

DIFFERENTIATING BETWEEN TYPES OF WIND SHEAR IN AVIATION FORECASTING

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Abstract

This paper examines wind shear in the bottom 2,000 feet of the atmosphere in its various manifestations, and discusses the importance of different types of shear to aviation meteorology. These shears are, to a significant extent, part of a continuous spectrum, but the National Weather Service divides them into distinct categories for the purpose of aviation forecasting, i.e., convective low-level wind shear, non-convective low-level wind shear, and turbulence. The author will show how these categories are effective, but at the same time can be misinterpreted if they are not properly defined or applied. The author will also discuss the NWS definitions of LLWS, as applied to TAF and TWEB forecasts and in-flight advisories (AIRMETs and SIGMETs). Three hundred pilot reports of low-level wind shear are analyzed to determine the atmospheric conditions that most frequently trigger pilot reports of low-level wind shear, to determine the frequency of reports versus wind speeds aloft and aircraft size, and to understand the pilot's perspective in the reporting process. It is found that the phenomena reported by pilots as low-level wind shear is often different from that inferred by aviation forecasters when they interpret these reports. Wind shear forecasting practices are also examined, and suggestions are offered that could lead to some clarification and improvement in the forecasting of this complex and multifaceted phenomena.

1. Introduction

The spectrum of wind shears and eddy motions associated with different synoptic, mesoscale, and microscale weather regimes is quite large, and their effects on aircraft performance are complicated in nature. Two of the most important types of wind shear for aviation are those commonly referred to as low-level wind shear, hereafter referred to as LLWS, and low-level turbulence. The term "low-level", as used in this report and also in most aviation forecasting is defined to be within 2,000 feet of the ground.

The segregation of shears into LLWS and low-level turbulence categories is to some extent artificial, since they are part of a continuous spectrum of shears in the boundary layer. For example, large turbulent eddies could be described as quickly changing LLWS. It is possible, however, to make operationally useful distinctions between the two, based on spacial and temporal charac-

teristics. The primary spacial difference between LLWS and low-level turbulence in their more discrete forms is that the first is an organized shear as might be found at the top of a strong inversion overridden by a low-level jet, or at the leading edge of a thunderstorm outflow boundary, and the latter a disorganized, hence turbulent, shear as might be found near the surface on a windy day. In a temporal sense, LLWS can be considered as the shear which changes slowly in time, and turbulence that shear which changes rapidly in time. Non-convective LLWS, for example, as in the case of a nocturnal inversion, usually evolves slowly over the course of a few hours. Convective LLWS changes more quickly, usually over the course of a few minutes as a gust front evolves (using the gust front as the frame of reference). Turbulent shear, on the other hand, changes quite rapidly in time, i.e., every few seconds, in any frame of reference. Being able to determine when these shears exist and being able to distinguish between them is critical to aviation forecasting.

The National Weather Service (NWS) makes several types of aviation forecasts which include LLWS and/or turbulence. Forecast offices, of which there are approximately 120, make terminal forecasts (TAFs) for airports (5 mile radius) and transcribed weather broadcasts (TWEBs) for airport vicinities (50 mile radius) and routes (out to 25 miles either side of the route). The NWS Aviation Weather Center (AWC) in Kansas City, Missouri, makes area forecasts (FAs) for large geographic areas, and issues in-flight advisories (AIRMETs and SIGMETs) which supplement the FAs for hazardous weather.

The NWS forecasts explicitly for non-convective LLWS in TAFs, TWEBs, and AIRMETs. Convective LLWS is implied in any TAF or TWEB that contains thunderstorms, and in any Convective SIGMET. Low-level turbulence, is not explicitly forecast in TAFs or TWEBs. Turbulence, including low-level turbulence, is forecast in AIRMETs and SIGMETs.

This paper will discuss the similarities and differences between non-convective LLWS, convective LLWS, and low-level turbulence, both in terms of their physical attributes and their operational definitions. Aircraft responses to each of these conditions are discussed. Also, three hundred and ninety (390) LLWS reports are examined to determine, when possible, the meteorological conditions that triggered each report, and to determine what patterns exist in reporting practices.

Next, forecast considerations are discussed. The aviation forecaster can use a variety of diagnostic and forecast

tools to distinguish between LLWS and low-level turbulence. Effective forecast formats and strategies are reviewed and inconsistencies in the definitions and reporting of LLWS and low-level turbulence are examined.

Finally, the author makes recommendations for additional research that might result in better quantification of the magnitudes of low-level shear and turbulence, and better operational definitions. Improvements in the understanding of these phenomena could provide forecasters with better tools for making LLWS and low-level turbulence forecasts.

2. Background

a. General boundary layer wind shears

Shear always exists in the boundary layer, which usually extends from a few hundred to a few thousand, and sometimes several thousand feet above the surface. This shear, however, is not usually enough to affect aircraft operations significantly. Within the bottom portion of the boundary layer, called the friction layer, which extends up to a height of maybe 100 to 200 feet AGL, the wind direction is usually nearly constant and the speed increases logarithmically with height. Above the friction layer, through the remainder of the boundary layer, winds begin to adjust to the higher geostrophic winds. This adjustment is usually in the form of an Ekman spiral with the wind turning clockwise with height and increasing in speed exponentially at a decreasing rate until it becomes geostrophic. The shape of an Ekman spiral will depend upon the atmospheric stability profile, cold and warm air advection, and other parameters. Sometimes, these other factors dominate to the point where there is not a recognizable spiral (Badner 1979).

Looking at the picture in terms of energy transfer, from the top of the boundary layer down to the surface, the transfer of geostrophic wind energy is effected primarily by two mechanisms, forced convection and free convection. Forced convection is caused by the geostrophic wind acting on the boundary layer, creating turbulent energy that mixes downward to the surface. Its strength is determined by the strength of the geostrophic wind, the stability profile of the boundary layer, and surface roughness. Free convection originates from the surface and is caused by surface heating. Its strength is determined by the stability profile and the amount of surface heating.

This paper will examine boundary layer shears that are greater than those encountered on a typical day, those that are strong enough to affect aircraft operations in a significant manner. These shears will be divided into two types, LLWS and low-level turbulence, with LLWS being subdivided into non-convective and convective categories.

b. LLWS

LLWS results from a decoupling or discontinuity in the vertical wind field. It can be either convective or non-convective in origin. For aviation purposes, the NWS Operations Manual (WSOM), Chapter D-31, addresses

non-convective LLWS explicitly; convective LLWS is implied in any forecast that contains thunderstorms.

