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Statistics from the Operation of the Low-Level Wind Shear Alert System (LLWAS) During the Joint Airport Weather Studies (JAWS) Project

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December 1984

Interim Report

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16. Abstract

The LLWAS system operated from May through September 1982 as a part of the JAWS experiment. The data base obtained provided statistics and case studies permitting evaluation of the LLWAS system and comparisons with other low-altitude measuring systems. Analyses of the data set indicate LLWAS capabilities requiring improvements. These include better spatial resolution, improved detection algorithms, and application of internal system checks for maintenance and evaluation. There is a great need to record and analyze existing LLWAS at airports not only to evaluate specific system operation but also to develop detailed climatologies of airport wind shear.

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TABLE OF CONTENTS

	Page
List of Figures	v
Summary	ix
Executive Summary	x
1. Introduction	1
1.1 The Context of the Experiment	2
1.2 Objectives of the Study	2
2. A Description of the LLWAS System	3
2.1 Basic Technical Description and the Mode of Operation in JAWS	3
2.2 Definition of Terms	6
3. General Statistics of the LLWAS in JAWS	9
3.1 Wind Speed Data	9
3.2 Wind Shear Summary	17
4. Comparison of LLWAS Alarms with Microburst Statistics	26
5. Evaluation of a Gust Magnitude Algorithm	46
6. Use of LLWAS Statistics as a Guide for Maintenance and System Evaluation	51
6.1 Detection of Errors in the Measurement of Wind Speed	57
6.2 Detection of Errors in the Measurement of Wind Direction	57
6.3 Analysis of Bad Data Points Typically Arising From Transmission Errors	57
6.4 Identification of Location or Terrain Problems	60
6.5 Development of Wind Statistics Depicting Local Meteorology	60
7. Limitations of the System	60
8. Preliminary Recommendations Regarding the LLWAS	63
9. Acknowledgments	65
10. References	67
Appendix	69

LIST OF FIGURES

Page

Figure 1. Summary of the operational characateristics of the LLWAS system. Changes for the LLWAS system as operated during the JAWS experiment are illustrated in brackets..... 4

Figure 2a. Schematic views illustrating the processes involved in thunderstorm gust fronts, microbursts, thermal plumes, aircraft wake vortices, and drainage flows..... 7

Figure 2b. Qualitative illustrations of the wind speed, temperature, and pressure changes accompanying thunderstorms and microbursts..... 8

Figure 3. Periods of successful LLWAS data recovery in JAWS (shaded), starting on 20 May and ending on 11 September; 1440 hours of data were successfully recorded, or 52% of the total time during 115 days of operation..... 10

Figure 4. Histogram of LLWAS wind speed data for the centerfield and all boundary remote sites in JAWS..... 14

Figure 5. Alternate presentation of same data in Figure 4: Log cumulative frequency distribution of wind speed data for each LLWAS site..... 15

Figure 6. Log cumulative frequency distribution of wind speed data sites combined into a single curve..... 16

Figure 7. Histogram of wind shear (actually wind difference in knots) for each LLWAS site. Calculation is made between centerfield and each outlying boundary remote site..... 18

Figure 8. Log cumulative frequency distribution of wind shear (wind vector difference) data for each LLWAS site..... 19

Figure 9. Log cumulative frequency distribution of wind shear (wind vector difference) for all sites combined..... 20

Figure 10. Histogram of all trigger events by time of day (MDT) for each site..... 22

Figure 11. Histogram of triggers by time of day (MDT) for all sites combined..... 23

Figure 12. Histogram of distribution of all LLWAS alarms as a function of number of triggers per alarm (groups of triggers) for each LLWAS site..... 24

Figure 13. Histogram of LLWAS alarms by number of triggers per alarm (groups of triggers) for all boundary sites combined..... 25

Figure 14a. JAWS research area, showing, among other things, the distribution of 27 PAM stations in the experimental network..... 27

Figure 14b. LLWAS boundary site locations relative to the airport..... 28

Figure 15. Algorithm for detecting microburst winds based on PAM winds measured at one-min intervals..... 29

Figure 16. Distribution of number of LLWAS alarms by day during the period 20 May to 8 August (during which time the NCAR PAM was operating) compared with the distribution of number of microbursts by day as determined by Fujita and Wakimoto (1983) within 8 mi of the Stapleton runways..... 31

Figure 17. Distribution of number of LLWAS alarms by day during the period 15 May to 11 September 1982..... 32

Figure 18a.1. Ten-minute segment of LLWAS data for 22 June 1982 (1540 to 1550 MDT). The winds at each site are shown, with the ordinate indicating speed magnitude in knots. The origin of each vector indicates the wind speed magnitude and the arrow indicates wind direction. An arrow pointing directly down indicates a wind from the north. * refers to an LLWAS trigger. Triggers on the north site are in part related to the low-sensitivity problem..... 36

Figure 18a.2. Wind vectors on 22 June 1982 (~1544 MDT) illustrating how the absence of strong winds at the northern site resulted in triggers... 37

Figure 18b.1. Ten-minute segment of LLWAS data for 30 June 1982 (1535 to 1545 MDT). The winds at each site are shown, with the ordinate indicating speed magnitude in knots. The origin of each vector indicates the wind speed magnitude and the arrow indicates wind direction. An arrow pointing directly down indicates a wind from the north. * refers to an LLWAS trigger. Note that the LLWAS triggered at times that are obviously not related to thunderstorm gust fronts or microbursts..... 38

Figure 18b.2. Wind vectors on 30 June 1982 (~1542 MDT) illustrating the SE LLWAS site detecting a flow from the south resulting in triggers when compared with the centerfield flow from the west..... 39

Figure 18c.1. Ten-minute segment of LLWAS data for 30 June 1982 (1750 to 1800 MDT). The winds at each site are shown, with the ordinate indicating speed magnitude in knots. The origin of each vector indicates the wind speed magnitude and the arrow indicates wind direction. An arrow pointing directly down indicates a wind from the north. * refers to an LLWAS trigger. Note that the LLWAS triggered because of a localized gust..... 40

Figure 18c.2. Wind vectors on 30 June 1982 (~1757 MDT) showing the gust measured on the NW site..... 41

Figure 18d.1. Ten-minute segment of LLWAS data for 20 July 1982 (1810 to 1820 MDT). The winds at each site are shown, with the ordinate indicating speed magnitude in knots. The origin of each vector indicates the wind speed magnitude and the arrow indicates wind direction. An arrow pointing directly down indicates a wind from the north. * refers

to an LLWAS trigger. Note that the LLWAS triggered at times that we could not relate to thunderstorm gust fronts or microbursts..... 42

Figure 18d.2. Wind vectors on 20 July 1982 (~1815 MDT)..... 43

Figure 18e.1. Ten-minute segment of LLWAS data for 21 July 1982 (1040 to 1050 MDT). The winds at each site are shown, with the ordinate indicating speed magnitude in knots. The origin of each vector indicates the wind speed magnitude and the arrow indicates wind direction. An arrow pointing directly down indicates a wind from the north. * refers to an LLWAS trigger. Note that the LLWAS triggered at times that are obviously not related to thunderstorm gust fronts or microbursts..... 44

Figure 18e.2. Wind vectors on 21 July 1982 (~2041 MDT) probably related to nocturnal drainage flows..... 45

Figure 18f.1. Fifteen-minute segment of LLWAS data for 2 August 1982 (1345 to 1400 MDT). The winds at each site are shown, with the ordinate indicating speed magnitude in knots. The origin of each vector indicates the wind speed magnitude and the arrow indicates wind direction. An arrow pointing directly down indicates a wind from the north. * refers to an LLWAS trigger. Note that the LLWAS triggered at times that are obviously not related to thunderstorm gust fronts or microbursts..... 47

Figure 18f.2. Wind vectors on 2 August 1982 (~1351 MDT)..... 48

Figure 18g.1. Ten-minute segment of LLWAS data for 7 August 1982 (1550 to 1600 MDT). The winds at each site are shown, with the ordinate indicating speed magnitude in knots. The origin of each vector indicates the wind speed magnitude and the arrow indicates wind direction. An arrow pointing directly down indicates a wind from the north. * refers to an LLWAS trigger. Note that the LLWAS triggered at times that are obviously not related to thunderstorm gust fronts or microbursts..... 49

Figure 18g.2. Wind vectors on 7 August 1982 (~1554 MDT) showing weak convergence over the airport..... 50

Figure 19a. Distribution of number of magnitude algorithm alarms by day during the period 20 May to 8 August (during which time the NCAR PAM was operating) compared with the distribution of number of microbursts by day as determined by Fujita and Wakimoto (1983) within 8 mi of the Stapleton runways..... 52

Figure 19b. Daily distribution of LLWAS alarms as calculated by the new running-mean algorithm..... 53

Figure 20. Example of LLWAS data for 14 July 1982 (1405 to 1415 MDT). Two versions of a running mean algorithm (shear and magnitude threshold) are shown..... 54

Figure 21. Histogram of LLWAS triggers for all sites, using the new running-mean algorithm..... 55

Figure 22. Histogram of LLWAS alarms by number of triggers per alarm (groups of triggers) using the new running-mean algorithm..... 56

Figure 23. Histogram of LLWAS wind speed data for 3 July 1982 (0715-2359 MDT) comparing three sites. The low-sensitivity problem with the north site becomes quite evident..... 58

Figure 24. Centerfield direction compared with the southwest site direction for the period 0000 to 2314 MDT on 2 August 1982. A consistent off-diagonal grouping of measurements would indicate a systematic wind direction problem..... 59

Figure 25. Wind speed difference between the southwest and centerfield site as a function of direction measured at the centerfield site. These data are shown for several wind regimes. Siting problems or localized flows would show as a deviation from a symmetrical distribution centered at 0 kts difference..... 61

Figure 26. Schematic view of the various stages of a microburst..... 64

Figure 27. Wind data for the southeast site for a microburst event on 14 July 1982, was reprocessed using a 15-scan average. This comparison shows the great influence of the centerfield averaging in preventing the detection of short-lived microbursts..... 66

SUMMARY

This report discusses the frequency and types of Low-Level Wind Shear Alert System (LLWAS) wind shear alarms for the period of the JAWS experiment during the thunderstorm season of 1982, reviewing distributions of wind speed and wind shear measurements. Over 2 million observations from the Stapleton LLWAS system form the basis for statistics developed in this report. We present examples when the LLWAS data were valuable in helping aircraft avoid hazardous wind shear situations. Conversely, some wind shear alarms occurred on days with few microbursts, and the flows causing many of these alarms, we find, are unlikely to be a hazard to aircraft.

Comparing LLWAS alarms with meteorological data from an array of surface stations and other sources we found that:

- 101 (16.3%) alarms were related to microbursts,
- 75 (12.1%) were related to gust fronts,
- 145 (23.3%) were related to isolated gusts,
- 300 (48.3%) were related to other sources.

It is this last group of alarms (clearly not related to gust fronts or microbursts) that need to be characterized in terms of meteorological sources and wind shear severity. Because we lack detailed meteorological data covering the lowest 300 meters for most alarms, we cannot perform a complete characterization in this report. An important observation is the large number (145) of alarms involving isolated gusts (one or two isolated triggers near the 15 kt threshold level). Our study suggests that a large number of false alarms could be eliminated by requiring an alarm to consist of 3 or more consecutive triggers. The FAA is currently testing this concept.

The data set indicates that denser sensor spacing and timely detection and dissemination are critical needs. Recommendations range from software changes (e.g., an additional processing path will increase the effectiveness of the centerfield sensor) to applications of advanced array processing theory. We recommend recording of LLWAS data at all operational sites to permit not only monitoring and evaluation of operating systems, but also the development of statistics on microburst frequency-of-occurrence. A key recommendation is that LLWAS systems be improved and these improvements installed at all major airports.

EXECUTIVE SUMMARY

This report discusses the frequency and types of Low-Level Wind Shear Alert System (LLWAS) wind shear alarms for the period of the JAWS experiment during the thunderstorm season of 1982, reviewing distributions of wind speed and wind shear measurements. Over 2 million observations from the Stapleton LLWAS system form the basis for statistics developed in this report. We present examples when the LLWAS data were valuable in helping aircraft avoid hazardous wind shear situations. Conversely, some wind shear alarms occurred on days with few microbursts, and the flows causing many of these alarms, we find, are unlikely to be a hazard to aircraft.

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- There are temporal and spatial resolution limitations restricting the reliable and timely detection of microbursts.
- Vertical motions are not sensed directly, and there is no prior warning of the descending downdraft until the hazardous, strong horizontal flows already exist.
- A variety of mechanisms (such as shallow temperature inversions near the surface) can prevent the horizontal winds from penetrating to surface-based wind sensors.
- Wind shear events outside of a 3 km radius of the airport are not covered, which may be a deficiency if a wind shear encounter occurs along the glide slope or departure path outside of this 3 km radius or if wind shear systems are translating from outside the covered region into the lower portions of the glide slope.

The data set indicates that denser sensor spacing and timely detection and dissemination are critical needs. Some of the key recommendations for improving the system are:

- Add an additional processing path to increase the effectiveness of the centerfield anemometer.

- Consider the application of signal processing techniques ranging from alternative algorithms to an exhaustive re-examination of sampling theory concepts providing improvements in wind shear detection and identification as well as reducing false alarms.

- Investigate the benefits of increasing the number of sensors and reducing the spacing between them.

- Investigate the effects of averaging on the detection of gust fronts and microbursts.

- Recommend recording of LLWAS data at all operational sites to permit not only improved monitoring and evaluation of operational systems, but also the development of nationwide statistics on microburst frequency-of-occurrence.

- Apply remote sensing technology to provide earlier warnings.

The LLWAS is the only currently available system for detecting wind shear on a regular basis. It is recommended that the LLWAS system be substantially improved and these improvements installed in existing LLWAS systems at all major airports.

STATISTICS FROM THE OPERATION OF THE LOW-LEVEL WIND SHEAR ALERT SYSTEM (LLWAS) DURING THE JAWS PROJECT:

AN INTERIM REPORT FROM THE JAWS PROJECT AT NCAR

A. J. Bedard, Jr., J. McCarthy, and T. Lefebvre

July 1983

ABSTRACT

The LLWAS system operated from May through September 1982 as a part of the JAWS experiment. The data base obtained provided statistics and case studies permitting evaluation of the LLWAS system and comparisons with other low-altitude measuring systems. Analyses of the data set indicate LLWAS capabilities requiring improvements. These include better spatial resolution, improved detection algorithms, and application of internal system checks for maintenance and evaluation. There is a great need to record and analyze existing LLWAS at airports not only to evaluate specific system operation, but also to develop detailed climatologies of airport wind shear.

1. INTRODUCTION

During the summer of 1982, the Joint Airport Weather Studies (JAWS) Project was conducted near Denver's Stapleton International Airport. The experiment had three major objectives: basic scientific examination of the convectively driven microburst, investigation of various aspects of aircraft performance in microburst situations, and examination of a number of detection and warning systems for low-altitude wind shear. The experiment was performed jointly by the National Center for Atmospheric Research (NCAR) and the University of Chicago, under grants, contracts, and agreements with the National Science Foundation (NSF), the Federal Aviation Administration,(FAA), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA).

Details regarding the scientific background of the JAWS Project can be found in Fujita and Byers (1977), Fujita and Caracena (1977), Fujita (1981), Bedard (1982), and McCarthy et al. (1982). Recent scientific results from the project are presented in McCarthy et al. (1983), Wilson and Roberts (1983), Kessinger et al. (1983), Frost et al. (1983), Caracena et al. (1983), and Fujita and Wakimoto (1983). The JAWS Project operational planning document and the data summary (see JAWS, 1982; 1983) are available from the JAWS Project at NCAR.

The capabilities of arrays of anemometers to detect and warn of approaching gust fronts are well documented in the literature [e.g., Goff (1980), Bedard et al. (1979)]. However, similar evaluations have not been made for anemometer detection of microbursts. Hence, an important focus of

this report is a comparison between LLWAS and microburst statistics. Although the LLWAS system was not designed to detect microbursts, we will attempt to identify strengths and weaknesses of the LLWAS for providing microburst warnings.

1.1 The Context of the Experiment

One of the three major objectives of the JAWS Project is the evaluation of a number of detection and warning systems for low-altitude wind shear, including the FAA's low-level wind shear alert detection system (LLWAS), a terminal Doppler radar concept, the NOAA pressure jump array system, and several airborne systems. The JAWS Project is testing as many of these systems as is feasible using a broad set of convective microburst data. By collecting complete details on such events from a large number of sensors, we can compare the full capabilities of the systems.

Ideally, any technological solution to wind shear detection and warning must provide the following to the users, presumably controllers and pilots:

(1) A high probability of detection
(2) A low number of false alarms
(3) Accurate measurement of the level of hazard
(4) A high degree of automation of the hazard information
(5) A clear, direct transfer of the hazard information to the aviation users.

The JAWS Project has investigated many but not all of these characteristics individually and comparatively. For example, many of the above qualities are addressed in Wilson and Roberts (1983) for a terminal Doppler radar as a remote detection and warning system.

1.2 Objectives of the Study

This is an interim report on the statistics of the LLWAS system using data from LLWAS recorded by the FAA at Stapleton International Airport during the JAWS Project. This report addresses the following subjects from a statistical point of view:

(1) General statistics of the LLWAS in JAWS:

- Statistical summary of wind speed events
- Statistical summary of wind shear events
- Statistical summary of triggers
- Statistical summary of alarms
- Summary statistics

(2) Comparison of LLWAS alarms with microburst statistics obtained with PAM system

(3) Preliminary discussion of simple algorithm improvements

(4) Suggestions for creating batch statistics on a routine basis as a means of checking operation and guiding maintenance

(5) Preliminary recommendations from this study regarding the future of the LLWAS.

A parallel effort is under way to evaluate the LLWAS operation using case study comparisons with NCAR's Portable Automated Mesonet (PAM) and other supporting meteorological data. The results of that study will be reported separately. Furthermore, an additional effort is underway to examine improved station geometry and detection algorithms, also to be reported separately.

2. A DESCRIPTION OF THE LLWAS SYSTEM

2.1 Basic Technical Description and the Mode of Operation in JAWS

The LLWAS was developed following the airline crashes of the mid-1970's and as a response of the FAA's Wind Shear Office. Initially recommended by NOAA's National Severe Storms Laboratory, the system is designed as a surface *in situ* wind measuring array centered on and around the airport.

A report by Goff (1980) reviews the bases for the design of the LLWAS and provides details of the hardware and software. Reports by Goff et al. (1977), Lee et al. (1978), and Bedard et al. (1979) provide more background on the use of surface sensors for the detection of low-altitude wind shear. In this section we review operational characteristics of the LLWAS to aid in understanding the statistics presented in this report.

A typical system consists of a centerfield sensor and five boundary sensors usually located about 3 km from the center site and situated to favor the instrument landing system middle marker location of each airport runway. The sensors are propeller/vane anemometer systems, sited at various heights from 6 to approximately 20 m AGL, to obtain clear airflow measurements above terrain and obstructions.

The LLWAS is controlled by a central miniprocessor (usually located in the control tower), which performs the following calculations:

(1) It maintains a 15 scan (~2 min) running average of the centerfield wind. This information is continuously displayed in the tower and is used by controllers and pilots. Standard gust component is also calculated and displayed for this site.

(2) Once every 7-10 s the miniprocessor compares the ~8 s RC low-pass filtered wind from each boundary site with the 15 scan (~2 min) average wind at centerfield. The filter is determined by values of a resistor (R) and capacitor (C) network connected to the anemometer output. A vector difference computation is made; and if a 15 kt threshold is reached or exceeded, an alert is given to the tower controller. Normally only the centerfield average wind, plus gust component if appropriate, is displayed; but if the wind shear threshold is exceeded, then the wind velocity at the appropriate boundary anemometer is displayed. The controller may, however, choose to display any or all sectors at one time.

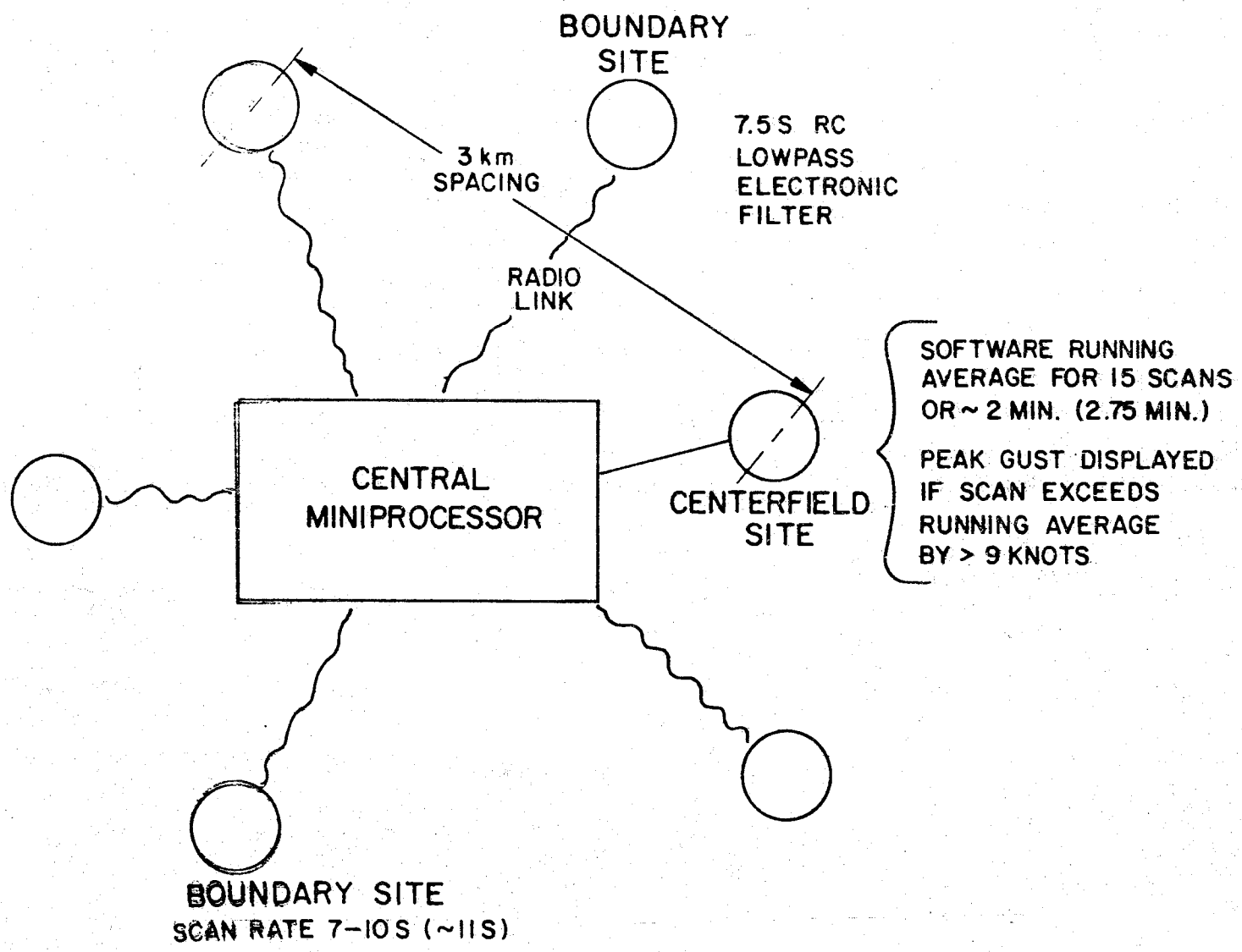

Figure 1. Summary of the operational characteristics of the LLWAS system. Changes for the LLWAS system as operated during the JAWS experiment are illustrated in brackets.

