UPDATE ON LOW-LEVEL WIND SHEAR FORECASTING

Barry A. Richwien

Center Weather Service Unit
Boston Air Traffic Control Center
Nashua, New Hampshire

Abstract

The National Weather Service (NWS) and Federal Aviation Administration (FAA) jointly sponsored a 6-month test of Northwest Orient Airlines' technique of forecasting low-level wind shear (LLWS) due to conventional fronts. The technique provided that any front moving $\geq$ 30 kt and/or whose temperature difference was $\geq 10^{\circ}$F should produce LLWS significant to aviation operations. This technique was verified by FAA reconnaissance, a Doppler acoustic-radar system, NWS radiosonde winds, and pilot reports.

A major conclusion was that successful and effective diagnosing and forecasting of mainly mesoscale features that produce significant LLWS will require unprecedented dedication of manpower and resources.

1. INTRODUCTION

For this discussion we shall define low-level wind shear (LLWS) to be the vertical shear of the horizontal wind which persists over one location (such as an airport) for 10's of minutes (vs. turbulence-induced shear which lasts only 10's of seconds). Low-level shall be meant to mean below about 600 m. The hazard of this steady-state type of shear to aviation is well documented. Several major airliner crashes of the past 5 years have been attributed, in large part, to this phenomenon. Most famous are the crashes of B727's at both Denver's Stapleton and New York's JFK airport in 1975. The LLWS contributing to those accidents was due to thunderstorms - probably the thunderstorm's gust front.

Less spectacular and more subtle is LLWS caused by warm and cold fronts. Only one clear-cut example of a crash due to the LLWS of a front could be found. It occurred at Boston's Logan International Airport when a DC-10 struck the approach lights due to a LLWS-induced rate of descent. Northwest Orient Airlines has for many years been forecasting frontal LLWS (see Sowa, 1974). Northwest's technique provides that any front whose temperature difference is 6°C or greater, and/or is moving at 30 knots or greater, should produce LLWS significant to aviation operations. Increasing concern about the hazard prompted the National Weather Service (NWS) and Federal Aviation Administration (FAA) to jointly sponsor a test of Northwest's technique. The test was to determine whether or not LLWS wind shear due to warm and cold fronts could be forecast up to 3 hours in advance with sufficient accuracy to be of use to landing and departing pilots.

2. NWS-FAA LLWS TEST

a. Test Particulars

The test was conducted for the six-month period from November 1976 through March 1977 between 0600 and 2200 hours each day of the week. Forecasts of LLWS (called LLWS Advisories) were prepared for 7 east coast airports, namely: Dulles International, Washington National, LaGuardia, JFK, Newark, Philadelphia and Atlantic City (home of the FAA National Aviation Flight Experiment Center, NAFEC). Advisories were prepared by NWS Forecast Offices in Washington, D.C., Philadelphia and New York City. They were then forwarded via direct telephone lines to the FAA Systems Command Center in downtown Washington, D.C. There, 1 of 2 meteorologists specially assigned for the test forwarded the Advisories to appropriate FAA towers and Air Route Traffic Control Centers via direct telephone lines. FAA tower personnel then recorded the information on Automatic Terminal Information Service (ATIS) or, if that was not available, the Advisory was verbally relayed to landing and departing pilots.

The initial format of the Advisories was very similar to that of Northwest Airlines and was as follows:

LOW-LEVEL (abrupt/gradual)

(cold/warm) FRONTAL WIND SHEAR (WITH (moderate/severe) TURBULENCE (cross out if not applicable)) IS EXPECTED AT (airport) BETWEEN ___Z AND ___Z. WIND BELOW FRONTAL SURFACE FROM ___ DEGREES AT ___ KNOTS AND WIND ABOVE FRONT FROM ___ DEGREES AT ___ KNOTS.

"Abrupt" shear was defined to be that occurring through a layer 30 m or less in vertical thickness; "gradual", between 30 and 100 m. Midway through the test this categorization of LLWS was eliminated because we had no real-time way of determining the layer thickness. Likewise, the turbulence clause was withdrawn because turbulence was forecast by NWS AIRMETS and SIGMETS. Forecasts had a lead-time of 1-3 hours and were valid for 3 hours or less unless cancelled sooner.