The WSOM defines LLWS that is to be included in TAF and TWEB forecasts in Chapter D-31, Section 7.2.8 (NWS 1997). **LLWS is a vector change in the wind of 10 knots or more per 100 feet of vertical distance in a layer more than 200 feet thick within 2,000 ft of the surface, that is not convective in origin.** LLWS is also included in the forecast if pilot reports (PIREPs) are received that are 20 knots or more that "the forecaster determines... reflect a valid non-convective LLWS event rather than mechanical turbulence due to strong surface winds." This magnitude of LLWS is considered sufficient to have a significant negative impact on aircraft operations. WSOM Chapter D-31 states that this shear may be associated with frontal passages, inversions, low-level jets, lee side mountain effects, sea breeze fronts, and Santa Ana winds. As will be discussed in later sections, however, wind shears in some of these conditions, most specifically fronts, will meet the Chapter D-31 20 knots in 200 feet definition of LLWS only in extreme cases. Most of the wind energy in frontal zones manifests itself as turbulence.

Other organizations and agencies have also recognized specific magnitudes of vertical shear as being significant for aircraft operations. The World Meteorological Organization (WMO) has suggested (Badner 1979) that vertical shears on the order of 10 knots per 100 feet are likely to "affect" Category I (large) aircraft. For Category II and III operations (medium-sized and small aircraft), they suggest a threshold of 5 knots per 100 feet. The FAA (FAA 1977) has referenced the 5 knots per 100 feet value as causing "significant" shear. ICAO (1987) characterizes 5 knots per 100 feet shear as moderate in intensity, and 10 knots per 100 feet shear as strong; shear above 12 knots per 100 feet is classified as severe.

For AIRMETs the WSOM (NWS 1991), Chapter D-22, In-flight Aviation Weather Advisories, Section 8.2.4, defines LLWS qualitatively, in contrast to the quantitative TAF definition. (Note: D-22 is currently being rewritten as D-32, but the draft for D-32 still has the same definition of LLWS as D-22 as of this writing.) It does not specify a specific shear magnitude, but rather the weather conditions in which LLWS can exist. These include: warm fronts, cold fronts, low-level jets above nocturnal inversions, cold-surface inversions (e.g., cold-air damming), friction-surface slowing (i.e., high winds interacting with terrain), nocturnal-valley inversions, and sea breeze fronts.

Non-convective LLWS results from a vertical decoupling of winds. It is associated with a boundary between different wind regimes that is usually oriented horizontally or quasi-horizontally (Djuric 1994; Houghton 1985). The disparate wind regimes can exist in such close proximity without losing their separate identities because of significant differences in their respective environments. Typically, a cool layer is trapped under a warmer atmosphere in an inversion. Very strong wind shears can develop at the interface due to the lack of mixing or "intermingling" between these environments.

Nocturnal inversions, which are often created by surface radiation under clear skies, produce some of the

best examples of non-convective LLWS. Valleys can intensify inversion development through cold air drainage (Badner 1979). To get significant LLWS, prevailing winds need to be light enough for the inversion to form but strong enough to favor low-level jet development just above the inversion once it has formed. The LLWS is located at the interface between the top of the inversion and the winds just above the inversion. Winds below the interface are often light, while winds above the interface are stronger and/or from a different direction. A supergeostrophic wind maximum that is 15% to 45% greater than the prevailing geostrophic wind can exist just above the inversion, often associated with a low-level jet of 50 knots or more (Beyrich and Klose 1988; Langland et al. 1989; Estournel and Guedalia 1990; Singh et al. 1993).

In contrast to a typical valley-aided nocturnal inversion, as described above, mountain-valley circulations can sometimes produce the opposite condition. In this situation, supergeostrophic flow develops near the ground, under an inversion cap, with lighter winds aloft (Koracin 1994).

Marine layers, such as on the West Coast during the summer, can produce very strong cases of non-convective LLWS (Carl Maddox 1998, personal communication). Temperature changes of 7 or 8°F in a couple of hundred feet can create LLWS of 15 knots or greater for small aircraft at the top of the layer. Typically, a marine layer increases in depth with time, with the top of the inversion lifting from around one thousand feet to four to five thousand feet through a 4- to 5-day period. Santa Ana winds coming down from the mountains and riding up over the top of this layer can accentuate this condition, producing very strong LLWS (Maddox 1998, personal communication).

Sea breeze fronts can also create non-convective LLWS (Chiba 1993; Krauss et al. 1990), although the depth of the sea breeze changes fairly rapidly with time, increasing a few thousand feet from mid-morning into the afternoon hours. If the sea breeze front is strong enough, and if there is a prevailing wind above the front, the vector change in winds aloft can meet the NWS non-convective LLWS criteria. An extreme case of this is when the West Coast marine layer moves onshore during the daytime as a sea breeze front and is overridden by a Santa Ana wind.

Wind shears across frontal boundaries don't usually meet the LLWS criteria in the WSOM for inclusion in TAFs. The shear across the frontal transition zone is usually more characteristic of turbulence. However, if the front is extremely strong, wind shears across a frontal boundary can meet NWS non-convective LLWS criteria (Gera and Weill 1991; Ray 1986). Badner (1979) suggests that a temperature contrast across a front of 10° F per 50 nm and a vector wind change of 20 knots, might be a minimum criteria for affecting aircraft operations, but this would be for shears on the order of 5 knots per 100 feet, or about half of the threshold for LLWS in TAFs.

Cold fronts can produce some of the strongest frontal shears, with the cold air wedge increasing in thickness after frontal passage to more than 2,000 feet in less than an hour. Strong downslope winds overriding shallow cold

fronts can produce strong LLWS. An example of this is Chinook winds overriding shallow arctic fronts in the lee of the Rockies (Ray Wolf 1998, personal communication). In the case of a warm front, the height of the frontal surface over a given point will usually change more slowly in time due to the shallow angle of the wedge (relative to a cold front). Wind shears associated with cold fronts are in the vicinity of or behind the front's surface position, while wind shears associated with warm fronts are ahead of its surface position. In addition, fronts that result from cold-air damming accompanied by overrunning, as occur for example in the Virginia and Carolinas piedmont during the cooler part of the year, can produce some significant shears.

Even though extremely strong fronts can produce NWS criteria, non-convective LLWS, most shears are 5 knots per 100 feet or less, as was shown for the case of a strong arctic front by Miller et al. (1996). The author developed a survey that was given to several pilots at fly-in's in North Carolina during 1993 and 1994. Results of this survey, along with conversations with pilots, tend to confirm that the great majority of traverses through frontal boundaries are experienced as turbulence, or quickly changing LLWS, and not the decoupled, slowly changing LLWS forecast in TAFs and TWEBs.

Wind shears associated with mountain waves on the lee side of mountains can also reach within 2,000 feet of the ground on occasion (ICAO 1987; NWS 1997), especially in the vicinity of low-level rotor clouds that are often associated with mountain waves (NWS 1974). Shears associated with these phenomena can be extreme.