Figure 1 summarizes the operational characteristics of the LLWAS system. In this figure the characteristics listed in brackets are those for the LLWAS system as operated during the JAWS Project. Normally data are not recorded for LLWAS systems. The addition of data recording to the Stapleton LLWAS during JAWS increased the scan interval from 7-10 s to ~11 s, with a consequent increase of the centerfield 15 scan running average to about 2.75 min.

When any given peak wind from the centerfield anemometer exceeds the centerfield 15 scan mean wind by 9 kts, the peak wind value appears on the control tower display. This peak wind value is displayed for 15 scans unless:

(a) on a new scan the old value is exceeded. If this happens the new scan value replaces the old;

(b) the centerfield mean wind increases to a value that is within 9 kts of the peak gust.

The wind shear calculation is based on a gust front advection hypothesis, which detects the sudden onset of a discrepancy between the wind from a boundary site and that from the centerfield site. The LLWAS was designed for the detection of advecting wind-shift lines occurring on scales of the size of the anemometer array (~6 km) or larger. The present system was not designed to detect microbursts. However, we will proceed to evalaute LLWAS potential for providing microburst warnings.

The LLWAS system used at Stapleton during the JAWS Project applied two software modifications (patches) intended to reduce the number of alarms under certain meteorological conditions. Data processed were subjected to the additional criteria described below.

Modification 1

Denver is frequently subjected for periods of many hours to strong winds during chinook or foehn wind conditions. The turbulence associated with these winds can cause sporadic triggers and audible alarms over long periods of time. This modification is intended to suppress the audible alarm during such downslope wind conditions. When the centerfield wind speed exceeds 35 knots all remote outputs are turned on for continuous display. A shear condition is registered by flashing digits but no audible alarm is sounded. This display persists until the centerfield wind speed falls below 25 knots. At that point normal operation resumes.

Modification 2

This modification is intended to reduce spurious alarms caused by random wind fluctuations. Sporadic wind speed and direction changes can be caused by obstructions or complex terrain and not represent the hazard posed by coherent wind-shift lines. The purpose of this modification is to reduce the sensitivity of the system to sporadic wind vector changes while retaining system sensitivity to gust fronts.

This is accomplished by making the trigger wind vector difference threshold a function of the wind direction difference between the center-

field and outlying anemometer site. The modification is summarized by the following:

Direction difference between outlying site and averaged centerfield wind	Vector difference for trigger threshold
>60°	> 15 knots
30° to 60°	> 20 knots
<30°	> 25 knots

Because of the complexity of the flow fields during daytime weak convection, it is unlikely that either of these two modifications would significantly reduce false alarms during these conditions.

Fifty-nine LLWAS arrays are now operational at selected airports and 51 additional systems will be installed by 1985.

2.2 Definition of Terms

Before describing the data from the LLWAS, it is necessary to define a number of terms:

THUNDERSTORM GUST FRONT (Figure 2a,b): The leading edge of the cold air outflow from a thunderstorm is termed a gust front. These density currents can occur at large distances (>20 miles) from downflow regions and are characterized by a wind-shift line, pressure jump, gust surge, and temperature drop. Figure 2b indicates qualitatively the form of the wind speed, temperature, and pressure chances accompanying a thunderstorm gust front.

THUNDERSTORM MICROBURST (Figure 2a): When the region of downflow is less than 4 km in width with the peak winds lasting usually from 2 to 5 minutes the system is called a microburst. In contrast to the thunderstorm gust front, the microburst is short lived, spatially concentrated, and exhibits complex near-surface effects. Figure 2b indicates qualitatively the form of the wind speed, temperature, and pressure changes accompanying a thunderstorm microburst.

WEAK CONVECTION (Figure 2a): Solar heating of the surface of the Earth produces regions of buoyant air which rise in the form of thermal plumes. The local convergence of air associated with a plume is responsible for the complex pattern of winds on a typical summer day.

AIRCRAFT WAKE VORTICES (Figure 2a): An airfoil producing lift generates a vortex pair in its wake. The vortex pairs associated with heavy aircraft moving at slow speeds in landing and takeoff are especially strong and long lived. The motion and decay processes can be quite complex and flows in excess of 40 knots occur frequently. The fact that the vortex core diameter is several meters or less tends to make the duration of a wind surge quite short (<10 seconds).

DRAINAGE FLOWS (Figure 2a): Near-surface cooling caused by nocturnal radiation loss can result in complex local flow patterns as the colder air

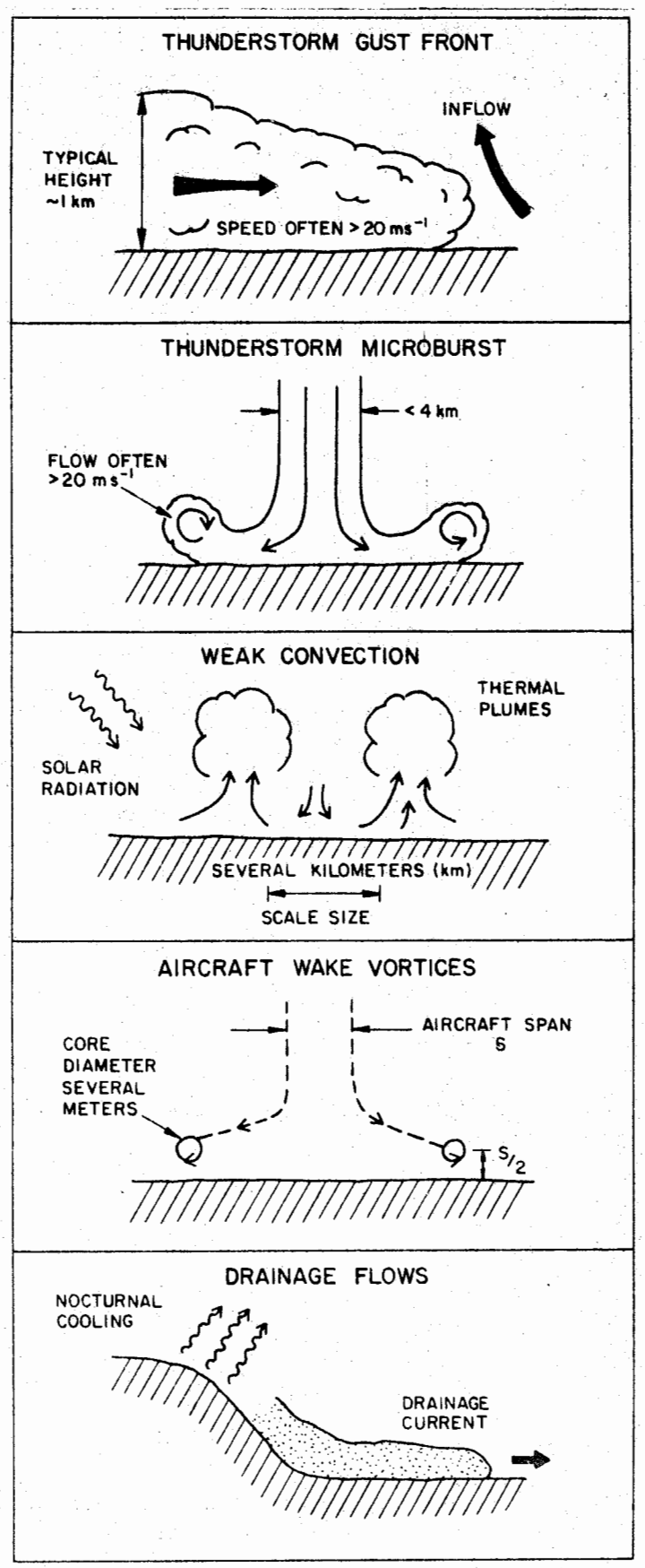

Figure 2a. Schematic views illustrating the processes involved in thunderstorm gust fronts, microbursts, thermal plumes, aircraft wake vortices, and drainage flows.

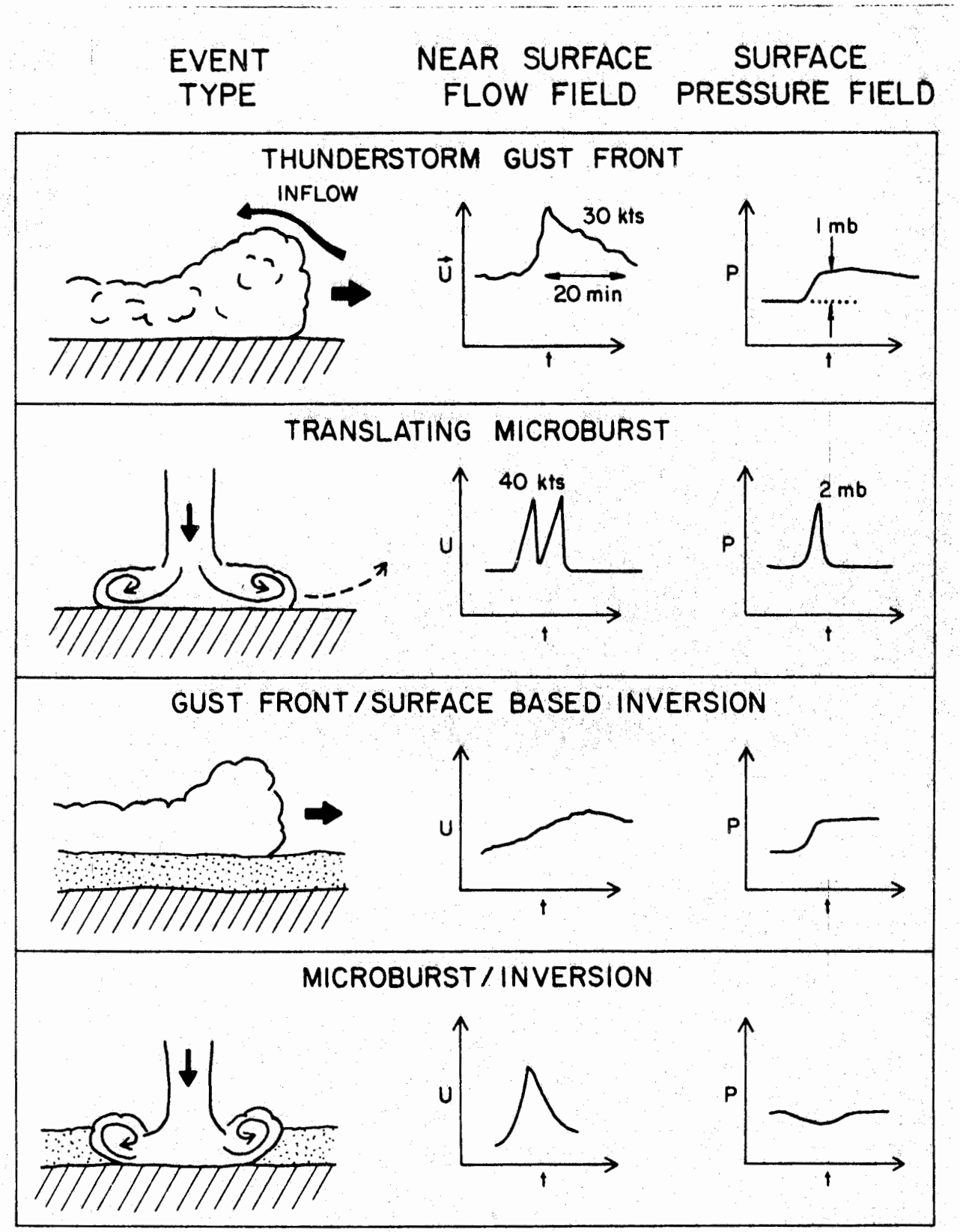

Figure 2b. Qualitative illustrations of the wind speed, temperature, and pressure changes accompanying thunderstorms and microbursts.

moves towards lower topography. Such currents are usually significantly weaker (<8 m s^{-1}) than thunderstorm gust front or microburst flows (often >20 m s^{-1}). However, the effects of several interacting drainage flows could produce vector differences large enough to exceed thresholds for gust front or microburst algorithms.

SCAN: LLWAS sampling interval. For the system examined in JAWS, the computer polled each remote site once each 11 s, so the scan interval was 11 s. The normal 7-10 s scan interval was increased to 11 s because of the requirement to record all data.

BAD DATA: Any scan listing a wind speed of 99 kts. This value is listed when system checks for valid data are unsuccessful.

TRIGGER: When the vector difference between the centerfield running average and a boundary site equals or exceeds 15 kts and a trigger flag appears for a given scan.

ALARM: An isolated trigger or a group of triggers occurring within three consecutive scans of any trigger in the group. Thus a trigger is a solitary threshold crossing event, which becomes an alarm if it is not followed within three scans by another trigger. However, if a trigger is followed by another trigger from the same site within three subsequent scans, the collection of triggers (from the same site) is an alarm. This definition of an alarm is used to simulate the fact that in the control tower alarms are held for three consecutive scans unless a larger shear value appears. This helps to reduce the intermittency that often occurs from atmospheric variability.

3. GENERAL STATISTICS OF THE LLWAS IN JAWS

During the JAWS Project the system operated continuously. In spite of some problems with hardware in early May and sporadic outages related to power line surges, an excellent data set was recorded. Recording was extended beyond the JAWS experimental period so that we obtained data disks between 20 May and 11 September 1982, covering about 1440 hours of system operation. Figure 3 and Table 1 summarize the intervals for which we were able to retrieve data. The data recovered from the disks included wind speed and wind direction for all outlying sites as well as a running numerical (15 scan) average for the centerfield with peak gust information. The scan interval with the particular software used was increased slightly to about 11 s between scans. Also the output of the detection algorithm (if the vector difference between an outlying site and centerfield average exceeded 15 kts) triggered an event that was recorded and processed.

3.1 Wind Speed Data

The fundamental data collected by the LLWAS are the wind speed and direction at each site, including the centerfield where the data are approximately 2 min running average values, and the boundary remote sites (southwest, southeast, northeast, northwest, and north) where the data are 8 s RC filtered values, taken every 11 s. Figure 4 is a histogram of all data successfully recorded during JAWS for each site as a function of wind speed. The graphs show the number of values that occurred, displayed in 2.5 kt divi-

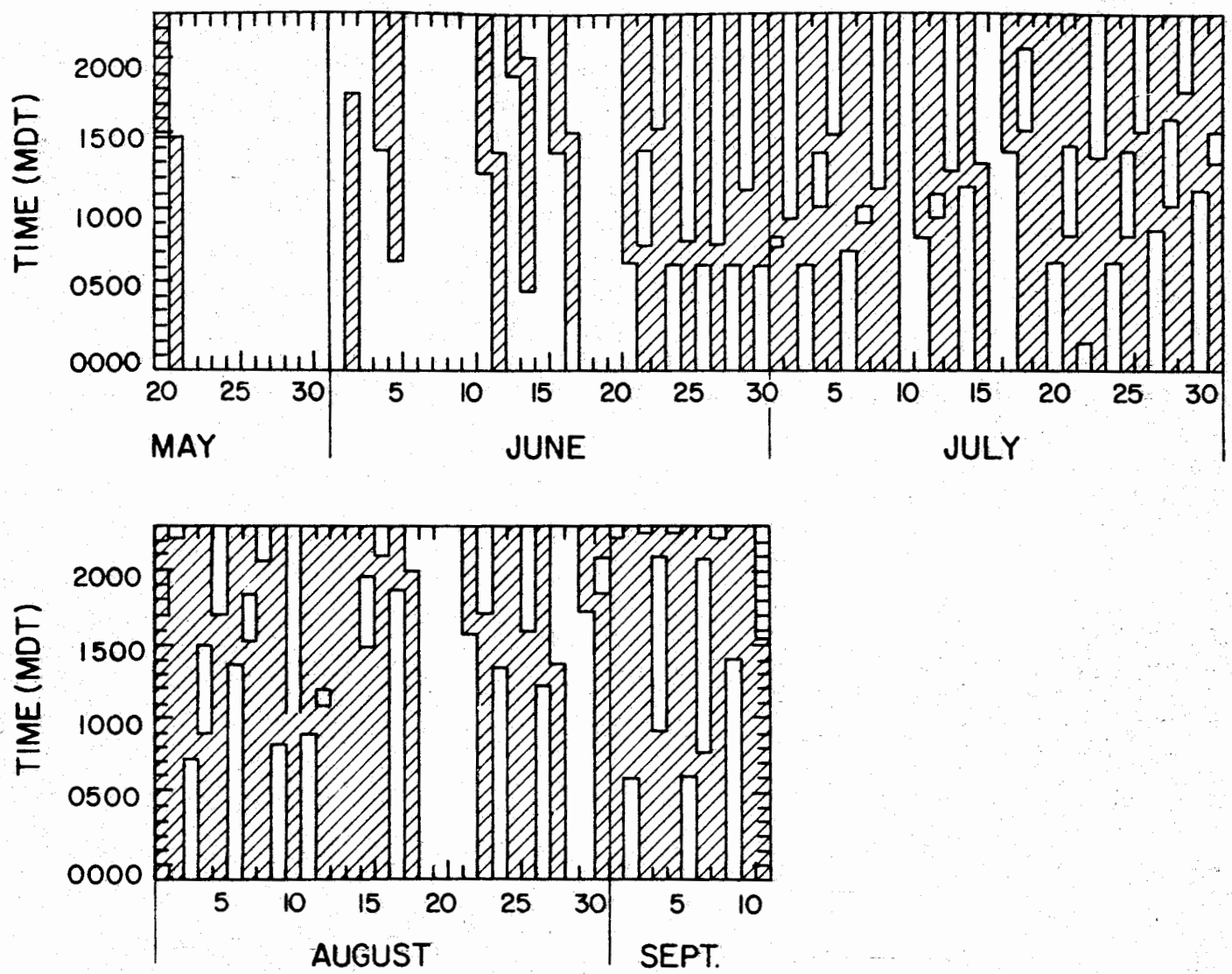

Figure 3. Periods of successful LLWAS data recovery in JAWS (shaded), starting on 20 May and ending on 11 September; 1440 hours of data were successfully recorded, or 52% of the total time during 115 days of operation.