Verification of Advisories was by 4 methods: 1) a dual (acoustic-radar) Doppler sounder located near Dulles Airport (see Hardesty, et. al. (1977) for a description), 2) a meteorologically instrumented FAA-NAFEC Aero Commander which was dispatched by meteorologists at FAA Systems Command Center to expected LLWS locations, 3) pilot reports and 4) NWS radiosonde winds.

b. Verification Difficulties

Although developing a verification scheme for most any meteorological parameter is a challenge, the phenomena to be verified are usually easily measured and criteria are pre-set. That was not the case with LLWS. Even though we were fortunate enough to have the most sophisticated of observing equipment available, the dual-Doppler system was only at one of the test airports, Dulles, and it used a 6-minute averaging system that masked some of the sudden wind shifts. Also, the FAA Aero Commander was able to fulfill only 25% of our reconnaissance requests due mainly to equipment malfunctions.

Problems with the other 2 observing methods were as follows. NWS radiosonde balloons are released only every 12 hours at set times. Therefore, the probability of one ascending through a frontal surface - especially a fast-moving cold front - is extremely small. Also, it is debatable whether the vertical interval usd for averaging winds is small enough to measure significant LLWS. The remaining method of observing LLWS, using pilot reports, suffered from a high degree of subjectivity. This is because there is as yet no universally accepted way of detecting or describing LLWS from the cockpit. It seemed to us that the most logical way of doing this was for the pilot to observe the change in Indicated Airspeed (ΔIAS) of the aircraft. Accordingly we developed and sent out to FAA towers pilot reporting forms which encouraged FAA personnel to ask for ΔIAS's from pilots reporting LLWS.

These observing problems aside, the next verification question was, given a high-resolution vertical wind profile, is the shear shown "significant" to aviation operations? There are varying opinions of what constitutes significant shear. The International Civil Aviation Organization at its 5th Air Navigation Conference suggested the following categories be used:

LLWS Intensity	Values (knots/30 m)
Light	0-4
Moderate	5-8
Strong	9-12
Severe	> 12

It has been pointed out by various authorities that one must also consider the integrated value of LLWS over a layer greater than 30 m. For example, Sowa (personal communication) has stated that a value of 5 knots/30 m over a 90 m layer is sufficient to cause a significant ΔIAS of 15 knots in an aircraft traversing through the layer. For this study we adopted flexible, consensus values of 3 to 5 knots/30 m as significant values.

3. RESULTS

a. Summary of Advisory-Events

During the 6-month test there were 22 days on which Advisories were issued. Twelve were for warm or stationary fronts and 8 for cold fronts. There were 2 days on which Advisories were issued for LLWS due to other causes. Wind profiles from the Dulles Doppler system (such as shown in Figure 1) were available after-the-fact for 10 of the 12 events there. Aero Commander printouts (such as shown in Figure 2) were obtained for about 25% of Advisory-Events at various test airports. Because of the previously outlined shortcomings of all other LLWS observing methods, we decided to use pilot reports as the primary method of verification. These were available for every event. And, after all, the bottom line of any such verification attempt should be the effect the vertical wind profile has on an aircraft traversing it.

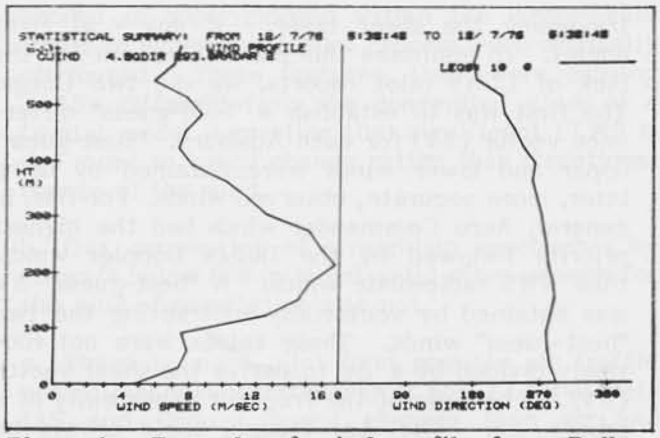

Figure 1. Example of wind profile from Dulles Doppler system after-the-fact. (Note low-level jet structure of profile.)

