the pilot to exercise sound judgement and react quickly when wind shear is encountered unexpectedly is through training.

6.1.2 It is impossible to overemphasize the necessity of developing a training programme to ensure that all those involved with aircraft operations are made aware of the hazardous, potentially lethal effects of low-level wind shear. The programme for flight crew must begin at an early stage of their training and continue 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 ATCOs 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 be made aware of wind shear hazards.

6.1.3 While certain aspects of the subject require varying degrees of emphasis based on 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.

6.1.4 Appendix 1 contains a statement of operational requirements. In paragraph 4 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. Since 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.

6.2 OBJECTIVES OF FLIGHT CREW TRAINING

6.2.1 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 they all develop the ability to recognize a wind shear encounter and understand 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.

6.2.2 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.

6.2.3 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.

6.3 FLIGHT CREW GROUND TRAINING

6.3.1 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 should cover objectives a) and b) of the training programme described in 6.2.2.

6.3.2 The *Training Manual*, Part F-1 — *Meteorology for Air Traffic Controllers and Pilots* (Doc 7192) contains details of wind shear training for the commercial pilot licence. Appropriate extracts are at Appendix 9 to this manual.

6.3.3 The FAA issued an excellent Wind Shear Training Aid in 1987,¹ which provides detailed explanations of the effects of wind shear on flight operations together with substantial supporting documentation.

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

- a) the way to avoid a disaster is to avoid an encounter;
- b) 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) 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.

6.3.5 There are a number of audio-visual training aids available to assist States and operators in the development of wind shear training programmes (see Appendix 10).

6.4 FLIGHT AND SIMULATOR TRAINING

6.4.1 The flight crew training programme must also 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.

6.4.2 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 wind shear is fortunately a rare occurrence, make it virtually impossible for realistic airborne flight training. Even if the potential hazards due to incorrect handling could somehow be minimized, it would still be impossible to reproduce the various wind shear conditions on demand. Therefore, it is 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. Another factor that should be borne in mind is that the recommended wind shear recovery flying techniques are counter-intuitive since the pilot is expected to pitch up the aircraft, if necessary to 15 degrees (while respecting the stick shaker), even though airspeed may be decreasing rapidly. Moreover, the pilot has no way of knowing that the angle of attack may also have decreased in strong vertical downdrafts. Only regular simulator training can develop the necessary instinctive reaction in the pilot to apply the recovery techniques immediately and with the confidence that these are the best ways to maximize the energy available to the aircraft in a wind shear encounter. Because simulator training is not normally available to non-airline flight crew, this is more reason for them to be able to recognize potential wind shear conditions and make every effort to avoid them.

6.4.3 It is essential that aircraft manufacturers and operators cooperate to develop techniques and procedures appropriate to particular aircraft types and available airborne equipment and that the operator's operations manual details these procedures. 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, training should be conducted on a type simulator having the necessary software to reproduce realistic wind shear models. Realistic three-dimensional models of convective wind shear (downbursts/microbursts), developed based on recreated accident data and wind field models, are readily available to simulator manufacturers. Operators must ensure that these modules are included in the specifications for any simulator system they install. There is, therefore, no reason for pilots of jet transport aircraft not to receive regular simulator training that includes encounters with these hazardous phenomena. Extensive information and guidance material related to the simulation requirements, validation and functions tests in a wind shear event can be found in the *Manual of Criteria for the Qualification of Flight Simulators* (Doc 9625).

6.4.4 Under its advanced simulation plan, the FAA provided guidelines on methods of conducting flight crew training in advanced aircraft simulators (see Federal Air Regulations, Part 121, Appendix 10).

Phase II of this three-phase plan contains a requirement for simulator models to include “representative crosswind 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.^{2,3} As mentioned in Chapter 4, the introduction of the vertical component (downdraft) into the model 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, is totally outside their experience. Representative wind profiles are included in United States Advisory Circular (AC) 120-41, *Criteria for Operational Approval of Airborne Wind Shear Alerting and Flight Guidance Systems* (see 5.2.12).

6.4.5 Many 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, that may be programmed to have the microburst centre placed along or offset from the flight path (see 3.5.16). This particular model was developed by the RAE in the United Kingdom; an illustration of the microburst model used is shown in Figure 3-16 a).^{4,5} 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.⁶

6.4.6 The operating procedures recommended for use in wind shear situations are normally contained in the operating manuals provided by manufacturers for each aircraft type and in operators’ operations manuals. Other sources of information are advisory circulars (such as FAA AC 00-54 (1988), paragraph 7) issued by States’ authorities. 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 11. While all the procedures are based on the same aerodynamic principles, each aircraft type/engine combination can be expected to react differently to wind shear to some extent and, depending on each operator’s equipment policy, may carry different flight deck instrumentation and equipment.

6.5 FAA INTEGRATED WIND SHEAR TRAINING PROGRAMME

There was 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. As previously mentioned, the FAA training programme became available in 1987; with the assistance of aircraft manufacturers and operators, its objective was the development of a definitive “wind shear training aid” that 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.

6.6 TRAINING FOR AIR TRAFFIC CONTROL PERSONNEL

6.6.1 The air traffic controller (ATCO) 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 mainly be 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 low-level wind shear.

6.6.2 The *Training Manual*, Part F-1 — *Meteorology for Air Traffic Controllers and Pilots* (Doc 7192) assists in the development of a suitable training programme for ATCOs. In particular, it includes under 3.4,

(Pressure-wind relationships) required knowledge of the definition of wind shear. It is also required to study under Item 3.10.2 the wind shear associated with thunderstorms (including gust fronts and dry and wet microbursts) and the effects of this phenomena on aircraft operations. The recommended level of required knowledge is described as "... a knowledge of the subject and the ability, where applicable, to apply it in practice with the help of reference materials and instructions."

6.6.3 The objectives for the wind shear training programme for ATCOs should be:

- a) to provide an understanding of wind shear and its 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 6.8).

6.6.4 Items 6.6.3 a) and b) cover much the same ground as that dealt with in the flight crew ground training programme in 6.3. As such, the material available for flight crew is useful for the training of ATCOs. 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.

6.7 TRAINING FOR METEOROLOGISTS

6.7.1 In accordance with the working arrangements agreed between ICAO and WMO, "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" (see Doc 7475). As a consequence of the foregoing arrangement, guidelines for the education and training of personnel in aeronautical meteorology were developed and published in WMO-No. 258, Chapters 2 and 4, and WMO/TD No. 1101, Chapter 3.3.

6.7.2 In the aforementioned WMO training publications, the recommended syllabi for specialization in aeronautical meteorology for meteorologist BIP-M1 and meteorological technicians BIP-MT are given in detail. The syllabi for meteorologist BIP-M1 in respect of aeronautical MET knowledge 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. As far as aeronautical meteorology is concerned, the level or standard of training should be the same as for pilot licences. Training for BIP-M1 meteorologists would also include extensive general forecasting training, covering forecasting specific phenomena that are known to produce low-level wind shear (low-level jets, temperature inversions, land and sea breezes, air mass fronts, thunderstorms, especially severe thunderstorms, etc.). Training should also cover operational aspects like the coding and decoding of wind shear warnings and their dissemination.

6.7.3 For MET technicians BIP-MT, the aeronautical MET knowledge recommended is less than for meteorologist BIP-M1, and the recommended syllabi for specialization only mentions wind shear regions in Chapter 4.3 of WMO-No. 258. However, general information on wind shear and phenomena that produce it is recommended for inclusion under 4.2 d) atmospheric motion; geostrophic flow, in the WMO training publication.⁷

6.7.4 A compendium of lecture notes for training all classes of meteorologists is also published by WMO in WMO-No. 364, Volume II. Part 2 of that publication is devoted to aeronautical meteorology for meteorologists and MET technicians. Low-level wind shear is covered in that publication, where appropriate.

6.8 TRAINING ASPECTS OF REPORTING WIND SHEAR

Since operational remote-sensing equipment to detect wind shear has been successfully developed, the most important advance towards a solution to the wind shear problem that could be made 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 manual would be a major step towards standardization worldwide. These comprise reporting formats both for aerodromes that have TDWR and/or LLWAS systems and those that do not but are affected by wind shear.

6.9 SUMMARY

6.9.1 Wind shear has always been present, although we have not always been aware of it. Following a number of fatal aircraft accidents, its potentially lethal characteristics have become increasingly known. At the same time our knowledge of the effects of wind shear has increased, and the means at our disposal to forecast and counter it have improved. 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. It should always be borne in mind that 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.

6.9.2 From all the knowledge and experience gained to date, the following key factors emerge that pilots especially must bear in mind:

- a) AVOID areas of known wind shear.
- b) Evaluate the weather and environmental conditions.
- c) Use and follow SOPs.
- d) Be alert and take the necessary precautions whenever there is a high probability of wind shear.
- e) Never hesitate to apply recovery procedures if wind shear is inadvertently encountered.
- f) If in doubt, delay 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.

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 6. Klehr, 1986: Wind shear simulation enters the fourth dimension, *ICAO Bulletin*.
 7. World Meteorological Organization, 2002: *Guidelines for the education and training of personnel in meteorology and operational hydrology*, WMO Publication No. 258, Volume I, Fourth Edition.
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Appendix 1

STATEMENT OF OPERATIONAL REQUIREMENTS

(Foreword refers)

1. INFORMATION PROVIDED 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 maintain safe control of the aircraft.

1.2 Pending 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 on the assessment of the current weather situation.

2. GROUND-BASED EQUIPMENT

There is an operational requirement for ground-based equipment from which to derive the following information that 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.— Five-hundred m (1 600 ft) should not be considered restrictive where local conditions require increases above this height.

3. AIRBORNE EQUIPMENT

There is an operational requirement for airborne equipment that can detect the presence of significant low-level wind shear and turbulence irrespective of its cause and can:

- a) provide the pilot with a timely warning and the information necessary to safely maintain the desired flight path or the action to take to avoid it; and
- b) indicate that the limits specified for certification of automatic landing equipment are being approached.

4. TRAINING

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 2

RECOMMENDATIONS OF THE UNITED STATES NATIONAL ACADEMY OF SCIENCES COMMITTEE ON LOW-ALTITUDE WIND SHEAR AND ITS HAZARD TO AVIATION (1983)

(3.9.2 and 3.9.3 refer)

Note.— The text below is reproduced with the permission of the United States National Academy of Sciences Committee.

The National Academy of Sciences Committee recommendations^a 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

Need for an integrated wind shear programme

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.

Wind shear education programme

1.2 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.

1.3 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.

a. While it is satisfying to report that, by the time this manual is published, many of the Committee's recommendations will have been implemented, the recommendations, nevertheless, have been reproduced here verbatim in order to illustrate the problems that have been faced in dealing with wind shear over the past two decades.

Pilot/controller communications

1.4 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.

Wind shear detection system development

1.5 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

The low-level wind shear alert system (LLWSAS)

2.1 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.

Record and analyse LLWSAS data

2.2 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.

Use of available radar data

2.3 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.

Next generation weather radar (NEXRAD)

2.4 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.

Airport terminal weather radar

2.5 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.

Use of airport terminal weather radar observations

2.6 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.

Airborne remote sensors

2.7 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

Wind shear effects on flight characteristics

3.1 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.

Aircraft operating procedures

3.2 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.

Guidance and control aids

3.3 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.

Standardization of wind shear models

3.4 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 subsystems 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.