Table 1. List of LLWAS data recorded in JAWS

Date (1982)	Julian Day	Start (MDT)	Stop (MDT)
5/20	DAY: 140	START: 1500	STOP: 2359
5/21	DAY: 141	START: 0000	STOP: 1540
6/2	DAY: 153	START: 0000	STOP: 1840
6/4	DAY: 155	START: 1442	STOP: 2359
6/5	DAY: 156	START: 0721	STOP: 1438
6/5	DAY: 156	START: 1439	STOP: 2324
6/11	DAY: 162	START: 1325	STOP: 1356
6/11	DAY: 162	START: 1400	STOP: 2359
6/12	DAY: 163	START: 0000	STOP: 1447
6/13	DAY: 164	START: 2000	STOP: 2359
6/14	DAY: 165	START: 0519	STOP: 2125
6/16	DAY: 167	START: 1445	STOP; 2359
6/17	DAY: 168	START: 0000	STOP: 1605
6/21	DAY: 172	START: 0715	STOP: 2359
6/22	DAY: 173	START: 0000	STOP: 0837
6/22	DAY: 173	START: 1508	STOP: 2359
6/23	DAY: 174	START: 0000	STOP: 1630
6/24	DAY: 175	START: 0720	STOP: 2359
6/25	DAY: 176	START: 0000	STOP: 0842
6/26	DAY: 177	START: 0719	STOP: 2359
6/27	DAY: 178	START: 0000	STOP: 0836
6/28	DAY: 179	START: 0731	STOP: 2359
6/29	DAY: 180	START: 0000	STOP: 1221
6/30	DAY: 181	START: 0711	STOP: 2359
7/1	DAY: 182	START: 0000	STOP: 0830
7/1	DAY: 182	START: 0903	STOP: 2359
7/2	DAY: 183	START: 0000	STOP: 1021
7/3	DAY: 184	START: 0715	STOP: 2359
7/4	DAY: 185	START: 0000	STOP: 1114
7/4	DAY: 185	START: 1445	STOP: 2359
7/5	DAY: 186	START: 0000	STOP: 1609
7/6	DAY: 187	START: 0837	STOP: 2359
7/7	DAY: 188	START: 0000	STOP: 1003
7/7	DAY: 188	START: 1103	STOP: 2359
7/8	DAY: 189	START: 0000	STOP: 1225
7/8	DAY: 189	START: 2216	STOP: 2359
7/9	DAY: 190	START: 0000	STOP: 2339
7/11	DAY: 192	START: 0906	STOP: 2359
7/12	DAY: 193	START: 0000	STOP: 1026
7/12	DAY: 193	START: 1208	STOP: 2359
7/13	DAY: 194	START: 0000	STOP: 1331
7/14	DAY: 195	START: 1239	STOP: 2359
7/15	DAY: 196	START: 0000	STOP; 1402
7/17	DAY: 198	START: 1456	STOP: 2359
7/18	DAY: 199	START: 0000	STOP: 1623
7/18	DAY: 199	START: 2212	STOP: 2359
7/19	DAY: 200	START: 0000	STOP: 2335
7/20	DAY: 201	START: 0741	STOP: 2359

Date (1982)	Julian Day	Start (MDT)	Stop (MDT)
7/21	DAY: 202	START: 0000	STOP: 0904
7/21	DAY: 202	START: 1518	STOP: 2359
7/22	DAY: 203	START: 0212	STOP: 1303
7/22	DAY: 203	START: 1307	STOP: 2359
7/23	DAY: 204	START: 0000	STOP: 1430
7/24	DAY: 205	START: 0740	STOP: 2359
7/25	DAY: 206	START: 0000	STOP: 0905
7/25	DAY: 206	START: 1500	STOP: 2359
7/26	DAY: 207	START: 0000	STOP: 1625
7/27	DAY: 208	START: 0953	STOP: 2359
7/28	DAY: 209	START: 0000	STOP: 1119
7/28	DAY: 209	START: 1735	STOP: 2359
7/29	DAY: 210	START: 0000	STOP: 1905
7/30	DAY: 211	START: 1227	STOP: 2359
7/31	DAY: 212	START: 0000	STOP: 1412
7/31	DAY: 212	START: 1605	STOP: 2359
8/1	DAY: 213	START: 0000	STOP: 1758
8/1	DAY: 213	START: 2101	STOP: 2359
8/2	DAY: 214	START: 0000	STOP: 2314
8/3	DAY: 215	START: 0806	STOP: 2359
8/4	DAY: 216	START: 0000	STOP: 0959
8/4	DAY: 216	START: 1614	STOP: 2359
8/5	DAY: 217	START: 0000	STOP: 1749
8/6	DAY: 218	START: 1443	STOP: 2359
8/7	DAY: 219	START: 0000	STOP: 1619
8/7	DAY: 219	START: 1933	STOP: 2359
8/8	DAY: 220	START: 0000	STOP: 2132
8/9	DAY: 221	START: 0933	STOP: 2359
8/10	DAY: 222	START: 0000	STOP: 1108
8/11	DAY: 223	START: 1012	STOP: 2359
8/12	DAY: 224	START: 0000	STOP: 1141
8/12	DAY: 224	START: 1259	STOP: 2359
8/13	DAY: 225	START: 0000	STOP: 1408
8/13	DAY: 225	START: 1412	STOP: 2359
8/14	DAY: 226	START: 0000	STOP: 1425
8/14	DAY: 226	START: 1429	STOP: 2359
8/15	DAY: 227	START: 0000	STOP: 1546
8/15	DAY: 227	START: 2043	STOP: 2359
8/16	DAY: 228	START: 0000	STOP: 2201
8/17	DAY: 229	START: 1946	STOP: 2359
8/18	DAY: 230	START: 0000	STOP: 2101
8/22	DAY: 234	START: 1640	STOP: 2359
8/23	DAY: 235	START: 0000	STOP: 1759
8/24	DAY: 236	START: 1446	STOP: 2359
8/25	DAY: 237	START: 0000	STOP: 1506
8/25	DAY: 237	START: 1516	STOP: 2359
8/26	DAY: 238	START: 0000	STOP: 1655
8/27	DAY: 239	START: 1328	STOP: 2359
8/28	DAY: 240	START: 0000	STOP: 1449
8/30	DAY: 242	START: 1819	STOP: 2359
8/31	DAY: 243	START: 0000	STOP: 1936
8/31	DAY: 243	START: 2200	STOP: 2359

Date (1982)	Julian Day	Start (MDT)	Stop (MDT)
9/1	DAY: 244	START: 0000	STOP: 2317
9/2	DAY: 245	START: 0718	STOP: 2359
9/3	DAY: 246	START: 0000	STOP: 0835
9/3	DAY: 246	START: 0904	STOP: 2359
9/4	DAY: 247	START: 0000	STOP: 1019
9/4	DAY: 247	START: 2224	STOP: 2359
9/5	DAY: 248	START: 0000	STOP: 2348
9/6	DAY: 249	START: 0723	STOP: 2359
9/7	DAY: 250	START: 0000	STOP: 0844
9/7	DAY: 250	START: 2202	STOP: 2359
9/8	DAY: 251	START: 0000	STOP: 2323
9/9	DAY: 252	START: 1524	STOP: 2359
9/10	DAY: 253	START: 0018	STOP: 1459
9/10	DAY: 253	START: 1504	STOP: 2359
9/11	DAY: 254	START: 0000	STOP: 1626

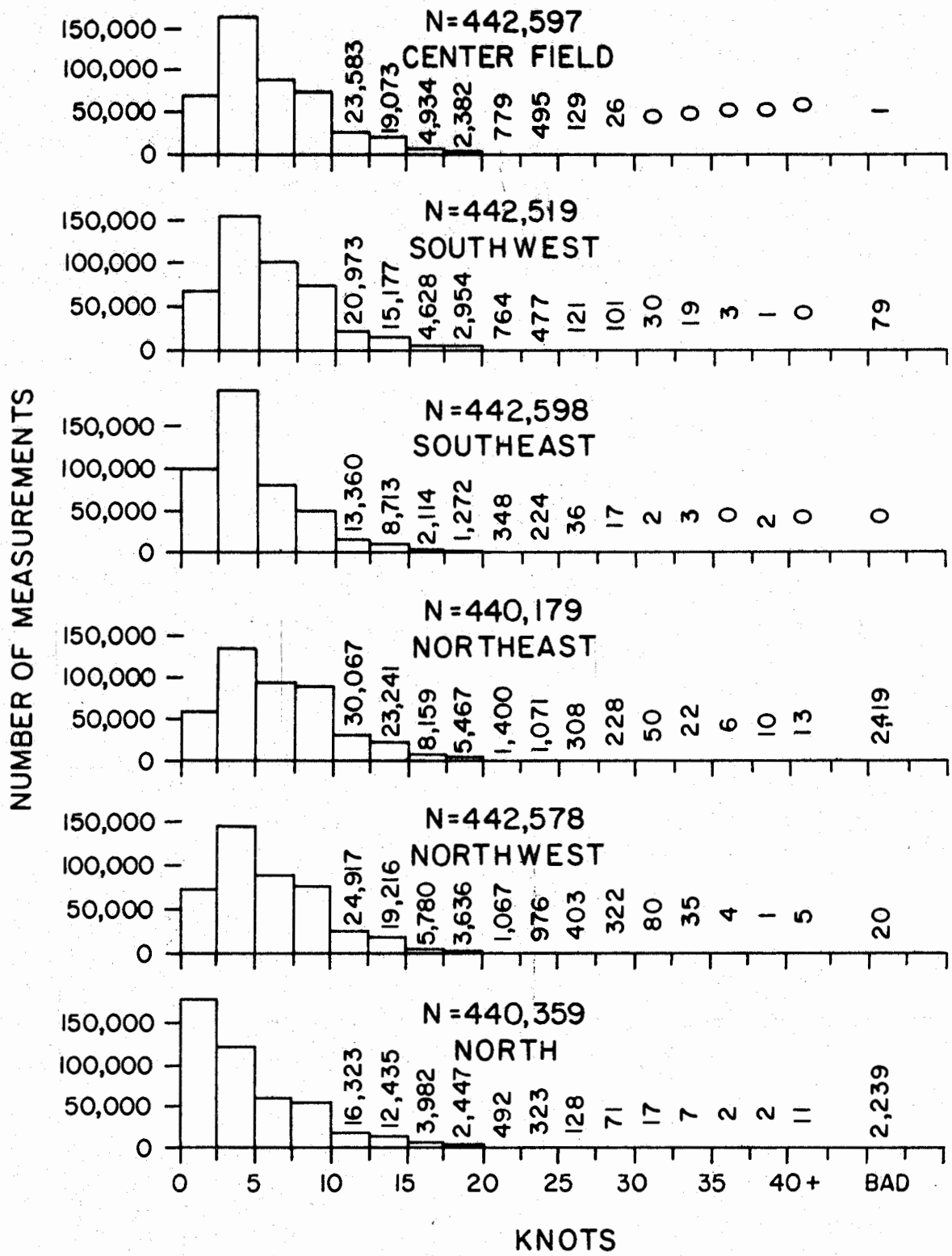

Figure 4. Histogram of LLWAS wind speed data for the centerfield and all boundary remote sites in JAWS.

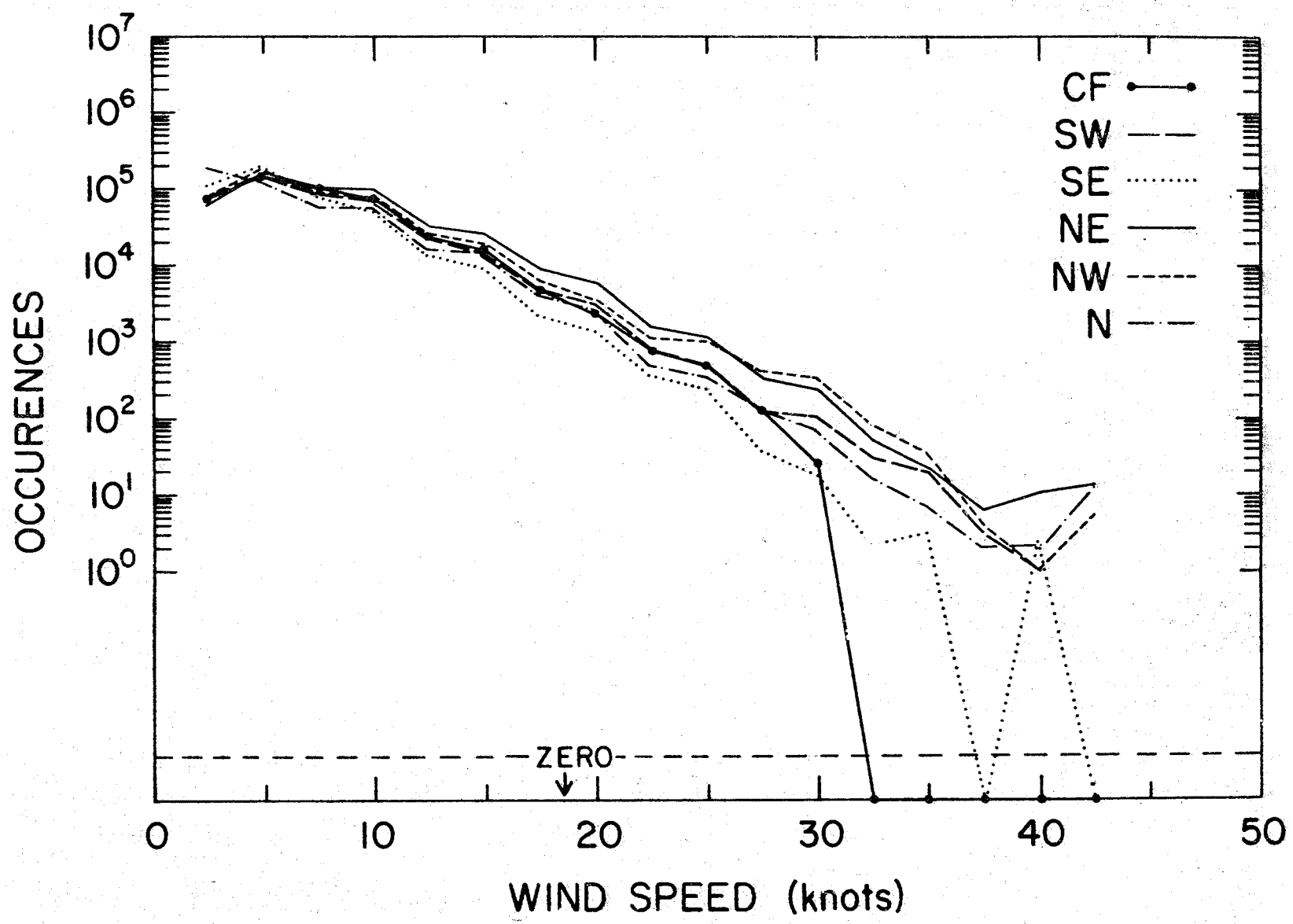

Figure 5. Alternate presentation of same data in Figure 4: Log cumulative frequency distribution of wind speed data for each LLWAS site.

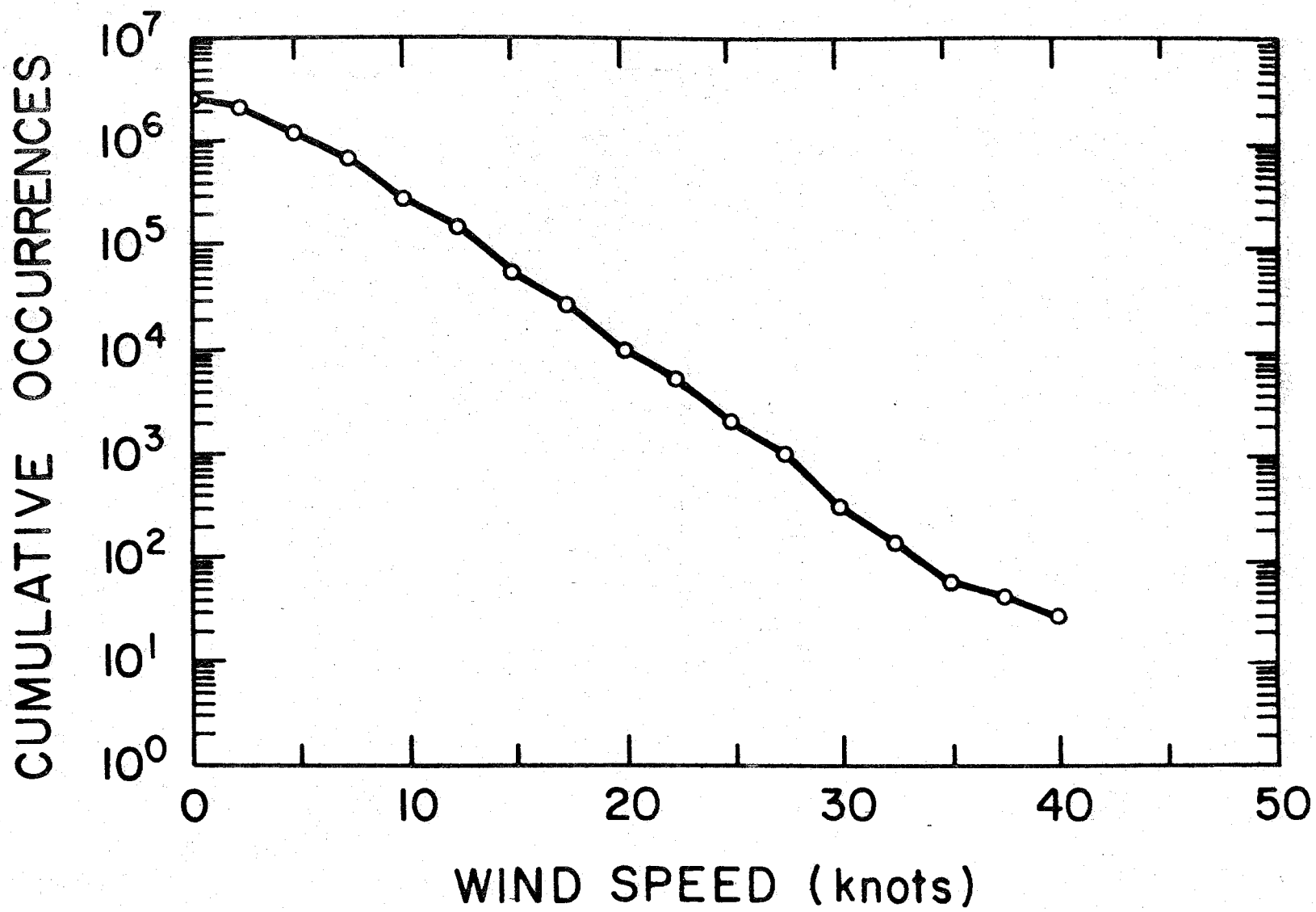

Figure 6. Log cumulative frequency distribution of wind speed data sites combined into a single curve.

sions, with any value 40 kts or greater grouped at the right side of the histograms. A count of the bad values (shown as 99 kts) is given at the extreme right. Above 20 kts, the actual number of events per division is shown directly on the graph as a line or number. The general distributions of wind speeds are similar, with peaks in the 2.5-5 kts range. The obvious exception to this pattern is in the north boundary remote sensor, where the wind speed is consistently low. In fact, on the average this site is 8 kts lower than the other remote sites. This error went undetected by routine FAA maintenance from 20 May until 23 July, when the problem was corrected. The anemometer was apparently defective and consistently read low.

Another observation from Figure 4 is the indication that the centerfield site observed consistently fewer higher wind speeds than the remote sites (except, of course, for the defective north site). This is certainly expected because of the much longer averaging period of the center site. For example, the center site had no wind readings in excess of 30 kts in contrast with the other sites.

There were 4,758 bad values out of 2,656,828 recorded (0.18% bad data), (99.82% good data), with essentially all at the northeast and north sites. We believe these values are due primarily to failures in the communications link from the sites to the computer base station. There is an existing "housekeeping" computer output from LLWAS which provides technicians with a means for assessing communications efficiency. In addition a simple examination of batch wind speed statistics such as those of Figure 4 could provide early indications of system malfunctions to system engineers and technicians.

So that the wind speed statistics for each site could be better compared, we arranged them in an alternative presentation (see Fig. 5). The fewer high wind speed values for the centerfield site are most obvious here. All of the wind speed data for all sites have been grouped into a single graph presented in Figure 6. The axes are the same as in Figure 5. This graph is useful in identifying the total number of wind speed events for the LLWAS. For example, approximately 10,000 events exceeded 20 kts, while about 20 singular events exceeded 40 kts.

3.2 Wind Shear Summary

The LLWAS system addresses "wind shear" by computing the vector difference between each boundary remote site and the centerfield site. If on any single computer sampling scan the vector difference between any two comparisons equals or exceeds 15 kts, that compared scan is identified as a trigger event. By convention, this trigger event is termed wind shear, but in fact is in the units of wind difference (units of knots). For the sake of consistency with those who use the LLWAS, we will continue the useful convention of calling the units of a trigger event "wind shear."

Figure 7 is a histogram of the LLWAS wind shear data, where the vector difference between the centerfield and each boundary remote site has been calculated for each scan (each 11 s). Although the actual calculation is wind velocity (speed and direction) vector difference, only the wind vector difference magnitude is shown in Figure 7. The consequences of various trigger thresholds are obvious; clearly, the number of wind shear events

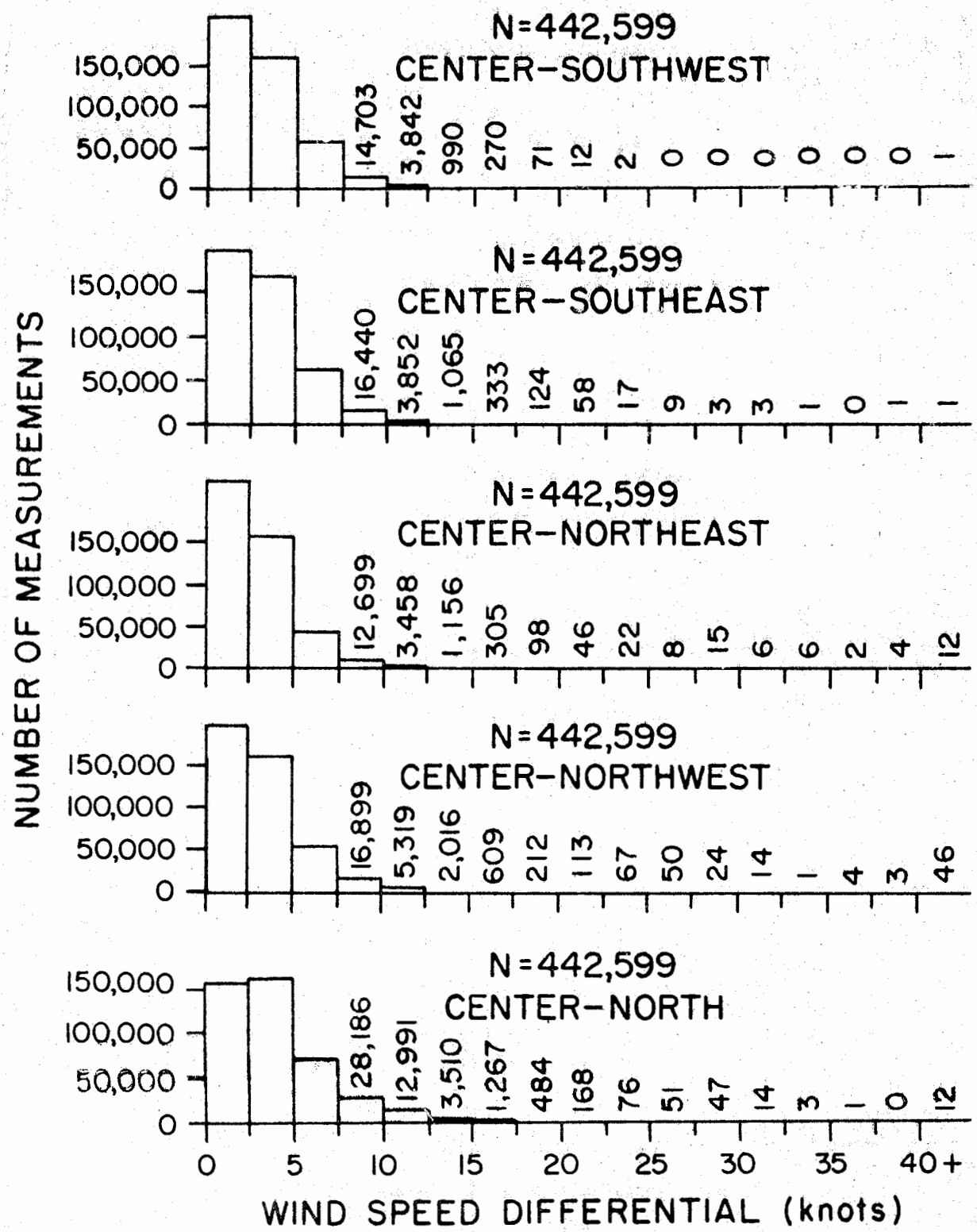

Figure 7. Histogram of wind shear (actually wind difference in knots) for each LLWAS site. Calculation is made between centerfield and each outlying boundary remote site.