Place	Time (Z)	Aircraft Type	Altitude (meters)	Airspeed Change (kt)	Runway	Surface Wind	Remarks	Svc. A?	Shear due Front?	Why not?	Probable Cause
ACY	2215	NAFEC AC68	230-200	-20	13	1423G31	IAS went from 130 to 110 kts		no	front north	INV
EWR	2220	B727	600-100		04	0310	Descending at 1500ft/min to hold glideslope		yes		
LGA	2224	DC9	560	0	04	0315G23			yes		
JFK	2250	DC9	130	-10	13L	1115G20			yes		
JFK	2319	B727	100	-(10-15)	"	"			yes		
EWR	2340	B727	touch-down		04	1315	shear at touchdown		yes		
JFK	2349	H75	400-300		13L	1212G18			yes		
EWR	2350	B727	600-000		04	1315	90° wind from right to touch-down		yes		
ACY	0110	NAFEC AC68	100	-30		1520G27	IAS went from 130 to 100 kts	X	no	front north	INV
LGA	0015	B727	200		04	0415			yes		
EWR	0140	B727	300-000		22	1515	20° left cross- to 30° right crosswind		yes		
JFK	0143	H75	130	-15	13L	1315G22	dropped 100 ft		no	front north	INV
EWR	0300	B747	760-100		22?	1708	gradual		no	front north	unknown

Table 1. Example of form used to scrutinize and determine cause of LLWS pilot reports on Advisory-Event days.

b. Interpretation of Pilot Reports

Pilot reports from each Advisory-Event were collected in 3 ways: 1) by verbal relay from FAA towers to FAA-Systems Command Center meteorologists, 2) mail forwarding of pilot reporting forms and 3) by normal Service A teletype pilot report messages.

Pilot reports were then listed in chronological order for each event as shown in Table 1. Then, by using all available vertical wind profiles, NWS National Meteorological Center (NMC) and our local surface weather analyses and FAA runway logs, each of approximately 400 pilot reports was carefully scrutinized and a judgment was made whether or not the LLWS report was due to the front for which the Advisory was issued. That decision for each report is shown on the right-hand side of Table 1 followed by a "Probable Cause" if one was obvious. Table 2 shows that an astounding number of pilot reports on Advisory-Event days were attributed to causes other than fronts.

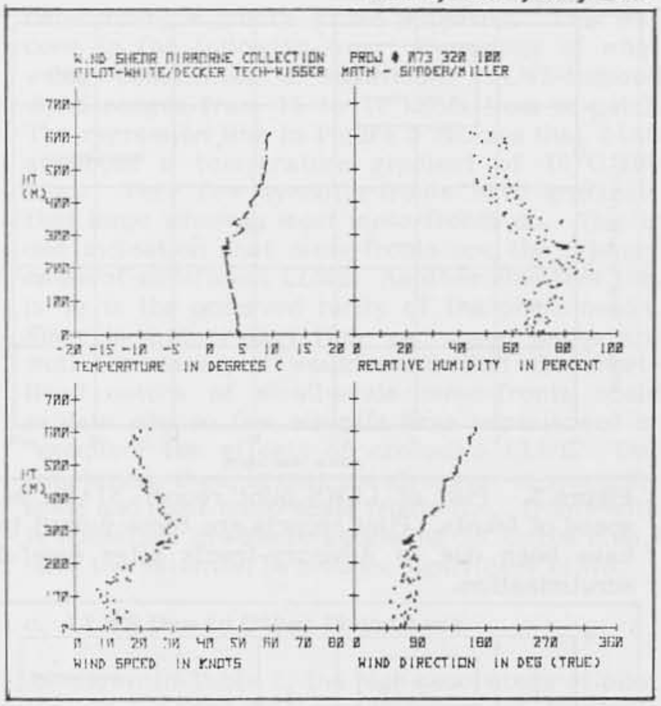

Figure 2. Example of vertical profiles obtained by FAA-NAFEC Aero Commander. (Note slight low-level jet.)

	Total No. of Pilot Reports	No. Attributed to Advisory Front	No. Attributed to Other Causes		
			Low-level jet and/or Inversion	Friction and/or obstacles	Other
Cold Front Advisory Days (8)	52	10 (19%)	12 (23%)	21 (40%)	9 (18%)
Warm Front Advisory Days (12)	165	69 (42%)	56 (34%)	24 (15%)	16 (9%)
TOTAL Advisory-Event Days (20)	217	79 (36%)	68 (31%)	45 (21%)	25 (12%)

Table 2. Breakdown of the causes of LLWS pilot reports on Advisory-Event days.

Having all this information, the next step was to correlate the manifestation of frontal-LLWS on aircraft (i.e. ΔIAS's) with our forecast parameters; ΔT and speed of fronts. Of 79 pilot reports judged to have been due to fronts, 44 included ΔIAS's. These 44 are plotted vs. speed of fronts in Figure 3 and vs. temperature gradient (ΔT/100 n.mi.) in Figure 4.