Certification of on-board systems

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

Wind shear simulation training

3.6 The FAA and the industry should cooperate 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

Effects of heavy rain

4.1 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.

Research on the nature of low-altitude wind shear

4.2 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.

4.3 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 south-eastern 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 3

MATHEMATICAL ANALYSIS OF THE EFFECT OF WIND SHEAR ON LIFT

Note.— The text^a below is reproduced with the permission of Dr. T.T. Fujita. The table and figures have been renumbered by ICAO for use in this appendix.

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:

$$W = iu + jv + kw \quad (1)$$

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:

$$\frac{\Delta W}{\Delta t} = G \frac{\partial W}{\partial L} + \frac{\partial W}{\partial t} \quad (2)$$

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 A3-1, we define the shear of the three component winds u, v, w by:

$$\frac{\Delta u}{\Delta t} = \text{Headwind shear, + headwind; — tailwind} \quad (3)$$

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

$$\frac{\Delta w}{\Delta t} = \text{Vertical wind shear, + upward; — downward} \quad (5)$$

a. Extract from Dr. Fujita's book "The Downburst", published by the Satellite and Mesometeorological Research Project (SMRP), Department of the Geophysical Sciences, University of Chicago.

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 A3-1, the lift force can be expressed by:

$$F = \frac{1}{2} \rho A^2 C_L S \quad (6)$$

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:

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

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

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

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

Using Equations 7 and 8, we simplify Equation 9 into

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

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

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.

**Table A3-1. 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 tailwind	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

A representative curve of a lift coefficient for swept-wing aircraft during a flap-down take-off configuration is shown in Figure A3-2. Values in Table A3-1, 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.

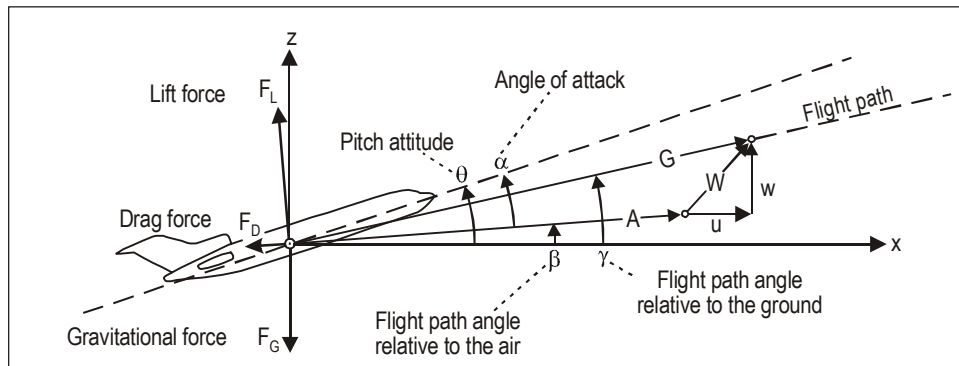


Figure A3-1. Definition of the quantities used in this chapter F_L = lift force; F_G = gravitational force; F_D = drag force; α = angle of attack; β = flight path angle relative to the air; γ = flight path angle relative to the ground; θ = pitch attitude; W = wind vector, u, v, w being the x, y, z components of wind vector; A = true airspeed; and G = ground speed

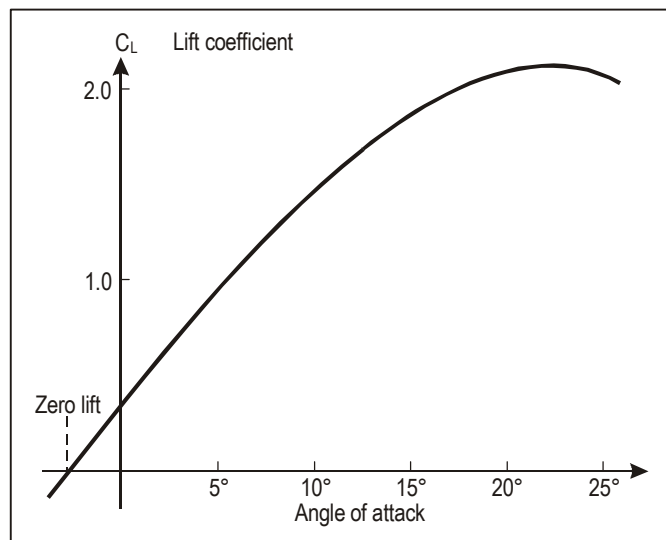


Figure A3-2. Lift coefficient of swept-wing aircraft with a 15-degree flap setting and gear-up configuration. The angle of attack is fuselage-relative. The wind-relative angle of attack is approximately 2 degrees larger than the fuselage-relative angle of attack.

Appendix 4

WIND SHEAR AND TURBULENCE ALERTING IN HONG KONG, CHINA

(5.1.39 refers)

Note.— The text below is reproduced with the permission of the Hong Kong Observatory, Hong Kong, China. The figures have been renumbered by ICAO for use in this appendix.

1. BACKGROUND

1.1 The Hong Kong Observatory (HKO) is responsible for the provision of aviation weather services to the Hong Kong International Airport (HKIA) at Chek Lap Kok. It issues alerts of wind shear (for a change in 15 knots or more in the headwind or tailwind) and turbulence (for moderate or severe turbulence).

1.2 Geographically, HKIA was built on reclaimed land to the north of the rather mountainous Lantau Island which has peaks rising to nearly 1 000 m with valleys as low as about 400 m in between. Figure A4-1 illustrates the terrain of the island and the location of HKIA relative to this terrain. To the north-east of HKIA, there are a number of smaller hills with peaks rising to between 400 and 600 m. Under this coastal and hilly environment, a wide variety of weather phenomena can bring wind shear and turbulence to HKIA. These include:

- a) winds blowing across hilly terrain, i.e. terrain induced (Figure A4-2);
- b) microburst and gust front, i.e. thunderstorm induced (Figures A4-3 and A4-4);
- c) convergence of sea breeze with background winds (Figure A4-5); and
- d) low-level jet stream (Figure A4-6).

2. WIND SHEAR AND TURBULENCE ALERTING

2.1 Weather sensors for monitoring wind shear and turbulence in and around HKIA include:

- a) a terminal Doppler weather radar (TDWR) strategically installed at about 12 km north-east of the airport (Figure A4-7);
- b) a network of anemometers on the surface, valleys and hilltops;
- c) three weather buoys (Figure A4-8) over the waters at around one to two nautical miles (NM) from the runway thresholds;
- d) two wind profilers over Lantau Island; and

- e) a pulsed Doppler light detection and ranging (LIDAR) system at the airport (Figure A4-8).

See Figure A4-1 for the location of these weather sensors.

2.2 The TDWR is proven in detecting thunderstorm-induced microburst and gust front in the presence of precipitation. The LIDAR is to supplement the TDWR in detecting wind shear under fine weather conditions. Anemometers at different locations provide information on the horizontal and vertical wind shear. The wind profilers measure winds at different heights to provide information on the vertical wind shear.

2.3 Alerts for possible wind shear and turbulence within 3 NM of the runway thresholds are automatically generated by computation algorithms using data from the suite of weather sensors. These alerts are updated at a frequency of at least once per minute for relay to aircraft.

2.4 Actual pilot reports of wind shear and turbulence encountered below 500 m (1 600 ft) and received within a short time by HKO are also issued as alerts for broadcast to ensuing aircraft. Such alerts are normally effective for at least one hour after the time of the pilot report concerned.

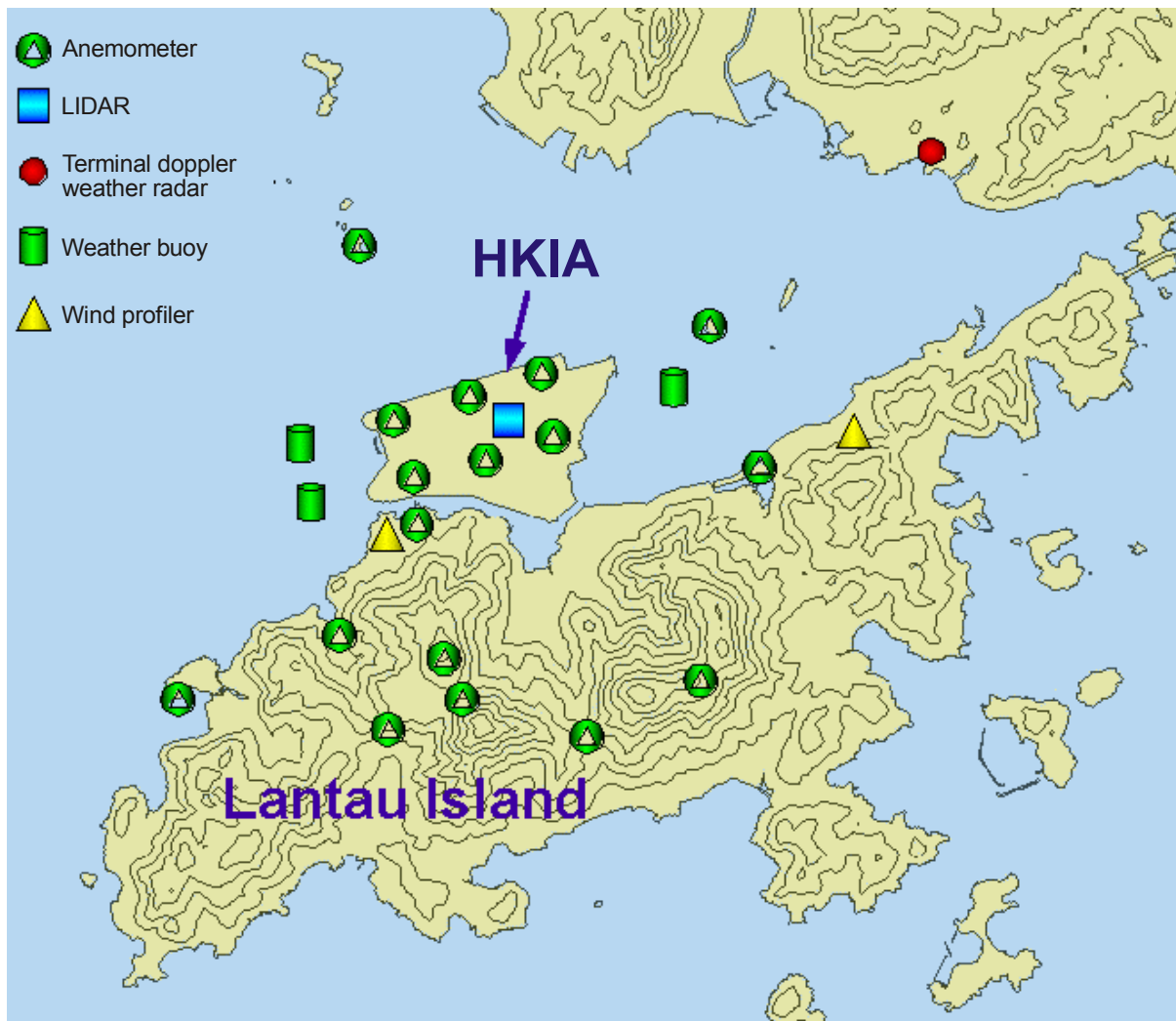


Figure A4-1. Map of Hong Kong International Airport (HKIA) and its surrounding areas. Terrain contours are given in 100-m intervals.