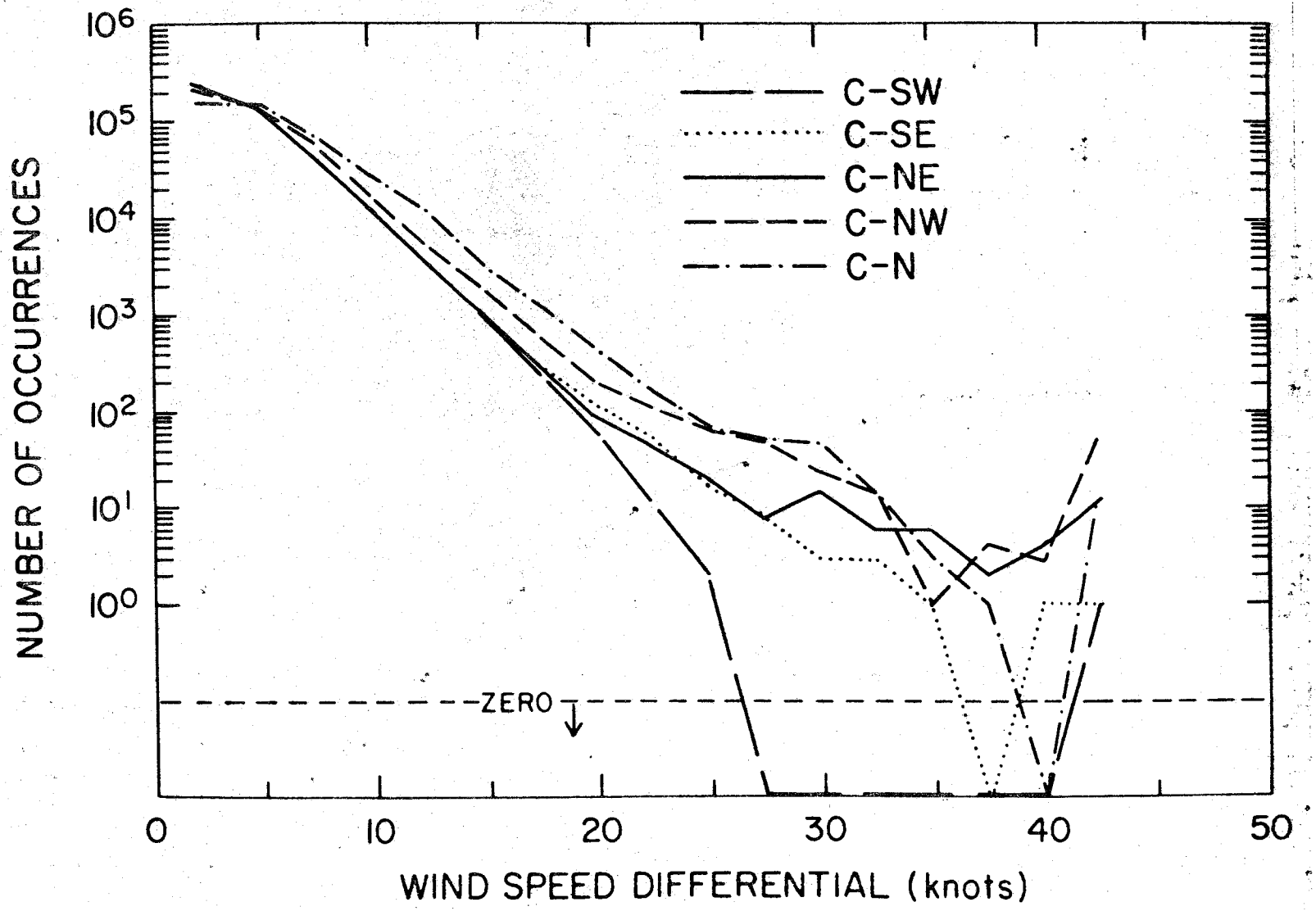

Figure 8. Log cumulative frequency distribution of wind shear (wind vector difference) data for each LLWAS site.

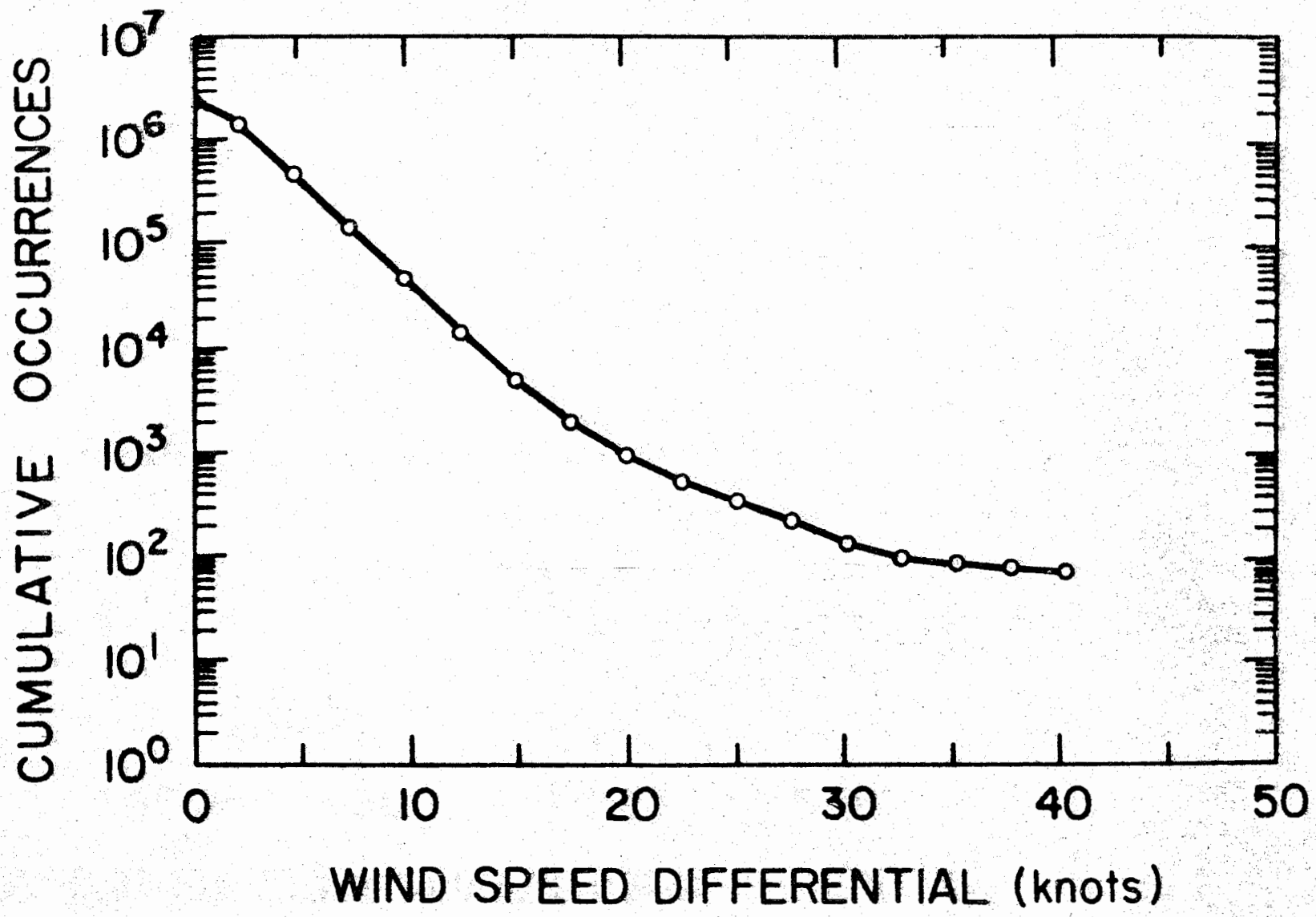

Figure 9. Log cumulative frequency distribution of wind shear (wind vector difference) for all sites combined.

falls drastically with increasing threshold. The malfunction of the north boundary remote site appears again in the form of an excessively large number of wind difference (center-north) readings in excess of 5 knots. The number of large shear values is significantly higher for the centerfield-to-north comparison partly because of the system's sporadic interpretation of the low response of the north site as a wind shear event when the wind is stronger at the centerfield. For example, if the centerfield site were to show a mean wind from the north at 20 kts, the low response of the north site might indicate a mean wind of 12 kts. Sporadic gusts causing readings from 4-14 kts at the north site would produce sporadic triggers. In effect, this defective sensing at the north site causes an inversion of the normal wind shear calculation if strong mean winds occur at the centerfield site (i.e., interprets weak winds at north site as wind shears).

Figure 8 is an alternate form of the same wind shear statistic. Figure 9 depicts the cumulative wind shear statistic for all comparisons. Again, the effect of thresholding can be examined in this figure. For example, for a 15 kt threshold 3907 triggers occur. If the threshold were changed to 20 or 25 kts, the number of measurements would decrease to about 1000 and 400, respectively. Thus, such data can be used to predict the impact of an algorithm threshold change in terms of number of triggers. However, until we examine the presence of wind shear events independently it is not meaningful to adjust the LLWAS threshold. At first we thought such a high number of events would saturate the LLWAS warning system. However, as we will see later, the number of alarms (grouped triggers) was much lower.

Figure 10 shows the distribution of triggers by time of day (MDT) for all boundary remote sites, while Figure 11 shows the same temporal distribution for all sites combined. The bimodal distribution is similar to that seen in the distribution of microburst statistics reported in McCarthy et al. (1983) using Doppler radar data from JAWS, and to that reported by Fujita and Wakimoto (1983) using PAM data. In general, the variability in the occurrences of triggers as a function of time from site to site is quite similar, with most occurring between about 1200 and 2000 MDT. All sites indicate a peak near 1600 MDT related to late afternoon convection. Although almost all of the wind shear events identified by the LLWAS occurred in the afternoon and early evening, a number of events were not related to convection. Note that several peaks occur at unusual times. One at 0100 MDT on the southeast site is probably related to nocturnal drainage flows associated with a terrain depression (creek bed). The other peak (0900-1100) on the southwest site may be caused by aircraft wake vortices. The combination of atmospheric stability and high aircraft traffic in the early morning may increase the probability of a wake vortex impact. Detailed investigations will be necessary to identify the actual causes of unusual peaks.

As mentioned earlier, the total number of triggers seemed excessive. In the design of the LLWAS, the FAA clearly recognized the sporadic nature of low-level wind shear and therefore had the system group triggers into alarms (see definition of terms, section 2.2). When a trigger occurs at a boundary remote site, the alert light in the control tower remains on for three consecutive scans. Then it goes out, unless in one of the three scans a shear of 15 kts or greater magnitude is seen in the same remote-centerfield comparison. Essentially, the alert light may stay on because of a single

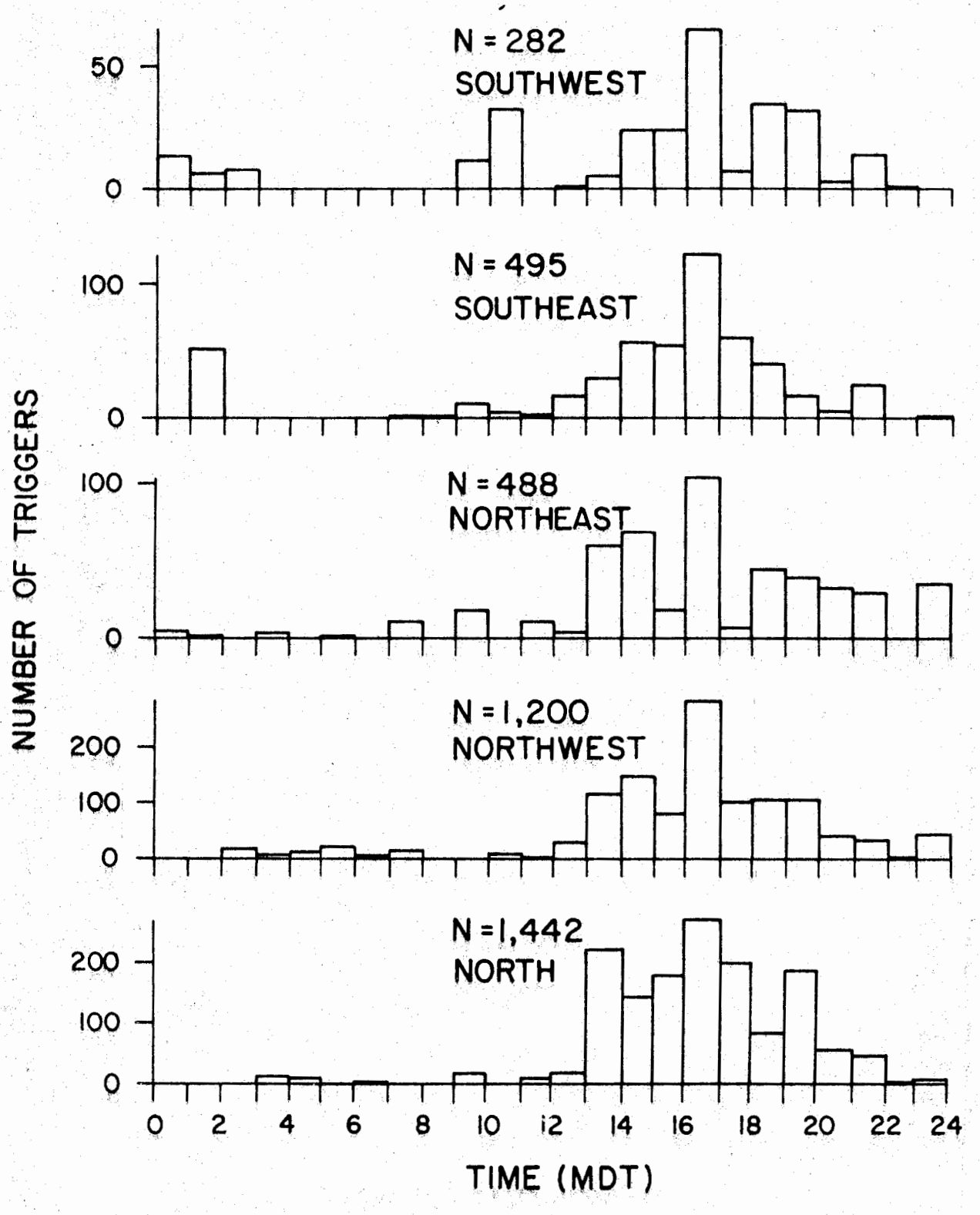

Figure 10. Histogram of all trigger events by time of day (MDT) for each site.

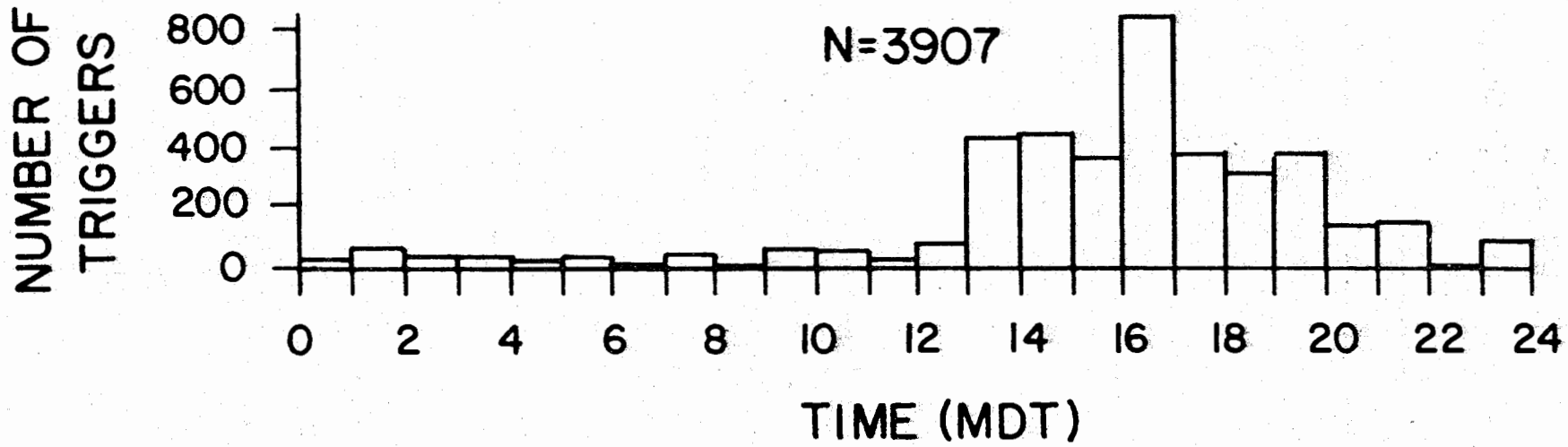

Figure 11. Histogram of triggers by time of day (MDT) for all sites combined.

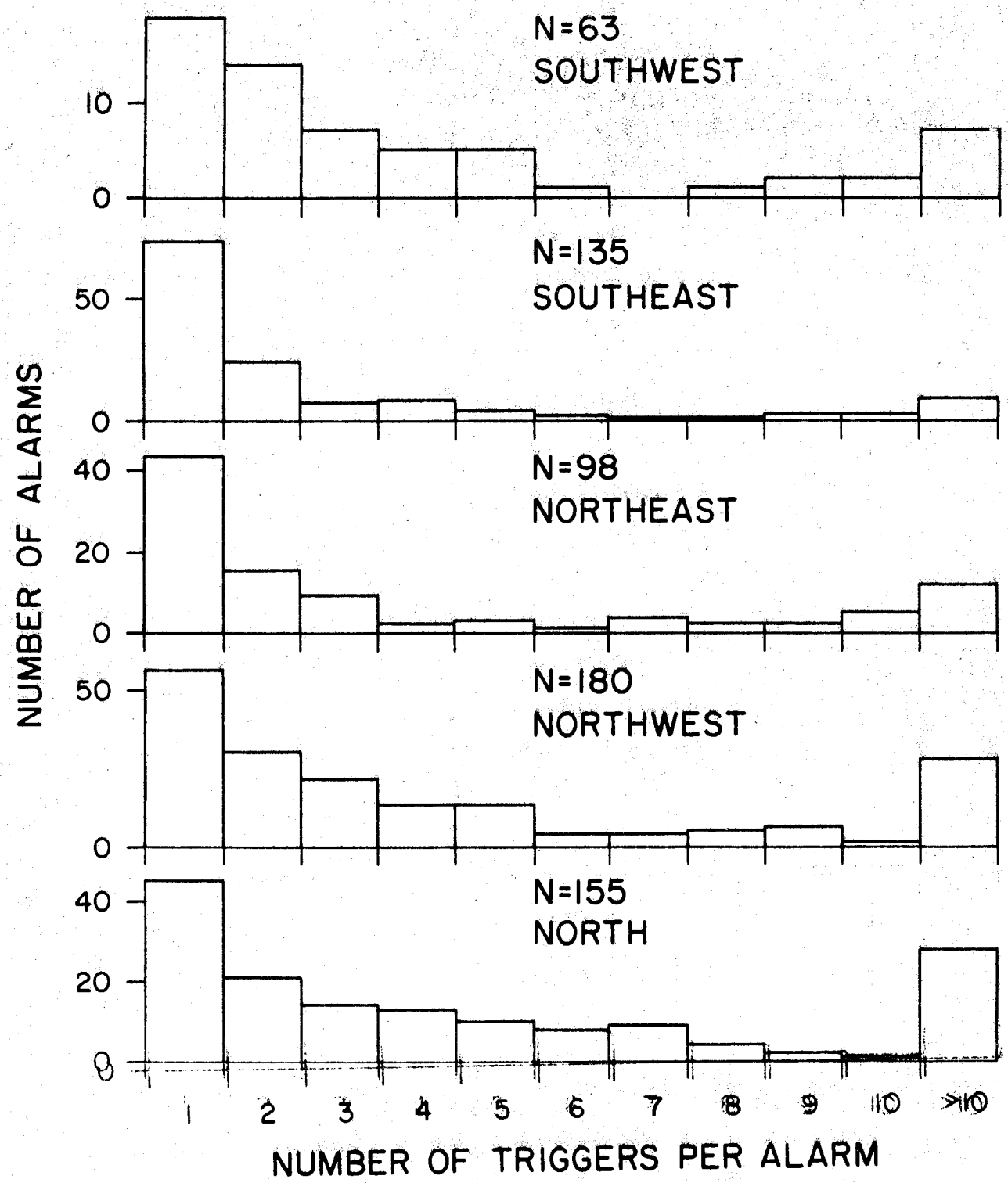

Figure 12. Histogram of distribution of all LLWAS alarms as a function of number of triggers per alarm (groups of triggers) for each LLWAS site.