Convective LLWS is associated with showers and thunderstorms. It results from the discontinuity between the ambient environmental winds and the gust front, and from discontinuities within the outflow region behind the gust front (Badner 1979). The first area where LLWS is encountered is at the leading edge of the gust front, and in particular at the gust front nose, which is often elevated and forward of the surface gust front position. Behind the nose is the outflow head, which transports high momentum air downward and which can also contain LLWS. Behind the head is the wake region, which is known for intense low-level turbulence. Behind the wake region is the main downdraft associated with the rain shaft; strong LLWS can exist at the interface where the downdraft begins. This is an idealized view of a thunderstorm outflow region. In actuality, this picture will change depending upon the symmetry of the outflow, or lack thereof, the strength of the outflow, and the stage of development. Also, outflow regions from different thunderstorms can interact, further complicating the situation.

The width of the downdraft usually ranges from several hundred meters to a couple of kilometers, spreading in its horizontal phase to between several kilometers and several tens of kilometers across (Caracena et al. 1989, 1990; Fujita 1985; Kessler 1985). In their most intense form, downdrafts and the resulting outflows are referred to as downbursts. Microbursts are a subset of downbursts at the smaller end of the downburst scale in terms of physical dimensions that can generate shears even stronger than larger downbursts (Fujita 1985).

c. Low-level turbulence

Chapter D-22, Section 8.2.3 (NWS 1991) states that turbulence due to strong surface winds should be included in in-flight advisories. If sustained surface winds of 30 knots or more are expected or occurring, then an AIRMET is issued. If severe or extreme turbulence due to "strong low-level winds" is forecast or occurring, then a SIGMET is issued.

The wind shears associated with low-level turbulence usually occur at a smaller, more irregular scale than either convective or non-convective LLWS, and consist of eddies or waves on the order of a few meters to a few hundred meters across (Ellsaesser 1960; Waters 1970). Low-level turbulence results primarily from: 1) mechanical mixing caused by high winds aloft mixing down to the surface and interacting with the terrain, 2) solar heating, 3) convection (i.e., showers and thunderstorms), 4) frontal surfaces and boundaries, 5) gravity waves, and 6) aircraft wake effect. Over rough terrain, even light to moderate winds can produce significant turbulence (Dornbrack and Schumann 1993).

Some of the mechanisms listed above as causing low-level turbulence also cause LLWS. This shows the inter-related nature of the two phenomena. For example, the strong shears that can exist in fronts and at the top of nocturnal inversions will also create turbulence at boundary interfaces. In fact, the vast majority of fronts do not have decoupled shears strong enough to meet LLWS criteria, and are rather narrow zones of turbulence separating different air masses with different mean vector winds. Even LLWS associated with nocturnal low-level jets and inversions will brake up in the morning into an elevated layer of turbulent mixing while dissipating.

Another example of the close relationship between LLWS and low-level turbulence is seen in thunderstorm environments. Strong LLWS can exist at the leading edge or nose of the gust front, usually accompanied by turbulence, translating to all turbulence behind the gust front and head in the wake region. The turbulence in the wake region can be intense in nature. The distinction between LLWS and low-level turbulence in this kind of environment can, therefore, be hard to define. The turbulence in thunderstorms can often pose as great a risk as the LLWS.

Clear-air turbulence (CAT) and most mountain wave turbulence occur above 2,000 ft AGL. However, rotors associated with mountain waves can extend to within 2,000 ft of the surface and sometimes to the surface itself (ICAO 1987; Holets and Swanson 1988).

d. Effects of LLWS and low-level turbulence on aircraft performance

Non-convective LLWS, convective LLWS, and low-level turbulence can all affect aircraft performance, sometimes to the extent that an accident results. Sometimes these phenomena will occur together, as is the case with thunderstorms, which produce both LLWS and low-level turbulence. The pilot's response to perceived and real conditions determines how well the aircraft will respond to the rapid changes associated with wind shear and turbulence.

This response can be to change the aircraft's power settings and/or its attitude (angle of attack or pitch). These changes will in turn alter the aircraft's IAS (indicated air speed) and/or its climb or descent rate. An aircraft's size, weight, and speed are also critical factors in determining its response to a given shear environment.

A pilot encountering non-convective LLWS has a few options. If the shear is an increasing tailwind, the pilot can increase power to increase IAS. This will prevent decreased lift to the wings, which diminishes the response of control surfaces and drops the aircraft below the desired flight path or glide slope or may even stall the aircraft (FAA 1984; ICAO 1987). If the shear is an increasing headwind, the pilot will usually cut back on power; otherwise the aircraft will rise above the desired flight path or glide slope. If the pilot is unsure about the direction of the shear, or thinks that the reported (or forecast) non-convective LLWS might really be low-level turbulence, he or she will usually increase power to be on the safe side. For some situations a change in the aircraft's attitude or pitch can help accomplish the desired results in non-convective LLWS encounters.

A pilot's response to convective LLWS will often need to be different from that for non-convective LLWS. Operationally, the primary difference between non-convective LLWS and convective LLWS is that while non-convective LLWS usually presents the pilot with one wind shift or vector wind change, convective LLWS often presents the pilot with multiple wind shifts along the flight path. In an idealized scenario, an aircraft may first experience a headwind, followed by a downdraft, followed by a tailwind (FAA 1990). If, on encountering the initial headwind, the pilot reduces power, the aircraft will have little or no speed margin (the difference between airspeed and stall speed) when it encounters the downdraft. Three things happen to the aircraft upon entering the downdraft environment. First, it loses airspeed from the disappearing headwind. Second, it loses part or all of its positive angle of attack due to the vertical wind component downward. And third, it is physically shoved toward the ground. Having made it through the headwind and downdraft phases of the storm, the pilot is now faced with the increasing tailwind phase that further robs the aircraft of lift.

More typically, the aircraft flying into an approaching thunderstorm with a mature outflow region might first go through a gust front, encountering its first LLWS, then go through the head, encountering a strong downdraft, then through the wake region where it encounters strong turbulence, then through the main downdraft interface where it again encounters LLWS, then into the main downdraft itself, and finally through the rear outflow region of the storm. The downdraft in the head region can sometimes be stronger than in the main downdraft. Secondary surges, similar to that in the gust front, can also exist in the outflow region. Such surges, which form behind the initial head, result from multiple main downdrafts, which are caused by thunderstorm cells forming and collapsing in sequence within a given thunderstorm complex.

If the aircraft approaches a thunderstorm from the opposite direction, from the rear instead of head-on, it

would experience these same phenomena in reverse order. To further complicate matters, the scenario will also depend upon the outflow's stage of development, symmetry, and strength. In addition, outflows from entirely independent thunderstorms or thunderstorm complexes can interact with each other. A downburst or microburst will intensify the conditions encountered. Downbursts and microbursts are responsible for a significant number of major aircraft accidents (FAA 1984, 1990).