Figure 3 shows that only a few pilot reports were received with fronts moving 30 knots or greater so no correlation was attempted. The large number of reports near fronts moving at 10 knots or less reflects a greater number of LLWS pilot reports with warm frontal events. Since the scatter of those reports was so great and since the test criteria did not predict significant LLWS with fronts moving at less than 30 knots, a regression line was not computed for that region.

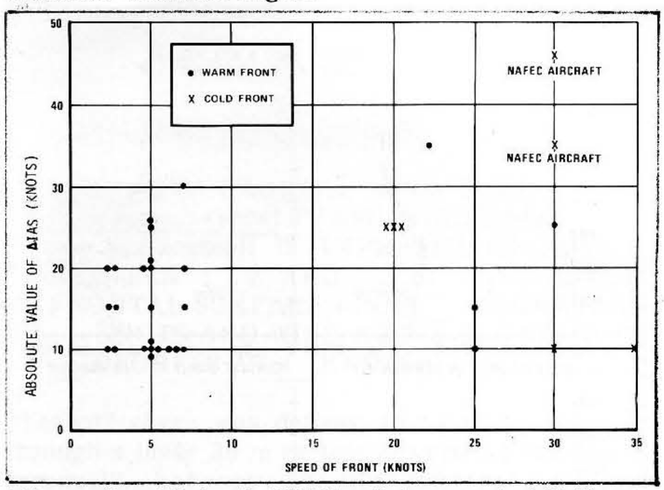

Figure 3. Plot of LLWS pilot report ΔIAS's vs. speed of fronts. Pilot reports are those judged to have been due to Advisory-fronts after careful scrutinization.

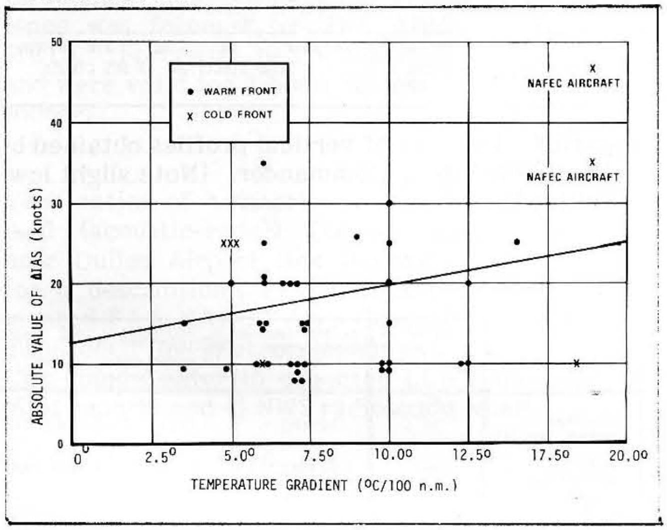

Figure 4. Plot of LLWS pilot reports ΔIAS's vs. temperature gradients as determined from local surface analyses.

To the eye, the scatter of points in Figure 4 looks less random than in Figure 3. Thus, a regression line was computed and is shown. The correlation coefficient for that line is only 0.26; statistically significant at the 1% level. This small correlation between temperature gradient and ΔIAS suggested to us that the problem was more complex than we had hoped.

One factor that the data in Figures 3 and 4 in no way took account of was the absence of pilot reports. During many events Advisories were in effect for hours while aircraft were landing and departing at the rate of 1 every 5 minutes and absolutely no pilot reports were received - even while being solicited by FAA tower personnel. It was thought that this could be due to aircraft traversing the shear layer - if any - at right angles. To minimize this possible reason for the lack of LLWS pilot reports, we did two things. The first was to establish a "best-guess" difference vector ($\Delta \underline{V}$) for each Advisory. "Best-guess" upper and lower winds were obtained by using later, more accurate, observed winds. For this, in general, Aero Commander winds had the highest priority followed by the Dulles Doppler winds, then NWS radiosonde winds. A "best-guess" $\Delta \underline{V}$ was obtained by vectorially subtracting the two "best-guess" winds. These values were not routinely divided by a Δz to derive the shear vector ($\Delta \underline{V}/\Delta z$) because of the frequent uncertainty of a proper Δz. The Δz, though, shold always be thought of as ranging between 200 and 600 m.