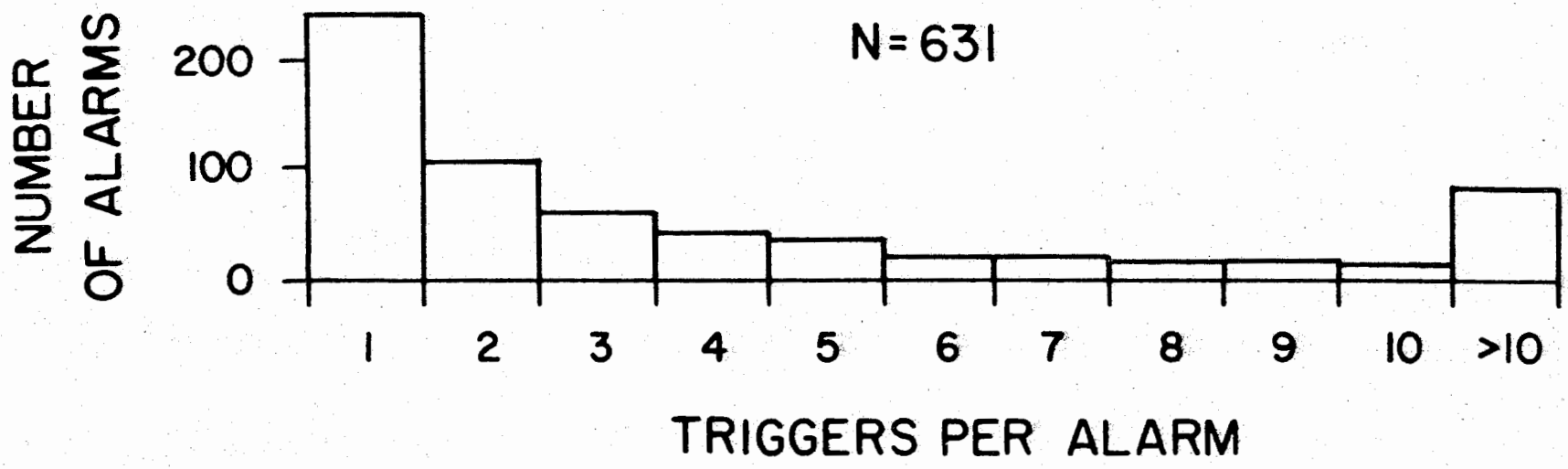

Figure 13. Histogram of LLWAS alarms by number of triggers per alarm (groups of triggers) for all boundary sites combined.

triggering event, or may stay on for a group of triggering events, according to the above concept. An alarm is defined as such a group of triggers, from one to many.

When the basic LLWAS data set is examined in terms of groups of triggers, or alarms, some intriguing statistics emerge. (1) The total number of alarms was 631, while the total number of triggers was 3,907. So the alarms represent a more realistic picture of wind shear events, in that separate shear events are better identified by alarms than by triggers. (2) From Figure 12, the northwest and north sites recorded the greatest number of alarms consisting of groups of more than 10 triggers. (3) Figure 13 shows the distribution of alarms as a function of number in the group. Single triggers account for a large number (236) of the total alarms (631), and the one and two-trigger events (340 events) account for over half of the alarms. (4) The physical differences between wind shear events are clearly identified in Figures 12 and 13. Events seen on the left side of the figures (one or two triggers per alarm) represent short-lived and small-scale wind shear events, while events seen on the right side of the figures (9, 10, or >10 triggers per alarm) represent longer-lived and larger-scale wind shear events. We would like to assume that microbursts are indicated on the left and gust fronts at the right. However, as we will see in the next section, that is probably an incorrect assumption.

4. COMPARISON OF LLWAS ALARMS WITH MICROBURST STATISTICS

Throughout the JAWS Project, the NCAR Portable Automated Mesonet (PAM) was deployed in the Stapleton Airport area, as shown on Figure 14a. This system provides 27 surface weather stations that automatically record dry bulb temperature, wet bulb temperature, wind speed and direction, station pressure, and rainfall. These data are sampled once each second, and a one-minute block average recorded, along with the peak one-second windspeed gust that occurred during the one-minute block. The wind measurements are made 4 meters above ground. A more complete description of the PAM system can be found in Brock and Govind (1977).

The PAM system was deployed in a manner which coincided with the LLWAS, since we were uncertain that the latter would be recorded during JAWS. However, the availability of both measuring systems made it possible to conduct a suitable comparison. Figure 14b shows the locations of the LLWAS measuring sites relative to the airport.

Fujita (1983) has scrutinized the PAM data set during JAWS, for the purpose of identifying the number of microbursts that occurred there. He made the assumption that a microburst produces a short-lived windspeed maximum, which lasts less than 4 minutes at a single station.

Figure 15 shows a hypothetical microburst profile for a single station hit, and this figure demonstrates the basis of Fujita's algorithm for microburst detection.

First, the pre- and post-peak means are defined by

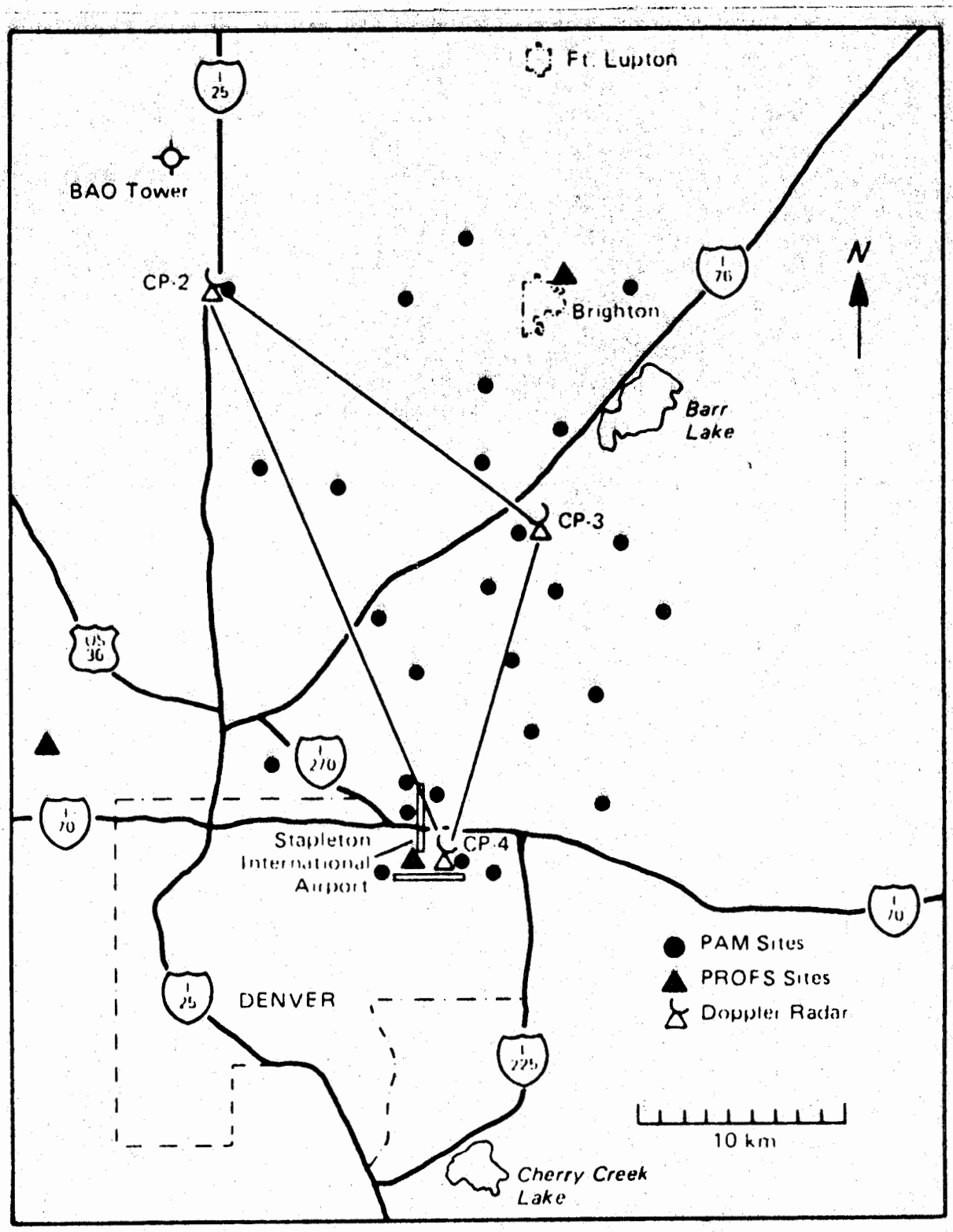

Figure 14a. JAWS research area, showing, among other things, the distribution of 27 PAM stations in the experimental network.

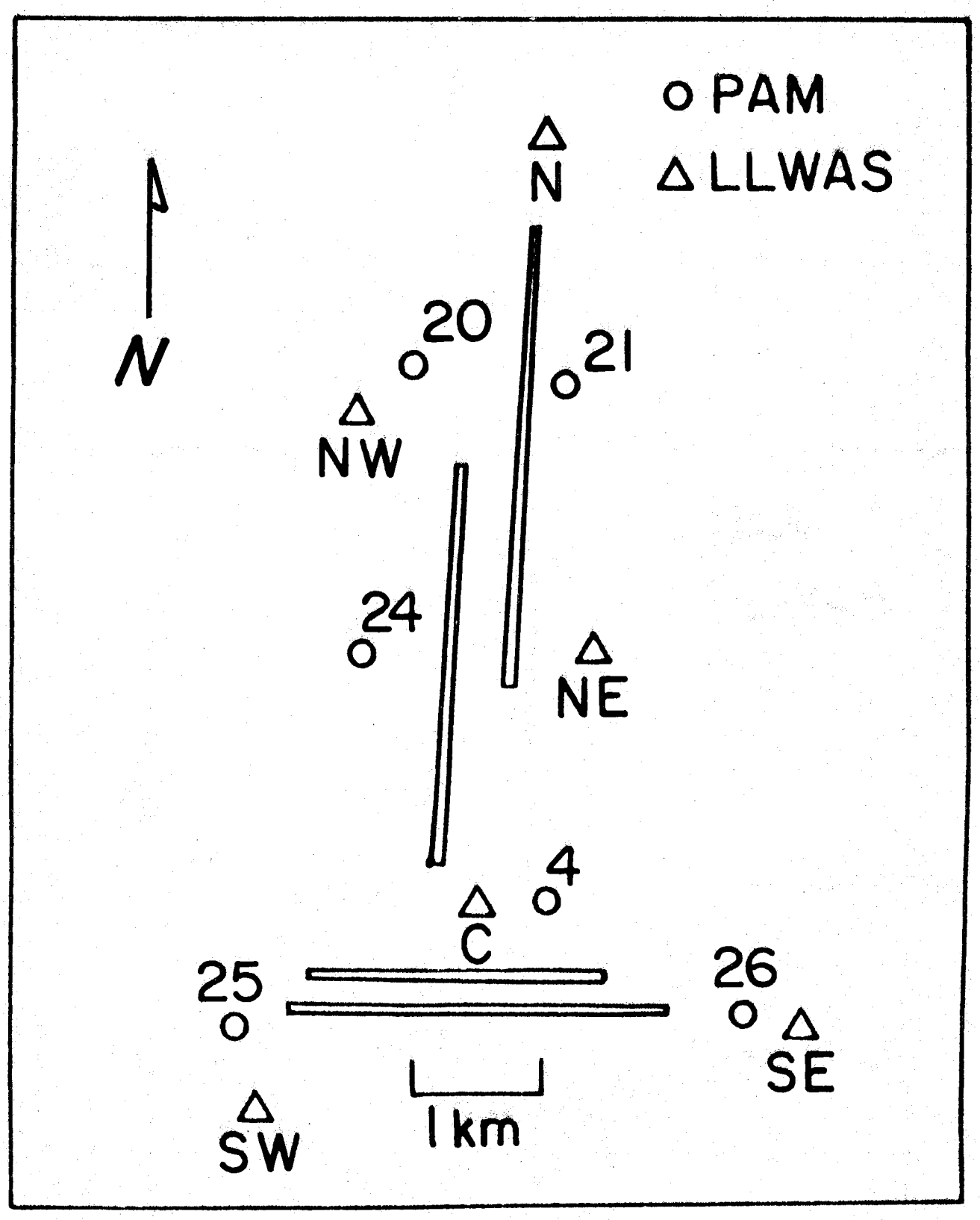

Figure 14b. LLWAS boundary site locations relative to the airport.

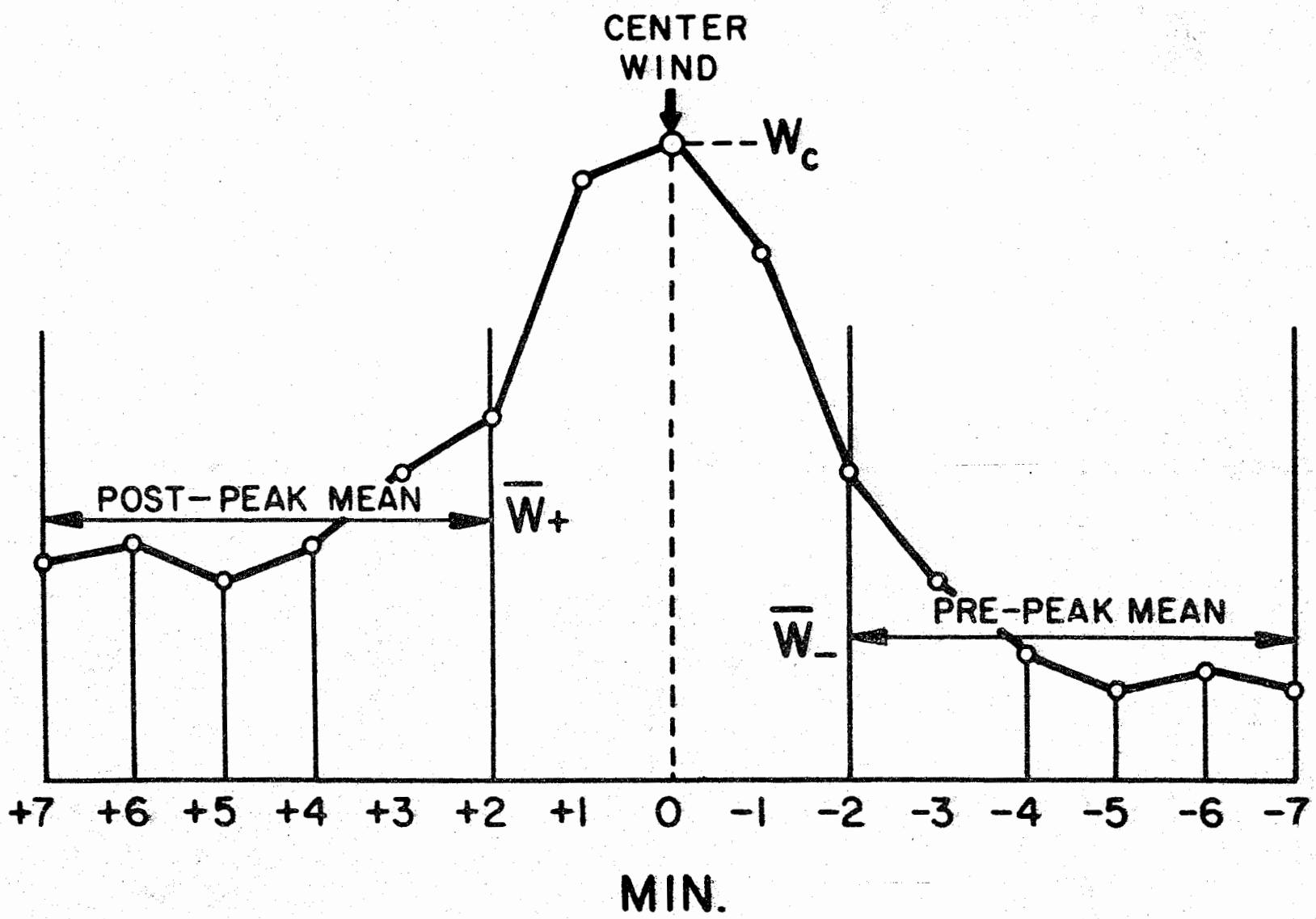

Figure 15. Algorithm for detecting microburst winds based on PAM winds measured at one-min intervals.

$$\bar{W}_- = \frac{1}{6} \sum_{-2\ min}^{-7\ min} W_{max} \quad \text{....pre-peak mean speed} \tag{a1}$$

$$\bar{W}_+ = \frac{1}{6} \sum_{+2\ min}^{+7\ min} W_{max} \quad \text{....post-peak mean speed} \tag{a2}$$

which are the mean wind speeds on both sides of a given time (see Figure 15).

Then a computer listing of the time (day, hr, min) of the winds which satisfied simultaneously the following six conditions was obtained:

Condition 1, $W_c > 10$ m/sec = 19.4 kts (a3)

Condition 2, $W_c > \bar{W}_- + 5$ m/sec (a4)

Condition 3, $W_c > \bar{W}_+ + 5$ m/sec (a5)

Condition 4, $W_c > 1.25\ \bar{W}_-$ (a6)

Condition 5, $W_c > 1.25\ \bar{W}_+$ (a7)

Condition 6, $\bar{W}_+ < 1.5\ \bar{W}_-$ (a8)

Condition 1 specifies that the center wind W_c must be faster than 10 m/sec (19.4 kt) in order to be identified as a microburst. Every maximum wind measured by PAM was used as the center wind.

Conditions 2 and 3 state that the center wind must be at least 5 m/sec faster than the mean speeds before and after the center wind.

Conditions 4 and 5 specify that the center wind must be at least 25% faster than the mean wind speed before and after the center wind.

Condition 6 excludes the gust fronts which are often characterized by long-lasting post-frontal winds.

Using this algorithm, 436 peak winds in JAWS, throughout the PAM rationale, were identified using a computer as candidates for microburst winds. This very large number of "spike" winds was believed by Fujita to be excessive, and a detailed case-by-case hand analysis reduced the total number to 186 for the full PAM station domain, and to 123 microbursts within 8 nautical miles of Stapleton.

This count is believed to be an approximation of microburst counts, with the possibility of wake vortices, some double station counting, and other unknown contamination present in the statistics. In addition it should be clear that other forms of wind shear at the Earth's surface, such as gust fronts (meeting condition 6), have been eliminated.

We compared the daily totals of alarms for the LLWAS system during the test period with the daily counts of microbursts identified by Fujita (1983), and Fujita and Wakimoto (1983) as occurring within the PAM array, located within an 8 nautical mile radius of Stapleton Airport (Fig. 14b). Figure 16 is a histogram showing the comparison. This figure also appeared in Townsend (1983). On two important microburst days, 14 and 15 July 1982, a large

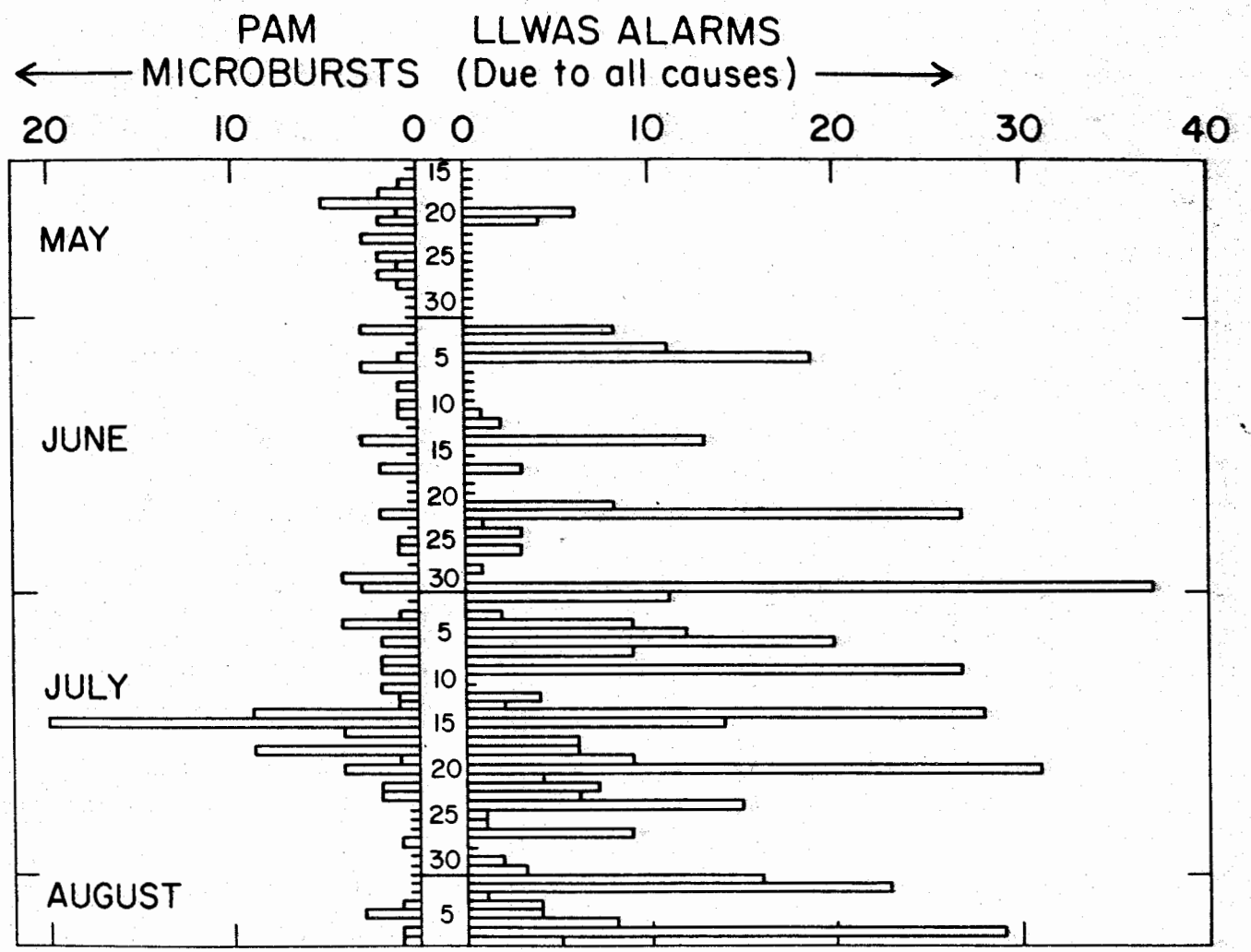

Figure 16. Distribution of number of LLWAS alarms by day during the period 20 May to 8 August (during which time the NCAR PAM was operating) compared with the distribution of number of microbursts by day as determined by Fujita and Wakimoto (1983) within 8 mi of the Stapleton runways.

