A Technical Memorandum NWS FCST-23

LOW-LEVEL WIND SHEAR: A Critical Review

Julius Badner

Meteorological Services Division
Silver Spring, Md.
April 1979

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Julius Badner

ABSTRACT. Wind shear is the local variation of the wind vector. Significant shear at low levels may be produced by synoptic scale fronts, sea breezes, low-level jets and mountain waves. Convective features producing wind shear are the thunderstorm gust front and the squall line. Theoretical and observational background information on the occurrence of low-level wind shear is provided. Aircraft takeoff, approach and landing incidents related to wind shear are cited. Graphs and tables which can aid in the forecasting of low-level wind shear under various conditions are provided.

The occurrence of wind shear with synoptic scale systems and with convective systems is described. This paper is intended to be a guide to the forecaster in predicting low-level wind shear and assessing its significance.

1. INTRODUCTION

With the advent of large, heavy modern aircraft, considerably more attention is focused on the phenomenon of wind shear near the ground and its relation to aircraft accidents. Wind shear has been defined simply by the World Meteorological Organization (WMO) (1) as "change of wind direction and/or speed in a relatively short amount of space."

When an aircraft is flying only slightly above the stall speed on approach or takeoff, a major change in wind velocity can lead to a significant gain or loss of lift. A loss of lift of such magnitude that power and/or control response are not adequate to correct the energy-deficient condition immediately can result in an excessive rate of descent. The altitude at which the wind shear encounter occurs, the pilot's reaction time, and the aircraft's response capability determine whether the descent can be slowed in sufficient time to prevent an accident. (See Appendix B.)

Wind shear may be defined further as the local variation of the wind vector or any of its components in a given direction. This variation can be a change in horizontal wind speed, and/or direction, and/or vertical speed with distance measured in a horizontal and/or vertical direction. There are nine different possibilities for these variations of the components u, v, and w, in the various directions x, y, and z.

Significant horizontal and/or vertical wind shear may be produced by such non-convective features as the low-level jet, synoptic scale fronts, sea breezes, "coastal fronts" (frontogenetic regions), and mountain waves. Convective features include the thunderstorm gust front and its progeny, the squall line. Shears can occur in the planetary boundary layer and particularly with flow over and around rough terrain, trees, and buildings near airports and runways.

Some degree of shear is encountered during most approach and takeoff aircraft operations. The strength of the shear and the degree to which it becomes hazardous is dependent on the existing combination of meteorological circumstances.

1.1 Background

The planetary boundary layer consists of the surface boundary, or friction, layer in which horizontal stresses and wind directions are nearly constant with height up to about 50m (range 10-100m) (2); and the Ekman layer, up to about 1000m, the lowest level at which the wind becomes geostrophic in the theory of the Ekman spiral. In this Ekman layer, the horizontal stresses decrease and the winds turn clockwise with height in the northern hemisphere. The wind near the surface blows across the isobars defining the geostrophic wind flow at an angle varying from 10° over the oceans to as much as 45° or more over rough land surfaces (3).

The geostrophic wind at the top of the planetary boundary layer results from synoptic and mesoscale pressure gradients. The surface of the earth exerts frictional drag on the air in the entire layer. Momentum is transferred downward from the geostrophic wind level to the ground where the shearing stress reduces the surface wind to zero. The result is wind shear in the layer. Turbulence, the primary mechanism for transfer of momentum, is produced by forced convection, which is a function of the degree of roughness of the underlying surface, and/or by free convection resulting from the buoyancy forces. The vertical motions induced by these features enhance mixing and reduce vertical wind shear. Over rough terrain, the wind shear decreases near the ground, but there is a relative increase higher in the layer. Unstable air tends to rise, enhancing vertical mixing and reducing vertical wind shear in most of the layer. Under temperature inversion conditions, vertical motion is damped and vertical wind shear can become quite large (4).

1.1.1 The Friction Layer

In the very lowest atmospheric layer (approximately the first 50m), the horizontal wind stresses are observed to be nearly constant with height and the wind direction is constant. The density of the air in this thin layer also is essentially constant.

1.1.1.1 The Logarithmic Wind Law

In the friction layer, an aircraft would experience wind shear because of the increase in wind speed vertically from the near zero speed close to the ground. If the temperature lapse rate in the layer is neutrally stable (adiabatic), the profile of the wind speed is given by the logarithmic wind law:

$$u = \frac{1}{k}\sqrt{\frac{\tau_o}{\rho}}\ \text{Ln}\ \frac{z}{z_o} \qquad \text{(Prandtl Equation)}$$

where u is the wind speed at height z; k is von Karman's constant, approximately 0.38; ρ is air density; τ_o is the drag of the wind per unit area; and z_o is the roughness parameter with dimensions of height, depending on the nature of the surface. The term $u_* = \sqrt{\frac{\tau_o}{\rho}}$ is called the friction velocity. At the height of z_o, u=o. This law has been thoroughly tested and has verified well for neutral conditions up to about 50m and sometimes considerably higher (5).

The roughness height can be specified for each airport for various wind directions. Typical values are usually between 1/10 and 1/30 the height of the effective surface obstacles (6), such as: snow surface, 0.1-0.6cm; low grass, 1.0-40cm; fallow field, 2.1-3.0cm; palmetto, 10-30cm; scrub oak, 100cm; suburbia, 100-200cm; and city, 100-400cm (7).

After the roughness length z_o has been determined for the particular airport and wind direction, one observed wind in the layer at height z provides the information necessary to solve the logarithmic wind law for the surface stress. The air density ρ, a function of the virtual temperature and pressure, can be read from tables. Then, the wind speed at any other height up to the top of the friction layer can be computed from the equation.

When obstacles around the airport are very high (trees, buildings), the wind speed is zero at some height above the surface z_o, the roughness length, which is called the zero plane displacement. When this height is subtracted from all measured heights z, the observed wind speeds give a better fit to the logarithmic wind law.

1.1.1.2 The Power Law

Various empirical laws which incorporate the stability have been suggested for the cases where the lapse rate is diabatic (not neutral). One of these is the power law which is applicable in the height range from 10-170m (5):

$$\frac{u}{u_1} = \left(\frac{z}{z_1}\right)^m$$

where u_1 is at some level z_1 within the layer, and m is a parameter independent of height and dependent on the lapse rate, roughness length, and geostrophic wind speed. The parameter m can be determined from the wind at two heights in the layer and varies from 0 to 1, the limiting values. At m=o, $u=u_1$, and there is no shear. At m=1, the wind speed varies linearly with height. The power law usually is applied for strong wind speeds when conditions approach adiabatic. Over smooth open country m is approximately 1/7 with this neutral lapse rate.

When increasing roughness increases m, the result is decreased shear close to the ground because of the increased turbulent mixing in the friction layer. Also, m increases with increasing stability; values are near zero, 0.001 and 0.002 for superadiabatic lapse rates, and 0.85 for very stable air.

1.1.2 The Ekman Layer

Above the friction layer, from about 50m to 100m upward, the horizontal stresses decrease with height up to the lowest level at which the wind becomes geostrophic, about 100m. At this level, there is a near balance between the pressure gradient and Coriolis forces, and the stress is correspondingly small. The layer, the Ekman layer, is about 10 times thicker than the friction layer.

Assumptions are made that in the Ekman layer: 1) there is horizontal mean motion; 2) horizontal mean wind shears are small compared to vertical; 3) there is a balance among Coriolis, pressure gradient and eddy viscosity forces at every level; and 4) there is an eddy exchange coefficient $\mu_e=\rho K$ which is independent of height and has a uniform value characteristic of the free atmosphere. K is approximately $5\times10^4 cm^2 s^{-1}$. The x-axis is oriented parallel to the surface isobars with a positive geostrophic wind u_g (2). The wind speed components are given by the equations:

$$u = u_g(1-e^{-az}\cos az)$$

$$v = u_g e^{-az}\sin az$$

$$\text{where } a = \frac{f}{2K} = \frac{f\rho}{2\mu_e}$$

The ratio of v to u is the tangent of the angle the wind makes with the eastward direction and, therefore, with the isobars. At z=o, and u=v=o the ratio is indeterminate. The ratio of the derivatives of $\frac{\partial u}{\partial z}/\frac{\partial v}{\partial z}$ approaches +1 as z approaches zero, so the wind direction at or close to the surface makes an angle of 45° across the isobars toward lower pressure. At z=o, the speed is zero but increases upward to a certain point, $z=\frac{\pi}{a}$, where the v component vanishes and the wind becomes parallel to the isobars. The wind turns clockwise continuously with height in the northern hemisphere up to about 100m, the geostrophic wind level indicated by observations.

The idealized Ekman spiral plotted in Figure 1A is seldom observed in the real atmosphere. The eddy exchange coefficient can vary considerably with stability and height. With daytime heating, the eddy viscosity becomes large and the wind changes more slowly with height than indicated by the Ekman spiral. At night, or under stable conditions, the geostrophic wind is approached at lower elevations. The wind varies more rapidly with height where viscosity is smaller and less rapidly where it is greater compared to winds indicated by the idealized Ekman spiral. However, these considerations should not prevent the wind from turning counterclockwise with height but may cause it to turn at a different rate.

Horizontal variations in temperature resulting in variations in the pressure gradient and, therefore, wind direction and speed with height are frequent in temperate latitudes in winter. In cold advection which turns the geostrophic wind counterclockwise with height, the clockwise turning because of viscosity may be completely reversed (2).

The equations of horizontal motion have been solved for variable geostrophic wind and exchange coefficient. Figures 1B, C, and D are examples (8).

1.2 Aircraft Accidents Associated with Low-Level Wind Shear

According to a study by ICAO of landing accidents and incidents with data from 26 states for the period 1953-1968, "more than 20% of the run-offs and more than 10% of the undershoot cases were due to wind difficulties. Many of these cases were believed to be related to low-level turbulence and wind shear." (9).

An FAA study (10) of a total 19,332 aircraft accidents or incidents within the terminal area during takeoff, approach and landing filtered out 25 cases of large aircraft ($\geq$12,500 pounds) in which low-level wind shear could have been a factor. Of these, 13 cases were associated with thunderstorms, with rainfall ranging from none to heavy at the time of the accident. Heavy rain showers, but no thunderstorms, were observed in 4 other cases. Of the remaining 8 cases, 5 were associated with fronts (4 warm and 1 cold) and 2 with mountain waves.

Even apparently relatively low values of wind shear can cause landing problems for large aircraft. Table 1A contains the record of 9 missed approaches between 2152Z and 2354Z on January 4, 1971, at John F. Kennedy Airport, New York. A warm front moving up from the south arrived at approximately 2300Z. Observed winds (Table 1B) indicated an average wind shear of $1 ms^{-1}/30m$ (2kt/100ft) in the lowest 300m (1000 ft). The wind shear conceivably could have been greater close to the surface where the wind was 040°/7Kt prior to the warm front passage. During this period a DC-3 crashed at LaGuardia Field where the abrupt change in wind at the frontal surface could have resulted in considerably more wind shear close to the ground. The probable cause of this accident was reported as the

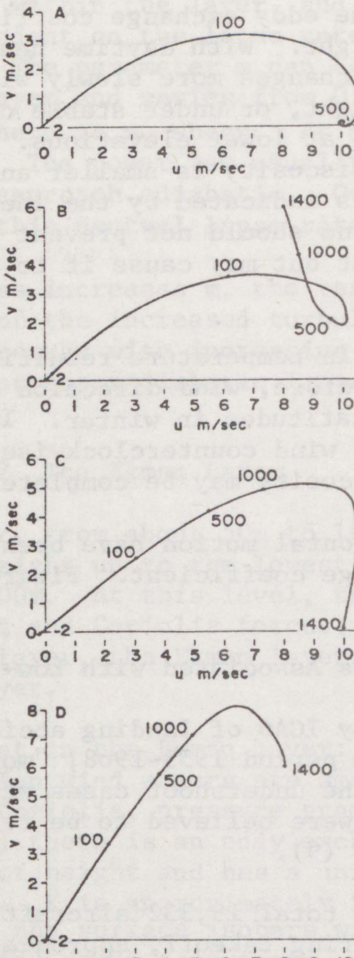

Figure 1.--Variation of the wind with height (indicated on curves in meters) with different idealized conditions. a) Ekman spiral, Eq. (19a, b), explained in text; b) Same as (a) except u_g decreases from 10 m/sec at surface to 6 m/sec at 1400 m; c) Same as (a) except μ varies according to a cubic equation with values 1 kg m^{-1} sec^{-1} at 2 m height, 104.5 kg m^{-1} sec^{-1} at 466 m and zero at 1400 m; d) Variations of wind and exchange coefficients of the previous examples are both present. (After Schaefer (8).

TABLE 1A

DATA FROM TOWER LOG OF A MAJOR AIRPORT (34)

Time (Z)	Aircraft	Comment
2152	Twin Turbo	Missed approach & diverted
2200	Wide-body	Landed
2237	4-Engine Jet	Missed approach
2300	4-Engine Jet	Landed second approach
2302	Wide-body	Missed approach & diverted
2304	4-Engine Jet	Missed approach
2329	Tri-Jet	Missed approach
2333	4-Engine Jet	Missed approach
2341	4-Engine Jet	Landed second approach
2346	Tri-Jet	Landed second approach
2349	Wide-body	Missed approach
2353	4-Engine Jet	Landed second approach
2354	Wide-body	Missed approach
0013		Changed from runway 04R to 22
0020	Wide-body	Landed second approach
0023	Wide-body	Landed second approach

TABLE 1B

WINDS OVER JFK ON JANUARY 4, 1971 (18)

2330Z

Direction/Speed (kts)	Altitude
220/05	Surface
215/26	1000 ft.
220/46	2600 ft.

failure of the pilot to recognize the wind shear conditions and compensate for them.

2. FORECASTING LOW-LEVEL WIND SHEAR

The association of low-level wind shear with recent major aircraft accidents (an average of one per year by U.S. air carriers since 1974) has given impetus to the development of programs to provide information to pilots for landing and takeoff operations. The WMO has distributed a proposed statement of requirements for low-level wind shear and turbulence information (1). This includes the statement that, "...aircraft should be informed of ...available information on the existence of horizontal wind shear or turbulence along the final approach or takeoff flight paths."

Investigations are underway by the Federal Aviation Administration (FAA) to: 1) better characterize low-level wind shear; 2) better define the hazards of wind shear for the aviation community; 3) develop ground-based devices for hazardous wind-shear detection and movement; 4) develop, or modify, existing airborne equipment to detect hazardous wind shear; and 5) improve techniques for recognition of the presence and prediction of low-level wind shear. Final reports of this research will not become available until 1980.

Meanwhile, the National Weather Service, the USAF Air Weather Service, and the airlines all agree that it is essential that as much as possible be done now to alert pilots to the potential for and existence of possibly dangerous low-level wind shear. Tests in manned flight simulators have shown that pilots usually can compensate for this phenomenon and reduce its deleterious effects if they are forewarned of its presence at a terminal. The Air Weather Service already has begun an advisory program as of March 1978 (Appendix C).

2.1 The Forecast Problem

The boundary layer of the atmosphere always exhibits some degree of shear. The WMO (1) has estimated the following worldwide frequencies of a two-minute average vector wind shear for a 30m-thick layer with base at 10m above ground:

3kt ($1.5 ms^{-1}$) - 50%

5kt ($2.6 ms^{-1}$) - 17%

8kt ($4.1 ms^{-1}$) - 2%

10kt ($5.1 ms^{-1}$) - 0.4%

The larger shears may occur also at somewhat higher levels above ground, especially in stable atmospheric conditions.

The WMO has postulated that vertical wind shears $\geq$10kt/30m ($5.1ms^{-1}$/30m) are likely to affect aircraft in Category I operations. For category II and III* operations, the criterion may be lowered to 5kt/30m ($2.6ms^{-1}$/30m). Sowa (personal communication) (11) considers shear, from a pilot's point of view, to be significant when a change in airspeed greater than $8.4ms^{-1}$ occurs within 100m, equivalent to $2.5ms^{-1}$/30m vertical wind shear across frontal discontinuities. An FAA study (11) has adopted this value for significant shear.

Grossman and Beran (12) summarized existing literature and concluded that: 1) extreme wind shear ($\gtrsim 5ms^{-1}$/30m) is associated with stable rather than unstable boundary layer conditions; 2) frequently seems to be caused by changes in wind direction rather than changes in wind speed with height with direction remaining constant; and 3) often is found in the vicinity of frontal zones which carry with them the characteristics of stable conditions in the lowest layers and wind direction shifts noted in 1) and 2).

The 5th Air Navigation Conference (1967) recommended description of vertical wind shear in qualitative terms using the following interim criteria:

Light:	0-4kt/30m	($0-2.1ms^{-1}$/30m)
Moderate:	5-8kt/30m	($2.6-4.1ms^{-1}$/30m)
Strong:	9-12kt/30m	($4.6-6.2ms^{-1}$/30m)
Severe:	>12kt/30m	($>6.2ms^{-1}$/30m)

Unfortunately, wind shear can be neither measured nor forecast directly with sufficient precision to categorize it at most airports. Meteorological conditions associated with significant wind shear can be forecast for varying intervals from initial time with accuracy increasing with decreasing interval. Some related features can be supplied from relatively long-range forecasts of meteorological variables. Others can be diagnosed only from an analysis of existing features. Landing and takeoff aircraft operations require only relatively short-range forecasts of significant wind shear. Some forecast and diagnostic procedures can supply quantitative approximations of wind shears. Others provide only qualitative estimates of wind-shear potential.

2.2 Forecast Considerations

Low-level wind shear is caused by a number of differential motions in the atmosphere. The geostrophic wind which flows parallel to the surface isobars is turned and retarded by frictional forces downward from the top of the boundary layer to the earth's surface. The resultant wind shear

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*Categories define minimum runway visual range (RVR) and decision height is always present to some degree.

Wind shear may be enhanced by synoptic and mesoscale discontinuities or other features which have stable layers under low-level inversions. The stability inhibits mixing and momentum transfer, cutting off the effect of friction from the layer above the inversion. Winds at the top of the inversion then can increase and even become supergeostrophic in response to the stronger winds above.

The various features which can produce significant low-level wind shear are discussed in the following sections.

2.2.1 Strong Winds

Strong surface winds are indicative of wind shear in the boundary layer because of the effect of surface friction. Very close to the ground, the shear depends on the surface roughness. This is illustrated in Figure 2a which plots wind profiles derived from the logarithmic wind law from the assumed zero speed at the zero-plane level up to 9m, the anemometer height. Wind speed profiles are drawn for various values of z_o, the surface roughness length around airports, of: 3cm, low grass; 30cm, scrub oak; 100cm, suburbia; and 200cm, city. Airport buildings, of course, also contribute to the mean roughness length. Shears in this layer increase with increasing roughness length.

Above this layer, wind speed profiles depend on the stability; lapse rates in the layer surface to 100m approach adiabatic in the strong wind regimes. Figure 2b contains wind profiles derived from the power law using 1/7 as the stability parameter for 25, 30 and 35kt winds at 9m anemometer level. Wind shear direction is assumed to be constant in the friction layer up to about 100m. In the theory of the Ekman spiral, the wind turns a maximum or 45° (clockwise) up to the level of the geostrophic wind. Typical turning angles on the order of 20-30° are predicted by theory for a neutral barotropic boundary layer (13).

The vertical wind shears from the theoretically-computed wind profiles for 25, 30 and 35kt surface winds on Figure 2b exceed the proposed WMO criterion for Category II and III aircraft operations of $2.6ms^{-1}/30m$, but not the $5.1ms^{-1}$ for Category I, only in the lowest 30m above 9m. In the turning layer above 9m, assuming a 30° direction change and 45kt geostrophic wind (surface wind speed assumed approximately 70% of geostrophic), vertical wind shear would average only about $.4ms^{-1}/30m$.

With strong winds, mechanical turbulence is induced as a result of the surface roughness and neutral lapse rate, and this is enhanced by buoyancy forces in the daytime boundary layer with unstable lapse rate. The mixing resulting from the turbulence tends to diminish shear close to the ground (decreasing wind speed) with a corresponding increase in shear above. The large fluctuating shears produced by the turbulence have short duration times. An airplane could fly in and out of the shear

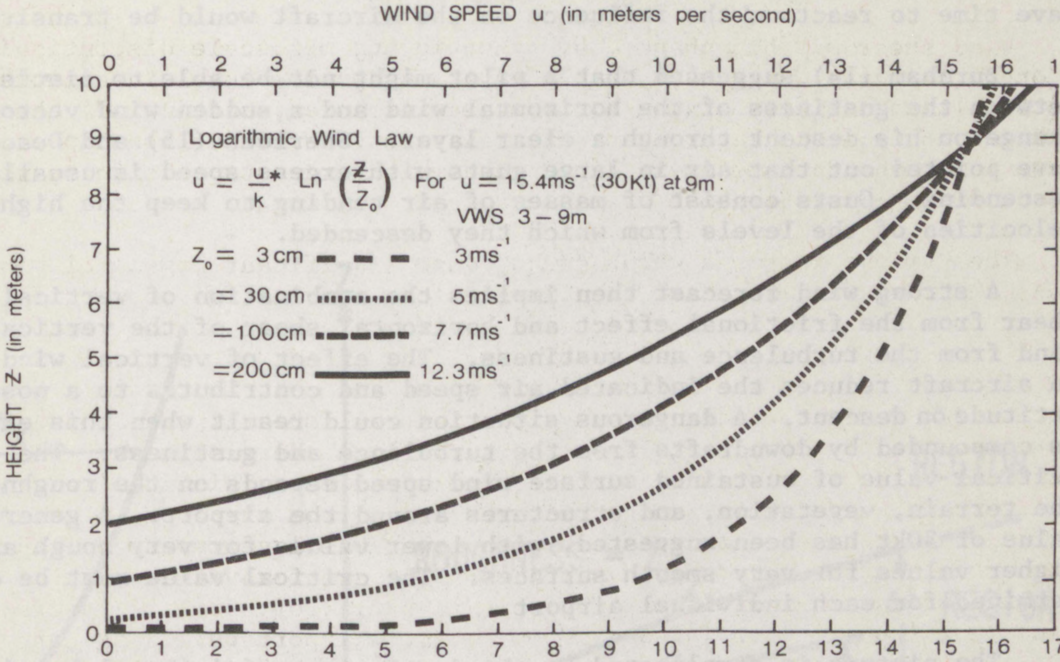


Figure 2a.--Wind profiles using logarithmic wind law.