Wind shear alerts

2.5 The automated alerts for wind shear are classified into two levels: “microburst alert” (MBA) for wind shear with headwind loss of 30 knots or greater and accompanied by precipitation; and “wind shear alert” (WSA) for wind shear with headwind loss or gain of 15 knots or greater (except MBA). A consolidated alert is given for each approach/departure corridor based on a priority system which takes into consideration the severity of the alerts and the confidence level of the different data sources which generate the alerts.

2.6 Utilizing data from the suite of weather sensors, the HKO aviation forecaster also issues wind shear alerts to supplement the automated alerts based on techniques developed through studies of pilot reports of wind shear and the associated weather patterns. These techniques are progressively automated on the basis of their established performance upon verification with on-board flight data and pilot reports.

Turbulence alerts

2.7 The automated alerts for turbulence are classified into two levels based on the same intensity thresholds as those adopted for automatic aircraft turbulence reporting and are issued with reference to heavy category aircraft: “moderate turbulence” for turbulence with eddy dissipation rate (EDR) falling between 0.3 and 0.5; and severe turbulence for turbulence with EDR of 0.5 or above. The magnitude of the terrain-induced turbulence over the arrival/departure corridors is determined from the wind speed and direction and their fluctuations measured by the anemometer network.

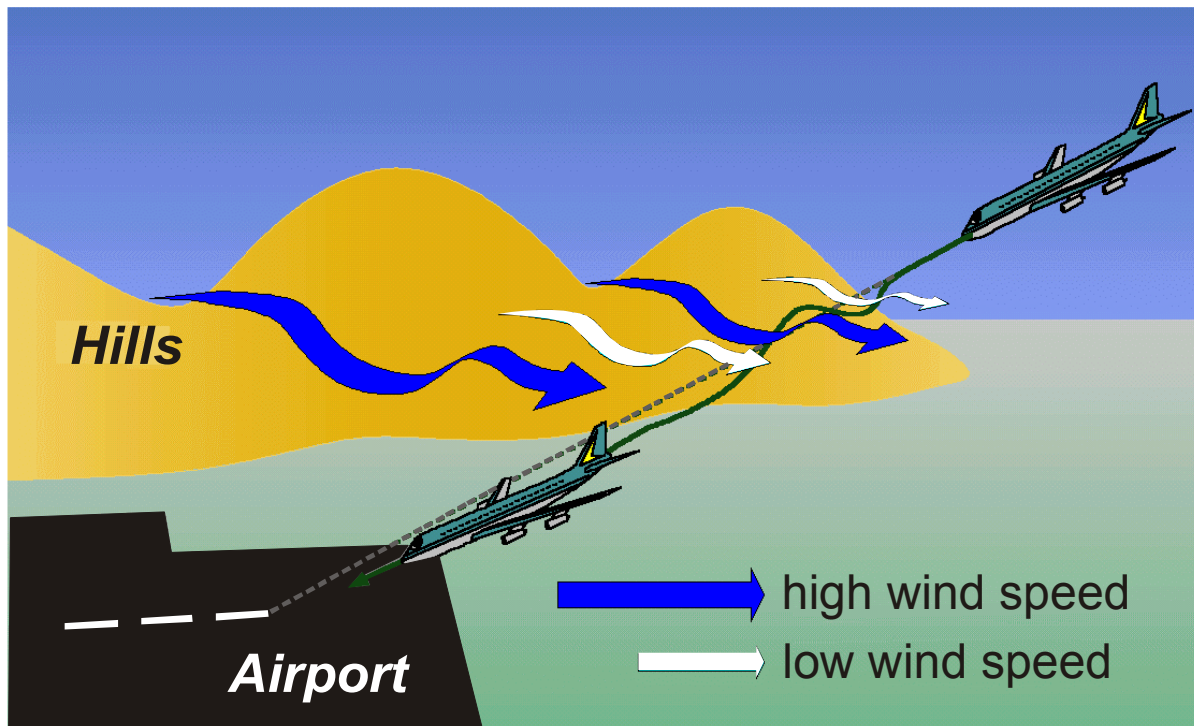


Figure A4-2. A typical terrain-induced airflow pattern, with high-speed airstreams downwind of valleys and low-speed airstreams downwind of peaks