A pilot encountering low-level turbulence on take-off or final approach on a windy day will usually increase power, although not necessarily as much as for an increasing tailwind LLWS encounter. This will keep the fluctuating air speed from dropping below the stall speed (Aircraft Owners and Pilots Association (AOPA) 1994). This response contrasts to that which would be employed if the aircraft encounters turbulence at cruising speed and cruising altitude; in this case, the pilot would slow the aircraft down to near the maneuvering, or turbulence penetration, speed. The maneuvering speed is a predefined reduced speed unique to each type of aircraft that is designed to minimize excessive wing loading in turbulence. Usually, however, when an aircraft is flying at its cruise speed, it is above 2,000 feet AGL.

In summary, there are distinct differences in both the pilot's and aircraft's responses to LLWS and low-level turbulence. LLWS will usually produce a sustained change in air speed and rate of climb or descent, although in the case of convective LLWS this sustained change may be short-lived. The pilot's response can be to increase, decrease, or maintain power, depending on the situation. If the pilot is facing an increased tailwind and/or downdraft, as would be the case in a strong convective LLWS event such as a downburst, the necessary increase in power can push the aircraft to its operating limits. Low-level turbulence, on the other hand, will usually produce a fluctuating airspeed and rate of climb or descent but with no sustained change in either direction, except when transiting a front or flying through a thunderstorm outflow environment. The pilot will usually increase power to avoid having the air speed drop below the stall speed. Low-level turbulence is often more dangerous to small aircraft than large aircraft because: 1) small aircraft usually operate closer to their stall speed on take-off and landing, and 2) their smaller wings allow them to be influenced by smaller scales of turbulence.

For both LLWS and low-level turbulence, the dangers for approach are different from those for take-off. Approach can be dangerous because the aircraft has downward momentum, is in a nose-down attitude (until final flair out), and has throttled-back engines. It could have a hard time recovering from an unexpectedly strong tailwind, especially in a downburst situation where there is a downward component. On take-off an aircraft has upward momentum, is in a nose-up attitude, and is at full throttle; it is often in a more favorable position to cope with LLWS (AOPA 1994). However, two significant disadvantages on take-off are: 1) that the aircraft weight is usually significantly higher, and 2) that this extra weight is fuel, which will prove more deadly if a crash occurs.

The dangers of LLWS and low-level turbulence also depend on aircraft characteristics, specifically power to weight ratio, engine type, and aircraft size. For example, an aircraft with a low power to weight ratio will be more susceptible to the effects of LLWS than an aircraft with a high ratio because of its longer response time. Likewise, a jet-powered aircraft will usually have a longer response time than a comparable piston-engine propeller aircraft. Lastly, the size of an aircraft will determine its response to different scales of low-level turbulence. For example, a large aircraft will probably not be affected by small-scale turbulence as much as a small aircraft.

The three wind regimes - convective LLWS, non-convective LLWS, and low-level turbulence - are illustrated schematically in Fig. 1. Each of the three presents an aircraft with a different shear scenario.

e. LLWS and low-level turbulence associated with aircraft accidents

The National Transportation Safety Board (NTSB 1998) has developed statistics on wind-related aircraft accidents for 14 categories of wind fields: crosswind, downdraft, gusts, high wind, microburst, mountain wave, tailwind, low-level turbulence, turbulence in clouds, turbulence in thunderstorms, clear-air turbulence, unfavorable wind, updraft, and low-level wind shear. For the 14 year period from 1983 through 1996, the six highest categories, accounting for 71.3% of the fatalities, were: unfavorable wind 15.0%, low-level turbulence 14.7%, downdraft 12.7%, gusts 9.9%, low-level wind shear 9.6%, and high wind 9.4%. It can be seen that low-level turbulence and LLWS account for a significant percentage of the fatalities. If one considers that several of the other categories probably include events in which low-level turbulence or LLWS were factors, then the percentages would be even higher.

Windshear Training Aid, a FAA publication (1990), points in this same direction, concluding that a large percentage of wind-related accidents are related to LLWS and low-level turbulence. It further concludes that most LLWS and low-level turbulence accidents are associated with thunderstorms. One reason for this is that thunderstorms contain both LLWS and turbulence, sometimes at their most violent extremes. Out of 51 fatal accidents reviewed in this document, 33 were caused by thunderstorms, 7 by fronts, 2 by strong surface winds, 2 by unstable or turbulent air, 1 by decoupling associated with an inversion, and 6 by unknown factors. It is interesting to note that only one was caused by the classical non-convective wind shear that is forecast in NWS TAF's and TWEB's as LLWS. Seven events were caused by fronts, which as discussed earlier sometimes, though not usually, meet the NWS criteria for LLWS.

3. Pilot Reports

Pilot reports (UAs) and urgent pilot reports (UUs) of LLWS and low-level turbulence are collected and disseminated by Federal Aviation Administration (FAA) flight service stations and other air traffic facilities. All LLWS reports and low-level turbulence reports of