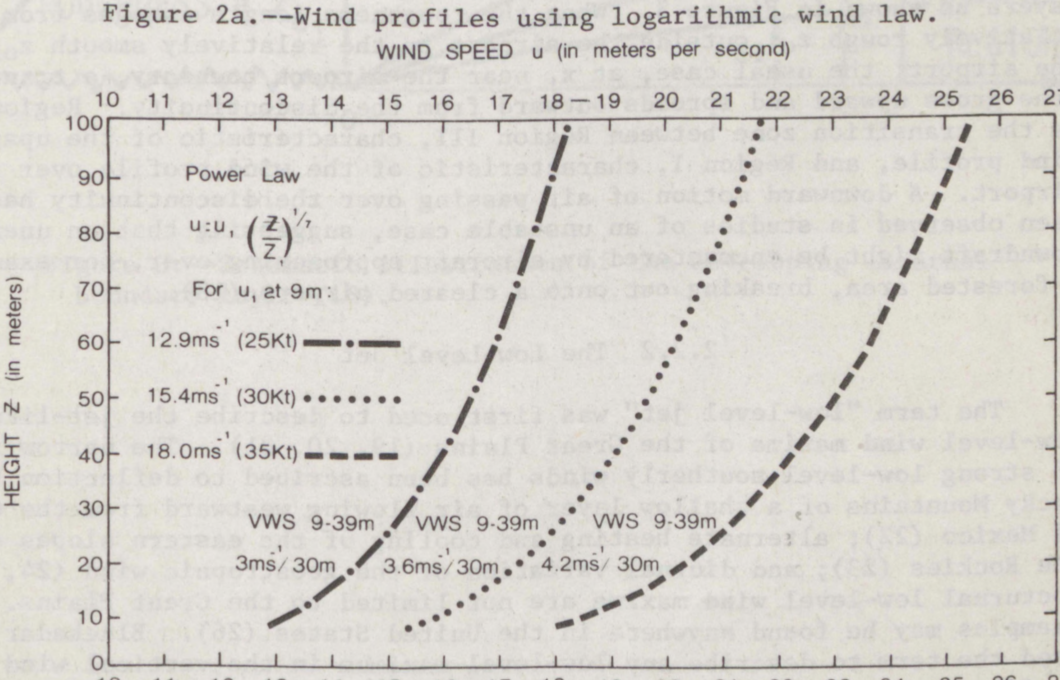


Figure 2b.--Wind profiles derived from the power law.

condition (horizontal shear of the vertical wind) before the pilot would have time to react and the influence on the aircraft would be transitory.

Burnham (14) suggested that a pilot might not be able to distinguish between the gustiness of the horizontal wind and a sudden wind vector change on his descent through a clear layer. Sherlock (15) and Deacon (16) have pointed out that air in large gusts with excess speed is usually descending. Gusts consist of masses of air tending to keep the higher velocities of the levels from which they descended.

A strong wind forecast then implies the combination of vertical wind shear from the frictional effect and horizontal shear of the vertical wind from the turbulence and gustiness. The effect of vertical wind shear on aircraft reduces the indicated air speed and contributes to a nose-down attitude on descent. A dangerous situation could result when this effect is compounded by downdrafts from the turbulence and gustiness. The critical value of sustained surface wind speed depends on the roughness of the terrain, vegetation, and structures around the airport. A general value of 30kt has been suggested, with lower values for very rough and higher values for very smooth surfaces. The critical value must be determined for each individual airport.

The picture is complicated by the development of internal boundary layers as shown in Figure 3. When the roughness length changes from the relatively rough z_{o1} outside the airport to the relatively smooth z_{o2} on the airport, the usual case, at x, near the airport boundary, a transition zone grows upward and spreads outward from the discontinuity. Region II is the transition zone between Region III, characteristic of the upstream wind profile, and Region I, characteristic of the wind profile over the airport. A downward motion of air passing over the discontinuity has been observed in studies of an unstable case, suggesting that an unexpected downdraft might be encountered by aircraft approaching over, for example, a forested area, breaking out onto a cleared airport (18).

2.2.2 The Low-Level Jet

The term "low-level jet" was first used to describe the jet-like low-level wind maxima of the Great Plains (19, 20, 21). The narrow zone of strong low-level southerly winds has been ascribed to deflection by the Rocky Mountains of a shallow layer of air flowing westward from the Gulf of Mexico (22); alternate heating and cooling of the eastern slopes of the Rockies (23); and diurnal variation of the geostrophic wind (24, 25). Nocturnal low-level wind maxima are not limited to the Great Plains. Examples may be found anywhere in the United States (26). Blackadar (27) used the term to describe any low-level maximum in the vertical wind speed profile at any point, a more universal phenomenon. His low-level jet is accentuated by the factors which produce the Great Plains jet, and it is most prevalent in this area.

The jet usually is found below 500m at night under clear skies when a

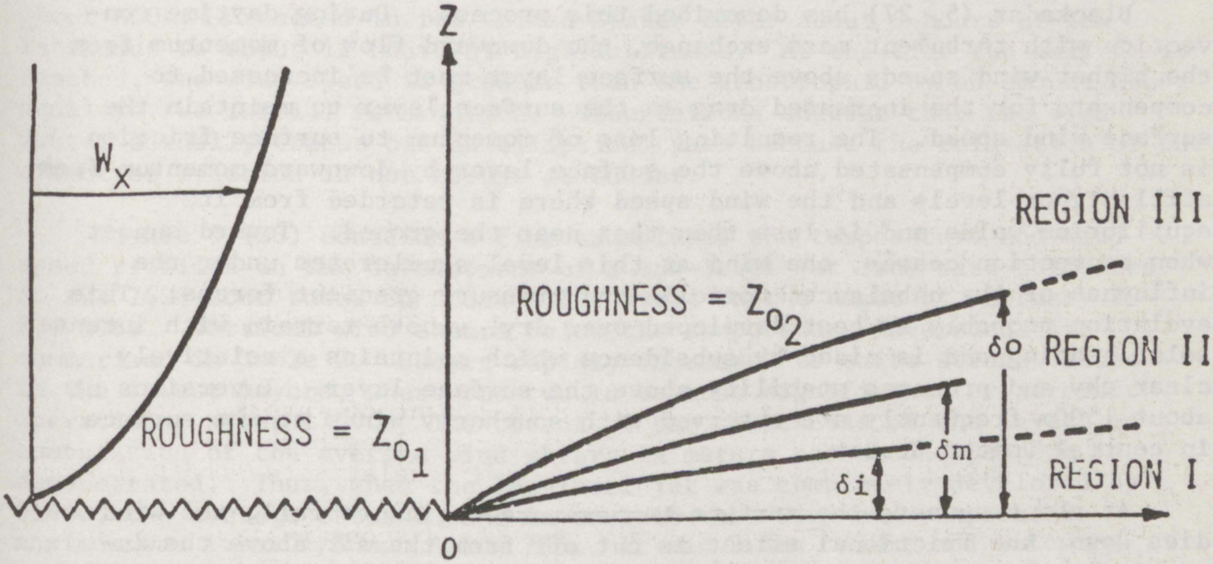


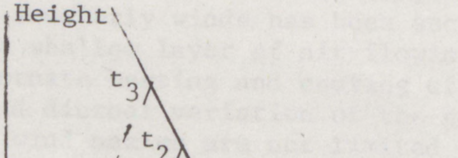
Figure 3.--Schematic illustration of the developing internal boundary layer (18).

strong radiation temperature inversion develops. The stability below the inversion suppresses mixing and momentum transfer from the large-scale flow above the inversion to the ground where the winds become light. With frictional forces cut off effectively from the wind above the inversion, a wind speed maximum develops at the top of the inversion, with significant vertical wind shear developing between the jet and the surface.

2.2.2.1 Evolution of Low-Level Jet

Blackadar (5, 27) has described this process. During daytime convection with turbulent mass exchange, the downward flow of momentum from the higher wind speeds above the surface layer must be increased to compensate for the increased drag on the surface layer to maintain the surface wind speed. The resulting loss of momentum to surface friction is not fully compensated above the surface layer by downward momentum from still higher levels and the wind speed there is retarded from its equilibrium value and is less than that near the ground. Toward sunset when convection ceases, the wind at this level accelerates under the influence of the unbalanced Coriolis and pressure granient forces. This evolution probably is best developed over dry, smooth terrain with intense solar heating and is aided by subsidence which maintains a relatively clear sky and promotes stability above the surface layer. Inversions at about 1500m frequently are observed with southerly winds at the surface in central United States.

At about sunset, the surface temperature begins to fall, the wind dies down, the frictional effect is cut off from the air above the inversion, and shear develops below. Some turbulence continues because of the wind shear, and heat is transferred downward to the ground where it is lost by radiation. The noncompensated heat loss near the top of the inversion results in continued upward growth, as in the following diagram:



As the inversion grows upward during the night, the wind above the inversion in the layer where it was retarded during the daytime continues to increase to supergeostrophic speeds. Figure 4 illustrates this evolution. $\vec{W}_o$ is the deviation from the geostrophic wind $\vec{V}_{gs}$ of the initial wind $\vec{V}_o$ above the inversion at about sunset. $\vec{W}_o$ rotates to the right without change in magnitude at an angular speed of f (the Corolis parameter) radians per second. The circle marks the locus of positions of the wind vector as a function of time. If the initial wind direction is close to the geostrophic at initial time, the maximum wind speed, generally at about 600m, is reached in the United States after about 8 hours at low latitudes to about 12 hours at high latitudes. At the time the maximum is reached, the wind speed is greater than the geostrophic by an amount about equal to the initial retardation. Observations suggest that the wind vector actually traces out an elliptical path because the relaxation of the effect of friction is not abrupt at sunset.

Figure 5 (28) contains a fine example of the temperature and wind speed profiles in the development of a low-level jet from data collected at the 1428-foot tower in Cedar Hill, Tex., on the night of February 22-23, 1961. Vertical wind shears below the temperature inversions are summarized in Table 2. Shears rapidly increased to quite strong values in the lowest layers, where they would be most significant for aircraft operations, after 1700C. The effect of the thickness of the layers on computation of the average wind shears in meters per second per 30m is demonstrated. Thus, when the low-level jet was completely developed by 0140C, the average shear in the layer below the wind and temperature maximum was $1.9ms^{-1}/30m$. Below 135m, it was $3.4ms^{-1}/30m$; and below 45m, $4.8ms^{-1}/30m$. These were much more indicative of the dangerous character of this low-level jet.

Izumi (29) described the breakdown of the low-level jet using data from the same tower, as follows:

1) Warming at upper levels before sunrise, probably because of subsidence.

2) Continued but more rapid warming after sunrise.

3) Marked cooling after sunrise at the intermediate levels below the layer of warming and above the layer of surface heating.

4) Lifting of the large elevated temperature inversion with marked cooling in the inversion layer and steady warming beneath the inversion.

Turbulent mixing, which intensifies at or soon after sunrise, is responsible for the breakdown of the nocturnal temperature inversion and rapid dissipation of the low-level jet. The mixing process begins in the surface layer and proceeds upward destabilizing each successive layer.

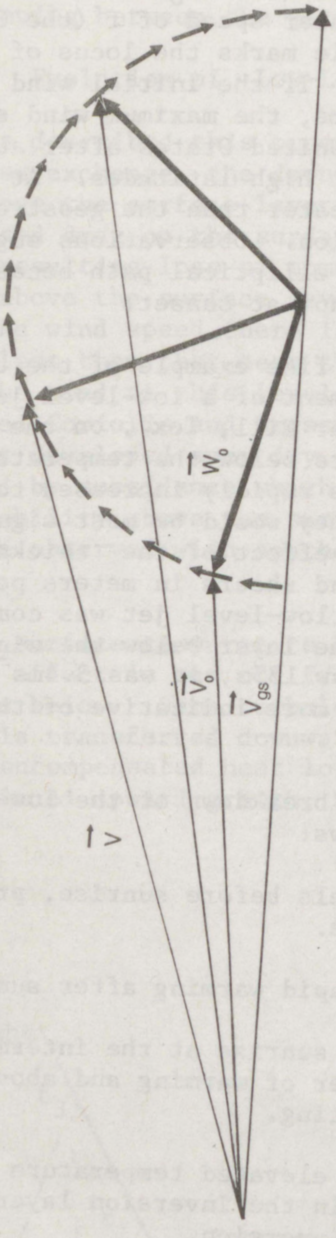


Figure 4.--Development of supergeostrophic winds in the low-level jet (5).

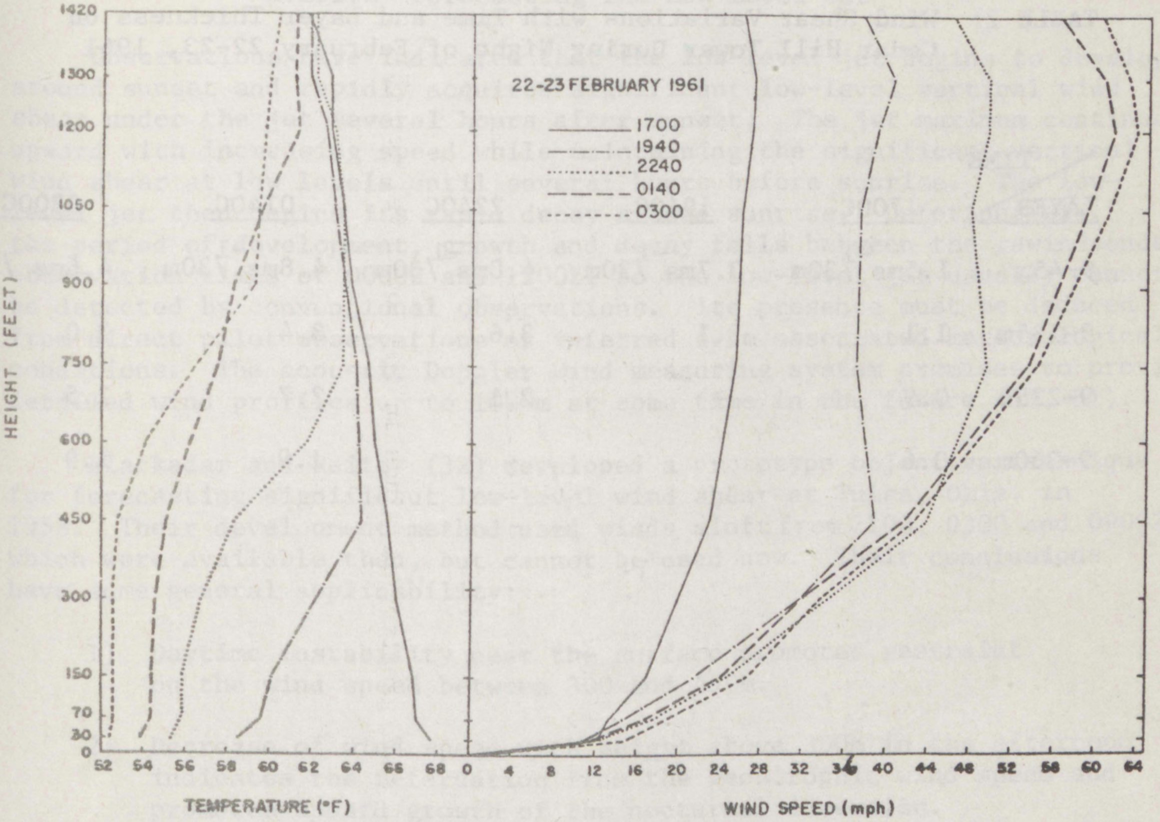


Figure 5.--Time variation of temperature and wind speed profiles measured on the Cedar Hill tower during the night of 22-23 February 1971 (28).

TABLE 2: Wind Shear Variations with Time and Layer Thickness on Cedar Hill Tower During Night of February 22-23, 1961

LAYER \ TIME	1700C	1940C	2240C	0140C	0300C
9-45m	1.5ms^{-1}/30m	3.7ms^{-1}/30m	4.8ms^{-1}/30m	4.8ms^{-1}/30m	4.6ms^{-1}/30m
9-135m	1.1	3.1	3.6	3.4	3.0
9-225m	0.9	-	2.1	2.7	2.5
9-360m	0.6	-	-	1.9	1.9

The temperature and wind velocity profiles evolve from the nocturnal inversion and marked velocity maximum to the daytime lapse rate with nearly uniform velocity.

2.2.2.2 Forecasting the Low-Level Jet

Observations have indicated that the low-level jet begins to develop around sunset and rapidly acquires significant low-level vertical wind shear under the jet several hours after sunset. The jet maximum continues upward with increasing speed while maintaining the significant vertical wind shear at low levels until several hours before sunrise. The low-level jet then begins its rapid decay around sunrise. Unfortunately, the period of development, growth and decay falls between the rawindsonde observation times of 0000Z and 1200Z, so the low-level jet usually cannot be detected by conventional observations. Its presence must be deduced from direct pilot observations or inferred from associated meteorological conditions. The acoustic Doppler wind measuring system promises to provide detailed wind profiles up to 1000m at some time in the future (30, 31).

Blackadar and Reiter (32) developed a prototype objective technique for forecasting significant low-level wind shear at Tulsa, Okla. in 1958. Their development method used winds aloft from 2100, 0300 and 0900Z which were available then, but cannot be used now. Their conclusions have some general applicability:

1) Daytime instability near the surface promotes restraint on the wind speed between 300 and 450m.

2) Decrease of wind speed with height above 300m in the afternoon indicates the retardation from the geostrophic wind speed and promotes upward growth of the nocturnal inversion.

3) Most cases of large wind shear occurred when the wind direction was from the south or south-southwest. This was one of their predictors. (Wind from 120° to 279°).

4) A reasonably strong pressure gradient and, therefore, relatively strong geostrophic wind is required.

5) Cloud cover must not interfere with the normal cycle of daytime heating and nocturnal cooling.

A wind shear of $1.25 ms^{-1}/30m$, determined by taking the difference between the surface and 500m winds at 0300Z and 0900Z and using the larger value, was selected as the critical value separating significant from non-significant shear. This value, though not a hazard in itself, because it was an average in a nearly 300m thick layer, was presumed to be indicative of the presence of a situation where dangerous wind shear could occur.

Because of restrictions imposed by data availability at the present time, the development of the low-level jet may be deduced using the following considerations:

1) There should be little cloud cover, with daytime heating producing an unstable lapse rate near the ground during the afternoon. An inversion near 850mb is desirable to cap the low-level instability. These conditions can be determined from the 1200Z and 0000Z RAOB's and the maximum temperature during the afternoon.

2) Surface winds should be from the southerly sector with near geostrophic speed as determined from isobaric spacing on afternoon surface maps $\geq 10ms^{-1}$. The pressure gradient should not relax below the spacing sufficient to produce the maximum $10ms^{-1}$ wind speed during the night.

3) Wind speed should decrease with height above the low-level inversion in the lowest 900m thick layer around sunset. This may be evident from the 0000Z upper winds.

4) 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 from the pressure gradient on the 2100Z or 0000Z surface analysis chart can be determined from Table 3.

   If the value obtained from Table 3 exceeds $15ms^{-1}$, then significant wind shear could occur. Next assume that a minimum vector difference of $15ms^{-1}$ in the layer from the surface wind observation level of 9m to the low-level jet's presumed height of 360m (1200 ft) is necessary to produce an average vertical wind shear loss of $1.28ms^{-1}/30m$, $15ms^{-1}/351m = 15x\frac{30}{351} = 15x.085$ $= 1.28ms^{-1}/30m$ (or say, $1.3ms^{-1}/30m$). This average shear in the layer 351m thick suggests that the shear will be at least twice as much in the lowest 90m. (Compare the observed profile in Figure 5.) The minimum value of $2.6ms^{-1}/30m$ in this lower layer would meet the proposed WMO criterion for hazard in Category II and III aircraft operations.

The low-level wind shear which is always present to a degree below these nocturnal jet-like wind speed profiles is at best a nuisance in tending to cause aircraft to land short on the runway. Occurrences of abnormally large shears are hazardous because of the rapid loss of lift suffered while letting down into layers of decreasing wind component.

Table 3.--Wind shear computation table given the wind speed W_1 at one level, wind speed W_2 at the other level, and the angular difference between the two wind vectors.