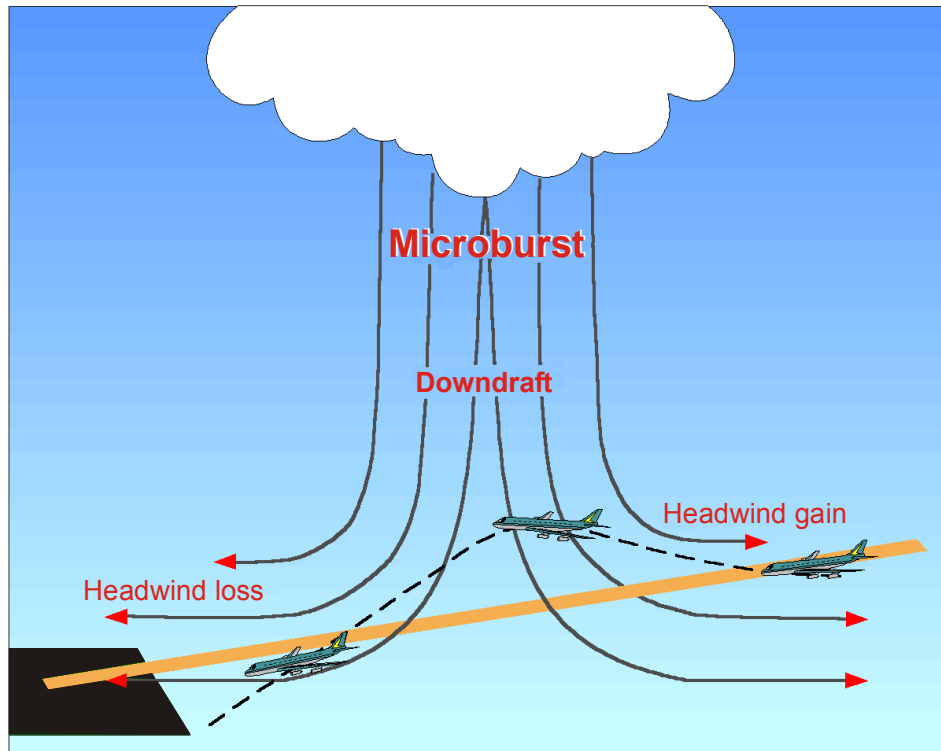


Figure A4-3. Wind shear brought by a microburst

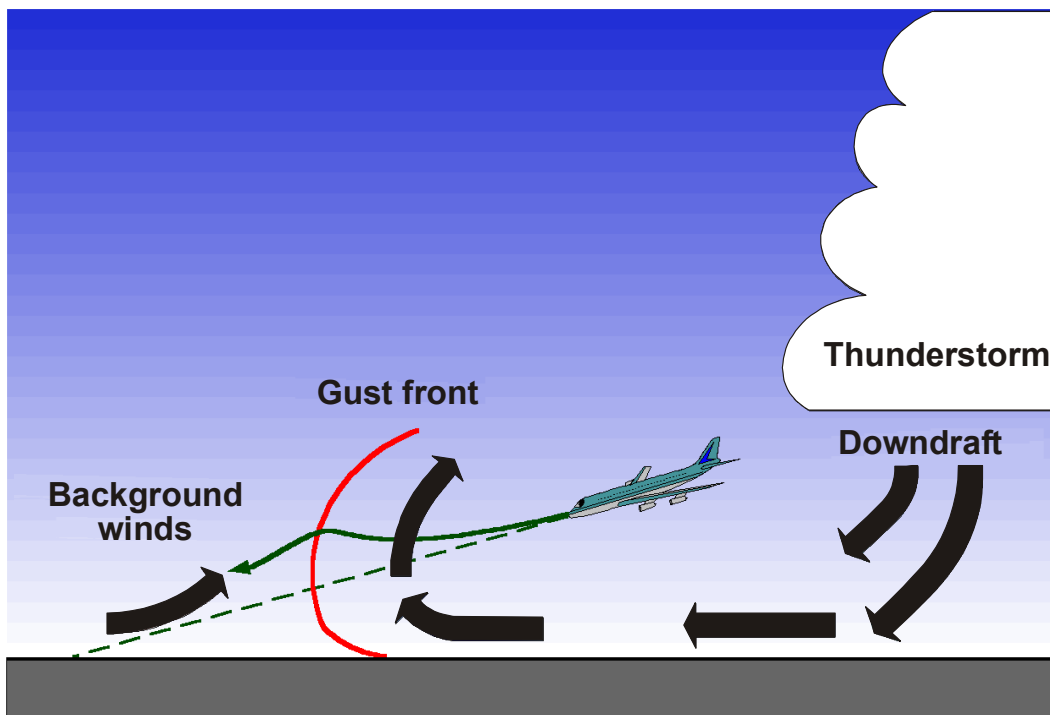


Figure A4-4. Wind shear brought by a gust front

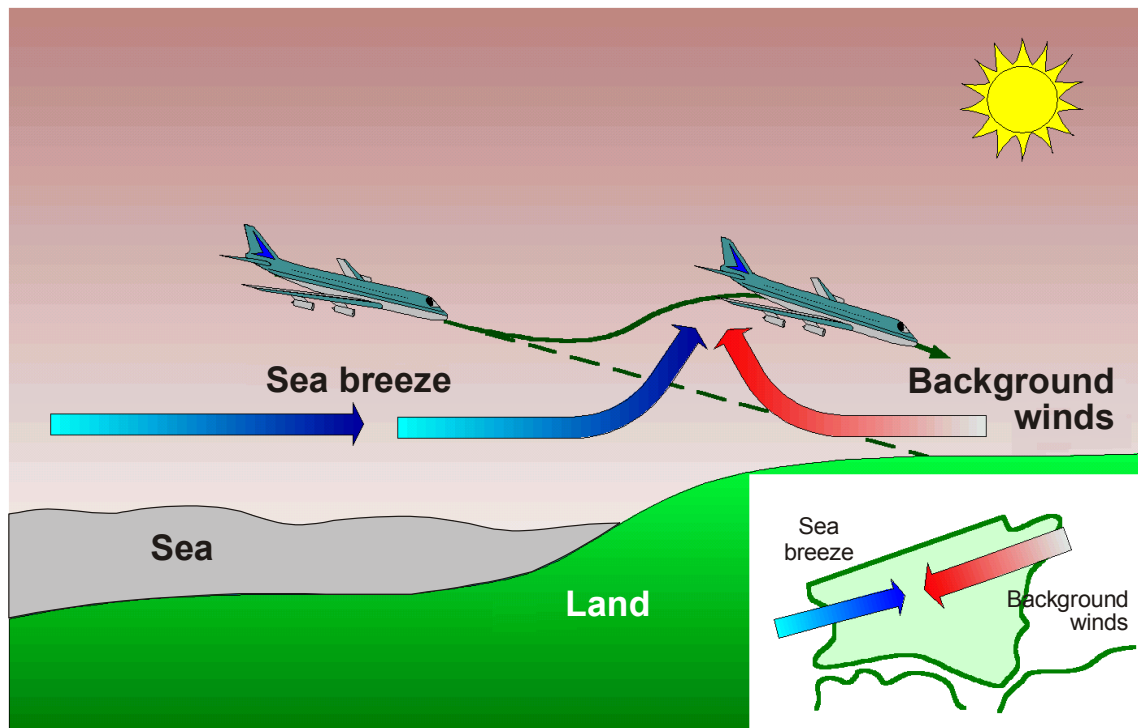


Figure A4-5. Wind shear brought by a sea breeze

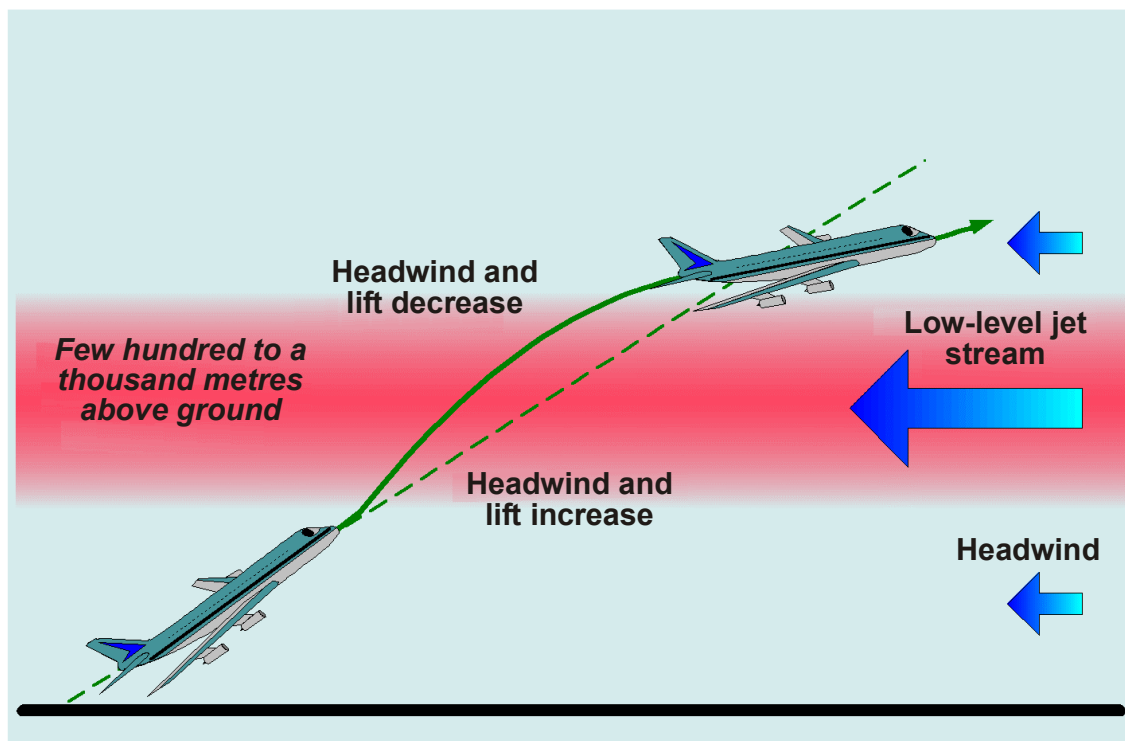


Figure A4-6. Wind shear brought by a low-level jet stream



Figure A4-7. The terminal Doppler weather radar in Hong Kong



Figure A4-8. Wind shear detection facilities implemented in the early 2000s — weather buoy (left) and LIDAR (right)

Appendix 5

UHF WIND PROFILER AT THE NICE CÔTE D'AZUR AIRPORT

(Raw output data from the wind profiler system
2 September 2000, 1400–1700 UTC)

(5.1.43 refers)

Note.— The table and figure below are reproduced with the permission of Météo, France, and have been numbered by ICAO for use in this appendix.

Table A5-1. Wind shear messages of 2 September 2000

1656 h and 1657 h L	1658 h and 1659 h L	1700 h L	1701 h L
Shear independent of runway orientation:	Shear independent of runway orientation:	Shear independent of runway orientation:	Shear independent of runway orientation:
Moderate at 142 m Moderate at 195 m Moderate at 285 m Strong at 321 m Strong at 428 m Strong at 464 m Light at 554 m Strong at 643 m	Moderate at 142 m Strong at 213 m Strong at 249 m Strong at 285 m Strong at 536 m	Strong at 106 m Strong at 142 m Strong at 321 m Strong at 392 m Strong at 464 m Strong at 536 m Strong at 643 m	Strong at 321 m Strong at 392 m Strong at 464 m Strong at 536 m Strong at 643 m
Runway orientation: 40	Runway orientation: 40	Runway orientation: 40	Runway orientation: 40
Moderate at 195 m: opposite direction to runway Light at 285 m: perpendicular to runway Moderate at 321 m: same direction as runway Strong at 321 m: perpendicular to runway Moderate at 428 m: same direction as runway Light at 428 m: perpendicular to runway Moderate at 464 m: opposite direction to runway Moderate at 464 m: perpendicular to runway Strong at 643 m: opposite direction to runway Moderate at 643 m: perpendicular to runway	Moderate at 142 m: perpendicular to runway Strong at 213 m: opposite direction to runway Strong at 249 m: same direction as runway Strong at 285 m: opposite direction to runway Moderate at 285 m: perpendicular to runway Moderate at 536 m: same direction as runway Moderate at 536 m: perpendicular to runway	Light at 106 m: same direction as runway Moderate at 106 m: perpendicular to runway Moderate at 142 m: perpendicular to runway Moderate at 321 m: opposite direction to runway Moderate at 321 m: perpendicular to runway Moderate at 392 m: same direction as runway Moderate at 392 m: perpendicular to runway Moderate at 464 m: opposite direction to runway Light at 464 m: perpendicular to runway Strong at 536 m: same direction as runway Moderate at 536 m: perpendicular to runway Strong at 536 m: same direction as runway Light at 536 m: perpendicular to runway Moderate at 643 m: opposite direction to runway Moderate at 643 m: perpendicular to runway	Moderate at 321 m: opposite direction to runway Moderate at 321 m: perpendicular to runway Strong at 392 m: same direction as runway Moderate at 392 m: perpendicular to runway Moderate at 464 m: opposite direction to runway Light at 464 m: perpendicular to runway Strong at 536 m: same direction as runway Light at 536 m: perpendicular to runway Moderate at 643 m: opposite direction to runway Moderate at 643 m: perpendicular to runway

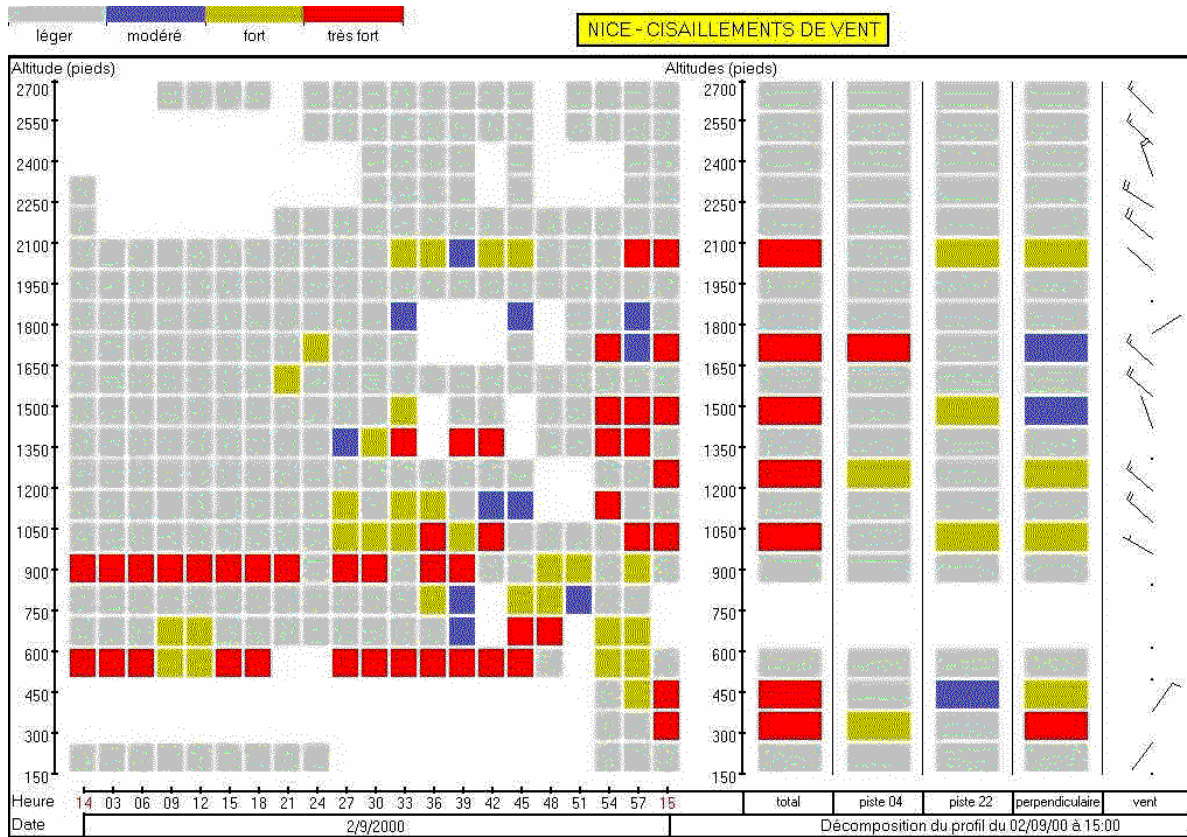


Figure A5-1. Graphical visualization agreed with the approach control centre of the Nice Côte d'Azur Airport for use by air traffic controllers

Appendix 6

LOW-ALTITUDE WIND SHEAR SYSTEM EQUIPMENT REQUIREMENTS

(5.1.52 refers)

Note.— The text below is extracted from the United States Code of Federal Regulations, 14 CFR, Chapter 1, Part 121, and reproduced with the permission of the Federal Aviation Administration.

- (a) *Airplanes manufactured after January 2, 1991.* No person may operate a turbine-powered airplane manufactured after January 2, 1991, unless it is equipped with either an approved airborne wind shear warning and flight guidance system, an approved airborne detection and avoidance system, or an approved combination of these systems.
- (b) *Airplanes manufactured before January 3, 1991.* Except as provided in paragraph (c) of this section, after January 2, 1991, no person may operate a turbine-powered airplane manufactured before January 3, 1991 unless it meets one of the following requirements as applicable:
 - (1) The makes/models/series listed below must be equipped with either an approved airborne wind shear warning and flight guidance system, an approved airborne detection and avoidance system, or an approved combination of these systems:
 - (i) A-300-600;
 - (ii) A-310 — all series;
 - (iii) A-320 — all series;
 - (iv) B-737-300, 400, and 500 series;
 - (v) B-747-400;
 - (vi) B-757 — all series;
 - (vii) B-767 — all series;
 - (viii) F-100 — all series;
 - (ix) MD-11 — all series; and
 - (x) MD-80 series equipped with an EFIS and Honeywell-970 digital flight guidance computer.
 - (2) All other turbine-powered airplanes not listed above must be equipped with as a minimum requirement, an approved airborne windshear warning system. These

airplanes may be equipped with an approved airborne windshear detection and avoidance system, or an approved combination of these systems.