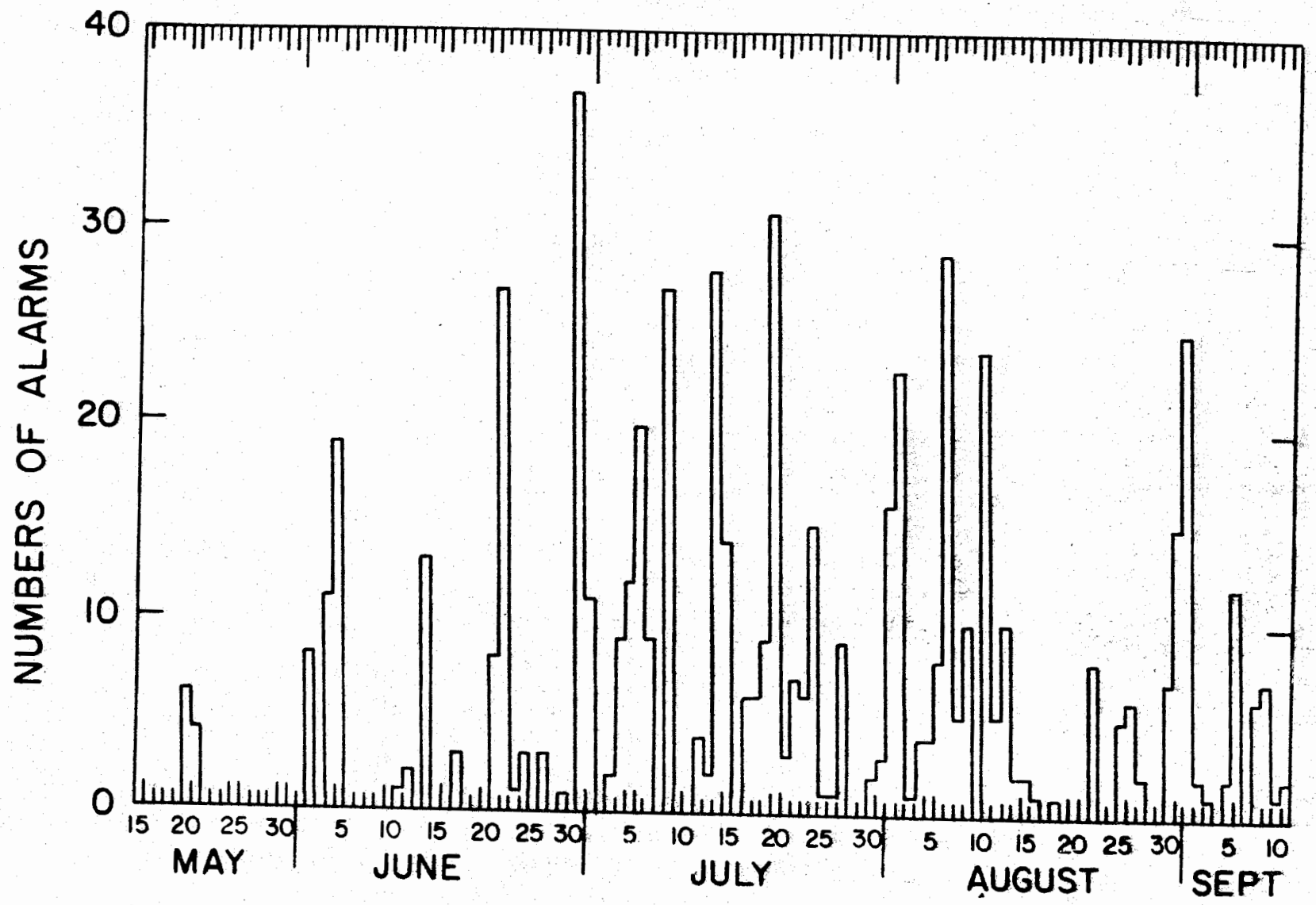

Figure 17. Distribution of number of LLWAS alarms by day during the period 15 May to 11 September 1982.

occurred. However, many days with many alarms were not "microburst days." Remember, however, the LLWAS system includes microburst wind shear with other forms of wind shear, whereas results of Fujita are based upon an algorithm designed to suppress gust fronts. Thus one word of caution is necessary when making this comparison: the microburst statistics shown in Figure 16 do not indicate the presence of larger-scale events such as gust fronts. A parallel study in progress (to be published separately) examines case studies that document the effective operation of the LLWAS system during strong wind shear events. However, a purpose here is to examine the types of flows related to the alarms that occurred on days with apparently only weak convective activity. We are looking for the sources of alarms during weak flow events. Figure 17 is an alternate presentation of LLWAS alarms by day, extending into September 1982.

During the JAWS experiment there were 631 alarms. Comparing LLWAS alarms with meteorological data from PAM and other sources we related 101 (16.3%) alarms to microbursts, 75 (12.1%) to gust fronts, 145 (23.3%) to isolated gusts, and 300 (48.3%) to other sources. It is this last group of alarms that need to be characterized in terms of meteorological sources and wind shear severity. Because we lack detailed meteorological data covering the lowest 300 meters for most alarms, we cannot address such a characterization in this report. However, following sections provide examples for some alarms and the associated meteorology derived from PAM and/or radar data. An important observation is the large number (145) of alarms involving isolated gusts (one or two isolated triggers near the 15 kt threshold level). Our study suggests that a large number of false alarms could be eliminated by requiring an alarm to consist of 3 or more consecutive triggers.

Several days with high numbers of LLWAS alarms and few detected microbursts were examined to investigate the nature of the system alarms. Table 2 summarizes the results, and Figures 18a through 18g present the actual data for segments of each of the intervals for each day presented in the table. The few observed microbursts indicated in Figure 16 are more significant since they are based upon a larger area covered within 8 nautical miles of the airport by the PAM array. We chose 6 days for study each of which showed a significant number of LLWAS alarms and no or few microbursts on the PAM array. After reviewing the LLWAS data for each day we identified intervals representative of the types of flow causing the alarms. On each of the days weak wind gusts marginally near the 15 kt threshold caused sporadic triggers. An example on 22 June 82 (Fig. 18a) shows the north site low sensitivity interpreted as a wind shear relative to the centerfield site, thus producing triggers (in this case false alarms). Another example on 30 June 82 (Fig. 18c) indicates how a localized gust occurring in a convectively disturbed situation can cause a trigger. Such gusts probably occur over small scale sizes. Such local gusts and weak flows causing marginal triggers may not present a significant hazard to aircraft. The following section discusses the meteorology for each of the cases described in Figures 18a through 18f. JAWS Doppler radar scans are used to help identify flow features.

Table 2. Summary of the nature of LLWAS alarms for selected days when the LLWAS indicated many alarms but few microburst wind shear events were seen on the PAM system.

Date	Number of LLWAS Alarms	Number of Microbursts	Nature of Alarms
22 June 82	27	3	(a) Weak flows (no gusts over 20 kts) causing sporadic alarms (b) 1609 MDT weak microburst (c) North site triggers because of equipment problem (Fig. 16a)
30 June 82	37	3	(a) Marginal sporadic windshear from SE site much of the day (Fig. 16b) (b) Event at 1810 MDT (c) 1757 MDT example of trigger from localized gust (Fig. 16c)
20 July 82	31	3	Marginal 15 kt vector difference triggers occur sporadically (Fig. 16d)
21 July 82	3	0	Marginal 15 kt vector difference triggers occur sporadically (Fig. 16e)
2 August 82	23	1	Marginal 15 kt vector difference triggers occur sporadically (Fig. 16f)
7 August 82	29	2	Marginal 15 kt vector difference triggers occur sporadically (Fig. 16g)

22 June 1982 (1540-1550 MDT) (Figs. 18a.1 and 18a.2)

There were no triggers associated with the initial motion of a weak gust front moving from south-to-north over the LLWAS array. However, when two northern sites (N and NW) were not as yet in the cold outflow air, triggers occurred because the outflow caused the centerfield mean wind to exceed the 15 knot vector difference relative to the N and NW sites. Figure 18a.2 shows this situation. Although a microburst occurred to the north of the airport at 1547, it was too far away (~10 km) to influence flows over the airport. This case is notable in that it represents an "inverse" detection of a gust front. The leading edge of the gust front did not cause triggers as it entered the airport boundary; but the absence of the gust front at two north LLWAS locations did cause triggers.

30 June 1982 (1535-1545 MDT) (Figs. 18b.1 and 18b.2)

Between 1530 and 1600 MDT there was a flow from SE to NW measured on the surface sites to the east of the airport. A boundary between a weak flow from west to east and this flow from the southeast occurred over the airport. Figure 18b.2 shows the wind vector fields at 15:42:28 MDT. The fact that the southeast (SE) LLWAS site was not in the west-to-east flow caused that site to initiate an LLWAS trigger marginally above the 15 knot vector difference.

30 June 1982 (1750-1800 MDT) (Figs. 18c.1 and 18c.2)

A convective boundary developed over the airport oriented NE to SW. No precipitation was measured and there was no radar evidence of diverging flows or microbursts. The simple gust and associated trigger on the NW site could not be related to any specific meteorological event. Figure 18c.2 indicates that the mean flow was from NW to SE on the northern LLWAS sites. Such flows (in excess of 10 knots) should have prevented the advection of wake vortices from the N-S runways to the NW LLWAS site.

20 July 1982 (1810-1820 MDT) (Figs. 18d.1 and 18d.2)

Marginal triggers occurred for the NE and SE LLWAS sites from about 1812 to 1816. There is no evidence of a thunderstorm gust front or the small scale divergence that would indicate a microburst. Radar indicated a cyclonic flow across the airport and a line of virga was observed over the airport. A display of the wind vector fields (Fig. 18d.2) at 18:15:28 MDT indicate a complex pattern of surface flows probably caused by a combination of weak convective flows interacting with a mesoscale eddy.

21 July 1982 (2040-2049 MDT) (Figs. 18e.1 and 18e.2)

The height contours across Stapleton International Airport range from about 5300 ft near the south boundary to 5200 ft north of the airport. The land rises to the east and north to typically 5300 to 5400 ft within 1 to 2 miles of the airport. Triggers marginally above the 15 knot vector difference threshold occurred with the NW LLWAS site from 2040 to 2050 MDT. Figure 18e.2 shows the complex pattern of surface flows that occurred at 20:41:26 MDT. The flow patterns are typical of nocturnal drainage flows, strengthening and weakening at sporadic intervals during the evening hours.

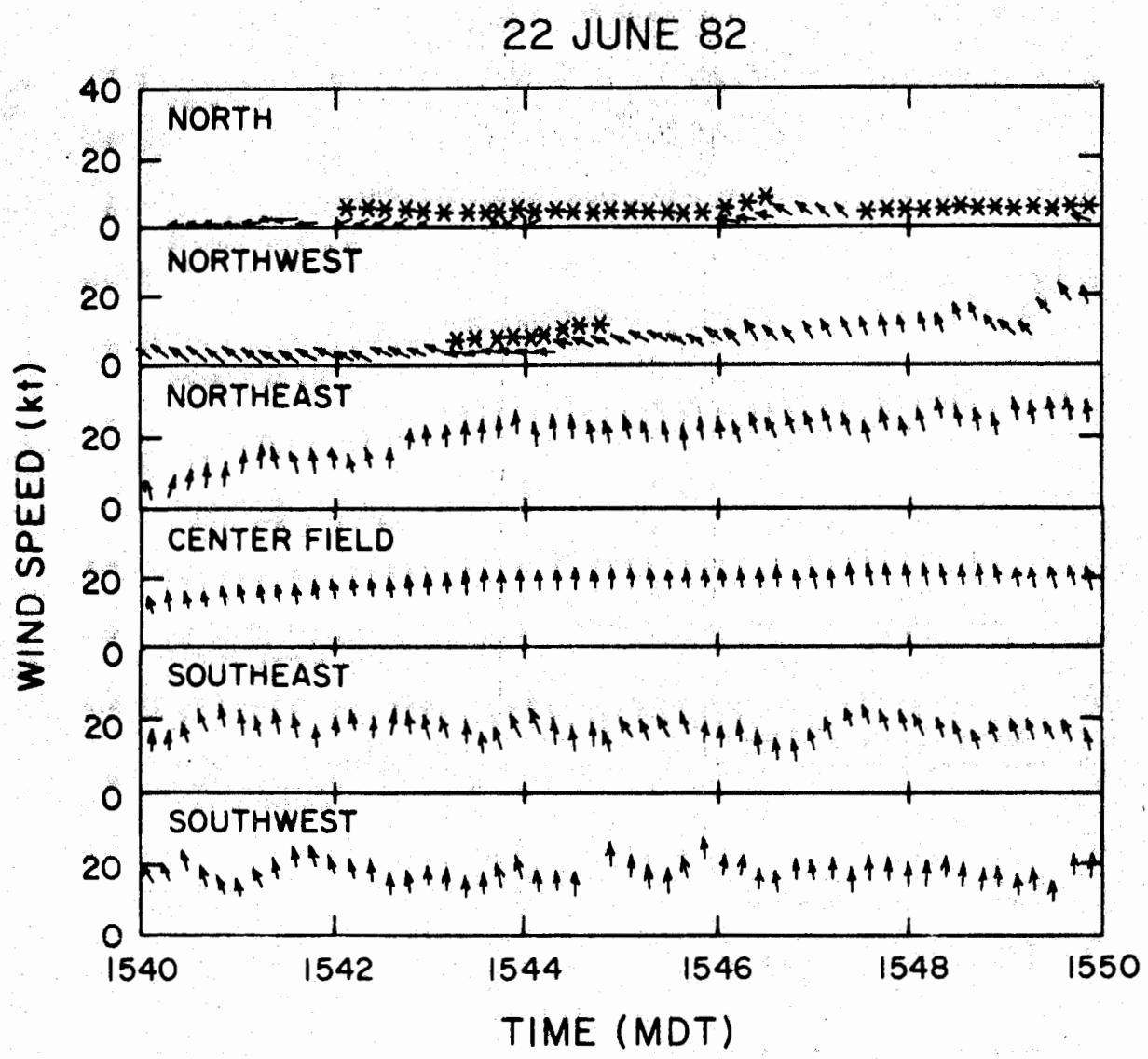

Figure 18a.1. Ten-minute segment of LLWAS data for 22 June 1982 (1540 to 1550 MDT). The winds at each site are shown, with the ordinate indicating speed magnitude in knots. The origin of each vector indicates the wind speed magnitude and the arrow indicates wind direction. An arrow pointing directly down indicates a wind from the north. * refers to an LLWAS trigger. Triggers on the north site are in part related to the low-sensitivity problem.

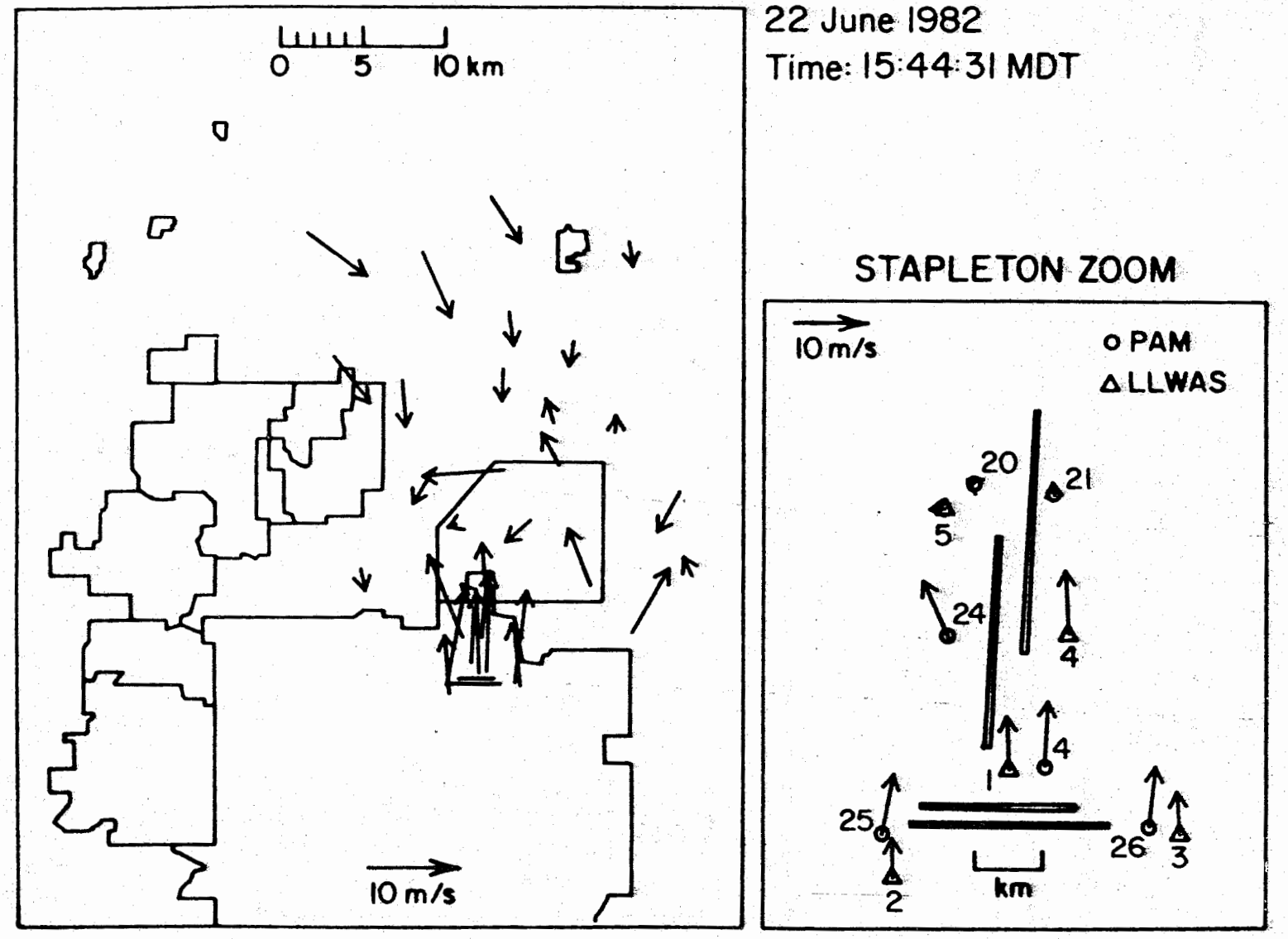

Figure 18a.2. Wind vectors on 22 June 1982 (~1544 MDT) illustrating how the absence of strong winds at the northern site resulted in triggers.

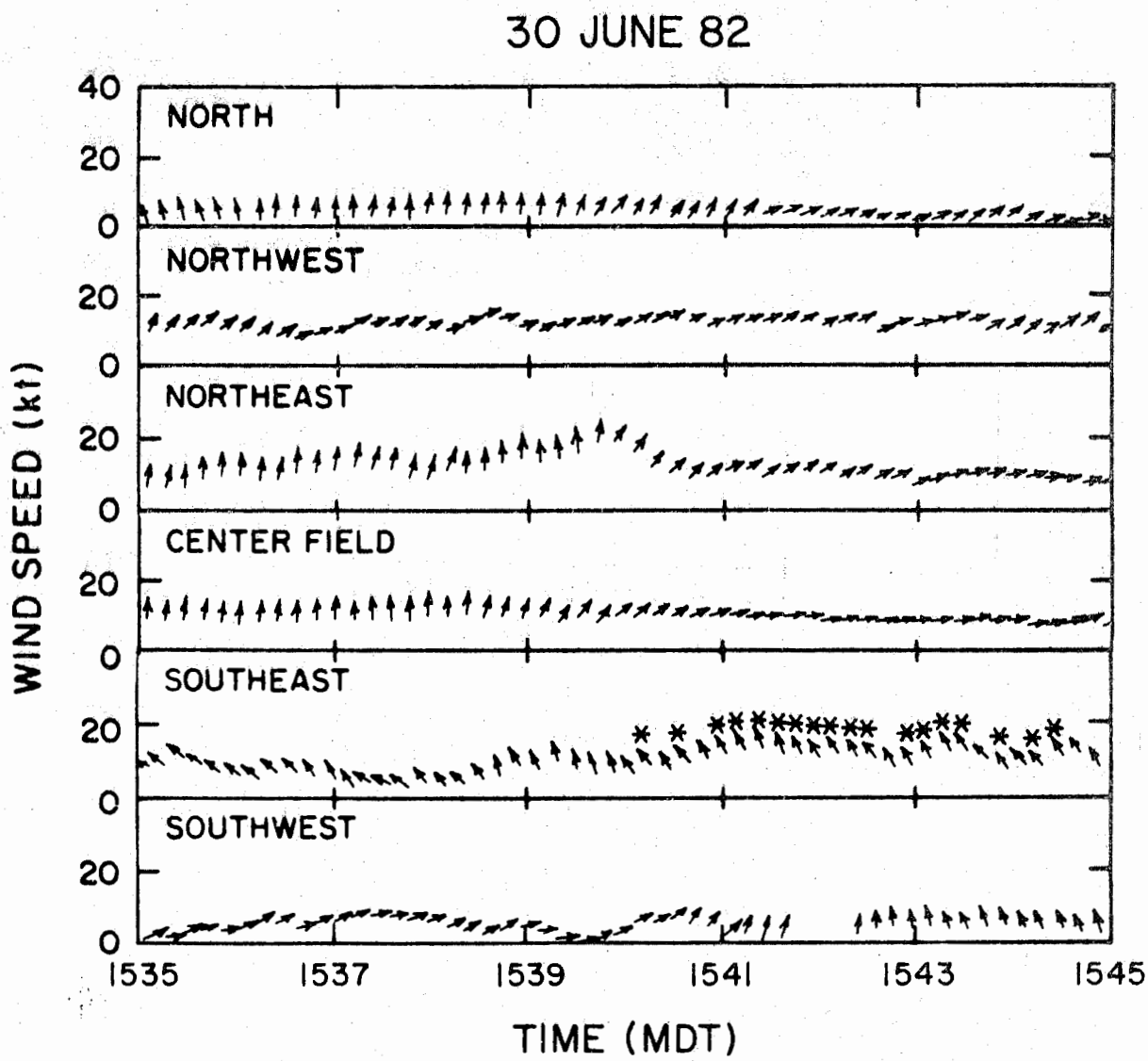

Figure 18b.1. Ten-minute segment of LLWAS data for 30 June 1982 (1535 to 1545 MDT). The winds at each site are shown, with the ordinate indicating speed magnitude in knots. The origin of each vector indicates the wind speed magnitude and the arrow indicates wind direction. An arrow pointing directly down indicates a wind from the north. * refers to an LLWAS trigger. Note that the LLWAS triggered at times that are obviously not related to thunderstorm gust fronts or microbursts.