WIND SHEAR (ms^{-1})

W_1	W_2	0°	30°	60°	90°	120°	150°	180°
2.5	2.5	0.0	1.3	2.5	3.5	4.3	4.8	5.0
	5	2.5	3.1	4.3	5.6	6.6	7.3	7.5
	7.5	5.0	5.5	6.6	7.9	9.0	9.7	10.0
	10	7.5	7.9	9.0	10.3	11.5	12.2	12.5
	12.5	10.0	10.4	11.5	12.7	13.9	14.7	15.0
	15	12.5	12.9	13.9	15.2	16.4	17.2	17.5
	17.5	15.0	15.4	16.4	17.7	18.9	19.7	20.0
	20	17.5	17.9	18.9	20.2	21.4	22.2	22.5
	22.5	20.0	20.4	21.4	22.6	23.8	24.7	25.0
	25	22.5	22.9	23.8	25.1	26.3	27.2	27.5
5	5	0.0	2.6	5.0	7.1	8.7	9.7	10.0
	7.5	2.5	4.0	6.6	9.0	10.9	12.1	12.5
	10	5.0	6.2	8.7	11.2	13.2	14.5	15.0
	12.5	7.5	8.5	10.9	13.5	15.6	17.0	17.5
	15	10.0	11.0	13.2	15.8	18.0	19.5	20.0
	17.5	12.5	13.4	15.6	18.2	20.5	22.0	22.5
	20	15.0	15.9	18.0	20.6	22.9	24.5	25.0
	22.5	17.5	18.3	20.5	23.0	25.4	26.9	27.5
	25	20.0	20.8	22.9	25.5	27.8	29.4	30.0
7.5	7.5	0.0	3.9	7.5	10.6	13.0	14.5	15.0
	10	2.5	5.1	9.0	12.5	15.2	16.9	17.5
	12.5	5.0	7.1	10.9	14.6	17.5	19.4	20.0
	15	7.5	9.3	13.0	16.8	19.8	21.8	22.5
	17.5	10.0	11.6	15.2	19.0	22.2	24.3	25.0
	20	12.5	14.0	17.5	21.4	24.6	26.8	27.5
	22.5	15.0	16.4	19.8	23.7	27.0	29.2	30.0
	25	17.5	18.9	22.2	26.1	29.5	31.7	32.5
10	10	0.0	5.2	10.0	14.1	17.3	19.3	20.0
	12.5	2.5	6.3	11.5	16.0	19.5	21.7	22.5
	15	5.0	8.1	13.2	18.0	21.8	24.2	25.0
	17.5	7.5	10.2	15.2	20.2	24.1	26.6	27.5
	20	10.0	12.4	17.3	22.4	26.5	29.1	30.0
	22.5	12.5	14.7	19.5	24.6	28.8	31.6	32.5
	25	15.0	17.1	21.8	26.9	31.2	34.0	35.0
12.5	12.5	0.0	6.5	12.5	17.7	21.7	24.1	25.0
	15	2.5	7.5	13.9	19.5	23.8	26.6	27.5
	17.5	5.0	9.1	15.6	21.5	26.1	29.0	30.0
	20	7.5	11.1	17.4	23.6	28.4	31.5	32.5
	22.5	10.0	13.2	19.5	25.7	30.7	33.9	35.0
	25	12.5	15.5	21.7	28.0	33.1	36.4	37.5
15	15	0.0	7.8	15.0	21.2	26.0	29.0	30.0
	17.5	2.5	8.8	16.4	23.0	28.2	31.4	32.5
	20	5.0	10.3	18.0	25.0	30.4	33.8	35.0
	22.5	7.5	12.1	19.8	27.0	32.7	36.3	37.5
	25	10.0	14.2	21.8	29.2	35.0	38.7	40.0
17.5	17.5	0.0	9.1	17.5	24.7	30.3	33.8	35.0
	20	2.5	10.0	18.9	26.6	32.5	36.2	37.5
	22.5	5.0	11.4	20.5	28.5	34.7	38.7	40.0
	25	7.5	13.2	22.2	30.5	37.0	41.1	42.5
20	20	0.0	10.4	20.0	28.3	34.6	38.6	40.0
	22.5	2.5	11.3	21.4	30.1	36.8	41.1	42.5
	25	5.0	12.6	22.9	32.0	39.1	43.5	45.0
22.5	22.5	0.0	11.6	22.5	31.8	39.0	43.5	45.0
	25	2.5	12.5	23.8	33.6	41.2	45.8	47.5
25	25	0.0	12.9	25.0	35.4	43.3	48.3	50.0

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The most important considerations are that shear increase very rapidly in the low-level jet development cycle and that they are most dangerous during the early stages when the jet is at relatively low levels above the ground.

2.2.3 Frontal Wind Shear

The differing wind regimes in the air masses separated by synoptic scale fronts produce horizontal and vertical wind shears through the interface. Only the relatively strong fronts with sharp transition zones in which the wind change is abrupt have wind shears large enough to affect aircraft operations. The denser air behind a cold front is retarded by friction near the ground and so presents a steep profile with slopes ranging from 1/50 to 1/100 or even steeper. Warmer, less dense air rides up over the cold air and warm front slopes range from 1/100 to 1/300 and probably even shallower (Figure 6) (11).

Because of the differing slopes and directions of cold and warm fronts, the wind shear across the interface is experienced behind the cold front and ahead of the warm front. Figure 7 (11) illustrates a hypothetical case. Surface winds at Airport A, behind the cold front, are northwest $7.5ms^{-1}$ and at Airport B, ahead of the warm front, are southwest $2.5ms^{-1}$. The surface winds in the warm sector are indicative of the winds above both cold and warm fronts, southwest $10ms^{-1}$. Table 3 may be used to compute the frontal wind shears. At Airport A W_1 is NW, $7.5ms^{-1}$, with W_2 above the front SW, $10ms^{-1}$. These values and the direction change of 90° give a vector wind shear magnitude of $12.5ms^{-1}$. Similarly above Airport B the vector wind shear through the transition zone is $10.3ms^{-1}$.

2.2.3.1 Cold Front Wind Shear

Some degree of wind shear accompanies the passage of all cold fronts. An estimate of the intensity of the shear is necessary to determine its significance for airport operations. Sowa (33) proposed a technique simple enough to be applied by pilots. His criteria were:

1) a temperature difference immediately across the front (at the surface) of 10°F (5.6°C) or more per 50 n.mi; and/or,

2) the front is moving 30 knots ($15ms^{-1}$) or more.

Both criteria are indicative of the intensity of the cold front. The speed of motion can be used to estimate the shear through the transition zone. A speed of 30 knots requires that the component of the wind normal to the front on the cold side be at least 30 knots, but probably more because of the effect of friction. If the front is moving toward the east and the winds are northwest in the cold air and light southwesterly in the warm air, the vector wind shear through the transition zone must be at least $15ms^{-1}$ (from Table 3). An aircraft landing toward the northwest

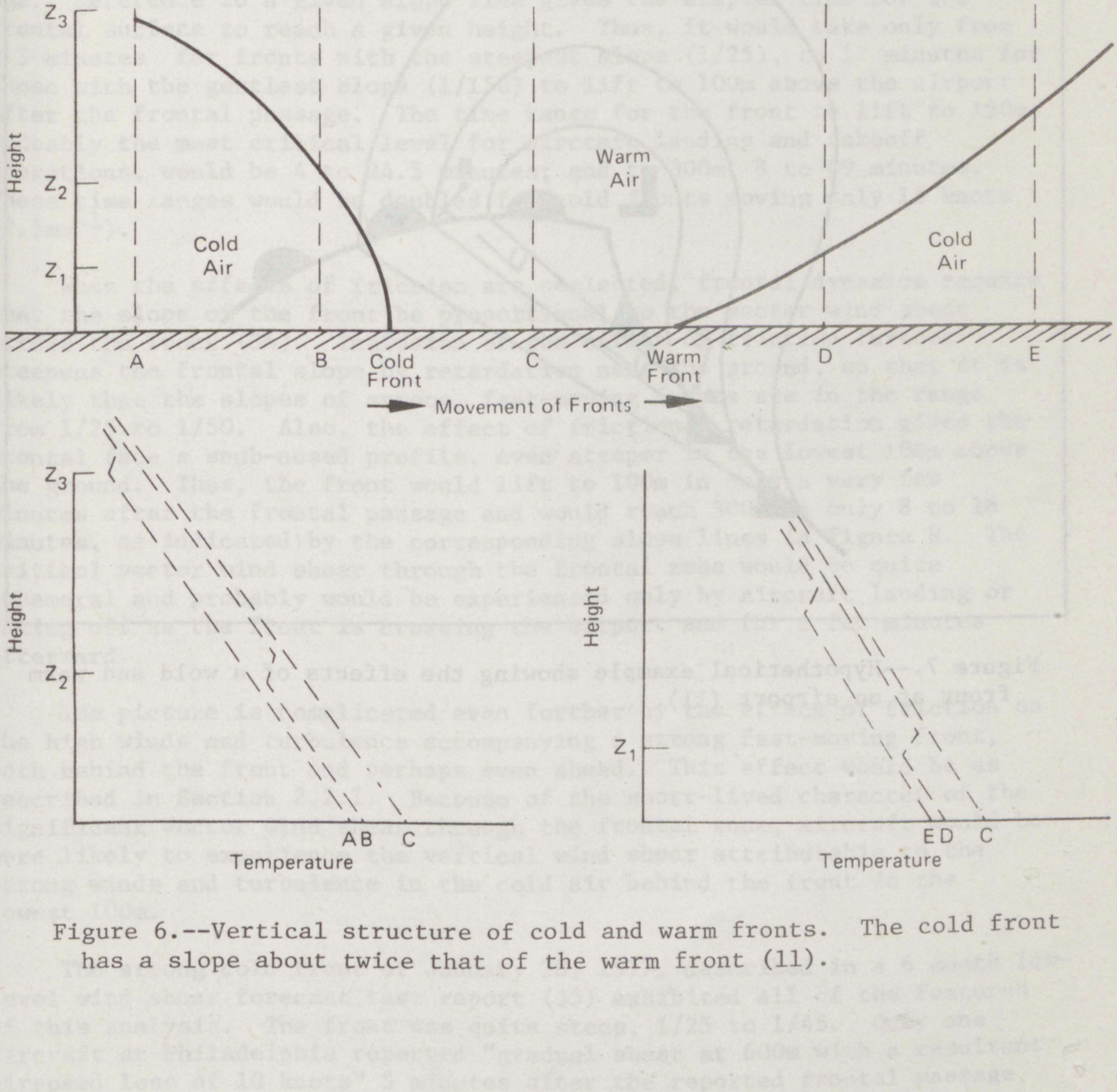


Figure 6.--Vertical structure of cold and warm fronts. The cold front has a slope about twice that of the warm front (11).

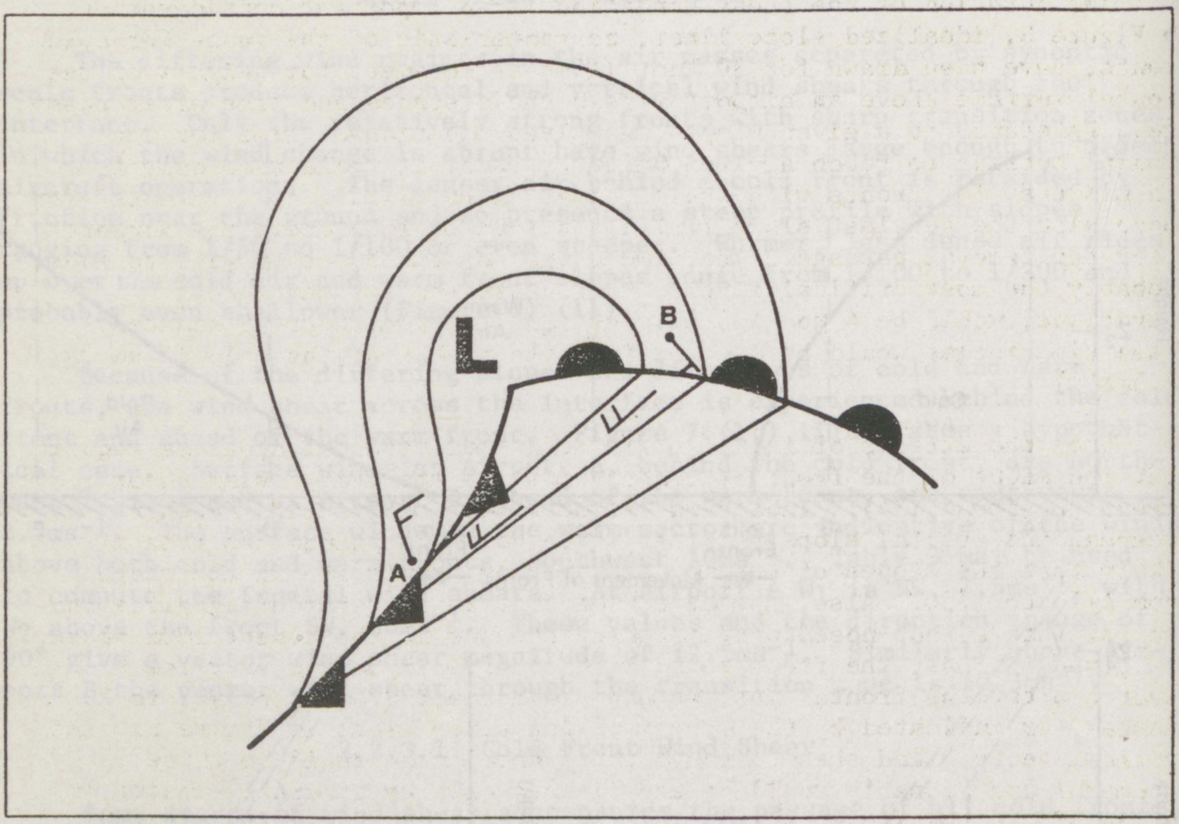


Figure 7.--Hypothetical example showing the effects of a wold and warm front at an airport (11).

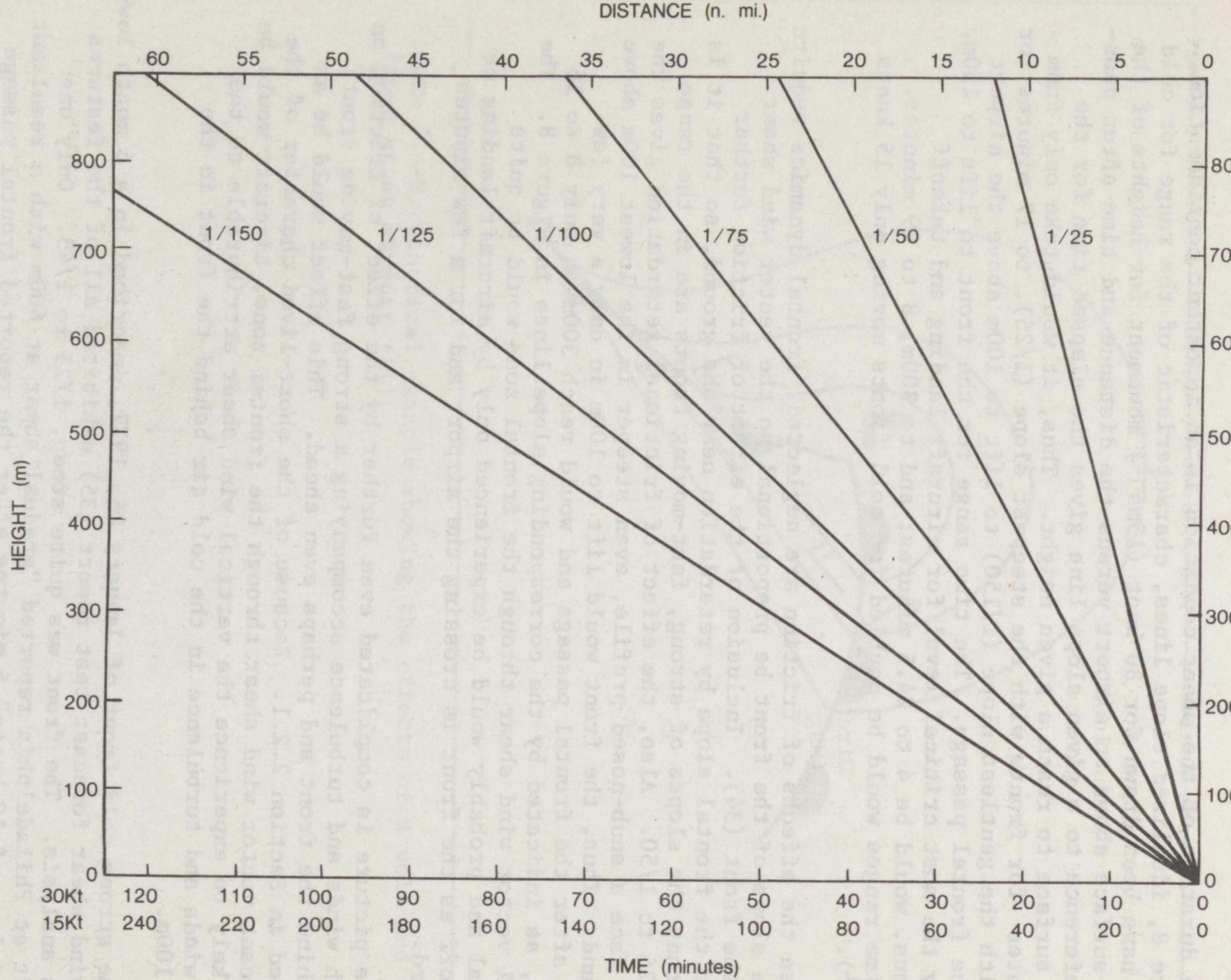
with a crosswind and no headwind suddenly will encounter a 30 knot or more headwind after passing through the frontal zone with consequent increase in airspeed by that amount. Recent test cases indicate that post-frontal wind speed shear may be as important as vector wind shear through the frontal zone.

The duration of the shear condition is an important consideration. In Figure 8, idealized slope lines, characteristic of the range for cold fronts, have been drawn for 30 knot ($15ms^{-1}$) movement for heights of the frontal surface above an airport versus the distance and time after passage. Reference to a given slope line gives the elapsed time for the frontal surface to reach a given height. Thus, it would take only from 2.5 minutes for fronts with the steepest slope (1/25), to 17 minutes for those with the gentlest slope (1/150) to lift to 100m above the airport after the frontal passage. The time range for the front to lift to 150m, probably the most critical level for aircraft landing and takeoff operations, would be 4 to 24.5 minutes; and to 300m, 8 to 49 minutes. These time ranges would be doubled for cold fronts moving only 15 knots ($7.5ms^{-1}$).

When the effects of friction are neglected, frontal dynamics require that the slope of the front be proportional to the vector wind shear across the front (34). Inclusion of the effect of friction further steepens the frontal slope by retardation near the ground, so that it is likely that the slopes of strong, fast-moving fronts are in the range from 1/25 to 1/50. Also, the effect of frictional retardation gives the frontal face a snub-nosed profile, even steeper in the lowest 100m above the ground. Thus, the front would lift to 100m in only a very few minutes after the frontal passage and would reach 300m in only 8 to 16 minutes, as indicated by the corresponding slope lines in Figure 8. The critical vector wind shear through the frontal zone would be quite ephemeral and probably would be experienced only by aircraft landing or taking off as the front is crossing the airport and for a few minutes afterward.

The picture is complicated even further by the effect of friction on the high winds and turbulence accompanying a strong fast-moving front, both behind the front and perhaps even ahead. This effect would be as described in Section 2.2.1. Because of the short-lived character of the significant vector wind shear through the frontal zone, aircraft would be more likely to experience the vertical wind shear attributable to the strong winds and turbulence in the cold air behind the front in the lowest 100m.

The strong cold front of January 28, 1977, described in a 6 month low-level wind shear forecast test report (35) exhibited all of the features of this analysis. The front was quite steep, 1/25 to 1/45. Only one aircraft at Philadelphia reported "gradual shear at 600m with a resultant airspeed loss of 10 knots" 5 minutes after the reported frontal passage at the surface.



15kt (7.5ms^{-1})

Figure 8.--Height of cold front moving 30kt (15ms^{-1}) vs distance/time from airport for various slopes.

From Figure 8, a front with a uniform 1/25 slope and moving at 30 knots would reach 600m in 16 minutes, but probably sooner with the even steeper slope probable at lower levels. Other pilot reports indicated only the low-level shear which could be attributed to the strong surface winds in the cold air behind the front.

2.2.3.1.1 Aircraft Accident Attributed to Cold Front Vector Wind Shear

An Iberia Lineas Aereas de Espana DC-10-30 crashed while making an ILS approach at Logan International Airport, Boston, Massachusetts, at about 1543 EST on December 17, 1973 (36). The aircraft struck approach light piers about 500 feet short of the threshold of the runway, then an embankment shearing its main landing gear, and skidded to a stop about 3000 feet beyond the threshold.