- (c) *Extension of the compliance date.* A certificate holder may obtain an extension of the compliance date in paragraph (b) of this section if it obtains FAA approval of a retrofit schedule. To obtain approval of a retrofit schedule and show continued compliance with that schedule, a certificate holder must do the following:
 - (1) Submit a request for approval of a retrofit schedule by June 1, 1990, to the Flight Standards Division Manager in the region of the certificate holding district office.
 - (2) Show that all of the certificate holder's airplanes required to be equipped in accordance with this section will be equipped by the final compliance date established for TCAS II retrofit.
 - (3) Comply with its retrofit schedule and submit status reports containing information acceptable to the Administrator. The initial report must be submitted by January 2, 1991, and subsequent reports must be submitted every six months thereafter until completion of the schedule. The reports must be submitted to the certificate holder's assigned Principal Avionics Inspector.
- (d) *Definitions.* For the purposes of this section the following definitions apply --
 - (1) *Turbine-powered airplane* includes, e.g., turbofan-, turbojet-, propfan-, and ultra-high bypass fan-powered airplanes. The definition specifically excludes turbo-propeller-powered airplanes.
 - (2) An airplane is considered manufactured on the date the inspection acceptance records reflect that the airplane is complete and meets the FAA Approved Type Design data.

[Doc. No. 25954, 55 FR 13242, Apr. 9, 1990]

Appendix H to Part 121 — Advanced Simulation

This appendix provides guidelines and a means for achieving flight crew training in advanced airplane simulators. This appendix describes the simulator and visual system requirements which must be achieved to obtain approval of certain types of training in the simulator. The requirements in this appendix are in addition to the simulator approval requirements in §121.407. Each simulator which is used under this appendix must be approved as a Level B, C, or D simulator, as appropriate.

To obtain FAA approval of the simulator for a specific level, the following must be demonstrated to the satisfaction of the Administrator:

1. Documented proof of compliance with the appropriate simulator, visual system, and additional training requirements of this appendix for the level for which approval is requested.
2. An evaluation of the simulator to ensure that its ground, flight, and landing performance matches the type of airplane simulated.
3. An evaluation of the appropriate simulator and visual system requirements of the level for which approval is requested.

CHANGES TO SIMULATOR PROGRAMING

While a need exists for some flexibility in making changes in the software program, strict scrutiny of these changes is essential to ensure that the simulator retains its ability to duplicate the airplane's flight and ground characteristics. Therefore, the following procedure must be followed to allow these changes without affecting the approval of an appendix H simulator:

1. Twenty-one calendar days before making changes to the software program which might impact flight or ground dynamics of an appendix H simulator, a complete list of these planned changes, including dynamics related to the motion and visual systems, must be provided in writing to the FAA office responsible for conducting the recurrent evaluation of that simulator.
2. If the FAA does not object to the planned change within 21 calendar days, the operator may make the change.
3. Changes which might affect the approved simulator Level B test guide must be tested by the operator in the simulator to determine the impact of the change before submission to the FAA.
4. Software changes actually installed must be summarized and provided to the FAA. When the operator's test shows a difference in simulator performance due to a change, an amended copy of the test guide page which includes the new simulator test results will also be provided to update the FAA's copy of the test guide.
5. The FAA may examine supporting data or flight check the simulator, or both, to ensure that the aerodynamic quality of the simulator has not been degraded by any change in software programing.
6. All requests for changes are evaluated on the basis of the same criteria used in the initial approval of the simulator for Level B, C, or D.

SIMULATOR MINIMUM EQUIPMENT LIST (MEL)

Because of the strict tolerances and other approval requirements of appendix H simulators, the simulator can provide realistic training with certain nonessential items inoperative. Therefore, an operator may operate its simulator under an MEL which has been approved by the Administrator for that simulator. The MEL includes simulator components and indicates the type of training or checking that is authorized if the component becomes inoperative. To accomplish this, the component is placed in one of the following categories along with any remarks applicable to the component's use in the training program:

1. No training or checking.
2. Training in specific maneuvers.
3. Certification and checking.
4. Line Oriented Flight Training (LOFT).

ADVANCED SIMULATION TRAINING PROGRAM

For an operator to conduct Level C or D training under this appendix all required simulator instruction and checks must be conducted under an advanced simulation training program which is approved by the Administrator for the operator. This program must also ensure that all instructors and check airmen used in

appendix H training and checking are highly qualified to provide the training required in the training program. The advanced simulation training program shall include the following:

1. The operator's initial, transition, upgrade, and recurrent simulator training programs and its procedures for re-establishing recency of experience in the simulator.
2. How the training program will integrate Level B, C, and D simulators with other simulators and training devices to maximize the total training, checking, and certification functions.
3. Documentation that each instructor and check airman has served for at least 1 year in that capacity in a certificate holder's approved program or has served for at least 1 year as a pilot in command or second in command in an airplane of the group in which that pilot is instructing or checking.
4. A procedure to ensure that each instructor and check airman actively participates in either an approved regularly scheduled line flying program as a flight crewmember or an approved line observation program in the same airplane type for which that person is instructing or checking.
5. A procedure to ensure that each instructor and check airman is given a minimum of 4 hours of training each year to become familiar with the operator's advanced simulation training program, or changes to it, and to emphasize their respective roles in the program. Training for simulator instructors and check airmen shall include training policies and procedures, instruction methods and techniques, operation of simulator controls (including environmental and trouble panels), limitations of the simulator, and minimum equipment required for each course of training.
6. A special Line Oriented Flight Training (LOFT) program to facilitate the transition from the simulator to line flying. This LOFT program consists of at least a 4-hour course of training for each flight crew. It also contains at least two representative flight segments of the operator's route. One of the flight segments contains strictly normal operating procedures from push back at one airport to arrival at another. Another flight segment contains training in appropriate abnormal and emergency flight operations.

LEVEL B

Training and checking permitted

1. Recency of experience (§121.439).
2. Night takeoffs and landings (part 121, appendix E).
3. Landings in a proficiency check without the landing on the line requirements (§121.441).

Simulator requirements

1. Aerodynamic programing to include:
 - a. Ground effect — for example, roundout, flare, and touchdown. This requires data on lift, drag, and pitching moment in ground effect.
 - b. Ground reaction — reaction of the airplane upon contact with the runway during landing to include strut deflections, tire friction, and side forces.

- c. Ground handling characteristics — steering inputs to include crosswind, braking, thrust reversing, deceleration, and turning radius.
2. Minimum of 3-axis freedom of motion systems.
3. Level B landing maneuver test guide to verify simulator data with actual airplane flight test data, and provide simulator performance tests for Level B initial approval.
4. Multichannel recorders capable of recording Level B performance tests.

Visual requirements

1. Visual system compatibility with aerodynamic programming.
2. Visual system response time from pilot control input to visual system output shall not exceed 300 milliseconds more than the movement of the airplane to a similar input. Visual system response time is defined as the completion of the visual display scan of the first video field containing different information resulting from an abrupt control input.
3. A means of recording the visual response time for comparison with airplane data.
4. Visual cues to assess sink rate and depth perception during landings.
5. Visual scene to instrument correlation to preclude perceptible lags.

LEVEL C

Training and checking permitted

1. For all pilots, transition training between airplanes in the same group, and for a pilot in command the certification check required by §61.153(g) this chapter.
2. Upgrade to pilot-in-command training and the certification check when the pilot —
 - a. has previously qualified as second in command in the equipment to which the pilot is upgrading;
 - b. has at least 500 hours of actual flight time while serving as second in command in an airplane of the same group; and
 - c. is currently serving as second in command in an airplane in this same group.
3. Initial pilot-in-command training and the certification check when the pilot —
 - a. is currently serving as second in command in an airplane of the same group;
 - b. has a minimum of 2,500 flight hours as second in command in an airplane of the same group; and
 - c. has served as second-in-command on at least two airplanes of the same group.

4. For all second-in-command pilot applicants who meet the aeronautical experience requirements of §61.159 of this chapter in the airplane, the initial and upgrade training and checking required by this part, and the certification check requirements of §61.153 of this chapter.

Simulator requirements

1. Representative crosswind and three-dimensional wind shear dynamics based on airplane related data.
2. Representative stopping and directional control forces for at least the following runway conditions based on airplane related data:
 - a. Dry.
 - b. Wet.
 - c. Icy.
 - d. Patchy wet.
 - e. Patchy icy.
 - f. Wet on rubber residue in touchdown zone.
3. Representative brake and tire failure dynamics (including antiskid) and decreased brake efficiency due to high brake temperatures based on airplane related data.
4. A motion system which provides motion cues equal to or better than those provided by a six-axis freedom of motion system.
5. Operational principal navigation systems, including electronic flight instrument systems, INS, and OMEGA, if applicable.
6. Means for quickly and effectively testing simulator programing and hardware.
7. Expanded simulator computer capacity, accuracy, resolution, and dynamic response to meet Level C demands. Resolution equivalent to that of at least a 32-bit word length computer is required for critical aerodynamic programs.
8. Timely permanent update of simulator hardware and programing subsequent to airplane modification.
9. Sound of precipitation and significant airplane noises perceptible to the pilot during normal operations and the sound of a crash when the simulator is landed in excess of landing gear limitations.
10. Aircraft control feel dynamics shall duplicate the airplane simulated. This shall be determined by comparing a recording of the control feel dynamics of the simulator to airplane measurements in the takeoff, cruise, and landing configuration.
11. Relative responses of the motion system, visual system, and cockpit instruments shall be coupled closely to provide integrated sensory cues. These systems shall respond to abrupt pitch, roll, and yaw inputs at the pilot's position within 150 milliseconds of the time, but not before the time, when the airplane would respond under the same conditions. Visual scene changes from steady state disturbance shall not occur before the resultant motion onset but within the system dynamic response tolerance of

150 milliseconds. The test to determine compliance with these requirements shall include simultaneously recording the analog output from the pilot's control column and rudders, the output from an accelerometer attached to the motion system platform located at an acceptable location near the pilots' seats, the output signal to the visual system display (including visual system analog delays), and the output signal to the pilot's attitude indicator or an equivalent test approved by the Administrator. The test results in a comparison of a recording of the simulator's response to actual airplane response data in the takeoff, cruise, and landing configuration.

Visual requirements

1. Dusk and night visual scenes with at least three specific airport representations, including a capability of at least 10 levels of occulting, general terrain characteristics, and significant landmarks.
2. Radio navigation aids properly oriented to the airport runway layout.
3. Test procedures to quickly confirm visual system color, RVR, focus, intensity, level horizon, and attitude as compared to the simulator attitude indicator.
4. For the approach and landing phase of flight, at and below an altitude of 2,000 feet height above the airport (HAA) and within a radius of 10 miles from the airport, weather representations including the following:
 - a. Variable cloud density.
 - b. Partial obscuration of ground scenes; that is, the effect of a scattered to broken cloud deck.
 - c. Gradual break out.
 - d. Patchy fog.
 - e. The effect of fog on airport lighting.
 - f. Category II and III weather conditions.
5. Continuous minimum visual field of view of 75° horizontal and 30° vertical per pilot seat. Visual gaps shall occur only as they would in the airplane simulated or as required by visual system hardware. Both pilot seat visual systems shall be able to be operated simultaneously.
6. Capability to present ground and air hazards such as another airplane crossing the active runway or converging airborne traffic.

LEVEL D

Training and checking permitted

Except for the requirements listed in the next sentence, all pilot flight training and checking required by this part and the certification check requirements of §61.153(g) of this chapter. The line check required by §121.440 of this part, the static airplane requirements of appendix E of this part, and the operating experience requirements of §121.434 of this part must still be performed in the airplane.