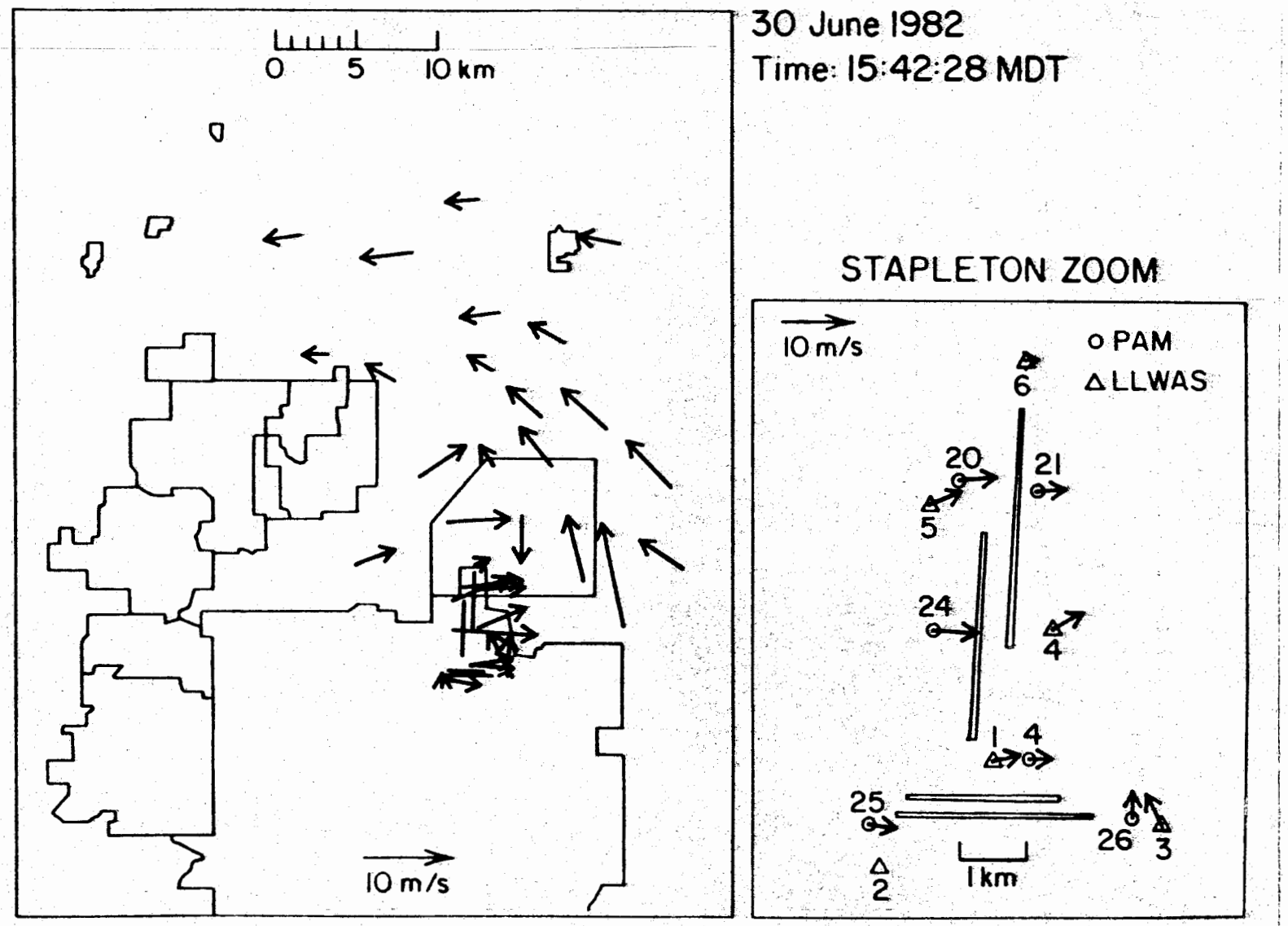

Figure18b.2. Wind vectors on 30 June 1982 (~1542 MDT) illustrating the SE LLWAS site detecting a flow from the south resulting in triggers when compared with the centerfield flow from the west.

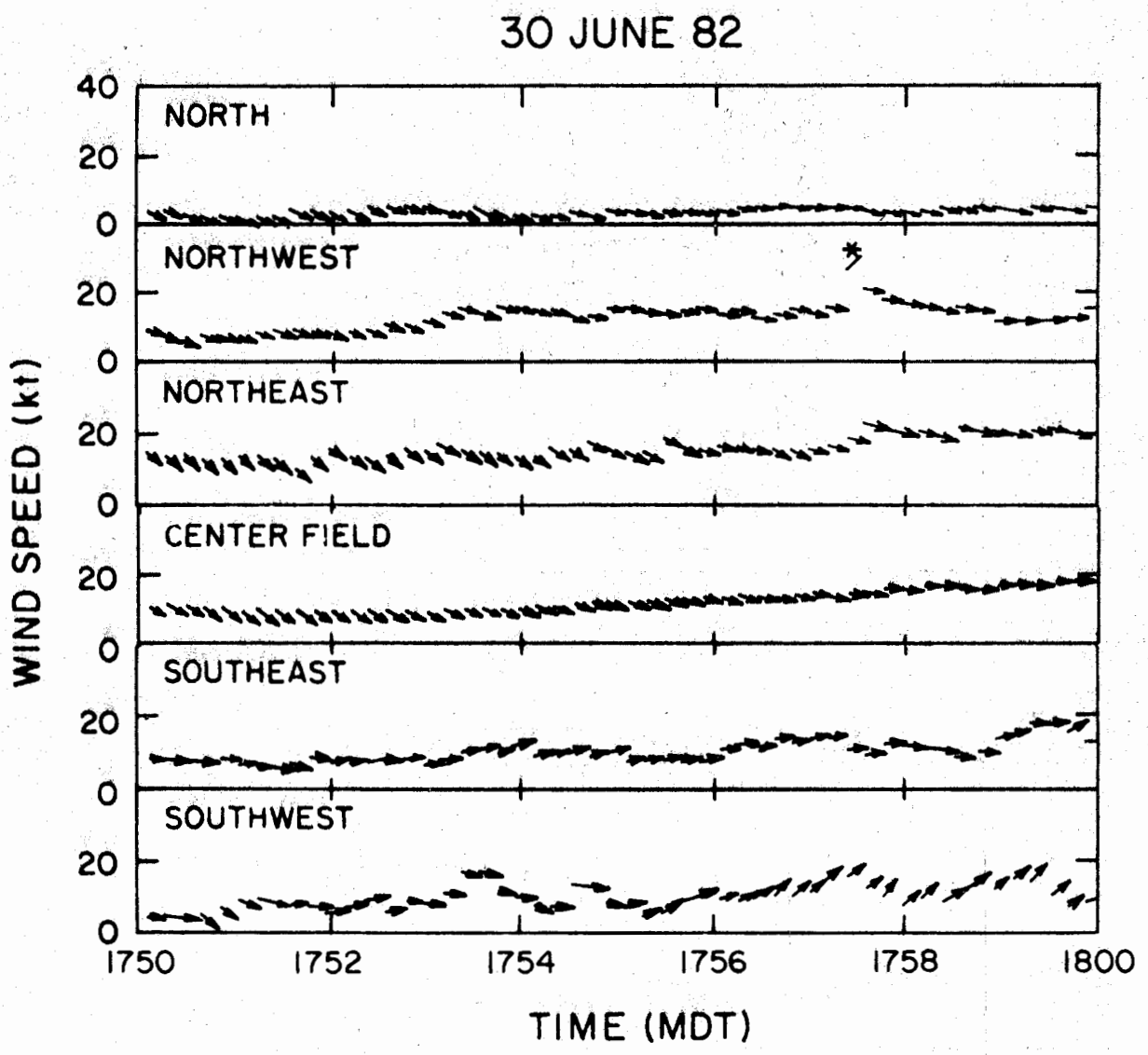

Figure 18c.1. Ten-minute segment of LLWAS data for 30 June 1982 (1750 to 1800 MDT). The winds at each site are shown, with the ordinate indicating speed magnitude in knots. The origin of each vector indicates the wind speed magnitude and the arrow indicates wind direction. An arrow pointing directly down indicates a wind from the north. * refers to an LLWAS trigger. Note that the LLWAS triggered because of a localized gust.

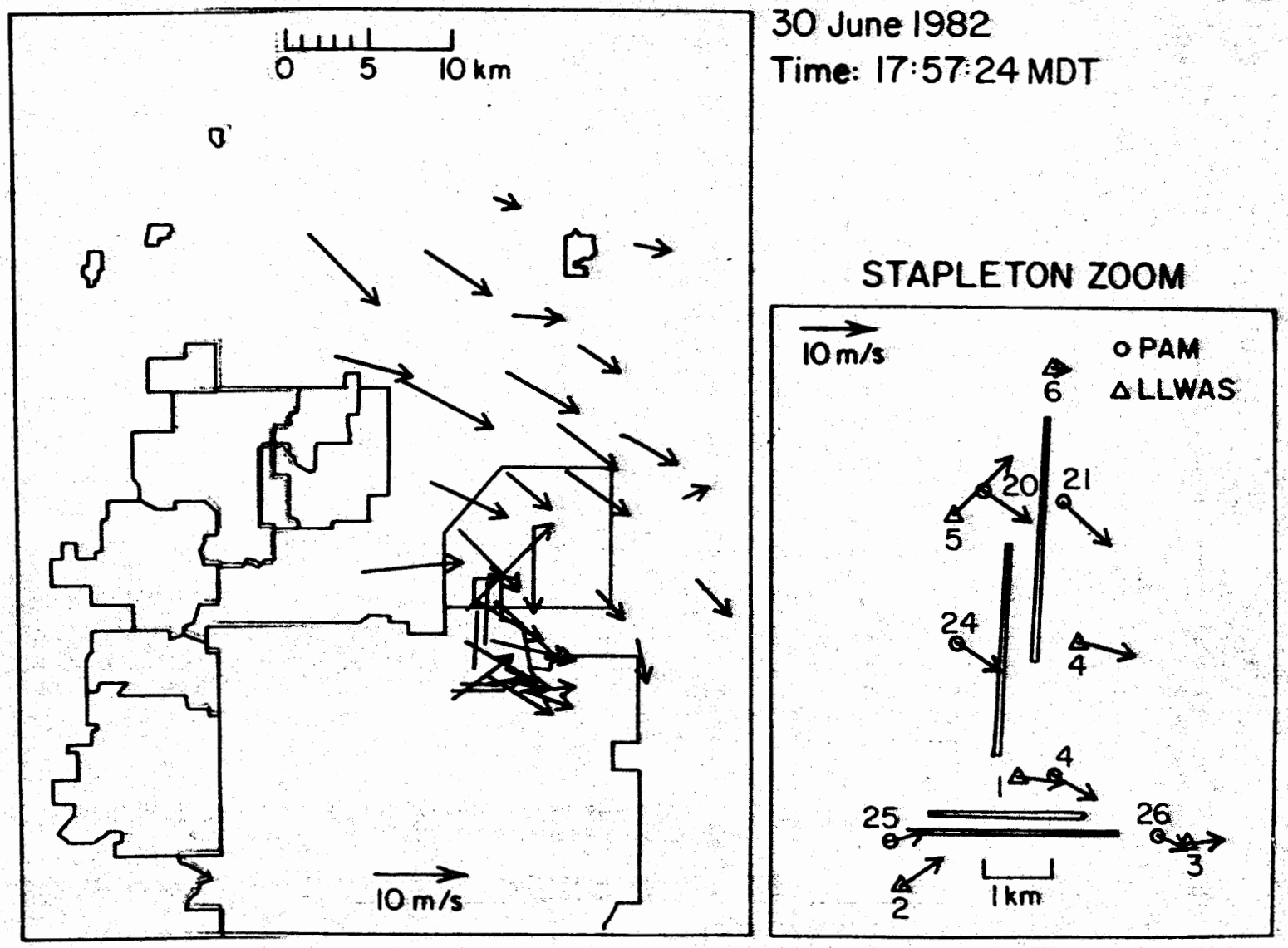

Figure 18c.2. Wind vectors on 30 June 1982 (~1757 MDT) showing the gust measured on the NW site.

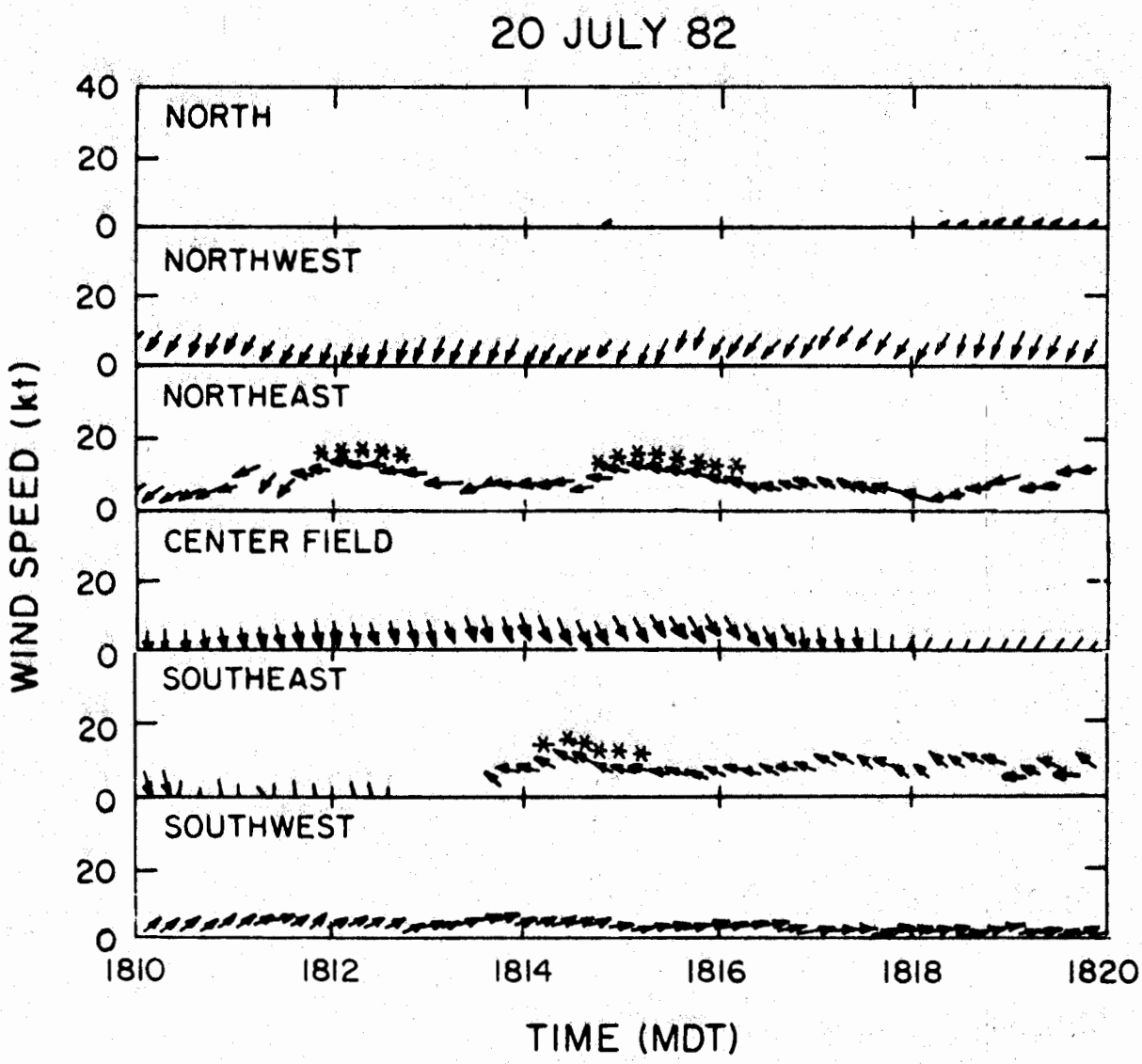

Figure 18d.1. Ten-minute segment of LLWAS data for 20 July 1982 (1810 to 1820 MDT). The winds at each site are shown, with the ordinate indicating speed magnitude in knots. The origin of each vector indicates the wind speed magnitude and the arrow indicates wind direction. An arrow pointing directly down indicates a wind from the north. * refers to an LLWAS trigger. Note that the LLWAS triggered at times that we could not relate to thunderstorm gust fronts or microbursts.

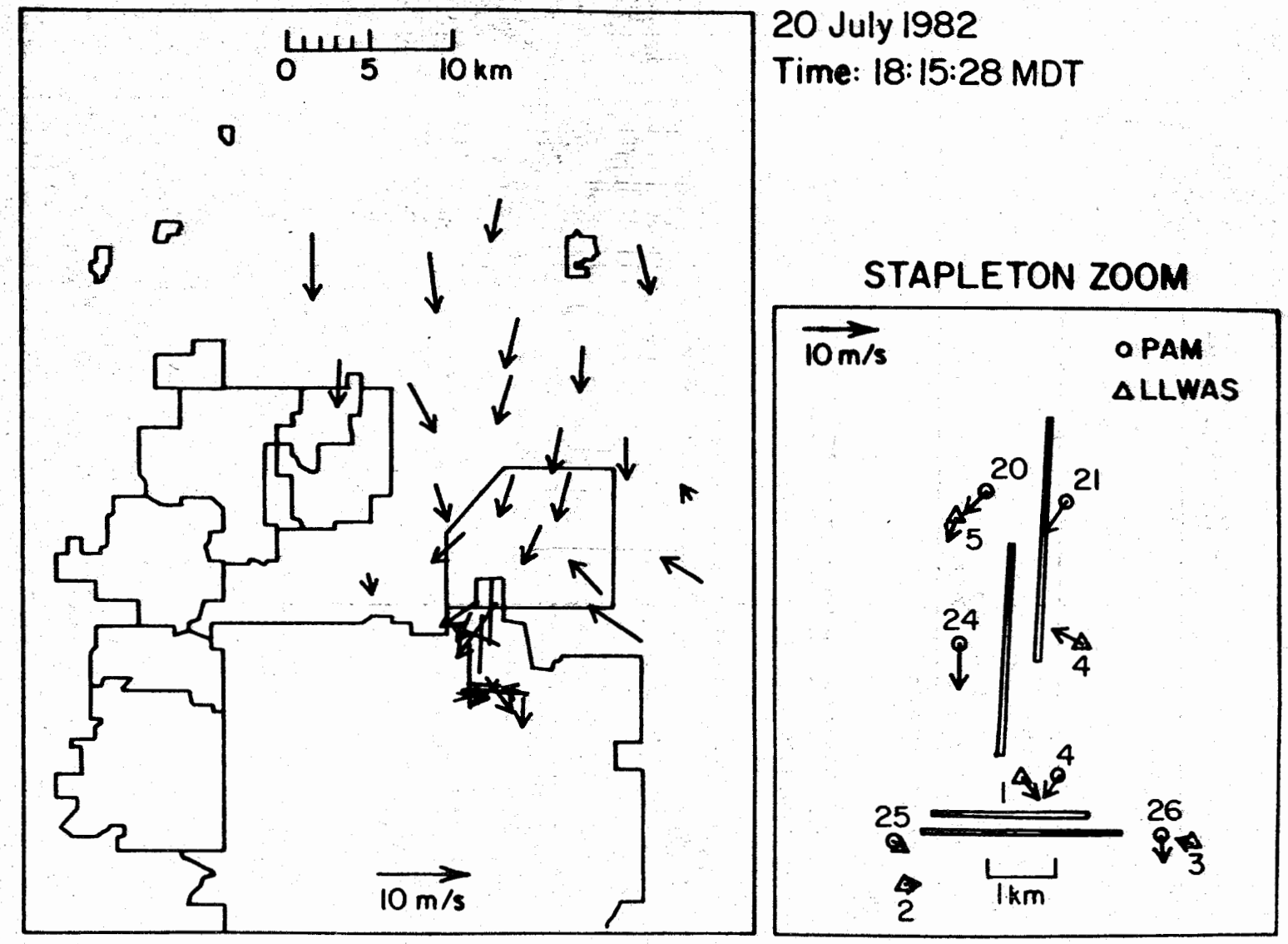

Figure 18d.2. Wind vectors on 20 July 1982 (~1815 MDT).