Winds derived from the flight recorder data and other considerations were as follows:

Altitude (Feet)	Direction (Magnetic)	Speed (Knots)	Speed (ms^{-1})
1000	191°	35	18
900	192°	34	18
800	191°	34	18
700	191°	33	17
600	192°	32	16
500	194°	29	15
400	199°	21	11
300	211°	13.5	6
200	278°	5	3
100	310°	6	3
Surface	308°	5	3

These were resolved into longitudinal and lateral components for the runway configuration and approach heading as follows:

Altitude (Feet)	Longitudinal Knots (ms^{-1})	Lateral Knots (ms^{-1})
1000	23.0 (11.8) tailwind	26.0 (13.3) left crosswind
900	22.6 (11.7) tailwind	25.7 (13.2) left crosswind
800	22.10 (11.4) tailwind	25.4 (13.1) left crosswind
700	21.7 (11.1) tailwind	25.1 (13.0) left crosswind

Altitude (Feet)	Longitudinal Knots ($m s^{-1}$)	Lateral Knots ($m s^{-1}$)
600	20.4 (10.6) tailwind	24.3 (12.5) left crosswind
500	18.0 (9.3) tailwind	23.0 (11.8) left crosswind
400	11.8 (6.1) tailwind	17.3 (8.9) left crosswind
300	5.8 (3.1) tailwind	12.1 (6.2) left crosswind
200	3.3 (1.7) headwind	4.1 (2.1) left crosswind
100	6.0 (3.1) headwind	2.0 (1.0) left crosswind
Surface	4.0 (2.1) headwind	2.0 (1.0) left crosswind

The shear zone between 300 and 200 feet (a difference of 30m) had a vertical vector wind shear of at least $5.5ms^{-1}/30m$ (interpolating from Table 3). The indicated airspeed loss from the longitudinal components between 300 and 200 feet was $4.55ms^{-1}$ (9.1 knots).

The flight recorder data indicated the effects of the wind shear on the aircraft. During the initial portion of the approach, the higher-than-normal rate of descent, the lower-than-normal pitch, and the thrust setting were consistent with the fairly constant tailwind. After passing 500 feet, a rapid increase in indicated airspeed and deviation to the left occurred; the aircraft pitched down and thrust was reduced to compensate. As it passed through 260 feet, the aircraft returned to glide slope and pitched up slightly with airspeed remaining constant because the deceleration approximated the change from the tailwind component. At 184 feet, the aircraft had a low-pitch attitude, a low-thrust condition, and was slightly to the left of the runway.

The Safety Board believed that the wind-shear conditions alone were not sufficient to cause an unmanageable problem. The need to change from automatic to manual flight control because the ILS was unuseable below 200 feet, the low ceiling and poor visibility in rain and fog, and the low wheel clearance of the aircraft were contributing factors in this accident.

2.2.3.1.2 Wind Shear Forecast Considerations

The two criteria proposed by Sowa as indicators of significant wind shear may not be sufficient in themselves. The 5.6°C (10°F) difference in tempreature across the front does provide a measure of the intensity of the front. A more useful designation would be in terms of temperature gradient; i.e., 5.6°C/90km (10°F/50 n mi). The cold front speed of 30 knots does indicate significant wind shear, but the probably rapid lifting of such a strong frontal zone over the airport after surface frontal passage suggests that the effect on aircraft landing and takeoff operations below 150 to 300m would be quite transitory.

Some more quantitative critical consideration is necessary. The various proposed rules by Sowa (33), the FAA, and the Air Weather Service rules of thumb (Appendix C) all suggest a vector wind difference of $10ms^{-1}$ for a short quasi-horizontal distance through the frontal interface is critical. This shear should result in an indicated airspeed change of $10ms^{-1}$ (20 knots) for an aircraft flying in the direction in which the shear is measured; i.e., the component of the shear vector parallel to the aircraft flight path.

Cold fronts moving at a speed less than 30 knots are more likely progenitors of significant wind shear which could affect aircraft operations during and after the frontal passage. A quantitative estimate of the shear value is possible from the following considerations:

1) The speed of the cold front may be determined from successive positions on surface analyses. Successive times of frontal passage at stations reported in hourly and special observations provide a more precise estimate.

2) The geostrophic wind measured in the warm sector is a good estimate of the wind speed and direction immediately above the frontal transition zone.

3) The geostrophic wind measured in the cold air behind the front provides a better estimate of the wind speed and direction below the frontal zone than the surface wind which is reduced by the effect of ground friction.

4) The vector wind shear in meters per second is the vector difference between the geostrophic winds measured in both sectors as read from Table 3. The vector wind shear may be resolved into components along and normal to the most probable runway to assess the effect on aircraft.

5) The slope of the cold front is determined from the surface position at a particular time as indicated by the surface analysis, or from hourly and special observations; and the height of the front at the same time at a given distance behind the surface position, as indicated by RAOB's, pilot reports, or the tops of stratiform clouds. Both height and distance should be in the same units.

6) The time required for the layer between the surface and 150m, 200m, or 300m below the frontal zone to pass the airport can be determined from Figure 8 which contains slope lines for elapsed times and heights plotted for about 30-knot frontal speed.

The time for the required layer to pass at that speed can be read from the appropriate slope line. Then for any other frontal speed:

$$\text{Time (Akt)} = \text{Time (30kt)} \times \frac{30\text{kt}}{\text{Akt}}$$

where A is the speed of the front. For instance, the layer from surface to 150m, the most critical for landing and takeoff operations, with a front moving at 20 knots and slope 1/100 would pass an airport in:

$$\text{Time (20kt)} = 16.5 \text{ minutes} \times \frac{30}{20} = 24.75 \text{ minutes.}$$

Considering that the slope probably is steeper in the lower layer, the actual time of passage could be somewhat less than this maximum time.

2.2.3.2 Warm Fronts

Warm fronts can contain more hazardous shear conditions than cold fronts. They move more slowly, even becoming stationary without loss of intensity, so the shear conditions preceding the front can continue for an appreciable time before ending with the passage of the front. Their slopes are half or less those of cold fronts, ranging from 1/100 to 1/300 or even shallower, so the shear condition can remain in the critical lower 150 to 200m layer for much longer periods of time.

2.2.3.2.1 Forecast Considerations

The temperature difference immediately across the front is a measure of the intensity of the warm front--the greater the difference, the sharper the transition zone. The 5.6°C (10°F) criterion is given as the critical value, although, as with cold fronts, this may be a necessary but not sufficient condition.

Slope, speed of movement, and, therefore, duration time of the most important surface to 150-200m layer above the airport can be determined using Figure 9 in the same manner as described for cold fronts. Surface winds in the cold air ahead of the surface position of the warm front may be taken as characteristic of the winds just under the frontal zone above the airport. The geostrophic wind measured from the pressure gradient in the warm air behind the front is representative of the wind above the frontal zone. Using directions and speeds of these two winds, an estimated vector wind shear may be read off from Table 3. As with cold fronts, the critical value for a significant vector differnece is $\geq 10\text{ms}^{-1}$ through the interface. The effect of the estimated shear on aircraft may be determined by resolving the wind shear vector into components parallel and normal to the most probable runway. The criterion here is a change of 10ms^{-1} (20kt) or more in indicated airspeed of the aircraft.

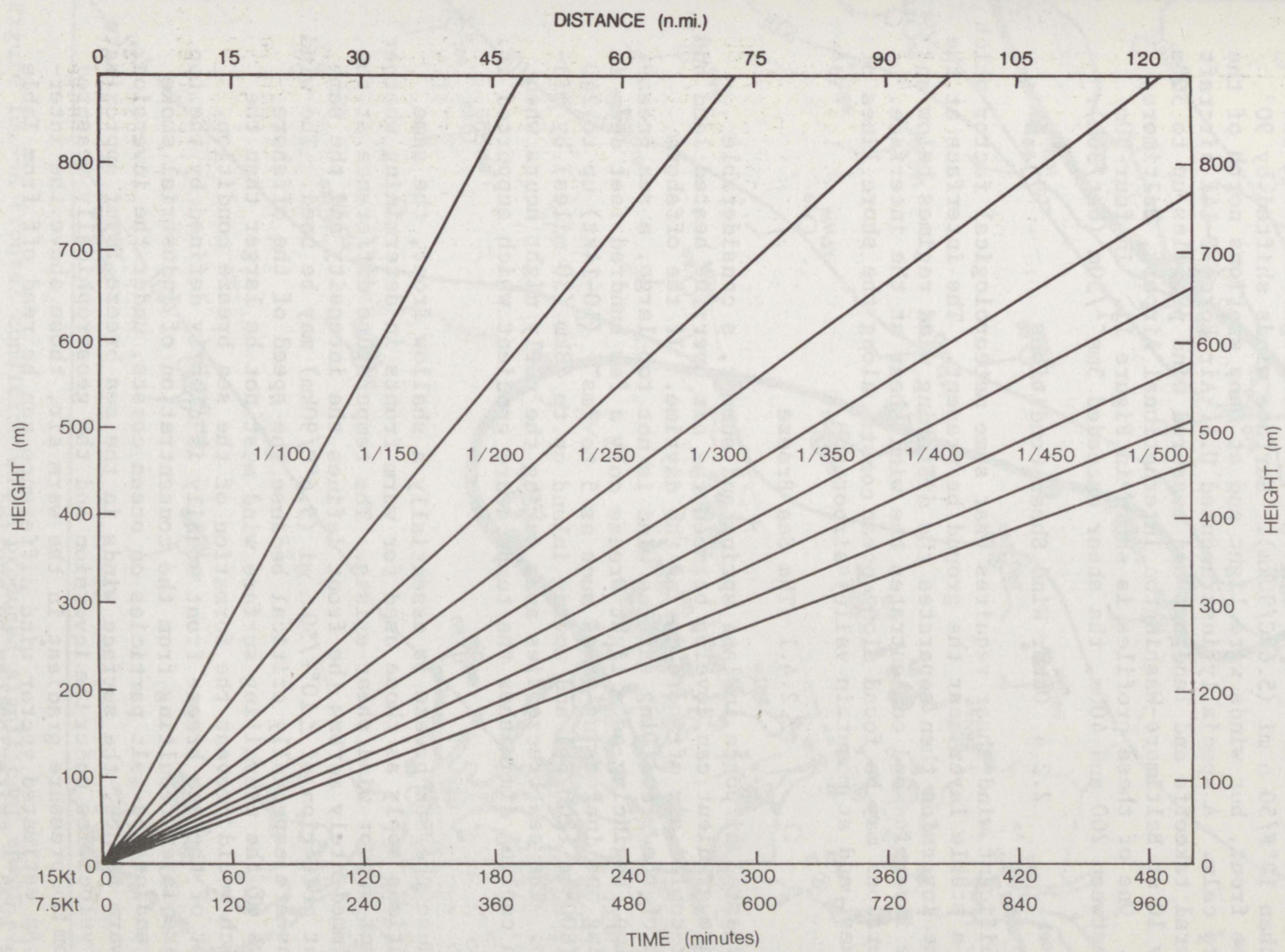


Figure 9.--Height of warm front moving 15kt/7.5kt ($7.5ms^{-1}/3.75ms^{-1}$) versus distance/time from airport for various slopes.

An example of the kind of wind shear that can occur with an apparently innocuous stationary front is contained in Figures 10 and 11 (11). The stationary front in the analysis shown in Figure 10 met the temperature criterion for fronts: the temperature gradient through the front was greater than 10°F/50 n mi (5.6°C/90km). Surface winds shifted by 90° across the front, but winds were light and at many stations north of the front were calm. A specially instrumented U.S. Air Force C-141 aircraft made several takeoffs and landings and measured wind profiles up to 500m on Runway 10 at Baltimore-Washington International Airport, Baltimore, Maryland. One of these profiles is shown in Figure 11. In four 30m layers, between 200 and 400m, the shear exceeded $3ms^{-1}/30m$ (6kt/30m).

2.2.4 Other Wind Shear Conditions

Significant wind shear requires that some meteorological factor which produces a stable layer near the ground be present. The interface at the top of the inversion then separates the differing wind regimes below and above the inversion and concentrates the wind shear at the interface. Such inversions may be found along ocean coasts, along the shore lines of large lakes, and at mountain valley airports.

2.2.4.1 The Sea Breeze

At coastal airports in late spring and summer, a considerable temperature gradient can develop between the air over the heated land and the water-cooled air offshore during the daytime. If the offshore component of the prevailing surface wind is not too large, a sea breeze can develop, beginning as a light breeze only a few hundred feet deep in mid-morning and increasing to as much as 5 to $7ms^{-1}$ (10-14kt) up to 240 to 360m (800 to 1200 ft) and moving inland up to 48km (30 miles) by mid-afternoon. The sea breeze dies away during the early night hours when radiation cooling diminishes the temperature gradient which supported it. (37).

Because the sea breeze is essentially a shallow front, the same considerations apply as those used for warm fronts in determining whether significant vector wind shear exists. The temperature difference at the surface immediately across the front defines the intensity and the same sufficient criterion of $\geq$10°F/50 n mi (5.6°C/90km) may be used. The wind conditions are especially critical because the speed of the offshore components of the prevailing surface wind must not be larger than the value which would prevent the formation of the sea breeze condition. The height of the sea breeze front usually is clearly defined by the top of the haze layer resulting from the concentration of industrial smoke and fog, and/or sea salt particles on ocean coasts, under the inversion. As with warm fronts, the surface winds in the sea breeze layer approximate the wind velocities under the inversion and the geostrophically measured winds from the pressure gradient in the warm air, those above the interfaces. An estimated vector wind difference can be read off from Table 3 and the $10ms^{-1}$ criterion can be applied.

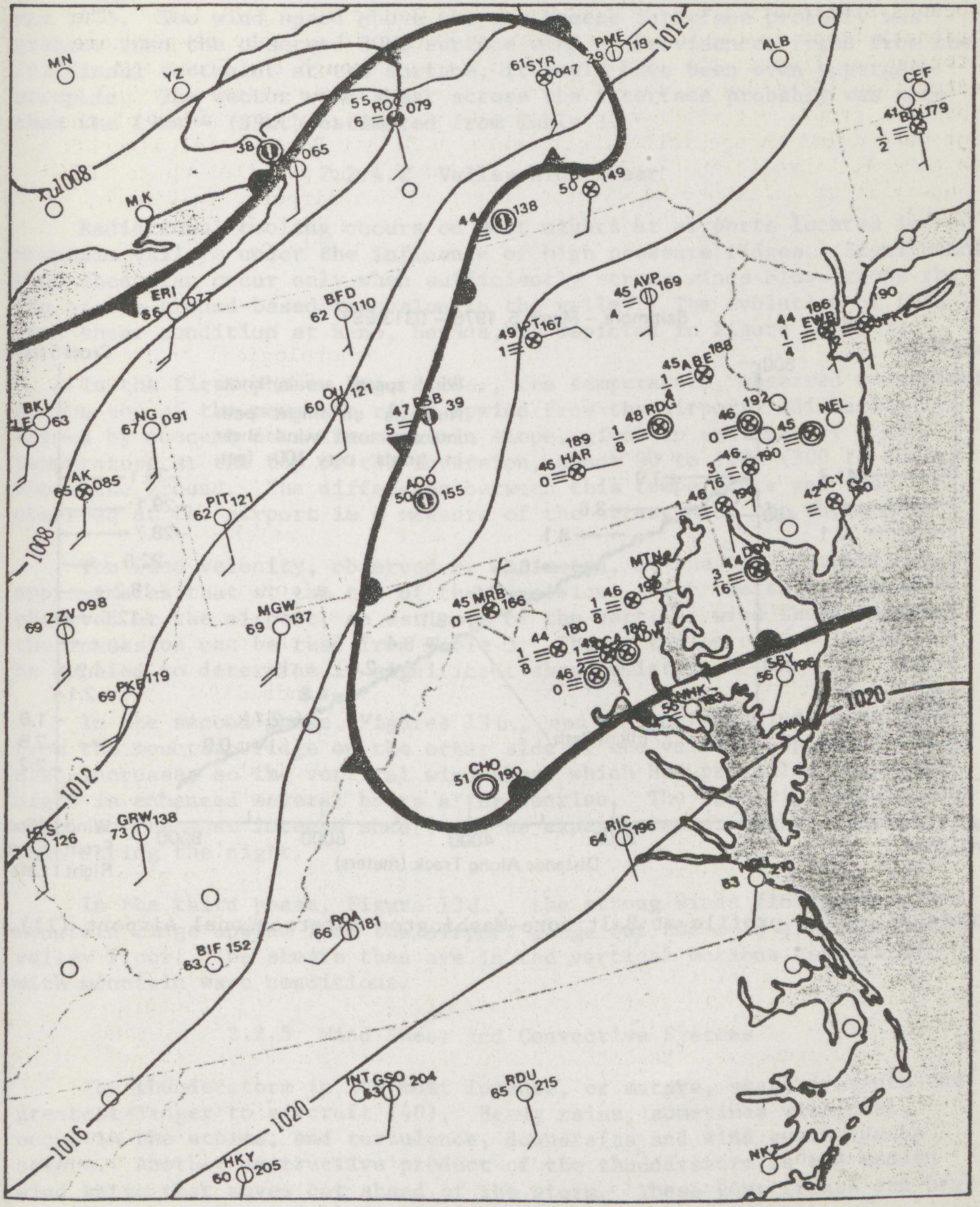


Figure 10.--A frontal condition which produced significant shear (11).

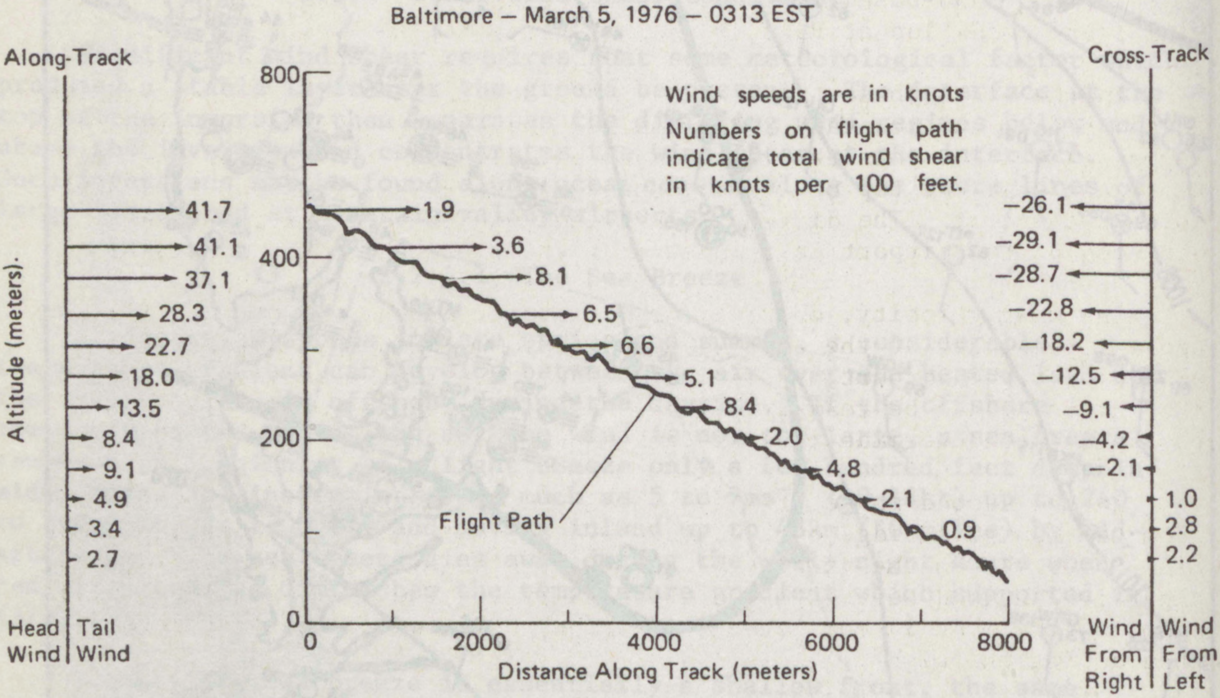


Figure 11.--Wind profile at Baltimore-Washington International Airport (11).

Figure 12 (38) illustrates an actual sea breeze case at Boston in May 1976. The wind speed above the sea breeze interface probably was greater than the observed 30kt surface wind at Providence; freed from the frictional restraint at the surface, it could have been even supergeostrophic. The vector wind shear across the interface probably was more than the $19ms^{-1}$ (39kt) estimated from Table 3.

2.2.4.2 Valley Wind Shear

Radiational cooling occurs on most nights at airports located in mountain valleys under the influence of high pressure ridges. Significant wind shear can occur only when sufficiently strong winds blow across the top of the ground-based inversion in the valley. The evolution of this wind shear condition at Reno, Nevada, is depicted in Figure 13 (39).

In the first phase, Figure 13a., the temperature, observed or estimated, at the top of the mountain ridge upwind from the airport, adiabatically warmed by descent down the mountain slope, gives an estimate of the temperature at the top of the inversion, about 90 to 120m (300 to 400ft) above the ground. The difference between this temperature and that observed at the airport is a measure of the strength of the inversion.

The wind velocity, observed or estimated, at the top of the ridge, approximates that at the top of the inversion. With the surface wind observed at the airport, an estimate of the vertical wind shear below the inversion can be read from Table 3. The criterion of $5ms^{-1}/30m$ can be applied to determine if significant shear exists.

In the second phase, Figures 13b., and c., surface winds blow down from the mountain ridge on the other side of the valley. Upper winds may also increase, so the vertical wind shear which had prevailed during the night is enhanced several hours after sunrise. The inversion level rises also, so the most intense shear will be experienced at higher levels than during the night.

In the third phase, Figure 13d., the strong winds flowing down the mountain ridge upwind from the airport gouge out the cold air from the valley floor. The shears then are in the vertical motions associated with mountain wave conditions.

2.2.5 Wind Shear and Convective Systems

The thunderstorm in its most intense, or mature, stage presents the greatest danger to aircraft (40). Heavy rains, sometimes with hail, occur in the storms, and turbulence, downdrafts and wind gusts can be severe. Another destructive product of the thunderstorm is the sudden wind surge that moves out ahead of the storm. These gust fronts can have a serious impact on aircraft operations.