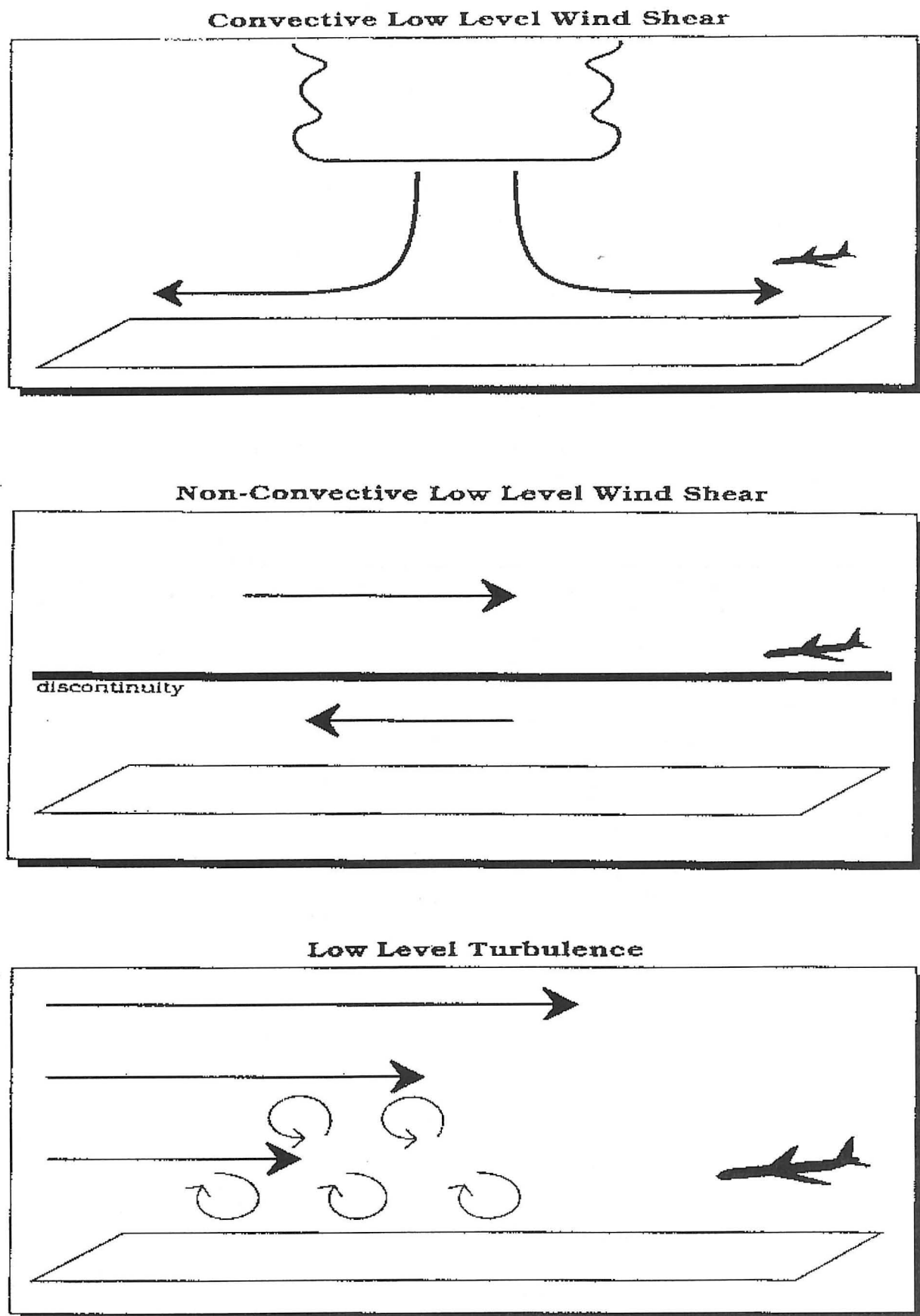


Fig. 1. Schematic illustrations of: a) convective low-level wind shear, b) non-convective low-level wind shear, and c) low-level turbulence.

severe or extreme intensity are disseminated as UUAs (FAA 1993). These reports can vary significantly in format. Pilots sometimes interchange these phenomena when reporting them. For example, a pilot on take-off or landing may report turbulence associated with high gradient winds as MOD or SEV turbulence or as LLWS +/- 10 or 20 knots. The size and speed of the aircraft are critical in determining the effect of a given shear. The pilot of a small, relatively slow-moving aircraft might be more apt to report large-scale turbulence as LLWS than the pilot of a larger, fast-moving aircraft because of the aircraft's longer residence time between apparent wind direction changes. Another example is transit through a frontal zone. The pilot of a jet flying through a very strong front may report the shear as LLWS, whereas the pilot of a slower-moving small aircraft will usually report turbulence.

Three hundred and ninety UUAs (urgent pilot reports) with LLWS from across the U.S. (excluding Alaska and Hawaii) for the spring, summer, fall, and early winter of 1995 were examined to determine the *actual* causative triggers, i.e., non-convective LLWS, convective LLWS, or low-level turbulence. Of these 390 cases, 90 were considered to be non-conclusive (i.e., no determining cause could be ascertained). A probable cause was determined for the remaining 300 cases.

The method of case selection was to choose days at random and examine all cases on those days from across the country. Only those reports that had a wind shear magnitude equal to or greater than 10 knots, specifically used the "LLWS" phraseology, and were within 2,000 feet of the surface were included. Duplicate UAs were excluded.

Cases were analyzed using surface and upper-air data to 850 mb (700 mb at higher elevations), and other data as available such as satellite, profiler, ACARS (Aircraft Communications Addressing and Reporting System), WSR-88D, etc. For each LLWS report, all other pilot reports filed within approximately two hours and 100 miles were collected and examined for relevant information relating to meteorological conditions.

a. *Weather patterns associated with pilot reports of LLWS*

LLWS reports that appeared to be triggered *in fact* by non-convective LLWS totaled 45, or 15% of the total. LLWS reports that appeared to be triggered *in fact* by convective LLWS totaled 66, or 22%. LLWS reports that appeared to be triggered *in fact* by low-level turbulence totaled 189, or 63%. Therefore, only one seventh of all LLWS UA's appeared to be triggered by the classical decoupling that is relevant to TAF and TWEB forecasting, while the great majority were triggered by either convective LLWS or low-level turbulence. An examination of LLWS reports of 20 knots or more and 30 knots or more showed similar percentages.

Overall, the types of conditions that triggered LLWS reports were quite varied. For LLWS reports triggered by low-level turbulence conditions, high winds ahead of and behind cold fronts were the most

common reason. In areas with rough terrain, these winds interacted with the surface to create low-level turbulence. Areas without rough terrain had significantly fewer reports during high wind events, but other mechanisms such as thermals came into play. Thermals or updrafts, created by differential heating, build into an otherwise smooth wind flow, creating turbulence (Streib 1991). Areas in the vicinity of ocean and lake coastlines were also prevalent locations for LLWS reports that were triggered by turbulence.

What is surprising is the small number of LLWS reports that appeared to be associated with true decoupling that meets NWS non-convective LLWS criteria. Of the 45 cases of true non-convective decoupling, 32 were associated with nocturnal inversions and nocturnal low-level jets, 10 were associated with sea or lake breeze fronts or marine layers, and 3 were associated with synoptic-scale fronts. There were several more cases of LLWS pilot reports associated with fronts, but these were judged, based on the data, not to meet NWS non-convective LLWS criteria.

Examples of pilot reports with LLWS and low-level turbulence, along with interpretive comments, are shown in Fig. 2. These examples illustrate the variability in reporting practices.

b. *Frequency and strength of LLWS reports versus magnitude of maximum winds aloft*

The strength of maximum winds within 5,000 feet of the surface was examined for each LLWS pilot report. In addition, the magnitude of the LLWS report itself, i.e., the magnitude of the reported shear (e.g., 10 knots, 20 knots), was compared to the magnitude of the maximum winds aloft. LLWS reports occurred with a wide range of maximum winds, ranging from 10 to 80 knots. Typically, maximum winds of 50 knots or more produced LLWS reporting "events" during which the frequency of LLWS reports was as much as ten times greater per unit time than for moderate winds of 30 knots. These findings agree with a study done in the Midwest and Ohio Valley (Faight and Rosemark 1992), which found that the frequency and magnitude of LLWS reports increased significantly with wind speeds at and above 45 knots.