The next step was to project these "best-guess" difference vectors onto active runways to give the longitudinal (head- and tailwind) components. The sign convention chosen was such that a positive projected $\Delta \underline{V}$ should have produced an IAS gain in an aircraft traversing the layer. Figure 5 shows the results. The fact that the LLWS pilot reports are scattered throughout all 4 quadrants rather than the 2 "proper" ones led us to the following possible conclusions in our order of priority:

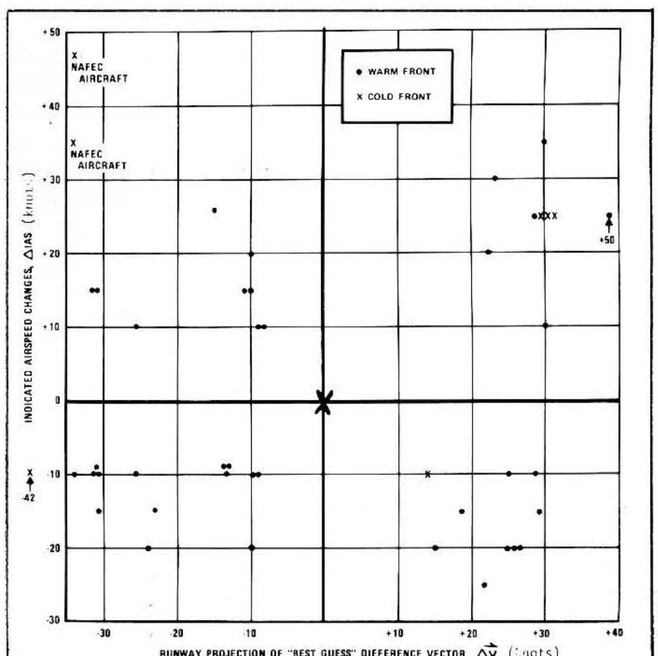

Figure 5. Plot of LLWS pilot report ΔIAS's vs. longitudinal components of "best-guess" difference vectors, $\Delta \mathbf{V}$. Pilot reports used are those judged to have been due to Advisory-fronts after careful scrutinization.

a. There were small-scale features (such as low-level jets or local inversions) which were embedded or superimposed within the larger-scale fronts to which these pilot reports were originally attributed. These features, then, were causing ΔIAS's different from the conceptual winds of a frontal model suggesting that significant LLWS is due more to speed change rather than directional change of the wind.

b. Our assumption of straight-in approaches by aircraft below 600 m is not valid often enough for this kind of correlation attempt.

c. There is more pilot (and possibly air traffic controller) misunderstanding of how LLWS affects IAS and Ground Speed changes than we had assumed.

4. CONCLUSIONS

a. Limitations of Test

Before discussing conclusions and giving recommendations based on this test, it is important to note its limitations. First, all test airports were located on the coastal plain of the northeastern United States where the terrain is relatively flat. Thus, terrain-induced LLWS was not investigated. Secondly, the test was conducted during an unusual winter. During the first half of the season the jetstream was unusually far south causing many weak or moderate cold frontal passages with few strong ones and a small number of warm front events. The latter half of the winter was more normal in the eastern U.S. We have tried our best to take these limitations into account. One of the ways this was done was to make a mental note of the weather situation whenever LLWS pilot reports appeared on the national Service A teletype printer at the FAA Systems Command Center. This gave us a rough regional and synoptic climatology of LLWS pilot reports.

b. Fronts

We have found it useful to divide the broad term of "front" into synoptic- and meso-scale categories. Synoptic fronts are the everyday, TV weather map types that extend vertically through much of the troposphere (i.e. have vertical height scales on the order of 10 km) and persist for a number of days. In contrast, meso-fronts have vertical scales on the order of 1 km and have life-times ranging from a few hours to, perhaps, a day. Examples of meso-fronts are "coastal" fronts (pseudo-warm or stationary fronts which from roughly parallel to portions of the U.S. east coast as described by Bosart et. al. (1972)), sea-breeze fronts and thunderstorm gust fronts.