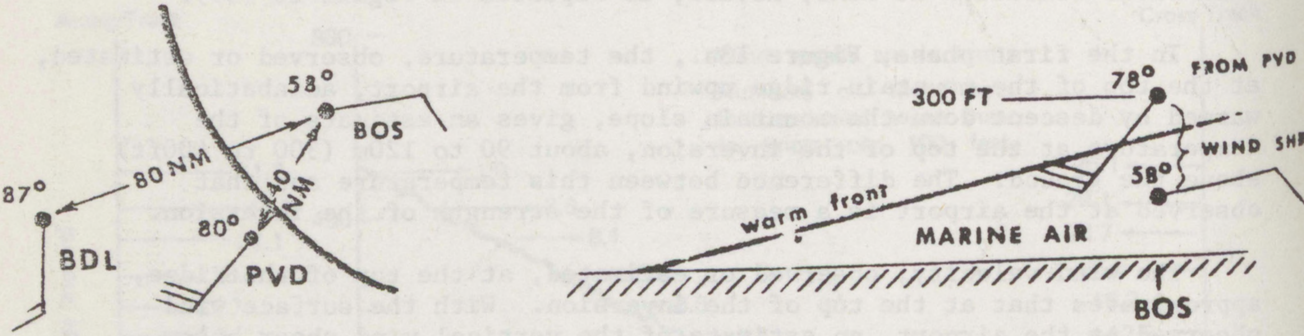
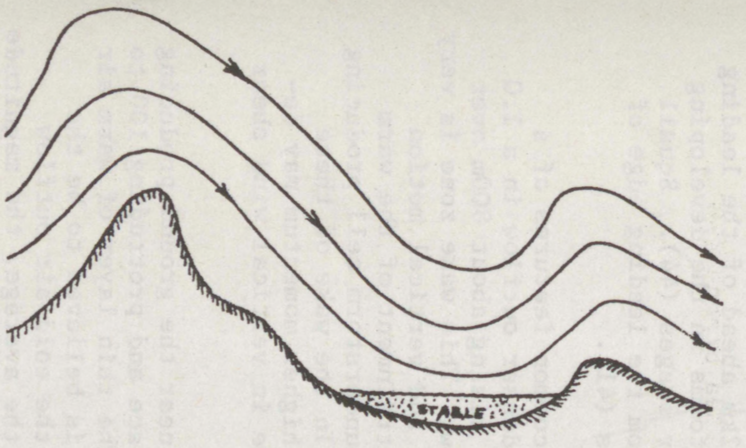
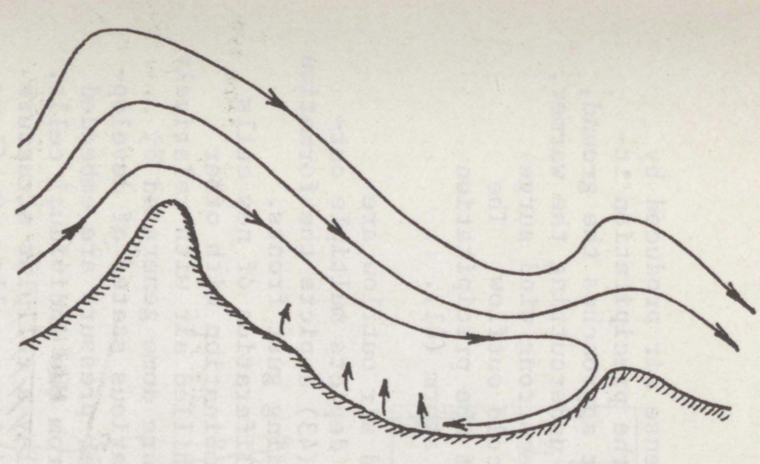


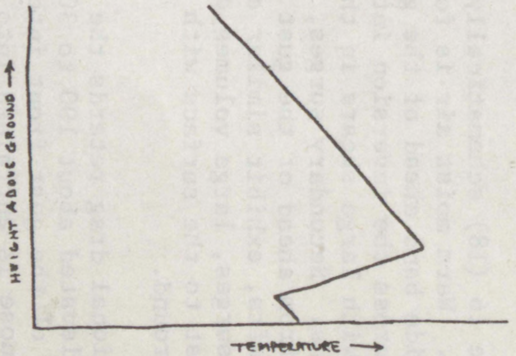
Figure 12.--Wind shear associated with a sea breeze (38).



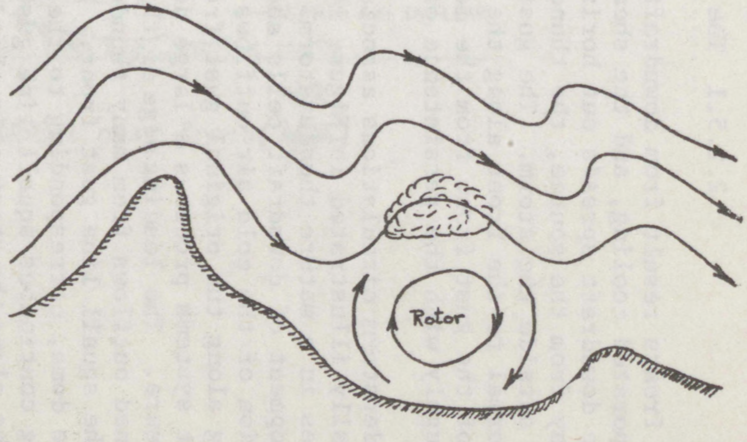
a. Skip shear. A shallow stable layer develops over the valley floor due to radiational cooling. Increasing winds aloft "skip" over this stable layer until sufficient velocity is reached to scour the valley.



b. Deflection shear. Morning heating of valley floor initiates weak rising motion. Air begins moving down the east slopes of the mountains to replace the rising air. This flow can become coupled with string westerly winds aloft producing moderate return flow at low levels.



c. Air close to ground becomes less stable due to solar heating after sunrise.



d. Rotor shear. Rotory action beneath terrain induced waves can produce shear and strong up and downdrafts over the valley.

Figure 13.--Mountain valley shear (39).

2.2.5.1 The Gust Front

Gust fronts result from downdrafts of cold, dense air produced by rain, evaporated cooling, and the shear weight of the precipitation itself. The downdraft spreads out horizontally as it approaches the ground, moving away from the source, the thunderstorm, and undercutting the warmer, dense air outside the storm. The gust front is the strong wind surge blowing normal to the front along the edge of the cold outflow. The distance of the gust front from the leading edge of the precipitation varies roughly with the persistence of the intense storm (41).

Thunderstorm circulations associated with cold air outflow are schematically illustrated in Figure 14 (42). This depicts multiple outflow surges in a mature thunderstorm. Figure 15 (43) depicts the formation and development of downdraft cells and their spreading gust fronts. Amalgamation of the cold air outflows from the proliferation of new cells developing along the original gust front and/or combination with other gust front systems produces a large dome of rain-chilled air with relatively high pressure. The leading edge of this high pressure dome generated by the combined outflows from many thunderstorms in various states of development is the squall line gust front. Peaks of higher pressure are embedded inside the dome, corresponding to the downdrafts from the individual cells. Thus, long continuous squall line gust fronts display a cellular structure with bulges along the storm axis ahead of the more intense cells. Outflows are directed generally normal to the axis.

The gust front may move out as far as 10 to 12km ahead of the leading edge of the precipitation from individual thunderstorms in the developing and mature stages (42) and as much as 20km in later stages (44). Squall line gust fronts tend to propogate farther away from the leading edge of the precipitation, up to 35km in some extreme cases (41).

Figure 16 (18) schematically illustrates the common features of a gust front. Warm moist air is forced up over the denser outflow in a 1.0 to 1.5km-wide band ahead of the gust front. After rising about 800m over the head across the inversion into the cold outflow. This wake zone is very turbulent with large shears in the horizontal wind and vertical motion oscillations. Secondary surges, resulting from entrainment of the warm moist air from ahead of the gust front into the thunderstorm cell producing new downdrafts, exhibit similar characteristics. In the wake of these secondary surges, large volumes of air with their higher momentum may descend almost to the surface with resultant increase in vertical wind shear near the ground.

Frictional drag retards the cold air outflow near the ground producing the nose elevated about 100 to 300m above the surface and protruding 100 to 300m ahead of the gust front into the warm air. The thin layer of warm air under the nose is entrained into the cold air and is believed to be the mechanism for dissipation of the gust front after the cold air outflow from the parent thunderstorm cell ceases (41). On the average, the magnitude

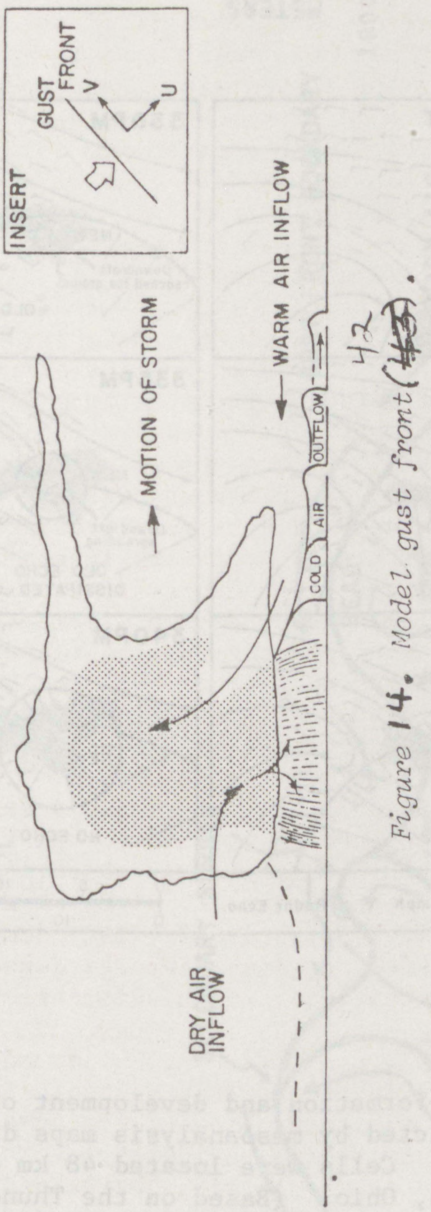


Figure 14.--Model gust front (42).

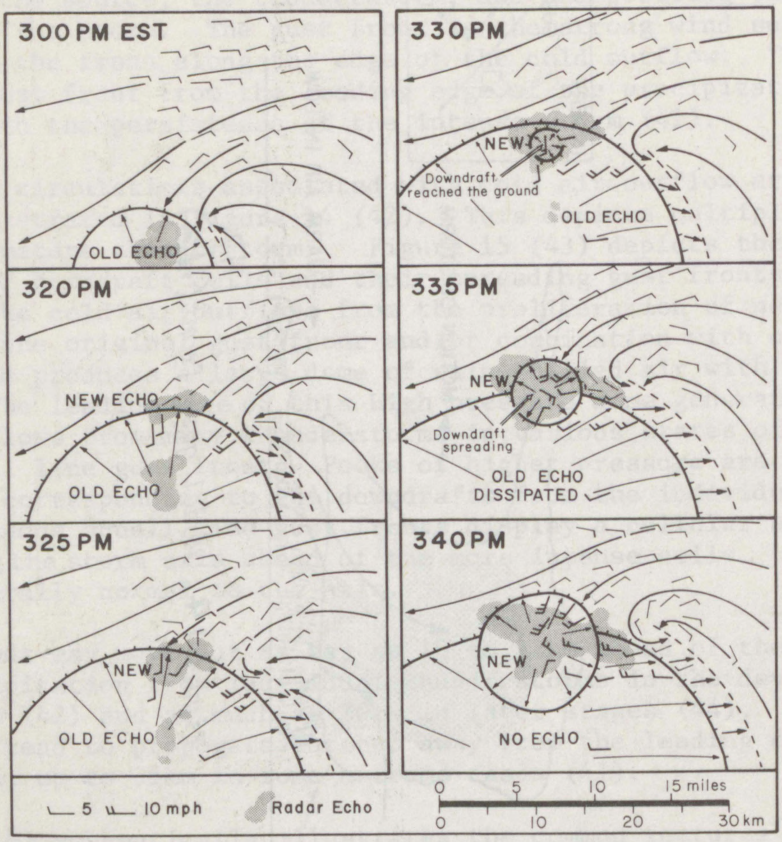


Figure 15.--Formation and development of downdraft cells depicted by mesoanalysis maps drawn at 5 min intervals. Cells were located 48 km east of Cincinnati, Ohio. (Based on the Thunderstorm Project data on August 13, 1947; analyzed by Fujita (45).)

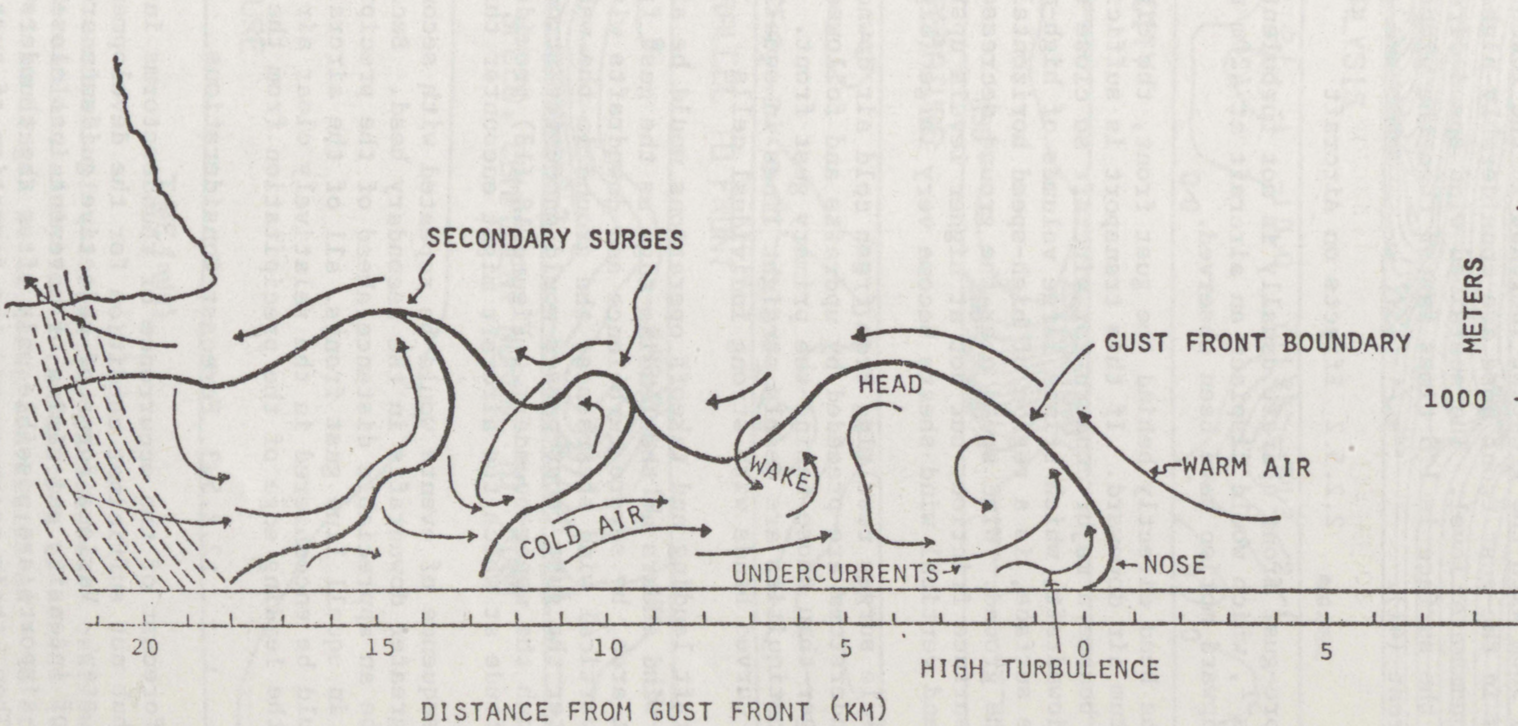


Figure 16.--Common features of a gust front (18).

of the wind speed behind the gust front increases about 50% between the surface and 500m with the greatest increase in the lowest 50m (44), so wind speeds in the gust front nose are considerably higher than those observed at anemometer level. The sustained wind speed directed normal to the front near the surface is 1.5 times faster than the propagation speed of the gust front (41).

2.2.5.2 Effects on Aircraft

The pre-gust front updraft usually is not turbulent and rarely exceeds $7ms^{-1}$, which would displace an aircraft at 420m per minute. Higher values of upward motion have been observed.

In the head directly behind the gust front, the circulation transports high momentum air downward. If this transport is sufficiently rapid, strong downdrafts become a major concern for aircraft so close to the ground. Under the downdraft, which brings large volumes of high-momentum air down to near the surface, is a region of high-speed horizontal flow reaching close to the ground. Wind speed near the ground decreases, probably as a result of surface friction, but not at higher levels upstream through the wake area and vertical wind shears become very large (Figure 17) (41).

Multiple surges resulting from fresh cold air downdrafts from the parent thunderstorm are preceded by updrafts and followed by downdrafts even stronger than those behind the primary gust front. The multiple surge discontinuities are nearly straight lines in squall line gust fronts and may be curved bands with strong individual cells.

Aircraft landing and takeoff operations would be affected by strong horizontal wind shears at the leading edge as the gust front moves through the airport area, by severe turbulence and downdrafts within the head, and by strong vertical wind shears near the ground in the wake area. Aircraft landing after the gust front passes would encounter strong vertical wind shear through the upper boundary. Figure 18 (18) provides a rough estimate of the altitude at which the aircraft might encounter this gust front.

The sequence of events would be repeated with secondary surges, but with even greater downdrafts in the secondary head. Because the gust front can be an appreciable distance ahead of the precipitation edge, especially in squall line gust fronts, all of the aircraft operation hazards would be encountered in the relatively clear air between the gust front and the leading edge of the precipitation from the thunderstorms.

2.2.5.3 Forecast Considerations

The forecast of the occurrence of thunderstorms in an area, a necessary but not sufficinet condition for the development of gust fronts, is a first step. Various forms of objective guidance are available. Estimates of intensity and timing of movement into close proximity with individual airports are possible only after the thunderstorms begin to develop. Then, their progress and the formation of gust fronts can be

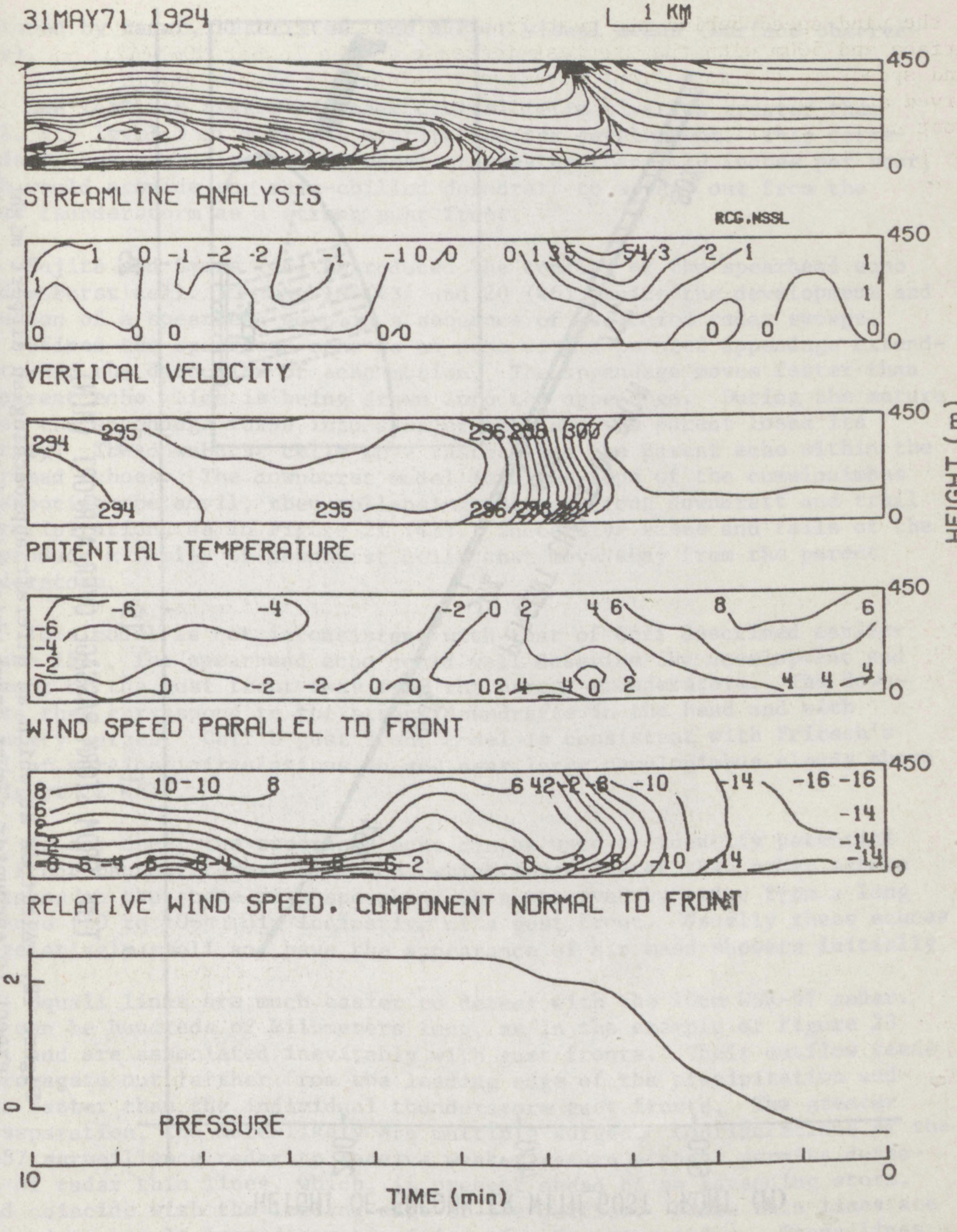


Figure 17.--Objective analysis of quasi-steady thunderstorm outflow. Units are ms^{-1} and °K. Streamline analysis is combination of second (υ) and fifth (u) panels. 1 km length scale using conversion $\Delta x = -c\ \Delta t$ is shown at top (42).