The magnitude of LLWS was also compared to the magnitude of maximum wind aloft for each of the three types of triggers: convective, non-convective, and turbulence. The results are shown in Fig. 3. The turbulence trigger was associated with the highest synoptic-scale winds and produced the strongest LLWS reports. In other words, many of the strongest LLWS cases of 25 knots or more were caused by turbulence resulting from very strong synoptic scale winds. During high wind days the increase in the frequency of LLWS pilot reports was most dramatic in mountainous areas. Of the 63% of LLWS reports that were triggered by actual low-level turbulence, slightly more than two-thirds were generated in areas with rough terrain. These areas included the Appalachians, the Ozarks, the Rockies, and the Coastal ranges. This large percentage of LLWS reports from mountainous areas shows the large impact that terrain has in producing turbulence in synoptic-scale high wind regimes.

MKL UUA /OV MKL/TM 2053/FL005/TP SF34/TB -15KTS @ 5 HND FT

Remarks: non-convective LLWS being reported as TB.

BFL UUA /OV BFL/TM 0023/FLUNKN/TP C500/RM LLWS FA 75FT AGL -20KTS IAS

Remarks: good report; indicates magnitude and height of LLWS.

COS UUA /OV COS/TM 1839/FLDURD/TP B727/RM LLWS -15KTS FAP 17R

Remarks: don't know altitude although final approach, so can assume within 2,000 ft of ground.

PHX UUA /OV PHX/TM 1917/FL001/TP C172/TB LLWS/RM -20KT LOSS ON SHORT FINAL RY21

Remarks: included LLWS in TB section rather than remarks; otherwise, good report. Meets 20 kt magnitude criteria for TAF/TWEB.

MLI UUA /OV MLI/TM 2117/FLUNKN/TP PAZT/RM LLWS +/- 10KTS FA 05 200AGL

Remarks: use of "+/-" very common; could mean that report is for LLWS but is not specific as to whether aircraft speed increased or decreased, but more likely means that aircraft is experiencing speed variations of +/- 10 kts due to turbulent eddies (low-level turbulence).

HVN UUA /OV HVN/TM 2135/FLUNKN/TP AT42/RM LLWS +20/-10KTS 004-003

Remarks: indicates an increase in speed followed by a decrease; probably LLWS but possibly low-level turbulence.

ERI UUA /OV ERI/TM 0214/FL020/TP MD80/RM LLWS +/- 15 KT FL020-SFC

Remarks: reporting through layer from 2,000 ft to surface so probably low-level turbulence.

IPT UUA /OV IPT/TM 1735/FLUNKN/TP PA28/TB MOD-SEV/RM 002-SFC TURB GOT STRONGER NEAR THE SFC

Remarks: good report; low-level turbulence being reported as such.

ASE UA /OV FA RY15/TM 2238/FL004/TP DH7/TB LLWS +/-20KTS/RM 001-002

Remarks: forgot the "UUA"; therefore, may not alert forecaster. See also remarks for MLI UUA above.

Fig. 2. Examples of pilot reports of low-level wind shear (LLWS) and low-level turbulence (TB).

c. LLWS reports versus aircraft size

Cases were further stratified by aircraft size to determine whether or not there was a correlation to magnitude and type of shear. Aircraft were divided into five weight classes based on maximum take-off weight (Arkell 1992). As expected, the highest frequency of reports came from light aircraft. Weight classes one and two, which include

most private aircraft, generated 56% of all LLWS reports. Weight classes three and four, which include most business and commuter aircraft, and light airliners, generated 30%. Weight class five, which includes medium and heavy airliners, generated 14% of all LLWS reports. A survey of pilot reports of *all types* (Arkell 1991) indicated that weight classes one and two filed 65% of all reports, weight classes three and four 20%, and weight class five 15%.

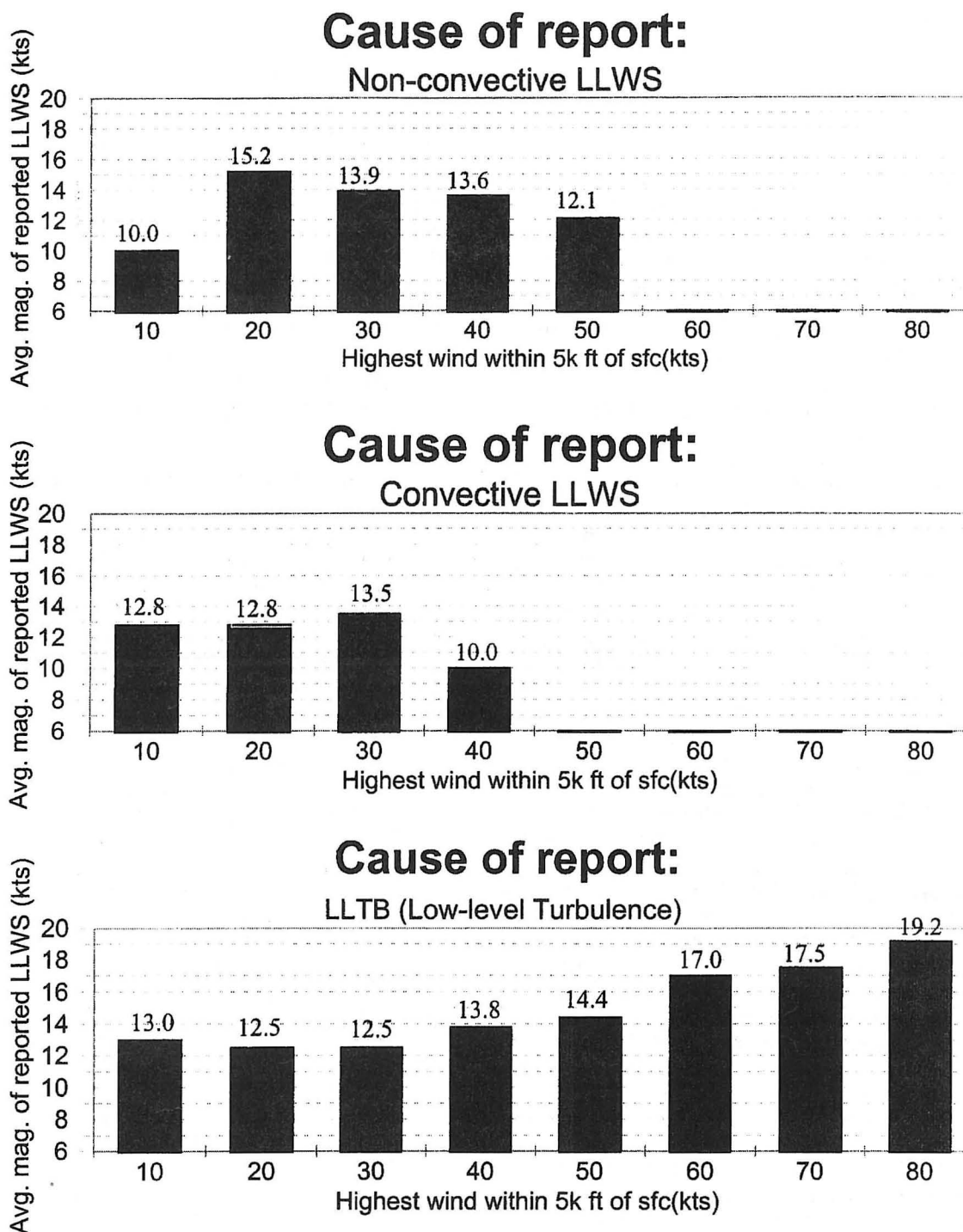


Fig. 3. The magnitude of low-level wind shear (LLWS) in pilot reports versus the magnitude of the maximum environmental winds within 5,000 feet of the surface for non-convective LLWS, convective LLWS, and low-level turbulence (LLTB) environments.