Simulator requirements

1. Characteristic buffet motions that result from operation of the airplane (for example, high-speed buffet, extended landing gear, flaps, nose-wheel scuffing, stall) which can be sensed at the flight deck. The simulator must be programmed and instrumented in such a manner that the characteristic buffet modes can be measured and compared to airplane data. Airplane data are also required to define flight deck motions when the airplane is subjected to atmospheric disturbances such as rough air and cobblestone turbulence. General purpose disturbance models that approximate demonstrable flight test data are acceptable.
2. Aerodynamic modeling for aircraft for which an original type certificate is issued after June 1, 1980, including low-altitude, level-flight ground effect, mach effect at high altitude, effects of airframe icing, normal and reverse dynamic thrust effect on control surfaces, aero-elastic representations, and representations of nonlinearities due to side slip based on airplane flight test data provided by the manufacturer.
3. Realistic amplitude and frequency of cockpit noises and sounds, including precipitation static and engine and airframe sounds. The sounds shall be coordinated with the weather representations required in visual requirement No. 3.
4. Self-testing for simulator hardware and programming to determine compliance with Level B, C, and D simulator requirements.
5. Diagnostic analysis printout of simulator malfunctions sufficient to determine MEL compliance. These printouts shall be retained by the operator between recurring FAA simulator evaluations as part of the daily discrepancy log required under §121.407(a)(5).

Visual requirements

1. Daylight, dusk, and night visual scenes with sufficient scene content to recognize a specific airport, the terrain, and major landmarks around that airport and to successfully accomplish a visual landing. The daylight visual scene must be part of a total daylight cockpit environment which at least represents the amount of light in the cockpit on an overcast day. For the purpose of this rule, daylight visual system is defined as a visual system capable of producing, as a minimum, full color presentations, scene content comparable in detail to that produced by 4,000 edges or 1,000 surfaces for daylight and 4,000 light points for night and dusk scenes, 6-foot lamberts of light at the pilot's eye (highlight brightness), 3-arc minutes resolution for the field of view at the pilot's eye, and a display which is free of apparent quantization and other distracting visual effects while the simulator is in motion. The simulation of cockpit ambient lighting shall be dynamically consistent with the visual scene displayed. For daylight scenes, such ambient lighting shall neither "washout" the displayed visual scene nor fall below 5-foot lamberts of light as reflected from an approach plate at knee height at the pilot's station and/or 2-foot lamberts of light as reflected from the pilot's face.
2. Visual scenes portraying representative physical relationships which are known to cause landing illusions in some pilots, including short runway, landing over water, runway gradient, visual topographic features, and rising terrain.
3. Special weather representations which include the sound, visual, and motion effects of entering light, medium, and heavy precipitation near a thunderstorm on takeoff, approach, and landings at and below an altitude of 2,000 feet HAA and within a radius of 10 miles from the airport.
4. Level C visual requirements in daylight as well as dusk and night representations.

5. Wet and, if appropriate for the operator, snow-covered runway representations, including runway lighting effects.
6. Realistic color and directionality of airport lighting.
7. Weather radar presentations in aircraft where radar information is presented on the pilot's navigation instruments. (Secs. 313, 601, 603, 604, Federal Aviation Act of 1958, as amended (49 U.S.C. 1354, 1421, 1423, 1424); sec. 6(c), Department of Transportation Act (49 U.S.C. 1655(c)).

[Doc. No. 19758, 45 FR 44183, June 30, 1980; 45 FR 48599, July 31, 1980, as amended by Amdt. 121-258, 61 FR 30732, June 17, 1996; 61 FR 39859, July 31, 1996; Amdt. 121-267, 62 FR 68137, Dec. 30, 1997]

APPENDIX 7

Wind Shear Simulation Data Sets

(5.1.4.3 refers)

Note.— The table and Notes 1 to 10 are reproduced with the permission of the FAA. The table has been numbered by ICAO for use in this Appendix.

Table A7-1. Wind shear simulation data sets

No.	NASA Terminal Area Simulation System (TASS) Data Set	Horz. grid spacing (meters) [1]	Max reflectivity (dBz)	Outflow reflectivity (dBz)	Approx. diameter of outflow @ peak_V (km)	Growth stage	Approx. peak 1 km FBAR [2]	Intervening rain [3]	Temp. lapse rate	Symmetry	Radar clutter model	Flight Scenario Location and Airspeed [4]
1	DFW Accident DATA SET/TIME: 111 Wet microburst with rain and hail	50	55	35 to 42	3.5	N/A	0.2	No	Adiabatic	Asym	Newark 4R/22L	Aligned for take-off to the east with the microburst leading edge 3.0 NM from brake release. Airspeed: 0 ktas [5]
2	DFW Accident DATA SET/TIME: 111 Wet microburst with rain and hail	50	55	35 to 42	3.5	N/A	0.14	No	Adiabatic	Asym	Newark 4R/22L	–3 degree straight in approach to the east with the microburst located at the middle marker 1.2 NM from runway threshold. Airspeed: 150 ktas
3	06/20/91 NASA Research Flight Orlando Florida DATA SET/TIME: 237 Wet microburst	100	50	37 to 45	3.5	N/A	0.14	Yes	Adiabatic	Rough	Newark 4R/22L	–3 degree straight in approach to the south with the microburst located at the middle marker 1.2 NM from runway threshold. Airspeed: 150 ktas
4	06/20/91 NASA Research Flight Orlando Florida DATA SET/TIME: 237 Wet microburst	100	50	37 to 45	3.5	Developing Below threshold case [6]	0.06	Yes	Adiabatic	Rough	Newark 4R/22L	–3 degree straight in approach to the east with the microburst located at the middle marker 1.2 NM from runway threshold. Airspeed: 150 ktas

No.	NASA Terminal Area Simulation System (TASS) Data Set	Horz. grid spacing (meters) [1]	Max reflectivity (dBz)	Outflow reflectivity (dBz)	Approx. diameter of outflow @ peak_V (km)	Growth stage	Approx. peak 1 km FBAR [2]	Intervening rain [3]	Temp. lapse rate	Symmetry	Radar clutter model	Flight Scenario Location and Airspeed [4]
5	06/20/91 NASA Research Flight Orlando Florida DATA SET/TIME: 237 Wet microburst	100	50	37 to 45	3.5	N/A	0.19	Yes	Adiabatic	Rough	Newark 4R/22L	Go-around at 100 ft to the west with the microburst 1.8 NM from the 100 ft point at the far end of the runway. Airspeed: 150 ktas
6	7/11/88 Incident Case Denver Colorado DATA SET/TIME: 349 Multiple microburst	100	35	10 to 16	3	Developing Below threshold case [6]	0.083	Light	Adiabatic	Varies between microburst	Newark 4R/22L	–3 degree straight in approach to the east with the microburst located at the middle marker ½ NM from runway threshold. Airspeed: 150 ktas
7	7/11/88 Incident Case Denver Colorado DATA SET/TIME: 349 Multiple microburst	100	37	10 to 16	3	Developing Below threshold case [6]	0.13	Yes	Adiabatic	Varies between microburst	Newark 4R/22L	–3 degree straight in approach to the north with the microburst located at the middle marker 12 NM from runway threshold. Airspeed: 150 ktas
8	7/11/88 Incident Case Denver Colorado DATA SET/TIME: 351 Multiple microburst	100	24	13 to 27	1.5–3.0	Developing Must Alert threshold case [6]	0.17	Yes	Adiabatic	Varies between microburst	Newark 4R/22L	Aligned for take-off to the north with the microburst leading edge placed such that the aeroplane is in the headwind conditions of the outflow. Airspeed: 0 ktas [5]
9	7/11/88 Incident Case Denver Colorado DATA SET/TIME: 351 Multiple microburst	100	25	13 to 27	1.5–3.0	N/A	0.19	Yes	Adiabatic	Varies between microburst	Newark 4R/22L	Aligned for take-off to the east with the microburst leading edge placed such that the aeroplane is in the headwind conditions of the outflow. Airspeed: 0 ktas [5]
10	7/11/88 Incident Case Denver Colorado DATA SET/TIME: 351 Multiple microburst	100	25	13 to 27	1.5–3.0	N/A	0.19	Yes	Adiabatic	Varies between microburst	Newark 4R/22L	Take-off at gear up height to the east with the microburst leading edge 3.0 NM from brake release. [5] Airspeed: 150 ktas [7]

No.	NASA Terminal Area Simulation System (TASS) Data Set	Horz. grid spacing (meters) [1]	Max reflectivity (dBz)	Outflow reflectivity (dBz)	Approx. diameter of outflow @ peak_V (km)	Growth stage	Approx. peak 1 km FBAR [2]	Intervening rain [3]	Temp. lapse rate	Symmetry	Radar clutter model	Flight Scenario Location and Airspeed [4]
11	7/11/88 Incident Case Denver Colorado DATA SET/TIME: 351 Multiple microburst	100	40	13 to 27	1.5–3.0	N/A	0.15	Yes	Adiabatic	Varies between microburst	Newark 4R/22L	–3 degree straight in approach to the north at a 360 degree heading. The microburst is located at the middle marker ½ NM from runway threshold. Airspeed: 150 ktas
12	7/11/88 Incident Case Denver Colorado DATA SET/TIME: 351 Multiple microburst	100	40	13 to 27	1.5–3.0	N/A	0.18	Yes	Adiabatic	Varies between microburst	Newark 4R/22L	–3 degree straight in approach to the northeast at a 45 degree heading. The microburst is located at the middle marker ½ NM from runway threshold. Airspeed: 150 ktas
13	7/11/88 Incident Case Denver Colorado DATA SET/TIME: 349 Multiple microburst	100	40	13 to 27	1.5–3.0	N/A	0.17	Yes	Adiabatic	Varies between microburst	Newark 4R/22L	–3 degree straight in approach to the east at a 90 degree heading. The microburst is located at the middle marker ½ NM from runway threshold. Airspeed: 150 ktas
14	7/11/83 Incident Case Denver Colorado DATA SET/TIME: 351 Multiple microburst	100	40	13 to 27	1.5–3.0	N/A	0.13	Yes	Adiabatic	Varies between microburst	Newark 4R/22L	–3 degree straight in approach to the southeast at a 135 degree heading. The microburst is located at the middle marker ½ NM from runway threshold. Airspeed: 150 ktas
15	7/11/88 Incident Case Denver Colorado DATA SET/TIME: 351 Multiple microburst	100	40	13 to 27	1.5–3.0	N/A	0.17	Yes	Adiabatic	Varies between microburst	Newark 4R/22L	–3 degree straight in approach to the west at a 270 degree heading. The microburst is located at the middle marker ½ NM from runway threshold. Airspeed: 150 ktas
16	7/11/88 Incident Case Denver Colorado DATA SET/TIME: 351 Multiple microburst	100	40	13 to 27	1.5–3.0	N/A	0.13	Yes	Adiabatic	Varies between microburst	Newark 4R/22L	–3 degree straight in approach to the northwest at a 315 degree heading. The microburst is located at the middle marker ½ NM from runway threshold. Airspeed: 150 ktas