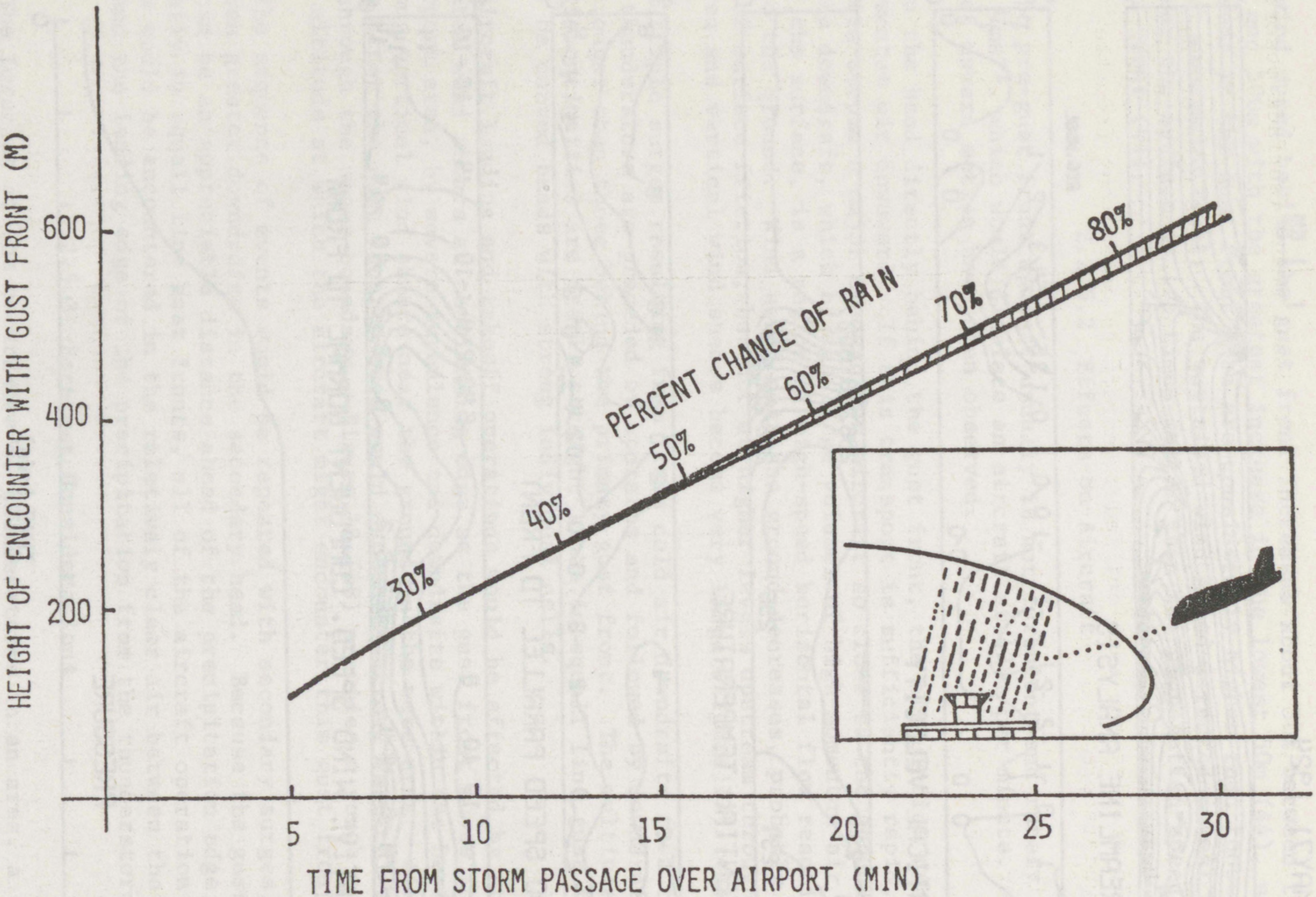


Figure 18.--Altitude at which an aircraft approaching an airport might expect to encounter a gust front which passed the airport earlier (18).

monitored by radar, satellites, and direct visual means (surface observations).

Lee (45) has suggested radar central reflectivities greater than 40dBZ, VIP level 3 or more, as a criterion for development. This corresponds to heavy precipitation, equal or greater than 1.10 inches per hour, which would provide the rain-chilled downdraft to spread out from the parent thunderstorm as a strong gust front.

Fujita and Byers (46) introduced the concept of the spearhead echo and downburst cell. Figures 19 (43) and 20 (46) depict the development and evolution of a spearhead echo in a sequence of contoured radar sweeps. They defined the spearhead echo as an echo with a pointed appendage extending toward the direction of echo motion. The appendage moves faster than the parent echo which is being drawn into the appendage. During the mature stage, the appendage turns into a major echo and the parent loses its identity. The downburst cells move faster than the parent echo within the spearhead echoes. The downburst model involves tops of the cumulonimbus overshooting the anvil, then collapsing into a strong downdraft and trail of precipitation, as in Figure 21 (43). Successive rises and falls of the top produce a family of downburst cells that move away from the parent thunderstorm.

This model is not inconsistent with that of Goff described earlier (Figure 15). The spearhead echo could well describe the development and movement of the gust front away from the parent thunderstorm. The downbursts then correspond to the strong downdrafts in the head and with secondary surges. Goff's gust front model is consistent with Fritsch's model of vertical circulations in and near large cumulonimbus clouds shown in Figure 22 (47).

In any case, the spearhead echo can be used to identify potential gust front thunderstorms. The echo which moves faster than other echoes and takes on the shape of a spearhead when observed by radar from a long distance (70 to 100n mi) is indicative of a gust front. Usually these echoes are relatively small and have the appearance of air mass showers initially.

Squall lines are much easier to detect with the 10cm WSR-57 radar. They can be hundreds of kilometers long, as in the example of Figure 23 (41), and are associated inevitably with gust fronts. Their outflow tends to propagate out farther from the leading edge of the precipitation and moves faster than the individual thunderstorm gust fronts. The greater the separation, the more likely are multiple surges. Configurations of the WSR-57 surveillance radar to receive weaker return signals permits detection of radar thin lines, which, if present ahead of an advancing storm, could coincide with the leading edge of the outflow. Radar thin lines are believed to result from discontinuities of refractive index. These lines may not always appear when strong gust fronts are known to be present and may appear when there are no thunderstorms. Large outflows may be visible in high resolution satellite imagery of arc lines formed by cumulus formation along the gust front, as in Figure 24 (48) (49).

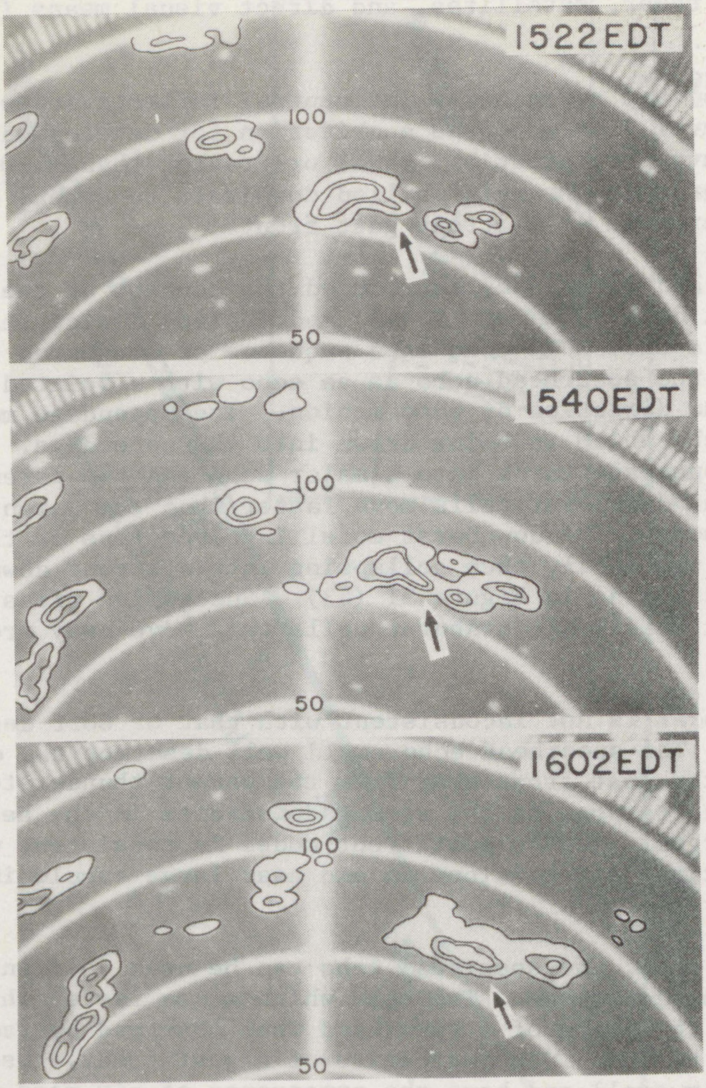


Figure 19.--Contour representation of the spearhead echo near JFK on June 24, 1975. The formative stage is seen in a picture at 1522 EDT. At 1540 EDT, the parent echo is being drawn into the spearhead section. Finally, at 1602 EDT, 3 min before the accident, the parent echo was absorbed entirely into the spearhead echo (43).

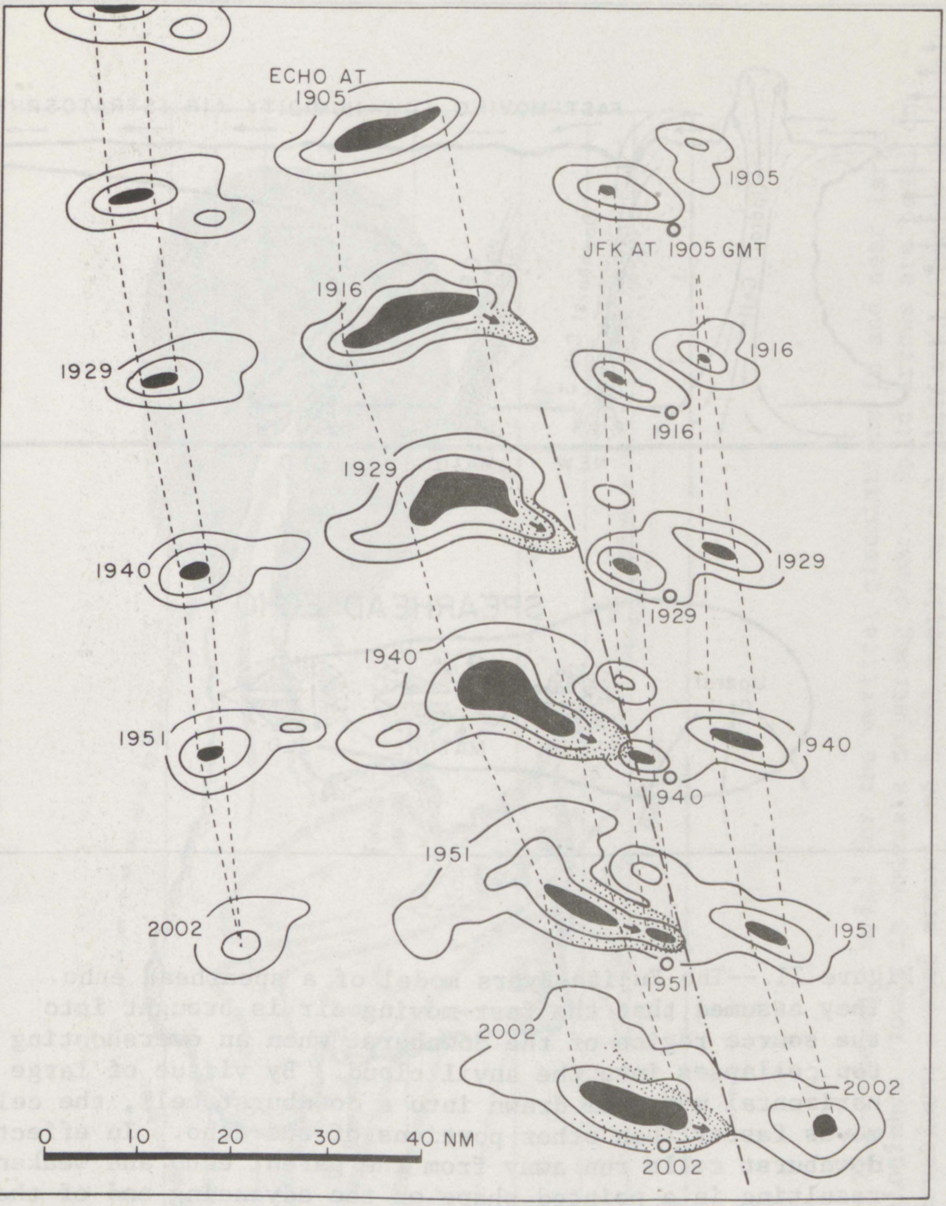


Figure 20.--Formation and advance of spearhead echo. Small circles show relative positions of JFK airport at the various times. Heavy dashed line marks the tip of the spearhead (46).

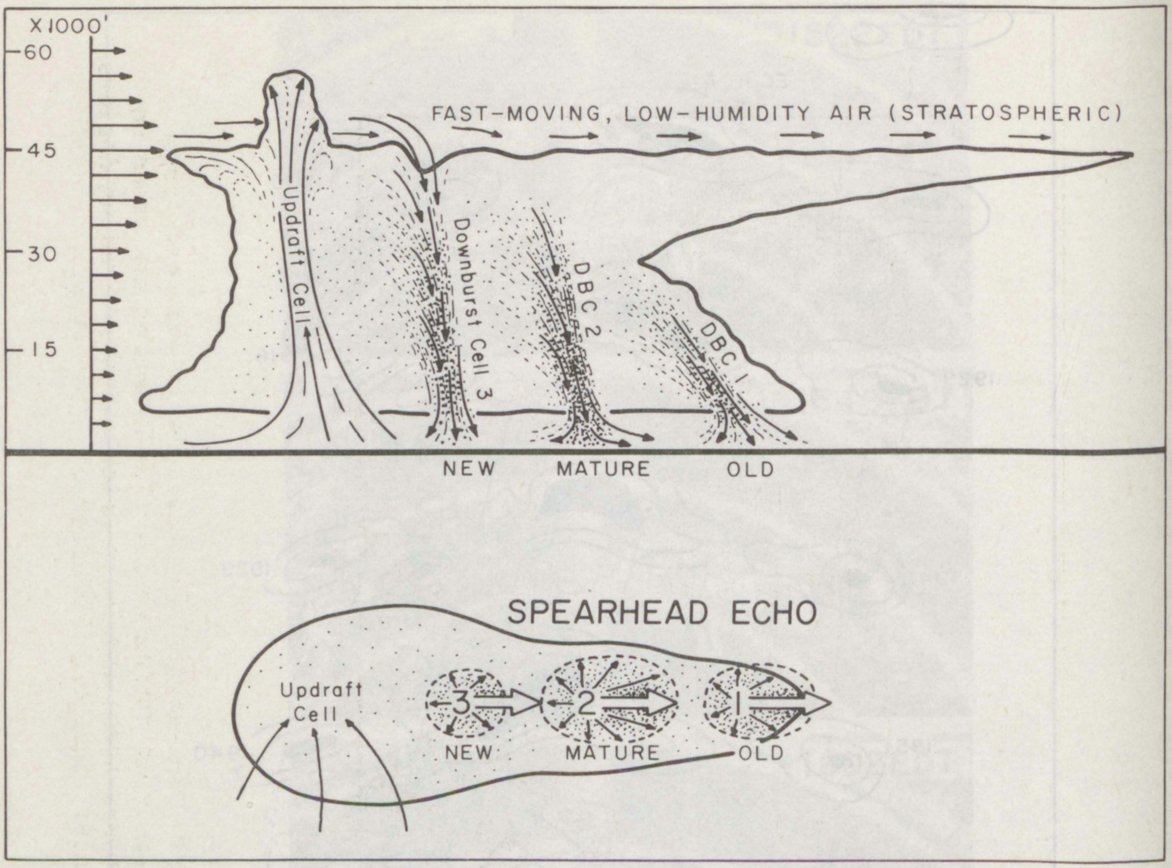


Figure 21.--The Fujita-Byers model of a spearhead echo. They assumed that the fast-moving air is brought into the source region of the downburst when an overshooting top collapses into the anvil cloud. By virtue of large horizontal momentum drawn into a downburst cell, the cell moves faster than other portions of the echo. In effect, downburst cells run away from the parent echo and weaken, resulting in a pointed shape on the advancing end of the echo. At close range, especially below the cloud base, the radar paints small circular echoes. (From Fujita (1976a) and Fujita and Byers (1977) (43).)

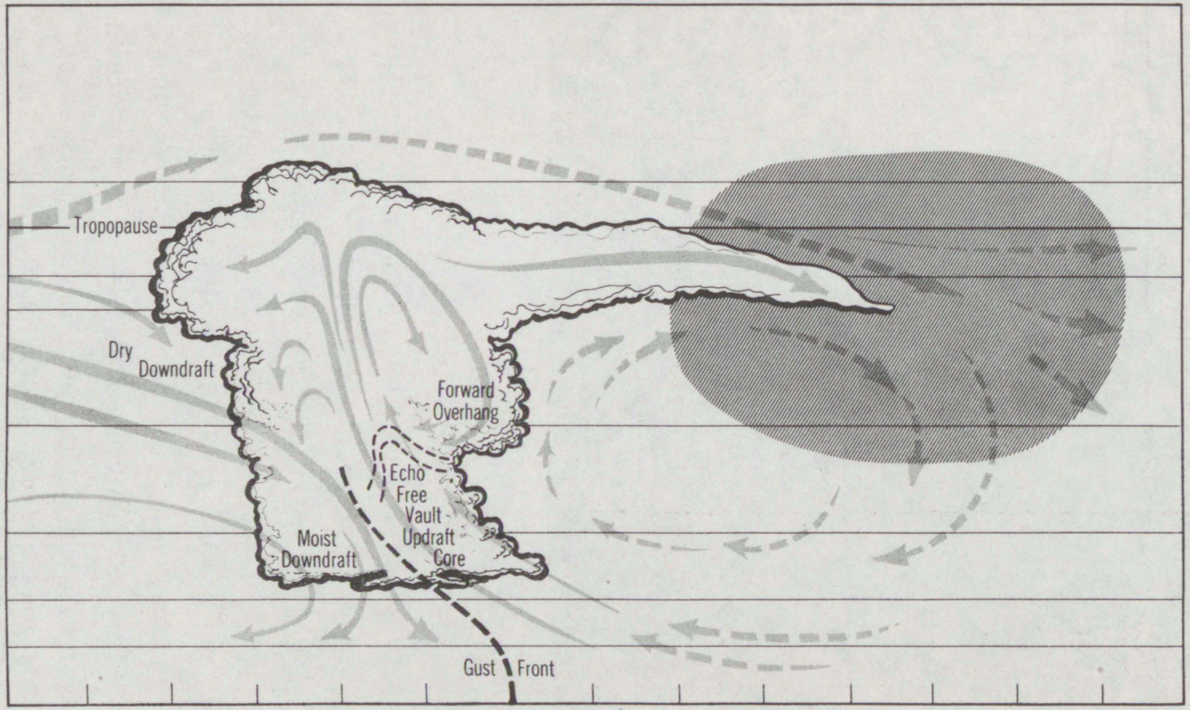
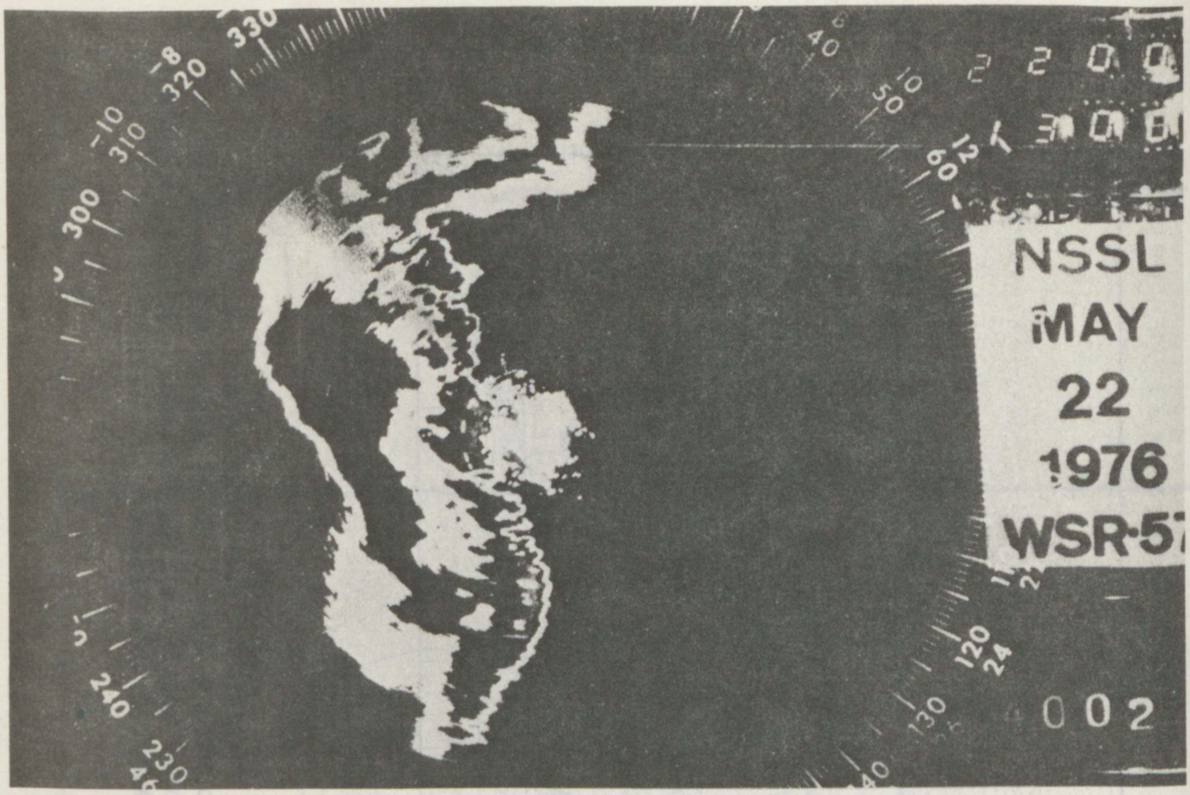


Figure 22.--Schematic model for the vertical circulations in and near large cumulonimbus clouds in moderate to strong shear. Solid arrows are based on observations; dashed arrows are based mostly on calculations. Shading depicts region of downwind subsidence. (Adapted from Fritsch, 1975 (47).)