One key goal of our research was to establish a temperature gradient criterion rather than simply using some "temperature difference" method of determining a front's LLWS potential. This was done in the following way. Consensus of what value constitutes a significant LLWS-induced *ΔIAS ranges from 15 to 20 knots (loss or gain).* The regression line in Figure 5 crosses that ΔIAS at about a temperature gradient of $10^{o}C/100$ n.mi. Very few synoptic-fronts have gradients that large whereas most meso-fronts do. This is one indication that meso-fronts are the primary cause of significant LLWS. Another clue that this is so is the observed rarity of the phenomenon. Since in meteorology time and space scales are well correlated, it would seem that the short-lived nature of small-scale meso-fronts could explain why so few aircraft have experienced or "sampled" the effects of excessive LLWS. Our conclusion, then, is that the strongest of synoptic-scale and most meso-scale fronts (i.e. fronts with temperature gradients exceeding $10^{o}C/100$ n.mi.) have the potential to produce significant LLWS.

c. LLWS Due to Other Phenomena

As shown in Table 2, the high percentage of pilot reports "weeded out" as not being due to fronts indicates that any advisory program should include that LLWS due to phenomena such as inversions, low-level jets (LLJs), and frictional drag. We are concerned that there may be too much emphasis being placed on LLWS caused by fronts - especially synoptic-scale ones. If an advisory program for only these fronts were to continue for a period of time, a substantial number of LLWS events would not be forecasted. For this reason the other 3 known causes of LLWS are discussed here.

At this point the distinction between fronts, LLJs, and inversions is not clear in our minds. The presence of an inversion is the common denominator for all causes of LLWS except frictional drag. This is not surprising for it is well-known that static stability inhibits vertical mixing of momentum. Blackadar et. al. (1958) developed a method of forecasting LLWS due to LLJs which is based on nocturnal inversion strength. Our study showed at least two cases of LLJs associated with fronts. One of those is shown in Figure 1 and, incidentally, coincided with a pressure jump sensor event at Dulles Airport as described by Bedard et. al. (1977). We think that many of the "incorrect" signs of ΔIAS's shown in Figure 5 could be explained by speed rather than directional shear associated with frontal LLJs. It is, incidentally, for this reason that we recommend not including expected winds in frontal LLWS advisories. A connection between LLJs and fronts has been noted by other researchers. Kreitzberg (1967) observed an 80-knot LLJ within 600 m of the ground near an occluded front in southern New England. He found that temperature gradient alone could not account for the vertical shear (using the thermal wind relation) and concluded that much of the shear had to be ageostrophic. Browning et. al. (1973) describes case studies of LLJs ahead of certain mid-latitude cold fronts in the British Isles. They found that the LLJs had maximum speeds of 50-60 knots, were embedded in a convective boundary layer, extended for 1000s of km and seemed to have little diurnal or isallobaric relation. It seems that the relation between fronts and LLJs should be more fully investigated.

Table 2 shows that fully 1/5 of all LLWS pilot reports on Advisory-Event days during our Test were due to frictional drag. Twice that fraction (40%) occurred with cold front events probably because of the usual strong flow behind them. There were many more unsolicited pilot reports on non-Advisory days that we attributed to the frictional drag on strong surface flow. Although some LLWS is routine to pilots due to lag- or power-law wind profiles, at some point that shear must become excessive as shown by these reports. Our experience was that when sustained surface winds reached about 20 knots, pilots began reporting IAS losses of 10-20 knots. In many cases Doppler and Aero Commander wind profiles confirmed LLWS as suggested by those pilot records.

5. GENERAL CONCLUSIONS

Based on the results of this test, we feel compelled to say that before any LLWS advisory program is attempted, a sound determination of its probable rate of success should first be made. That is, how much "crying wolf" too often will the credibility of LLWS advisories bear? Many times during our test, Advisories were out for hours and no pilot reports were received. Hopefully, the refinements made on the test criteria will eliminate many of the false alarms. But, the question remains, how much is enough?

Our final general conclusion is this. The small-scale nature of the LLWS problem has important implications to any forecast endeavors. First - with the exception of friction-induced LLWS - significant shear will only be detected by meso-analysis of fresh, closely spaced data. It was our experience during the test that NMC surface maps as received on facsimile were only useful for general self-briefing purposes. This is because they were received 2 hours after data time and did not include all available observations due to space limitation. Frequently, the data plotted on these maps was too cluttered to be easily interpreted. Therefore, hand-analyses were consistently used and are the key to any success that may have been achieved. Also, the finest resolution numerical model used by NMC, the Limited Fine Mesh (LFM), did not or could not be expected to resolve features that cause significant LLWS. In short, any success achieved in advising pilots of LLWS will only occur if resources and personnel are dedicated to the problem and have the time to do meso-scale analyses of all available data.

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