No.	NASA Terminal Area Simulation System (TASS) Data Set	Horz. grid spacing (meters) [1]	Max reflectivity (dBz)	Outflow reflectivity (dBz)	Approx. diameter of outflow @ peak_V (km)	Growth stage	Approx. peak 1 km FBAR [2]	Intervening rain [3]	Temp. lapse rate	Symmetry	Radar clutter model	Flight Scenario Location and Airspeed [4]
17	7/11/88 Incident Case Denver Colorado DATA SET/TIME: 351 Multiple microburst	100	40	13 to 27	1.5–3.0	N/A	0.15	Yes	Adiabatic	Varies between microburst	Denver 26L	1000 ft AGL level flight standard rate turn to the localizer. The microburst should be placed such that it is directly in front of the aircraft when localizer is captured. Airspeed: 200 ktas [8]
18	7/11/82 Temperature Inversion Denver Colorado DATA SET/TIME: 436 Multiple microburst	50	27	0 to 10	1.0	N/A	0.23	No	Stable layer	Asym	Newark 4R/22L	Aligned for take-off to the east with the microburst leading edge placed such that the aeroplane is in the headwind conditions of the outflow. Airspeed: 150 ktas
19	7/14/82 Temperature Inversion Denver Colorado DATA SET/TIME: 436 Multiple microburst	50	27	0 to 10	1.0	N/A	0.24	No	Stable layer	Asym	Newark 4R/22L	–3 degree straight in approach to the east with the microburst located at the middle marker ½ NM from the runway threshold. Airspeed: 150 ktas
20	7/14/82 Temperature Inversion Denver Colorado DATA SET/TIME: 436 Multiple microburst	50	27	–10 to –4	3.0	N/A	0.24	No	Stable Layer	Asym	Newark 4R/22L	–3 degree straight in approach to the east with a 25 degree draft angle. The microburst leading edge is placed at the runway threshold. Airspeed: 120 ktas [9]
21	7/8/89 Sounding Denver Colorado DATA SET/TIME: 540 Very dry microburst [10]	100	17 to 20	–10 to –4	3.0	N/A	0.18	No	Adiabatic	Rough	Newark 4R/22L	Take-off at gear up height to the west with the microburst leading edge 3.0 NM from brake release. Airspeed: 150 ktas [7]
22	7/8/89 Sounding Denver Colorado DATA SET/TIME: 540 Very dry microburst [10]	100	17 to 20	–10 to –4	3.0	N/A	0.16	No	Adiabatic	Rough	Newark 4R/22L	–3 degree straight in approach to the north with the microburst located at the middle marker 12 NM from the runway threshold. Airspeed: 150 ktas

No.	NASA Terminal Area Simulation System (TASS) Data Set	Horz. grid spacing (meters) [1]	Max reflectivity (dBz)	Outflow reflectivity (dBz)	Approx. diameter of outflow @ peak_V (km)	Growth stage	Approx. peak 1 km FBAR [2]	Intervening rain [3]	Temp. lapse rate	Symmetry	Radar clutter model	Flight Scenario Location and Airspeed [4]
23	7/8/89 Sounding Denver Colorado DATA SET/TIME: 540 Very dry microburst [10]	100	17 to 20	-10 to -4	3.0	N/A	0.12	No	Adiabatic	Rough	Newark 4R/22L	-3 degree straight in approach to the north with a 25 degree drift angle. The microburst leading edge is placed at the runway threshold. Airspeed: 120 ktas [9]
24	7/8/89 Sounding Denver Colorado DATA SET/TIME: 540 Very dry microburst [10]	100	17 to 20	-10 to -4	3.0	N/A	0.17	No	Adiabatic	Rough	Newark 4R/22L	Go-around at 100 ft to the north with the microburst 1.8 NM from the 100 ft. point at the far end of the runway. Airspeed: 150 ktas
25	7/8/89 Sounding Denver Colorado DATA SET/TIME: 540 Very dry microburst [10]	100	17 to 20	-10 to -4	3.0	N/A	0.16	No	Adiabatic	Rough	Denver 26L	1000 ft AGL level flight standard rate turn to the localizer, as limited by 25 degrees of bank. The microburst should be placed such that it is directly in front of the aircraft when localizer is captured. Airspeed: 200 ktas [8]
26	7/8/89 Sounding Denver Colorado DATA SET/TIME: 545 Extremely dry microburst Second Pulse [10]	100	5	-11	3.0	N/A	0.15	No	Adiabatic	Rough	Newark 4R/22L	-3 degree straight in approach to the north with the microburst located at the middle marker ½ NM from the runway threshold. Airspeed: 150 ktas
27	Derived Sounding Florida DATA SET/TIME: 614 Highly asymmetric microburst	100	50	40 to 47	1.0	N/A	0.11	Light	Adiabatic	Asym	Wash. National 18	1000 ft AGL level flight standard rate turn to the localizer, as limited by 25 degrees of bank. The microburst should be placed such that it is directly in front of the aircraft when localizer is captured. Airspeed: 200 ktas [8]

No.	NASA Terminal Area Simulation System (TASS) Data Set	Horz. grid spacing (meters) [1]	Max reflectivity (dBz)	Outflow reflectivity (dBz)	Approx. diameter of outflow @ peak_V (km)	Growth stage	Approx. peak 1 km FBAR [2]	Intervening rain [3]	Temp. lapse rate	Symmetry	Radar clutter model	Flight Scenario Location and Airspeed [4]
28	Derived Sounding Florida DATA SET/TIME: 614 Highly asymmetric microburst	100	50	40 to 47	1.0	N/A	0.15	Light	Adiabatic	Asym	Newark 4R/22L	–3 degree straight in approach to the north with a 360 degree heading. The microburst is located at the middle marker ½ NM from the runway threshold. Airspeed: 150 ktas
29	Derived Sounding Florida DATA SET/TIME: 614 Highly asymmetric microburst	100	50	40 to 47	1.0	N/A	0.17	Light	Adiabatic	Asym	Newark 4R/22L	–3 degree straight in approach to the northeast with a 45 degree heading. The microburst is located at the middle marker ½ NM from the runway threshold. Airspeed: 150 ktas
30	Derived Sounding Florida DATA SET/TIME: 614 Highly asymmetric microburst	100	50	40 to 47	1.0	N/A	0.15	Light	Adiabatic	Asym	Newark 4R/22L	–3 degree straight in approach to the south with a 180 degree heading. The microburst is located at the middle marker ½ NM from the runway threshold. Airspeed: 150 ktas
31	Derived Sounding Florida DATA SET/TIME: 614 Highly asymmetric microburst	50	50	40 to 47	1.0	N/A	0.19	Light	Adiabatic	Asym	Newark 4R/22L	–3 degree straight in approach to the southwest with a 225 degree heading. The microburst is located at the middle marker ½ NM from the runway threshold. Airspeed: 150 ktas
32	Derived Sounding Florida DATA SET/TIME: 614 Highly asymmetric microburst	50	50	40 to 47	1.0	N/A	0.13	Light	Adiabatic	Asym	Newark 4R/22L	–3 degree straight in approach to the west with a 270 degree heading. The microburst is located at the middle marker ½ NM from the runway threshold. Airspeed: 150 ktas
33	Derived Sounding Florida DATA SET/TIME: 614 Highly asymmetric microburst	100	50	40 to 47	1.0	N/A	0.13	Light	Adiabatic	Asym	Newark 4R/22L	–3 degree straight in approach to the northwest with a 315 degree heading. The microburst is located at the middle marker ½ NM from the runway threshold. Airspeed: 150 ktas

No.	NASA Terminal Area Simulation System (TASS) Data Set	Horz. grid spacing (meters) [1]	Max reflectivity (dBz)	Outflow reflectivity (dBz)	Approx. diameter of outflow @ peak_V (km)	Growth stage	Approx. peak 1 km FBAR [2]	Intervening rain [3]	Temp. lapse rate	Symmetry	Radar clutter model	Flight Scenario Location and Airspeed [4]
34	8/2/81 Adjusted Knowlton Sounding Montana DATA SET/TIME: 727 Gust front	100	20 In area of largest FBAR	18 to 20	N/A	N/A	0.12	No	Adiabatic	Asym	Newark 4R/22L	Aligned for take-off to the west with the microburst leading edge placed such that the aeroplane is in the headwind conditions of the outflow. Airspeed: 0 ktas [5]
35	8/2/81 Adjusted Knowlton Sounding Montana DATA SET/TIME: 727 Gust front	100	20 In area of largest FBAR	18 to 20	N/A	N/A	0.13	No	Adiabatic	Asym	Newark 4R/22L	–3 degree straight in approach to the west with the microburst located at the middle marker 12 NM from the runway threshold. Airspeed: 150 ktas

NOTES:

- [1] NASA TASS data sets will all be delivered with 50-metre resolution.
- [2] F-factors will differ in the data sets developed for airspeeds of 120, 150, and 200 KTAS. Since the calculation of F-factor is weakly dependent on the true airspeed (TAS) of the aeroplane, a typical airspeed of 150 knots has been chosen to standardize the evaluation of these systems. However, the wind shear system algorithms may be sensitive to true airspeed, and high airspeed is critical for system update rate evaluation relative to minimum detection time and low airspeed should be evaluated simply to show that the system will in fact actually work at low airspeeds. Therefore, a limited number of runs are to be evaluated at 120 KTAS and 200 KTAS. The 120 KTAS chosen is a typical minimum for lightweight maximum flap take-offs and landings at sea level standard day, and the 200 KTAS is a typical maximum for heavyweight minimum flap operation at high altitude airports on a hot day.
- [3] Intervening rain may adversely affect system performance. The system should be able to detect a hazardous wind shear with at least 10 seconds advance warning to be classified as a forward-looking system ("short or long range"). Since wind shears can be contained in an environment with heavy rain, they should be detectable in these conditions.

Analysis of TDWR data obtained at Orlando has shown that the largest difference in reflectivity seen between two microburst-producing cells within 5 kilometres of each other was 10 dBz. At Denver this number increased to a maximum of 30 dBz, which was only seen twice. Therefore, for the purpose of testing sensor performance in intervening rain, the flight paths depicted in Appendix E1 have been, where appropriate, oriented such that they pass through significant areas of rain prior to reaching the microburst hazard.

Flight paths as described in Appendix E have been oriented, where appropriate, to achieve areas of intervening rain prior to reaching the wind shear hazard.

- [4] These detection systems may have vertical look strategies that are fixed or variable. Since the aeroplane's pitch angle is a function of excess thrust, configuration, and flight mode, the system must perform satisfactorily over all expected circumstances.

a. Appendix E is not reproduced in this manual.

To require the entire test matrix to be evaluated for each configuration would be contentious; therefore, it is sensible for the system manufacturers to determine and justify the critical conditions (relative to detection, clutter suppression, display, etc.) for their systems.

Radar ground clutter collection flights should be conducted using the flight phases and characteristics described in Appendix E. All flight tests should be conducted using sensor/aeroplane pitch angles critical for system performance.

- [5] These flight scenarios are designed to demonstrate wind shear detection prior to brake release. If detection is not achieved prior to brake release, the take-off roll should be initiated and continued up to the detection point.
- [6] Flight paths and NASA TASS data sets, have been chosen to provide FBAR events close to the MUST-ALERT and MUST-NOT-ALERT boundary and within the MAY-ALERT criteria for several microburst events. These events have been chosen to depict characteristics of the developing, peak and decaying growth stages of these microbursts.