Case C

22 May 1976 2208 $c = 16.3\ m\ s^{-1}$ $\alpha = 352°$

Highly turbulent, relatively shallow outflow associated with long unbroken north-south squall line. Gust front at 2208 is followed 1 min. later by secondary surge. Strong updrafts precede both discontinuities. Potential temperature cross section after 2215 illustrates shallowness of outflow. Center of outflow wake occurs at 2216. Thickness of outflow is only 200 m at this point. Vertical velocity indicates wake region is highly turbulent. Wake is associated with third surge at 2214. Horizontal wind is strong after third surge compared with first two. Undulations on outflowtop (gust front envelope) after 2215 have 500 m amplitude. Coldest temperatures associated with onset of rainfall at 2231. No gust surge with rainfall onset. Gust front envelope rises above tower 6 min. prior to rainfall. Tower layer relatively tranquil thereafter, although strong horizontal winds accompany rainfall. No strong downdraft in rainfall.

Figure 23.--10cm WSR-57 conventional radar diagram, with echoe contouring, of a squall line (41).

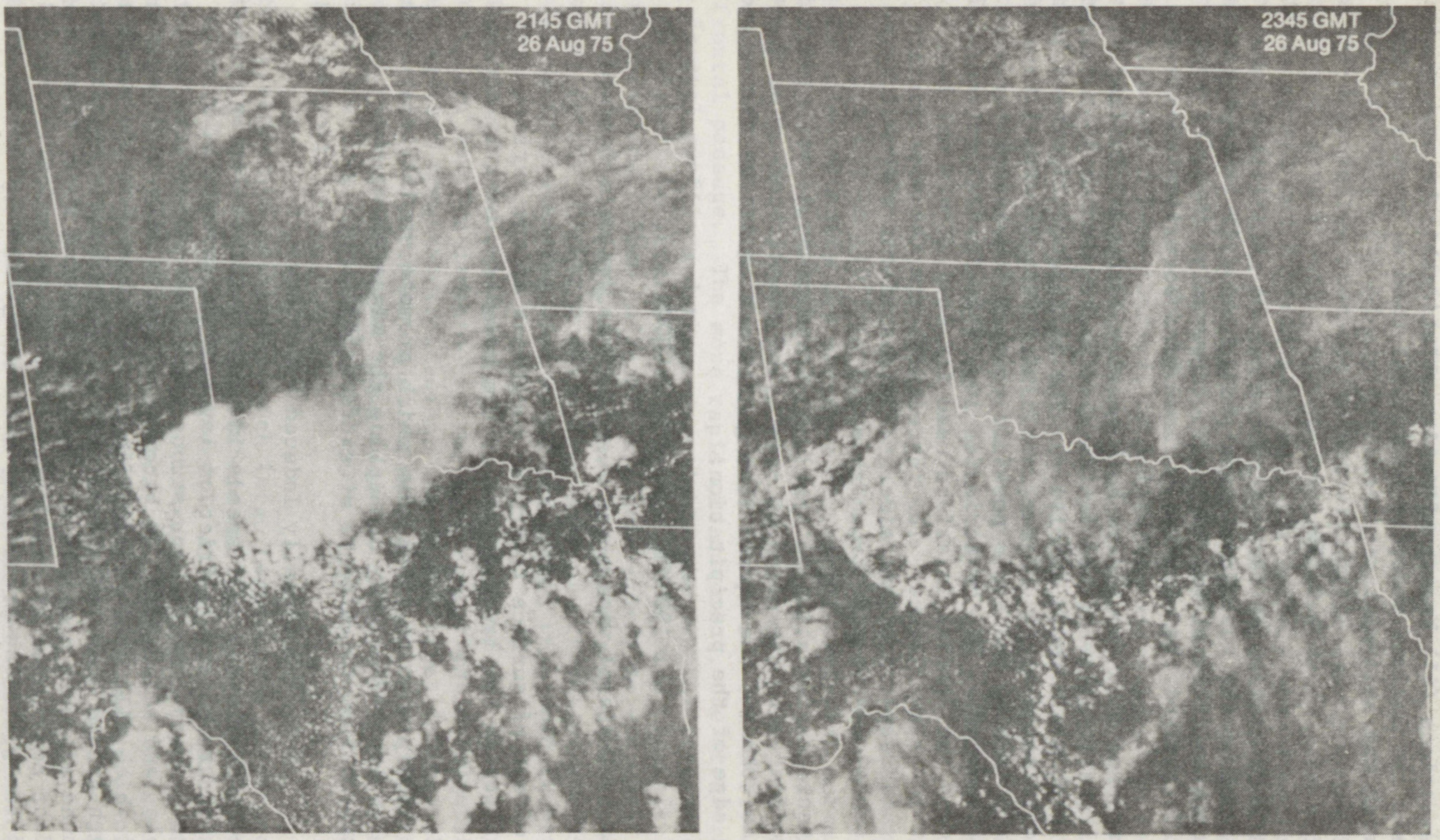


Figure 24.--Two-hour motion of an arc-cloud moving southwestward across Texas (48).

Many observations (41) have confirmed a relationship between gust front speed c and the maximum smoothed horizontal wind u_1 normal to the gust front axis in the cold air:

$$c = 0.67u_1$$

If the speed and orientation of the gust front can be established, the maximum wind normal to the gust front near the ground will be approximately 1.5 times faster than the gust front speed. Conversely, the gust front speed will be 2/3 that of the observed maximum wind normal to the front.

Gust fronts and cold fronts are both gravity currents, defined as the stable parallel gravity flow of one fluid relative to another that results from small differences in their densities. The differences in their leading edge characteristics are of degree, not kind. Gust fronts, like cold fronts, vary in intensity and it is possible to test for associated wind shear in the same manner. The criterion of $10ms^{-1}$ horizontal or vertical wind shear through the frontal interface used for cold fronts may be applied to test for significance. The ingredients are the near surface wind direction and speed on either side of the gust front with which an estimated wind shear can be read from Table 3.

An important consideration is that gust front passages are either dry, or almost coincident with the onset of rain. The thunderstorm gust front may be as far as 20km and the squall line gust front as far as 35km ahead of the leading edge of the precipitation.

3. SUMMARY AND CONCLUSIONS

Significant low-level wind shear results from two main features in the atmosphere:

1) the effect of surface friction, roughness of the surface, and stability in the lower strata of the boundary layer in strong wind regimes; and

2) inversion-producing mechanisms which promote stability at low levels, effectively decoupling the winds above the inversion from the effects of surface friction.

3.1 Frictionally Induced Wind Shear

In the boundary layer, wind speeds increase logarithmically from the zero value at the ground in the friction layer, then exponentially at a decreasing rate to near 100m. With strong winds, the atmosphere is neutrally stable, and adiabatic. It becomes necessary only to determine the wind speed which will produce significant wind shear for the particular roughness length around each individual airport. The hazard to aircraft operations around airports consists of the vertical wind shear from the frictional effect compounded by downdrafts from the mechanically-induced turbulence and the gustiness produced by descending higher velocity air.

3.2. Frontal Wind Shear

Paradoxically, the highly turbulent thunderstorm with its severe updrafts and downdrafts, produces relatively stable layers under inversions in the form of gust fronts. Strong downdrafts of dense rain and evaporation-cooled air spread out horizontally near the surface away from the precipitation area undercutting the warm, moist, unstable air surrounding the thunderstorms. Strong horizontal wind shear as the gust front crosses, the airport area followed by severe turbulence, downdrafts and vertical wind shear are the hazards. The effects are compounded in squall line gust fronts which can affect hundreds of kilometers as compared to the tens for the individual cells. Estimates of intensity and movement from surveillance by radar, satellite and visual observation are possible only after the thunderstorms begin to develop. The spearhead echo is the clue for development of gust fronts from individual cells. Squall line gust fronts are more readily identified. An important consideration is that the gust front can lead the precipitation by up to 12km with cells and up to 35km with squall lines.

Rapidly moving strong cold fronts with narrow transition zones, denoted by a 5.6°C/90km (10°F/50 n.mi. or more surface temperature gradient across the discontinuity and strong surface wind component normal to the front in the cold air, exhibit some of the characteristics of the gust front on a synopitc scale. Strong horizontal wind shear accompanies the front as it moves across the airport area and continues for a relatively short time after frontal passage. The more rapid the movement, the steeper the slope of the frontal profile and the more quickly the frontal interface lifts above the airport to levels where it no longer affects aircraft landing and takeoff operations. Then, aircraft are more likely to encounter only the fractionally-induced vertical wind shear in the strong wind regime following the surface front. Rather precise forecasts of frontal movement and slope are required for assessing wind shear associated with cold fronts.

Warm fronts, because of their slower movement and lesser slope steepness, can be more dangerous. The same criterion of 5.6°C/90km (10°F/59 n.mi. surface temperature gradient across the front defines the presence of a narrow transition zone across which wind shear sufficient to affect aircraft is present. Duration time from the slope and speed of movement determines how long the critical 150-200m layer above the surface will be above the airport.

Sea breezes are associated with large temperature differences developing between the water-cooled air offshore and the heated air over land during the day in late spring and summer. Although the sea breeze front moves inland as a meso-cold front, it exhibits characteristics similar to those of warm fronts as far as wind shear is concerned. The same critical surface temperature gradient across the front is the indicator of a sufficiently narrow transition zone across which there will be significant wind shear.

Estimates of probable wind shear with frontal discontinuities are possible. The geostrophically measured wind direction and speed in the warm sector can be assumed to be representative of the winds immediately above or ahead of the frontal interface. Estimates of wind direction and speed in the cold air, representative of the winds under and behind the frontal interface, can be made. Table 3 then provides a method of approximating the horizontal and vertical vector wind shear across the frontal transition zone. Resolution of the vector wind shear into components parallel to and normal to the most probable runway determines whether the critical value of change in indicated airspeed of 10kt ($5.1ms^{-1}$) or more will be met.

3.3 Inversions from Radiational Cooling

Temperature inversions developing around sunset effectively decouple the wind above the inversion from the surface frictional effect. In areas where the pressure gradient is sufficient to provide a generally southerly wind of $10ms^{-1}$ (20kt) or more during the daytime, a low-level jet with supergeostrophic wind speed develops. Vertical wind shears develop very rapidly and are most dangerous during the early stages when the jet is at relatively low levels above the ground. The wind speed above the inversion can be estimated. From the observed winds at the surface at sunset, vertical wind shear possible with low-level jet development can be approximated. The criterion of $2.6ms^{-1}$ /30m determines whether the estimated vertical wind shear will be significant for aircraft operations.

Radiational cooling in mountain valleys provides an inversion discontinuity at night. Increasing winds across the upstream mountain barrier increase the wind speed above the valley inversion, resulting in increasing wind shear across the inversion. Aircraft letting down into valley airports, or taking off from them would experience this wind shear. Wind shears can be approximated for significance from Table 3, as for fronts, using the same criteria of temperature and wind difference across the interface.

3.4 Conclusions

All of the meteorological features associated with wind shear are forecast at present: wind speed, thunderstorms, fronts, and temperatures --some more accurately than others. Wind-shear forecasts require that these elements be forecast with greater precision than for most other purposes. The relatively short range necessary for these forecasts to be useful for landing and takeoff operations at an airport makes this possible. A relatively small additional expenditure of effort should be necessary to assess the significance of the associated wind shear. The importance of wind shear for aircraft operations makes this a worthwhile endeavor.

Acknowledgements

A study by Barry A. Richwien and Robert J. McLeod, Jr., of National Weather Service (NWS), was a major first step in the current low-level wind shear forecast program. This study was based on a joint NWS and Federal Aviation Administration (FAA) low-level wind shear forecast test. Their contribution is referenced in this report and is the basis for much of Appendix A on forecasting guidelines.

Mr. Frank Coons, of the Systems Research and Development Service of the FAA, has strongly urged the initiation of the new NWS low-level wind shear forecast program and contributed to the planning of this report.

Finally, acknowledgement is made of the assistance of Major James A. Lindquist, Air Weather Service (AWS) Liaison Officer to the FAA, Mr. Edward M. Gross, Mr. Jerald Uecker, and Dr. Duane S. Cooley, all of the Meteorological Services Division, NWS Headquarters.

Thanks also to Claire Wethington and Kathryn Thompson for typing the manuscript.

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APPENDIX A

GUIDELINES FOR FORECASTING NON-CONVECTIVE LOW-LEVEL WIND SHEAR (LLWS)

The NWS LLWS program consists at this time of two parts. First, there is a generalized LLWS potential statement included in the Flight Precaution (FLT PRCTN) paragraph of the Area Forecast Program (FA). This should be considered the analog of a watch and should alert the user to the possibility of encountering LLWS somewhere within the FA area within the next 12 hours. This statement will be included in the FA only when certain conditions listed below are satisfied.

The second part of the program for now involves the use of LLWS statements in terminal forecasts (domestic FT's) when needed. This issuance in terminal forecasts is a temporary arrangement until communications are upgraded at the Air Route Traffic Control Centers (ARTCC) where the NWS Central Weather Service Units (CWSU) are located.

All FA Centers, WSFO's and CWSU's will participate in the LLWS program. The role of the CWSU will be discussed in some detail in Section 4.

A. FA LLWS Potential Statement

Experience has shown that LLWS will not occur if the wind in the first 2,000 feet above ground level (AGL) does not exceed 20 knots. But if the wind in the layer is observed or forecast in excess of 20 knots, we must assume the potential for LLWS exists, and we should begin examining conditions in more detail. All LLWS can be thought of as arising from either an inversion or friction. Inversions (including frontal) produce shear because they inhibit vertical mixing. Friction, on the other hand, slows the air flow nearest an object to produce a shear layer. These two basic causes can be subdivided as follows:

Inversions	Friction
Frontal (including meso-scale)	Surface
Nocturnal - Low-level Jet	Building/terrain deflection
Subsidence	
Cold-surface included	

Each of these is discussed below, and some guidelines are given on when to include a LLWS Potential Statement in the FA.

(1) Fronts. As used herein, the term "front" includes the traditional synoptic-scale fronts (i.e., cold, warm, etc.) and meso-scale phenomena such as thunderstorm gust fronts and coastal and sea breezes. We have found these "meso-fronts" are most likely to produce LLWS. Unfortunately, they are often difficult to forecast since they are relatively short-lived and we are not accustomed to analyzing them.

In any case, any front with a temperature gradient $\geq 10°F$ per 50 nautical miles (5.6° per 90 km) and with a wind ≥ 40 knots (20 ms^{-1}) at 2,000 ft AGL has the potential to produce LLWS. The threshold wind criterion separates dynamic fronts from static ones.

(2) Nocturnal Inversion/Low-Level Jet (LLJ). Nocturnal inversion and LLJ are grouped together here because the nocturnal inversion is thought to play a major role in the formation of a LLJ. For our purposes, a low-level jet refers to a wind speed profile of 0-8 knots at the surface, increasing with height to more than 25 knots between 650 and 1,500 feet and then decreasing in speed with height to approach the gradient level wind speed of about 15 knots or more. The LLJ is most frequent in the Midwest but has been observed along the East Coast and in parts of Great Britain. It is usually associated with general southerly flow.

Forecasting the formation of LLJ's is a problem. Forecasters should be on the lookout for evidence of LLJ in radiosonde wind observations. Also, experience on the East Coast has shown that, if in other than a storm situation, pilots are reporting wind ≥ 60 knots within 2,000 feet, there is probably a LLJ.

(3) Subsidence Inversion. Subsidence inversions are usually found above 2,000 AGL and are associated with a relatively weak wind field. Therefore, the vertical shear associated with subsidence inversions probably will not usually be significant to aircraft operations.

(4) Cold-Surfaced Induced Inversions. When warm air passes over cold surfaces such as lakes or oceans in the springtime or a snow-covered region during the winter, a surface-based inversion is induced by the cooling from below. Experienced along the East Coast of the U.S. has shown that this situation produces vertical shear if the inversion is $\geq 10°F$ and the wind between the inversion top and 2,000 feet is greater than 30 knots.

(5) Friction-Surface Slowing. LLWS Potential exists if the sustained surface wind is reported or forecast to be ≥ 25 knots. Perhaps this value should be subject to regional adjustment because of varying average wind speeds. For example, over the plains, a sustained 25-knot wind is rather frequent, so a 30-knot threshold may be more appropriate; whereas, in a protected valley, a sustained 20-knot wind might be quite unusual and thus be a more appropriate value.

(6) Friction - Building/Terrain Deflection. It is well known that buildings, local hills, adjacent forests, etc., cause deflection of the flow in the vicinity of many airports -- especially smaller ones -- and could thereby create LLWS. Because this effect is necessarily very localized and because pilots should already be aware of the local conditions, this cause of LLWS should not be dealt with in the area-oriented FA.

B. Examples of LLWS potential Statements in the Flight Precaution Paragraph of FA

In general, the forecasters should include as much information as they feel reasonably sure of. Experience has shown that the precise vertical wind profile is rarely known during a wind-shear event, so an exact wind should usually not be included. The following examples attempt to give some guidance on wording to be used in the flight precaution paragraph of FA.

BASIC FORMAT OF LOW-LVL WND SHEAR POTENTIAL STATEMENT TO BE INCLUDED ON FLIGHT PRECAUTION PARAGRAPH

LOW-LVL WIND SHEAR POTENTIAL <u>LOCATION</u>: <u>TIME</u>: <u>DUE TO CAUSE</u>:

(1) <u>Warm Front</u>. LOW-LVL WND SHEAR POTENTIAL OVR NRN OH FM 03Z to 05Z DUE TO STG WRMFNT

(2) <u>Cold Front</u>. LOW-LVL WND SHEAR POTENTIAL NRN PLAINS AND MIDWEST AS CDFNT MOVG THRU AREA INTSFYS

(3) <u>Low-Level Jet (LLJ)/Nocturnal Inversion</u>.
LOW-LVL SHEAR POTENTIAL ACROSS CNTRL PLAINS BTN 06Z AND 14Z DUE TO PSBL LOW-LVL JET (AND NIGHTTIME INVRN)

(4) <u>Cold-Surface Inversion</u>.
LOW-LVL WND SHEAR POTENTIAL ALC PACIFIC COAST FM 18Z TO 00Z DUE TO MARINE INVRN AND STG SLY FLOW

LOW-LVL WND SHEAR POTENTIAL ALG WRN LM SHORELINE FM 17Z TO 21Z DUE TO STG LK EFFECT INVRN AND STG WLY FLOW

(5) <u>Friction-Surface Slowing</u>.
LOW-LVL WND SHEAR POTENTIAL OVR MOST OF FA AREA AFT 03Z DUE TO FRICTIONAL SLOWING OF STG NWLY FLOW BHND CSTL LOW PRES CNTR

(6) <u>Nighttime/Valley Inversion</u>.
LOW-LVL WND SHEAR POTENTIAL ABV VLYS ON NY AND NEW ENGLAND AFT 06Z DUE TO STG NIGHTTIME INVRN AND INCRG SWLY FLOW ALF

C. Checklist for Issuing Terminal Forecasts with LLWS Statements

This is a temporary method of issuing information on LLWS. Our ultimate goal is to have the CWSUs and CFCF issue LLWS Advisories. Until communications are upgraded to permit this, LLWS will continue to be issued in terminal forecasts in the following manner.