Therefore, the correlation of LLWS reporting frequency to weight class was similar to that for all reports in general.

The LLWS reports were further analyzed by weight class for each of the three triggering mechanisms: non-convective LLWS, convective LLWS, and low-level turbulence. The percentage breakdown by weight class for each of these triggers was similar to the percentages for all LLWS reports taken together.

Lastly, the average magnitude of LLWS reports was computed for each of the five weight classes. The results were as follows: weight class one 14.8 knots, weight class two 13.7 knots, weight class three 13.5 knots, weight class four 13.4 knots, and weight class five 13.1 knots. It is surprising that large aircraft are affected almost as much as small ones, the average magnitude of reports for weight class five being only 1.7 knots lower than that for weight class one.

4. Discussion

a. Distinguishing between LLWS and low-level turbulence

LLWS and low-level turbulence are part of a spectrum of conditions that exists in non-uniform wind fields. Differences between the two result primarily from differences in scale, symmetry, and origin. Sometimes LLWS and low-level turbulence can exist in close proximity in the mesoscale and microscale environments. For example, some of the most dangerous low-level turbulence is that which is associated with convective LLWS in thunderstorms. In addition to being dangerous in its own right, low-level turbulence in thunderstorms can mask the sometimes more dangerous LLWS and delay recognition and response by the pilot.

Another complicating factor in differentiating between LLWS and low-level turbulence is that the phenomena reported by pilots is sometimes different from that which is actually occurring. The type and size of aircraft, the air speed, the ascent or descent rate, and the experience level and judgement of the pilot determine whether LLWS or low-level turbulence is reported. A survey by Jackson (1992) found that there is a lack of consensus among pilots concerning the use of low-level wind shear terminology.

Whereas pilots sometimes do not have the frame of reference, the necessary data, or the time to distinguish between LLWS and low-level turbulence, forecasters often do have the time and the tools to do this. They can use surface and upper-air analyses, wind profiler data, WSR-88D VAD wind profiles, ACARS data, other UAs, and forecast guidance to help delineate between the two conditions. As specified in WSOM Chapter D-31, Section 7.2.8, LLWS is included in a TAF if: 1) a UA of LLWS of 20 knots or more within 2,000 feet of the surface is received *which the forecaster determines is based on valid (non-convective) LLWS rather than low-level turbulence due to strong winds*, or 2) the analyzed and/or forecast low-level conditions indicate a shear of "10 knots or more per 100 feet in a layer more than 200 feet thick."

TAF and TWEB forecasts sometimes incorrectly include non-convective LLWS in a forecast based on UAs that were triggered *not* by non-convective LLWS, but rather by convective LLWS or low-level turbulence. It is essential for the forecaster to know the difference between these phenomena so that he or she does not provide incorrect or misleading forecast information to the pilot.

One of the most common errors in the TAF and TWEB forecasts is to include LLWS on high wind days when, although pilots are reporting LLWS, what is *in fact* occurring is low-level turbulence. The first thing that the forecaster should look at in these situations is the synoptic environment. For example, a typical environment for non-convective LLWS is a clear night with a nocturnal inversion overridden by a low-level jet; light winds below the inversion are decoupled from higher geostrophic or super-geostrophic winds above. The environment for low-level turbulence, on the other hand, is typically blustery, windy conditions, which result from a high synoptic-scale, or sometimes mesoscale, pressure gradient. The sustained vertical shear associated with the non-convective LLWS is

very strong but only through a very thin vertical layer at the top of the inversion. Although the instantaneous shears associated with low-level turbulence can be stronger than those of non-convective LLWS, the sustained mean shear through the entire vertical column is not as strong. Non-convective LLWS must be at least 10 knots per 100 feet for more than 200 feet in the vertical to be included in a TAF forecast. The sustained mean shear associated with high winds mixing down to the surface is usually on the order of 10 to 15 knots per 1,000 feet, or 1 to 1.5 knots per 100 feet (Knapp and Dumais 1995). Therefore, the sustained vertical shears associated with low-level turbulence are usually only 10 to 15 percent of the minimum requirement for non-convective LLWS, although they act through a much deeper layer.

There are rare cases when the sustained vertical shear through a column associated with low-level turbulence can be as much as 50% of the minimum requirement for non-convective LLWS. Badner (1979) discusses the differences between the decoupling shear, usually associated with fronts and inversions, and turbulent shear in *Low-Level Wind Shear: A Critical Review*. Based on this report, the combination of high gradient winds on the order of 60 knots or more and a rough surface can, in extreme cases, produce low-level vertical shear on the order of 10 knots per 200 feet. This is still only half the gradient required to include as LLWS in the forecast. It should be remembered, however, that stronger *instantaneous* shears, greater than those associated with non-convective LLWS, can exist within the convective environment associated with convective LLWS and the turbulent environment associated with low-level turbulence.

b. Forecasting LLWS and low-level turbulence

1) Non-convective LLWS

Non-convective LLWS can be forecast with some skill in cases involving nocturnal decoupling associated with nocturnal jets and/or cold air drainage. It can, on some occasions, also be forecast for synoptic-scale fronts, sea-breeze fronts, cold-air damming events, marine layers, and similar phenomena. In the case of fronts, three limitations need to be taken into account in the forecasting of LLWS. First, the height of the frontal interface above the surface can change rapidly with time. Second, the interface may be above the 2,000 foot upper limit for TAF and TWEB forecasting. And third, the shear across the interface will be less than the "10 knots per 100 feet for more than 200 feet" requirement in the vast majority of cases.

The transient nature of cold fronts in the vicinity of airports can be demonstrated with a few simple calculations using nomograms in Badner (1979). A cold front moving at 30 knots will move through the 10-statute mile diameter TAF forecast area in just under 20 minutes. If the front has a slope of 1/25, it will take just over 16 minutes at any given location to rise from the surface to 2,000 feet, and it will be resident within the 10-mile diameter 2,000-foot deep forecast volume for only 36 minutes. The same calculations for a warm front with a slope of 1/200 moving at 15 knots yields corresponding times of 4 hours 20 minutes and 5 hours.