The reflectivity, attenuation, relative strengths of the vertical and horizontal windfield, Case 237, 349, and 614 symmetry, etc., can change relatively as a microburst develops and decays. These tests are to show that the system is insensitive to specific modelled relationships. The F-factors for several of these cases are chosen to approximate the MUST-ALERT F-factor. However, depending upon the threshold chosen for alert, the events located within the MAY-ALERT criteria may not produce an alert. Also, several of these cases are to show that the system is free from nuisance alerts when the wind shear event is below the MUST-NOT-ALERT boundary.

- [7] The simulation run may begin at the take-off gear up height >50 ft AGL.
 - [8] Flight tests for clutter data should attempt to duplicate the specified ground track by making adjustments to bank angle, but bank angle should be at least 20 degrees.
 - [9] Ground clutter collection flights should be conducted with the aircraft at its maximum safe side slip angle in an attempt to simulate a 25 degree drift angle on approach. Any shortfall of 25 degrees should be made up by an acceptable adjustment means.
 - [10] Events dryer than a core reflectivity of 5 dBz are rare. A 5 dBz reflectivity corresponds to 0.001 inches of water/hour at the surface. Also see justification for NASA TASS case: 540 and 545.
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Appendix 8

FORECASTING RULES

Note.— The text below is reproduced with the permission of the United Kingdom Meteorological Office.

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: V_{10} = Surface (10-metre) wind (vector)
 $V_{10} = |V_{10}|$ = Surface wind speed (scalar)
 V_G = Gradient (600 m or 2 000 ft) wind (vector)
 $V_G = |V_G|$ = 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) $V_{10} \leq 10$ kt and $|V_G - V_{10}| \geq 40$ kt
- 4) $V_{10} \leq 10$ kt and $|V_G - V_{10}| \geq 30$ 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/climb-out
- 6) FRONTAL ZONE below 600 m on the approach/climb-out, 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^a)
- 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) $V_{10} \geq 30$ kt
- 2) Winter trial criterion not used in summer trial
- 3) $|V_G - V_{10}| \geq 40$ kt
- 4) $|V_G - V_{10}| \geq 30$ 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/climb-out 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.”

a. Appendix C is not reproduced in this manual.

- 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

$$T_a T_a (\text{max}) - T_a T_a \geq 10 \text{ C}$$

- 3) $V_{10} \leq 10 \text{ kt}$ and $V_{10} (\text{max}) \geq 10 \text{ kt}$
- 4) $V_G \geq 10 \text{ kt}$ and $V_G (\text{sunset}) \geq 10 \text{ kt}$
- 5) No surface front has passed through since 1200 GMT.

Notes

- 1) $V_{10} (\text{max})$ and $T_a T_a (\text{max})$ are the maximum reported values of V_{10} and $T_a T_a$ from 1300 to 1800 GMT inclusive (previous afternoon).
($T_a T_a$ 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**

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.

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.

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 9

METEOROLOGY FOR AIR TRAFFIC CONTROLLERS AND PILOTS

(6.3.2 refers)

Note.— The text below is extracted from the ICAO Training Manual, Part F-1 — Meteorology for Air Traffic Controllers and Pilots (Doc 7192)

1. The *Training Manual, Part F-1 — Meteorology for Air Traffic Controllers and Pilots* (Doc 7192) updates the meteorological part of the syllabus and provides guidance for the training of air traffic controllers.
2. The following extracts are from the relevant parts of Part F-1 of the *Training Manual* concerning wind shear and the minimum knowledge and skill that are necessary if the air traffic controllers (ATCOs), private pilots (PPs), commercial pilots (CPs) and airline transport pilots (ATPs) are to perform their duties efficiently and productively.

Chapter 3 SYLLABI

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3.4 PRESSURE-WIND RELATIONSHIPS

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3.4.2 Required knowledge and skill

Definitions and measurement of wind

- definitions:
 - wind
 - wind direction (magnetic and true)
 - wind speed
 - wind velocity
 - wind shear
 - veering
 - backing
- units of measurement
- conversions
- methods of measuring wind velocity

Horizontal forces acting on the air

- pressure gradient force
- Coriolis force

- centripetal force
- surface friction

Geostrophic wind (including Buys-Ballot Law)

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3.10 THUNDERSTORMS

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3.10.2 Required knowledge and skill

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Surface weather associated with thunderstorms

- gusty, turbulent winds:
 - wind shifts
- wind shear (including gust fronts and dry and wet microbursts)
- heavy precipitation (rain and/or hail)
- changes in temperature and pressure
- lightning

Effects on aircraft operations

- aircraft operations in thunderstorms should be avoided:
 - often impossible to get above or around the storm due to its great extent
 - severe turbulence (also above the storm)
 - severe icing
- aircraft take-off and landing affected by:
 - gusty, turbulent winds
 - wind shear (including gust fronts and microbursts)
 - reduced visibility due to heavy precipitation or hail
- effects of lightning on:
 - airframe
 - compass and radio communications

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3.23 MET SERVICE FOR INTERNATIONAL AIR NAVIGATION

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3.23.2 Required knowledge and skill

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Organization of aeronautical MET services within States

- role of the MET authority
- (aerodrome) MET office:
 - role
 - products and services provided:
- aerodrome, take-off and landing forecasts (TAF, trend forecasts) aerodrome warnings and wind shear warnings
- reliance on WAFS for en-route information for flight planning and flight documentation
- issuance of en-route forecasts for low-level flights
- briefing and consultation
- display of MET information

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3.26 AERONAUTICAL FORECASTS AND WARNINGS

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3.26.2 Required knowledge and skill

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Warnings

- SIGMET/AIRMET information:
 - en route
 - criteria for issuance
 - role of SIGMET information related to tropical cyclones and volcanic ash
 - format
- aerodrome warnings:
 - terminal area
 - content
- wind shear warnings:
 - terminal area
 - format
- wake turbulence

Classroom exercise

- examination of charts and forecasts used for flight planning and included in flight documentation
- practice in decoding and interpretation of aerodrome and trend-type landing forecasts
- practice in reading of aerodrome and wind shear warnings

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Appendix 10

AUDIO-VISUAL AIDS AVAILABLE FROM ICAO

(6.3.5 refers)

1. In order to assist States and operators in developing their various training programmes, ICAO has a large number of audio-visual training aids that may be purchased. These include posters and videos, some of which have been produced by ICAO and others made available to ICAO by Contracting States.
2. As far as wind shear is concerned, the poster *Gust Front Turbulence & Windshear* (P621) deals with the subject. It draws attention to the particular hazards of gust fronts associated with thunderstorms. Poster P683, *Windshear — Microburst*, stresses that avoidance is the best technique when it comes to microburst wind shear. There is also Poster P686, *Microburst — Wind Shear*, which describes and illustrates many of the characteristics of a typical microburst wind shear. There are two videos on wind shear entitled *Wind Shear — The Probable Cause* (V645) and *The Wind Shear Factor* (V647).
3. These audio-visual aids are especially suitable for those undergoing training. Full details of all posters and videos are contained in the *Catalogue of ICAO Publications and Audio-visual Training Aids*. Requests for copies of the Catalogue or orders for any training aids should be addressed to:

International Civil Aviation Organization
Attention: Document Sales Unit
999 University Street
Montréal, Quebec
H3C 5H7
Tel.: +1 (514) 954-8022
Facsimile: +1 (514) 954-6769
E-mail: sales@icao.int
Order online: www.icao.int

Appendix 11

B737 SUPPLEMENTARY PROCEDURES — ADVERSE WEATHER AND NON-NORMAL MANOEUVRES

(6.4.6 refers)

Note.— The text below is extracted from the B737 Operations Manual (2002) and is reproduced with the permission of the Boeing Company.

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 coordination 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), the maximum command speed should not exceed the lower of $V_{ref} + 20$ kt or landing flap placard speed minus 5 kt.
- Avoid large thrust reductions or trim changes in response to sudden airspeed increases as these may be followed by airspeed decreases.
- Crosscheck flight director commands using vertical flight path instruments.
- Crew coordination 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 monitoring and recognition time.

WIND SHEAR WARNING

Predictive wind shear warning during take-off roll: ("WINDSHEAR AHEAD, WINDSHEAR AHEAD" aural)

- prior to V1, reject take-off
- after V1, perform the Wind shear Escape Manoeuvre.

Wind shear encountered during take-off roll:

- If wind shear is encountered prior to V1, there may not be sufficient runway remaining to stop if an RTO is initiated at V1. At VR, rotate at a normal rate toward a 15 degree pitch attitude. Once airborne, perform the Wind shear Escape Manoeuvre.
- If wind shear is encountered near the normal rotation speed and airspeed suddenly decreases, there may not be sufficient runway left to accelerate back to normal take-off speed. If there is insufficient runway left to stop, initiate a normal rotation at least 2 000 feet 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. Ensure maximum thrust is set.

Predictive wind shear warning during approach: (“GO-AROUND, WIND SHEAR AHEAD” aural):

- perform the Wind shear Escape Manoeuvre, or, at pilot’s discretion, perform a normal go-around.

Wind shear encountered in flight:

- perform the Wind shear Escape Manoeuvre.

Note.— The following are indications the aeroplane is in wind shear:

- *wind shear warning (two-tone siren followed by “WINDSHEAR, WINDSHEAR, WINDSHEAR”) or*
- *unacceptable flight path deviations.*

Note.— Unacceptable flight path deviations are recognized as uncontrolled changes from normal steady state flight conditions below 1 000 feet AGL, in excess of any of the following:

- *15 knots indicated airspeed*
- *500 fpm vertical speed*
- *5° pitch attitude*
- *1 dot displacement from the glide slope*
- *unusual thrust lever position for a significant period of time.*

WIND SHEAR ESCAPE MANOEUVER**PILOT FLYING****PILOT NOT FLYING****Manual flight**

- | | |
|---|--|
| <ul style="list-style-type: none">— Disconnect autopilot— Press either TO/GA switch— Aggressively apply maximum* thrust— Disconnect auto throttle— Simultaneously roll wings level and rotate toward an initial pitch attitude of 15°— Retract speed brakes— Follow flight director TO/GA guidance (if available) | <ul style="list-style-type: none">— Assure maximum* thrust— Verify all required actions have been completed and call out any omissions. |
|---|--|

Automatic flight

- | | |
|--|--|
| <ul style="list-style-type: none">— Press either TO/GA switch**— Verify TO/GA mode annunciation— Verify thrust advances to GA power— Retract speed brakes— Monitor system performance***— Do not change flap or gear configuration until wind shear is no longer a factor— Monitor vertical speed and altitude— Do not attempt to regain lost airspeed until wind shear is no longer a factor | <ul style="list-style-type: none">— Monitor vertical speed and altitude— Call out any trend toward terrain contact, descending flight path, or significant airspeed changes |
|--|--|

Note.— Aft control column force increases as the airspeed decreases. In all cases, the pitch attitude that results in intermittent stick shaker or initial buffet is the upper pitch attitude limit. Flight at intermittent stick shaker may be required to obtain a positive terrain separation. Smooth, steady control will avoid a pitch attitude overshoot and stall.

**Note.— Maximum thrust means “maximum certified thrust”. On engines without electronic thrust limiting capability, over boost or “fire walling the thrust lever” should only be considered during emergency situations when all other available actions have been taken and terrain contact is imminent.*

***Note.— If TO/GA is not available, disconnect autopilot and auto throttle and fly manually.*

*****WARNING.** — Severe wind shear may exceed the performance of the AFDS. The pilot flying must be prepared to *disconnect* the autopilot and auto throttle and fly manually.

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— END —

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 worldwide 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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