Effective 1200 GMT April 16, 1979, the LLWS forecasts now included in the Terminal Forecasts will be:

a. limited to a maximum period of 12 hours from issuance time,

b. generally valid for up to 3-hour periods except under persistent conditions, and

c. indicated by using the term LOW LVL WIND SHEAR. We are now investigating the use of the contraction "LLWS" with the FAA. If approved it will help shorten the length of our FT's.

Include nonconvective LLWS within 2,000 feet of the surface in the remarks portion of the FT whenever:

a. PIREP's of shear causing an indicated airspeed loss or gain of 20 knots or more are received.

b. Horizontal shear of 20 knots or more are expected or reported in the vicinity of the airport.

c. Vertical shears of 10 knots or more per 100 feet in a layer more than 200 feet thick are expected or reported in the vicinity of the airport.

The FAA has identified these LLWS threshold values as being critical to aircraft operations. Forecasters should review NOAA Technical Memorandum NWS FCST-23 when it becomes available and develop local aids for forecasting LLWS.

D. Examples of LLWS Forecasts in FT's

Cold front
ORD 231010 C30 BKN 2310. 20Z CFP C20 OVC 2820G35 LOW LVL WIND SHEAR. 21Z 60 SCT 3015G35 LOW LVL WIND SHEAR. 22Z 80 SCT 3012. 04Z VFR CLR..

Inversion
ABI 231010 C20 BKN 1512 LOW LVL WIND SHEAR TIL 13Z WIND 1512 AT SFC 1950 AT 1500FT. 18Z 30 SCT 1815G25. 04Z VFR CLR..

Warm front
MCI FT AMD 1 241815 1755Z C8 4F 1212 LOW LVL WIND SHEAR. 19Z C3 OVC 3F 1520 LOW LVL WIND SHEAR. 21Z C20 BKN 2320. 00Z CLR 2415. 09Z VFR CLR..

Shallow high pressure system
JFK 231515 C15 OVC 0315 LOW LVL WIND SHEAR WIND 0315 AT SFC SWLY AT 1500 FT. 21Z C30 BKN LOW LVL WIND SHEAR TIL 22Z. 00Z 50 SCT 2215. 09Z VFR CLR..

Low level jet
ICT 232222 CLR 1410 LOW LVL WIND SHEAR 04Z-10Z WIND 1410 AT SFC SLY AT 2000FT. 16Z VFR CLR..

Sea breeze or Santa Ana
ONT 191616 CLR. 18Z 15 SCT 2812 LOW LVL WIND SHEAR WIND 2812 AT SFC ELY AT 2000FT. 21Z CLR 0815. 10Z VFR CLR..

Lee side effect
RNO 151010 80 SCT C150 BKN. 15Z C50 BKN 1815G30 LOW LVL WIND SHEAR WIND 1815G30 AT SFC WLY AT 2000FT. 18Z 20 SCT C40 OVC 1815G30 BRF C15 X 1SW- LOW LVL WIND SHEAR. 22Z 50 SCT C100 BKN 2717. 04Z VFR CLR..

Specific wind directions and speeds should be included in the first period of the FT, if known. However, more generalized wind information or merely the LLWS statement will suffice in subsequent periods, usually from 3 hours to 12 hours after issuance. Also note that the frontal examples do not contain specific wind shear data because of the variable nature of frontal slopes and erratic movements of frontal boundary zones.

The FT should be amended when LLWS:

a. occurs and is not forecast,

b. is forecast and it becomes apparent it will not occur, or

c. is expected but not forecast.

A LLWS Potential statement in the Area Forecast (see WSOM Chapter D-20) <u>will not automatically require the inclusion of LLWS in the FT or an amended FT</u>.

Forecast offices should contact the appropriate CWSU's or CFCF to solicit PIREP's or other information, especially when they suspect a possible LLWS problem but lack any specific information. At the same time CWSU's and CFCF should contact the forecast offices and provide them with pertinent reports as they become available.

APPENDIX B

EFFECT OF WIND SHEAR ON AIRCRAFT

(Excerpted from DOT, FAA Advisory Circular 00-50, 4/8/76, Low-Level Wind Shear)

Aircraft performance.

(1) Departure Area. Wind shear can create hazardous conditions during takeoff. The rule of thumb for the effect of wind shear on aircraft performance is as follows:

(a) An increasing headwind or decreasing tailwind when encountered will cause an increase in indicated airspeed. If the wind shear is great enough, the aircraft will initially pitch up due to the increase in lift. After encountering the shear, if the wind remains constant, aircraft groundspeed will gradually decrease and indicated airspeed will return to its original value. This situation would lead to increased aircraft performance. Normally, it should not cause a problem if the pilot is aware of how this shear affects the aircraft.

(b) The worst situation on departure occurs when the aircraft encounters an "altitude" wind on the other side of the front that is a tailwind or rapidly decreasing headwind. Taking off under these circumstances would lead to a decreased performance condition. An increasing tailwind or decreasing headwind, when encountered, will cause a decrease in indicated airspeed. If the wind shear is great enough, the aircraft will initially pitch down due to the decreased lift. After encountering the shear, if the wind remains constant, aircraft groundspeed will gradually increase and indicated airspeed will return to its original value.

(2) The Approach. The most hazardous consequences on approach occur when wind shear occurs close to the ground after power adjustments have been already made during the approach to compensate for wind. Figures 1 and 2 illustrate the situations when power is applied or reduced to compensate for the change in aircraft performance caused by wind shear.

(a) Consider an aircraft flying a 3° ILS on a stabilized approach at 140 knots IAS with a 20-knot headwind. Assume that the aircraft encounters an instantaneous wind shear where the 20-knot headwind shears away completely. At that instant, several things will happen: The airspeed will drop from 140 to 120 knots, the nose will begin to pitch down, and the aircraft will begin to drop below the glide slope. The aircraft will then be both slow and low--a "power deficient" state. The pilot may then pull the nose up to a point even higher than before the shear in an effort to recapture the glide slope. This will aggravate the airspeed situation even further until the pilot advances the power levers

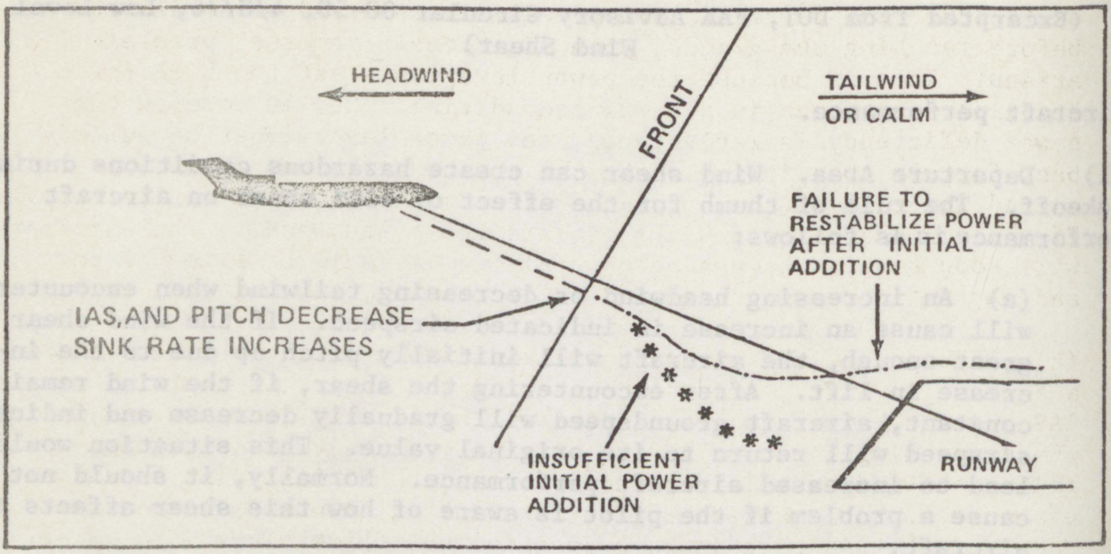

Figure 1.--Headwind shearing to tailwind or calm.

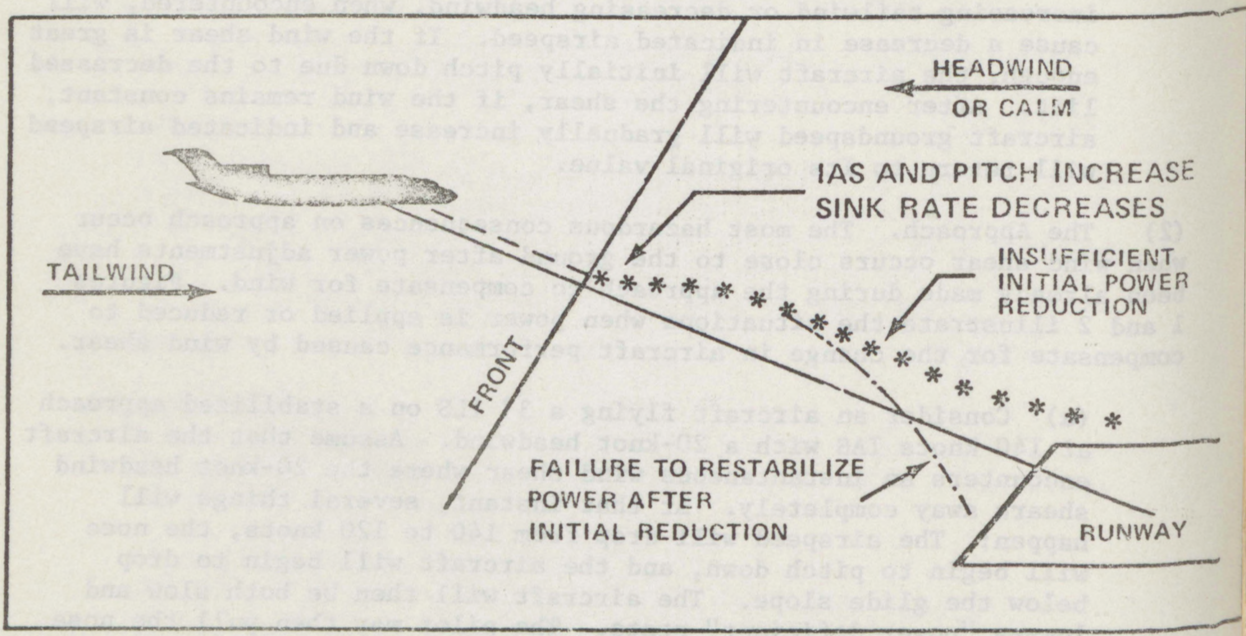

Figure 2.--Tailwind shearing to headwind or calm.

and sufficient time elapses at the higher power setting for the engines to replenish the power deficiency. If the aircraft reaches the ground before the power deficiency is corrected, the landing will be short, slow, and hard. However, if there is sufficient time to regain the proper airspeed and glide slope before reaching the ground, then the "double reverse" problem arises. This is because the power levers are set too high for a stabilized approach in a no-wind condition. So, as soon as the power deficiency is replenished, the power levers must be pulled back further than they were before the shear (because power required for a 3° ILS in no wind is less than for a 20-knot headwind). If the pilot does not quickly retard the power levers, the aircraft will soon have an excess of power--i.e., it will be high and fast and may not be able to stop in the available runway length (Figure 1).

(b) When on approach and in a tailwind condition that shears into a calm or headwind, the reverse of (a) is true. Initially, the IAS and pitch will increase and the aircraft will balloon above the glide slope. Power should initially be reduced to correct this condition or the approach may be high and fast with a danger of overshooting. However, after the initial power reduction is made and the aircraft is back on speed and glide slope, the "double reverse" again comes into play. An appropriate power increase will be necessary to restabilize in the headwind. If this power increase is not accomplished promptly, a high sink rate can develop and the landing may be short and hard (Figure 2).

APPENDIX C

THE AIR WEATHER SERVICE WIND-SHEAR ADVISORY PROGRAM

The Air Weather Service began a Wind-Shear Advisory Program on March 1, 1978. It was structured to provide advisories of significant wind shear in the layer from the surface to 2000 ft (600m) in the vicinity of the airfield for fixed-wing and rotary-wing aircraft. A description of the program follows:

In section 2a., "Wind-Shear Forecasting Rules of Thumb," application of Rules 2 and 3 would give average vertical wind shears in the 2000 ft (600m) layer of $\geq .75$ and $\geq .875\ ms^{-1}/30m$, respectively. The rules imply that the shear must be considerably greater in some layer, probably close to the surface, for these values to be significant. An inversion would be necessary, suggesting that Rules 2, 3, and 4 are nighttime versions of Rule 1, and that they also are equivalent to Rule 7, the existence of a low-level jet.

Application of the rules in section 2b. is limited to semi-arid areas. Downdrafts of rain-cooled air, further aggravated by rapid evaporational cooling in the very dry air below the cumuliform cloud, produce gust fronts with strong winds when they spread out near the surface.

Rule 6 includes Sowa's (34) criteria.

LOW LEVEL WIND SHEAR ADVISORY PROGRAM

INTRODUCTION

The AWS low level shear advisory program consists of two parts: issuance of advisories and collection of data.

A. The following will be incorporated into the unit's existing Met Watch program. Advisories will be issued for the airspace (surface to 2000 feet) within a 5 NM radius of the airfield. (Exception: 10 NM for wind shear associated with thunderstorms). Advisories can be based on observed (PIREPs) or forecast wind shear conditions. Advisories based on forecast wind shear will not be issued when a forecaster is not on duty, however, the observer may issue advisories based on pilot-reported wind shear. In accordance with AWSRs 105-15 and 105-17, wind shear advisories based on pilot reports will be issued locally as PIREPs.

B. Advisories should be phrased in terms that cannot be misinterpreted. Examples of suggested advisories are:

"Wind shear below 2000 feet reported outer marker BLV RWY 31. C-9 dropped 500 feet in 5 seconds. Severe turbulence encountered".

"Wind shear reported on final. KC135 gained 25 knots between 600 and 400 feet followed by a loss of 40 knots between 400 feet and surface".

"Wind shear below 2000 feet at ______________ AFB from 07/2300Z to 98/0300Z due to front. Wind at 2000 feet 200/45 kt and winds at 1000 feet 020/08 kt."

"Wind shear below 2000 feet at ______________ AFB due to low level jet from 0800 to 1100Z."

"Wind shear below 2000 feet due to thunderstorms can be expected within 10 NM (16 km) of ______________ AFB from 1330 to 1500Z."

C. Advisories will be disseminated to all required agencies in accordance with existing local procedures. These procedures must insure that the wind shear advisories are relayed by appropriate agencies to all departing and arriving aircraft. (See AFR 55-48, paragraph 3-2 ab).

D. Record advisories in accordance with AWSR 105-15, paragraph 9.

E. Forecasting Aids. To assist in the forecasting of wind shear, various aids are provided. These forecasting aids were developed from combinations of various methods and source material. They may require adjustment after we gain some experience and evaluate/verify data inputs. Use the rules provided as much as possible, but they should be tempered by your experience, local conditions and sound meteorological reasoning. Forward comments on the aids' usefulness and suggested changes through channels to AWS/DOU. Aids included are: (1) a shear; (2) rules of thumb, (3) vector wind difference tables to determine the magnitude of wind shear; (4) a nomogram relating speed of surface wind, tempreature difference across the front, and degree of turbulence; (5) a wind shear forecast checklist; and (6) a companion logic diagram.

1. <u>Meteorological Conditions.</u> Certain meteorological situations can produce wind shear hazardous to aircraft operations. These include the following:

a. <u>Thunderstorm Gust Front.</u> Clues to its location include rapid changes in wind direction and speed and pressure jumps noted on a barograph trace.

b. <u>Frontal Boundaries.</u> Wind direction and speed changes across frontal slopes create shear. Also, watch for minor troughs or wind intensification embedded in prevailing strong wind flow. Each frontal passage (FROPA) has to be considered according to its vertical structure. Low level wind shear may occur at your station up to 6 hours in advance of a warm frontal passage. Shear associated with approaching warm fronts is potentially one of the most dangerous types of low level wind shear an aircraft can encounter but often is not accompanied by turbulence. After a warm front passes a station low level wind shear associated with a frontal zone disappears. For cold front passage low level wind shear can exist 1 to 2 hours after FROPA or until the depth of the cold air reaches the gradient level.

c. Low-Level Jet. This phenomenon occurs frequently in mid-western plains states during the summer, mostly during night or early morning hours. The term "low-level jet" as used in this advisory program refers to a wind speed profile comprising, typically, 0-8 knots at the surface increasing with height to 25-40 knots or more at approximately 650-1500 feet (AGL) and then decreasing in speed with height to approach the gradient level wind speed, typically 15-30 knots.

d. Mountain Wave Conditions. The wind component normal to the top of the mountain range is 25 kt or greater and winds increasing with heights.

e. Gusty Surface Winds. A sudden brief increase in the speed of the wind. Consider terrain induced eddies, chinook winds, and other local effects such as Santa Ana winds in this category.

f. Land and Sea Breeze Interface. The complete cycle of diurnal local winds occuring on sea coasts due to difference in surface temperature of land and sea. This includes a persistent marine inversion layer such as that found in the San Francisco area.

g. Low Level Inversion with light surface winds and a strong gradient level wind (2000 feet).

2. Windshear Forecasting Rules of Thumb.

a. The British Meteorological Office has developed some rules for forecasting low level wind shear. These rules have been modified for use in this low level wind shear advisory program. The rules may be applied to forecast or observed conditions. However, the rules are not inclusive and advisories should be issued for local effects not covered by the rules (e.g., mountain waves, land-sea breeze interaction, local terrain effects, etc.). The gradient level is assumed to be 2000 feet above the station. Expect wind shear:

Rule 1. When the sustained surface wind is 30kt or greater.

Rule 2. When the sustained surface wind is 10kt or greater and the difference between the gradient wind speed and two times the surface wind speed is 20kt or greater.

Rule 3. When the sustained surface wind is less than 10kt and the absolute value of the vector difference between the gradient wind and the surface wind is 35kt or greater.

Rule 4. When the sustained surface wind is less than 10kt and the absolute value of the vector difference between the gradient wind and the surface wind is 30kt or greater and the inversion or isothermal layer is present below 2000 feet.

Rule 5. When thunderstorms are observed or forecast within 10 n.mi. of the airdrome.

Rule 6. When there is a frontal surface approaching or passing the base with either:

a. A vector wind difference across the front with a magnitude of 20kt or more per 50 n.mi.

b. A temperature difference across the front of 10 degrees F (5 degrees C) or more per 50 n.mi. or,

c. A frontal speed of 30kt or more.

Rule 7. When a significant low level jet is suspected or reported below 2000 feet.

b. Continental Air Lines uses the following criteria to alert aircrews to the potential for low level wind shear due to high level showers and thunderstorms. When these conditions exist aircrews and forecasters are reminded to ask for PIREPs from flights in the area.

(1) Cloud bases 8000' AGL

(2) Surface temperature 80°F

(3) Surface temperature/dew point spread 40°F

(4) Virga, RW or TRW within 10 n.mi. of approach zone.

NOTE: These rules apply to the western United States.

3. <u>Calculation of Vector Difference</u>. Some of the rules given above require that the wind vector difference be computed. Tables are provided to simplify those calculations. To use the tables:

Procedures	Example
a. Determine the angular difference between the two winds	Wind "A" is 030/11, wind "B" 110/19. Wind "A" 030°, wind "B" 110°. Difference is 080°
b. Select the table that corresponds to the angular difference between the two wind directions.	Use Table 3, page 21.

Procedures

c. Enter the table with the speeds for each wind, after rounding them to the nearest 5 knots, and read the resulting vector difference at the intersection.

Example

Wind "A": 11 knots, rounded to 10.
Wind "B": 19 knots, rounded to 20.
Entering the table and reading at the intersection, the result is 22 knots, the vector difference.

(Continued from inside front cover)

WBTM FCST 15 Weather Bureau Forecast Verification Scores 1968-69 and Some Performance Trends From 1966. Robert G. Derouin and Geraldine F. Cobb, May 1970. (PB-192-949)

NOAA Technical Memoranda

NWS FCST 16 Weather Bureau April 1969-March 1970 Verification Report With Special Emphasis on Performance Scores Within Echelons. Robert G. Derouin and Geraldine F. Cobb, April 1971. (COM-71-00555)

NWS FCST 17 National Weather Service May 1970-April 1971 Public Forecast Verification Summary. Robert G. Derouin and Geraldine F. Cobb, March 1972. (COM-72-10484)

NWS FCST 18 Long-Term Verification Trends of Forecasts by the National Weather Service. Duane S. Cooley and Robert G. Derouin, May 1972. (COM-72-11114)

NWS FCST 19 National Weather Service May 1971-April 1972 Public Forecast Verification Summary. Alexander F. Sadowski and Geraldine F. Cobb, July 1973. (COM-73-11-55 7-AS)

NWS FCST 20 National Weather Service Heavy Snow Forecast Verification 1962-1972. Alexander S. Sadowski and Geraldine F. Cobb, January 1974. (COM-74-10518)

NWS FCST 21 National Weather Service April 1972 to March 1973 Public Forecast Verification Summary. Alexander F. Sadowski and Geraldine F. Cobb, June 1974. (COM-74-1 1467/AS)

NWS FCST 22 Photochemical (Oxidant) Air Pollution Summary Information. Stephen W. Harned and Thomas Laufer, December 1977. (PB-283868/AS)

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