The key in LLWS forecasting is to be proactive. UA reports can be extremely valuable, but the forecaster should also use surface and upper-air analyses, wind profiler data, WSR-88D VAD wind profiles, ACARS data, and forecast guidance to help forecast non-convective LLWS *before* it is reported by pilots. The VAD wind profile can be especially helpful in determining if a low-level jet is present or forming.

Forecasting LLWS usually requires ascertaining whether or not various meteorological elements will come together in such a way as to create the condition. For example, a forecast of moderately strong low-level winds, combined with a forecast of clear skies and strong radiant cooling, would usually be favorable for LLWS. If, however, low-level winds are too strong, inversion development may be inhibited. Some parameters, such as the Richardson Number (Ri), have potential for use in forecasting LLWS, when applied to the lowest 2,000 feet of the atmosphere (Don McCann 1999, personal communication).

The aviation forecaster should be as specific as possible in non-convective LLWS forecasts, including, when known, the height of the inversion, and the wind direction and speed above it. For example, for an inversion at 1,500 feet with a 30 knot south wind above it, the forecaster would include WS015/18030KT in the TAF.

The NWS Aviation Weather Center (AWC) forecasts non-convective LLWS in the turbulence section of in-flight weather advisories if the coverage is expected to be over an area of at least 3,000 square miles. An example might be: "LLWS POTENTIAL OVR W TEXAS ENDING BY 14Z." It must be remembered, however, that in-flight weather advisories include "frictional-surface slowing" (low-level turbulence caused by high winds) in its definition of non-convective LLWS in the WSOM, Chapter D-22.

2) Convective LLWS

The forecaster should be as specific as possible when including thunderstorms, which imply convective LLWS, in aviation forecasts. This is especially true for TAFs and TWEBs because of their high spacial and temporal resolution. As was discussed in previous sections, convective LLWS associated with thunderstorms is more common than non-convective LLWS and is also one of the greatest causes of aircraft fatalities, especially in downburst events.

Using WSR-88D data, satellite data, and forecast guidance, the forecaster should provide as much information as possible on probability, timing, and intensity (as indicated by potential wind gusts) of thunderstorms. For example, an 1800Z TAF might have "PROB40 2302 VRB25G40KT 2SM TSRA OVC020CB" for a 40 percent probability of thunderstorms from 2300Z to 0200Z. As the event comes closer in time, the forecaster might refine the probability, time period, and intensity in an amendment that reads "TEMPO 0102 VRB25G50KT 1/2SM +TSRA OVC010CB" for a 50 percent (or greater) chance of severe thunderstorms from 0100Z to 0200Z.

Convective wind shear is implied in any FA or convective SIGMET issued by AWC that contains thunderstorms. Convective SIGMETs can specify thunderstorm intensity, trends, and tops as in the following examples; "LINE SEV

TS 25 MI WIDE MOV FROM 25015KT," and "INTSFYG AREA TS MOV FROM 25030KT. TOPS TO 450."

3) Low-level turbulence

Low-level turbulence is not forecast explicitly in TAF and TWEB forecasts. However, it is usually implied if the wind group contains sufficiently strong sustained surface winds. For example, a TAF wind group of "23024G36" would indicate the strong possibility of low-level turbulence. How much low-level turbulence would result would depend on the character of the terrain in the forecast area, and on atmospheric lapse rates.

In-flight advisories can provide more specific information about low-level turbulence. WSOM D-22 states, "if sustained surface winds of 30 knots or greater are expected ... the AIRMET bulletin header shall contain the statement "FOR TURBC AND STG SFC WINDS VALID UNTIL ddtttt." If severe or extreme turbulence is expected or occurring, then a SIGMET is issued. Forecasts for turbulence in AIRMETs and SIGMETs include altitudes up to 45,000 feet MSL, but can be specific to lower levels. For example, an AIRMET for moderate turbulence might read "OCNL MOD TURB BLW 020 DUE TO STG AND GUSTY LOW LVL WINDS", and a SIGMET for severe turbulence might read "OCNL SEV TURB BLW 060 INVOF MTNS DUE TO STG WINDS."

5. Summary and Conclusions

Both LLWS and low-level turbulence affect aircraft performance. Although there are similarities in the ways these phenomena affect performance, there are differences also. There are also differences in the ways small and large aircraft respond, and in the ways propeller-driven and jet-powered aircraft respond. Both LLWS and low-level turbulence are responsible for a significant number of aircraft accidents, with convective LLWS, i.e., thunderstorms, being one primary culprit, and turbulence associated with high winds being another.

Looking at reporting practices, the results of the statistical analyses show that a large percentage of LLWS pilot reports are associated with convective LLWS and low-level turbulence events. This means that the NWS aviation forecaster, who forecasts explicitly only for non-convective LLWS, should be very careful when using LLWS reports in UAs as a basis for aviation forecasts.

The aviation forecaster should be proactive in the forecast process. With non-convective LLWS, he or she should not wait for pilot reports but rather forecast these conditions when possible. For thunderstorms and their associated convective LLWS, the forecaster should be as specific as possible with regard to the timing and intensity of thunderstorms.

LLWS and low-level turbulence, taken together, are responsible for a significant portion of the loss of life in aviation in the United States. Therefore, reporting and forecasting these phenomena in an optimum manner is of paramount importance. However, the definitions of LLWS and low-level turbulence used by the FAA and NWS are not entirely consistent. This is possibly one reason why forecasters are sometimes inconsistent in their

forecasts, and why pilots and air traffic controllers are sometimes inconsistent in their reports. More coordination is needed within and between agencies to clarify the definitions of, and improve the forecasting of, LLWS and low-level turbulence.

Further research of shears in and just above the boundary layer would be of benefit. Analysis of existing data records, or new measurements using instrumented towers or remote sensing techniques, could better quantify the magnitudes of shears that actually exist. Existing sources of data include instrumented towers at nuclear power plants and boundary layer profilers operated by the NWS and NCAR (National Center for Atmospheric Research). Data from such systems might be able to answer several questions. For example, how often does the magnitude of vertical shear in a cold, warm, or sea breeze front meet the WSOM definition of LLWS (10 knots vertical shear per 100 ft through a depth of at least 200 ft) used in TAF forecasting? Also, how often is the character of this shear in a frontal zone actually more turbulent than decoupled in nature? Lastly, how often does the classic decoupled shear at the top of a nocturnal inversion overridden by a low-level jet meet the WSOM definition?

Current research, such as McCann's (1999) studies on boundary layer turbulence, indicates that one approach is to view these phenomena as part of a continuous spectrum defined by kinetic energy profiles which can in turn be estimated with such parameters as the Richardson number. Being able to answer these and related questions would certainly be of tremendous operational benefit. The potential benefit to the aviation community is evident.

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