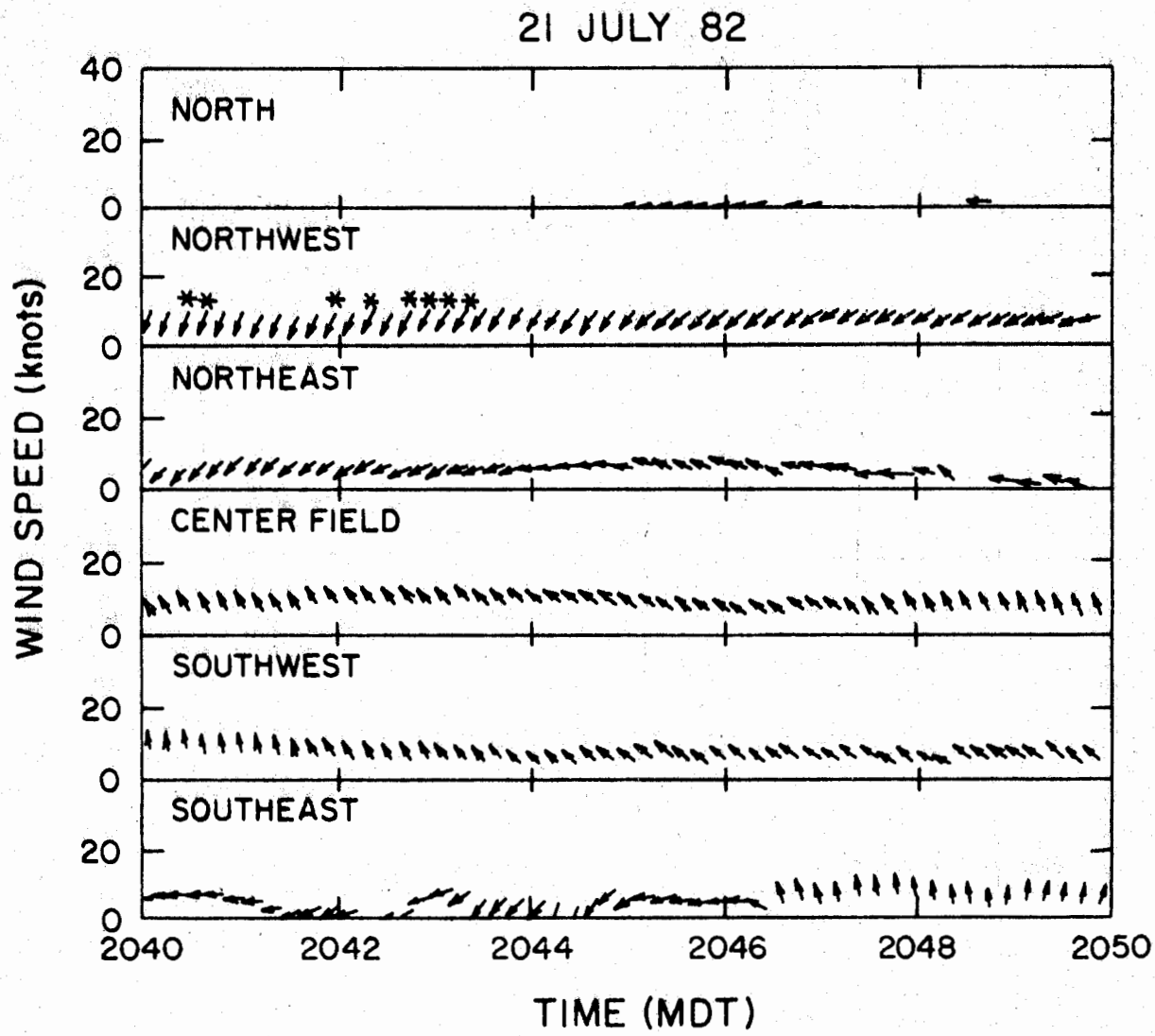

Figure 18e.1. Ten-minute segment of LLWAS data for 21 July 1982 (2040 to 2050 MDT). The winds at each site are shown, with the ordinate indicating speed magnitude in knots. The origin of each vector indicates the wind speed magnitude and the arrow indicates wind direction. An arrow pointing directly down indicates a wind from the north. * refers to an LLWAS trigger. Note that the LLWAS triggered at times that are obviously not related to thunderstorm gust fronts or microbursts.

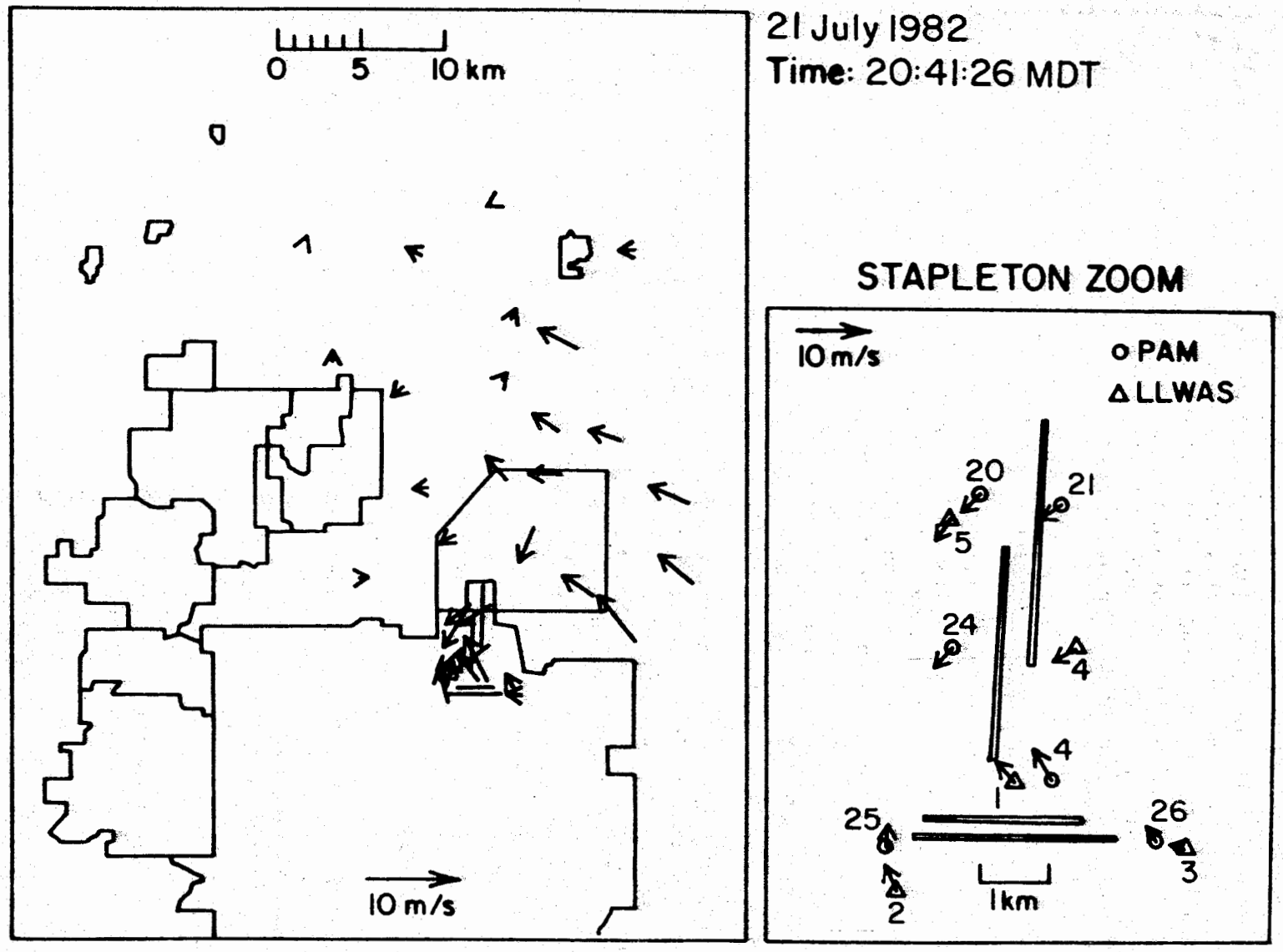

Figure 18e.2. Wind vectors on 21 July 1982 (~2041 MDT) probably related to nocturnal drainage flows.

We found no evidence of thunderstorm gust front or microburst activity causing these flows.

2 August 1982 (1345-1400 MDT) (Figs. 18f.1 and 18f.2)

A radar scan of the region at 1357 indicated no significant returns. Sporadic triggers occurred during this interval with the N and NW LLWAS sites. A vector plot of the winds at 13:51:33 MDT (Figs. 18f.2) indicates the complex pattern of surface winds occurring. We find no evidence of thunderstorm gust front or microburst induced flows. We deduce that the triggers were caused by the variable pattern of relatively weak flows in a convective boundary layer.

7 August 1982 (1550-1600 MDT) (Figs. 18g.1 and 18g.2)

A radar scan detected a strong flow from NE to SW also shown by the PAM array with no indication of significant divergence. Figure 18g.2 shows evidence of small scale convergence over the airport. The sporadic triggers on the N, NW, NE, and SE sites seem to be related to this region of weak convergence and not directly to the stronger flows occurring outside the airport boundary. The centerfield anemometer was in the region between the northerly flow south of the airport and the N-NW flow north of the airport. The low centerfield wind speed values (~1 kts from the south) produced the marginal 15 knot vector difference values causing the triggers.

We can conclude from Figures 16, 17, and 18, and Table 2 that the LLWAS system can have alarms from relatively weak or marginal wind shear situations that are not thunderstorm gust front or microburst events. This should then be addressed in making improvements to the system. Our general perspective is to guard against "quick fix" algorithms that may not deal with the physics of accurate sampling of low-altitude wind shear. However, in Section 5 we explore several points made at the end of the last section, and illustrate the value of a particular "quick fix." We have attempted to illustrate that it should be possible to improve the system significantly using alternate algorithms, based upon analysis of available data, without radical changes in basic system concept and design.

5. EVALUATION OF A GUST MAGNITUDE ALGORITHM

The current LLWAS operating algorithm is based on an advective concept that appears to favor gust front features, on detection of wind-shift lines advecting into the system from afar, by using a 2 min running average at centerfield as a reference. Case studies of strong microburst events typically show sudden wind magnitude changes together with complex direction changes. This is especially true near a microburst impact region. These observations suggest that a gust magnitude change might provide a means of preferentially detecting spatially concentrated microbursts when a reference based upon the winds for the total system is used.

As a reference for the new algorithm we used the average of the wind speed readings at boundary sites for approximately a 2 min period (10 scans). The centerfield anemometer was excluded from these calculations. The newest 8 s RC average wind reading from each site was compared with this running

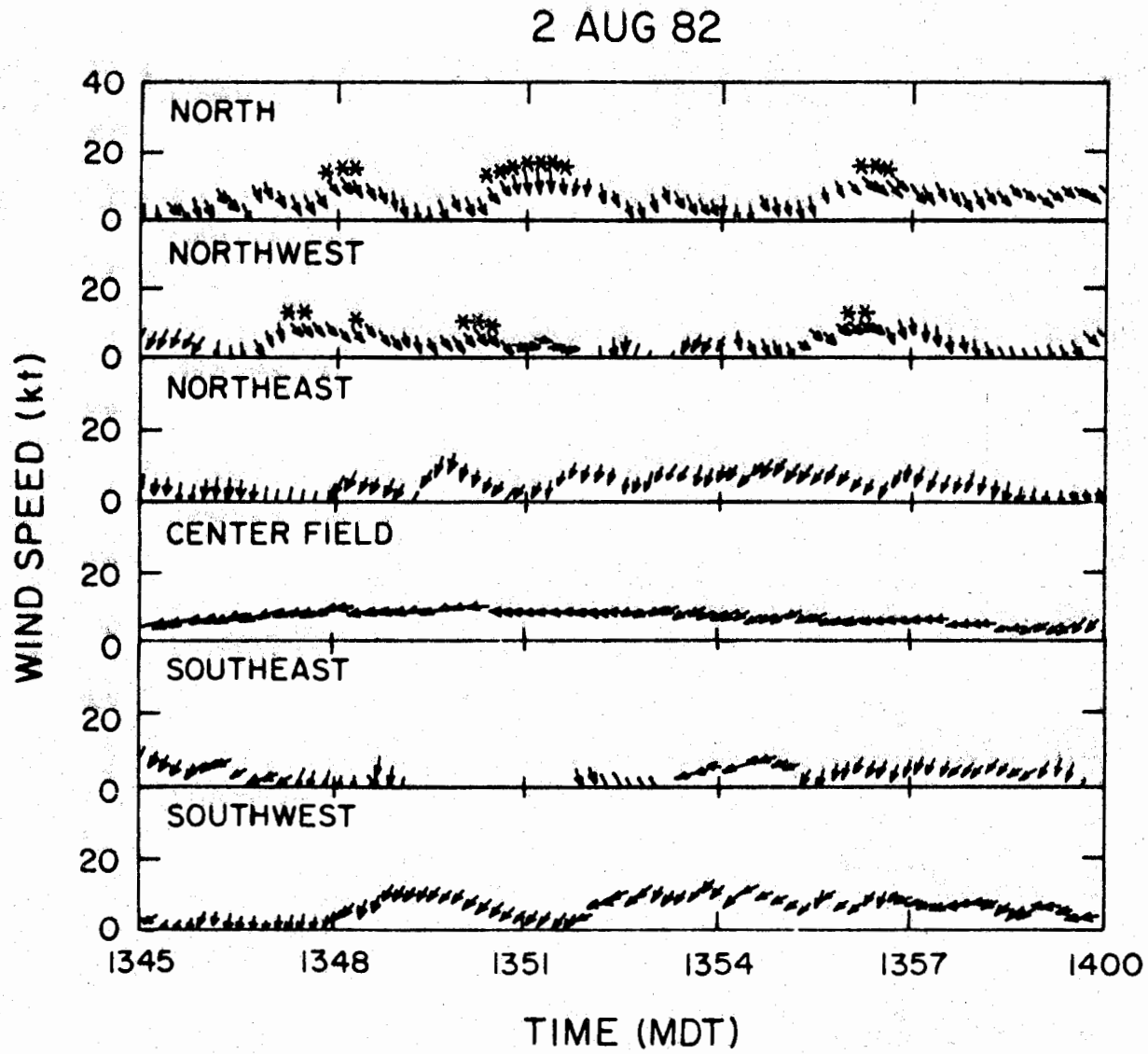

Figure 18f.1. Fifteen-minute segment of LLWAS data for 2 August 1982 (1345 to 1400 MDT). The winds at each site are shown, with the ordinate indicating speed magnitude in knots. The origin of each vector indicates the wind speed magnitude and the arrow indicates wind direction. An arrow pointing directly down indicates a wind from the north. * refers to an LLWAS trigger. Note that the LLWAS triggered at times that are obviously not related to thunderstorm gust fronts or microbursts.

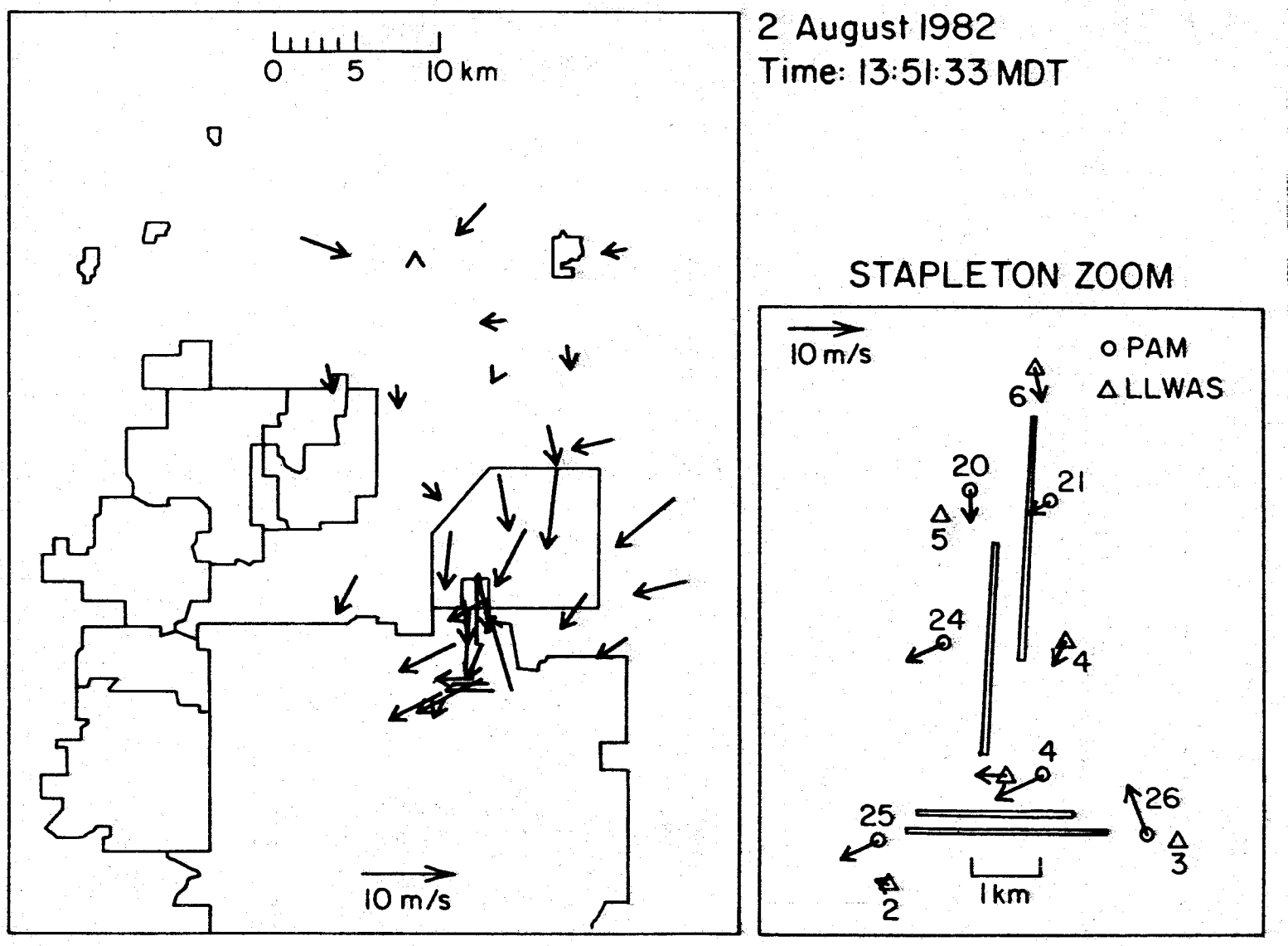

Figure 18f.2. Wind vectors on 2 August 1982 (~1351 MDT).

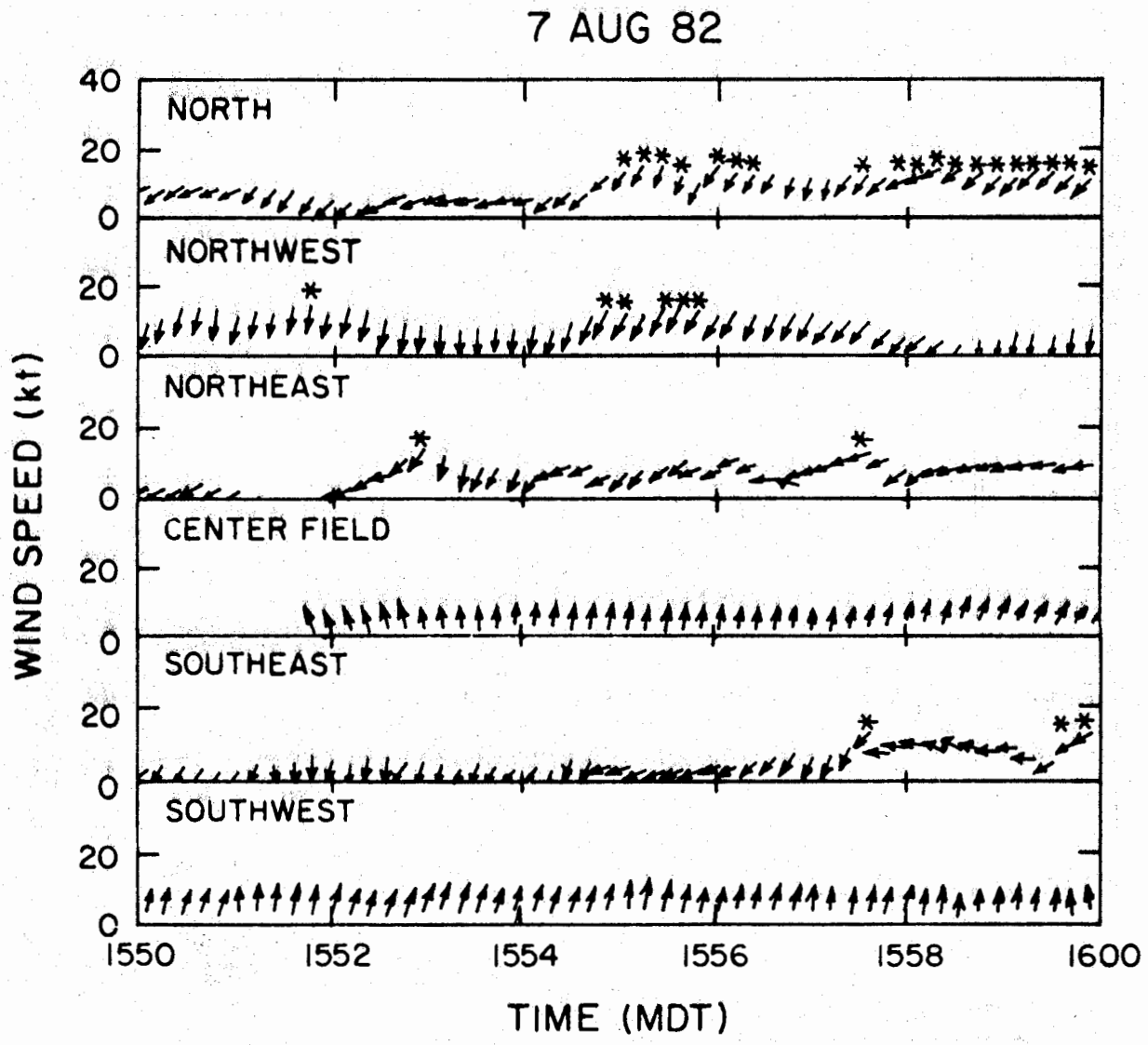

Figure 18g.1. Ten-minute segment of LLWAS data for 7 August 1982 (1550 to 1600 MDT). The winds at each site are shown, with the ordinate indicating speed magnitude in knots. The origin of each vector indicates the wind speed magnitude and the arrow indicates wind direction. An arrow pointing directly down indicates a wind from the north. * refers to an LLWAS trigger. Note that the LLWAS triggered at times that are obviously not related to thunderstorm gust fronts or microbursts.

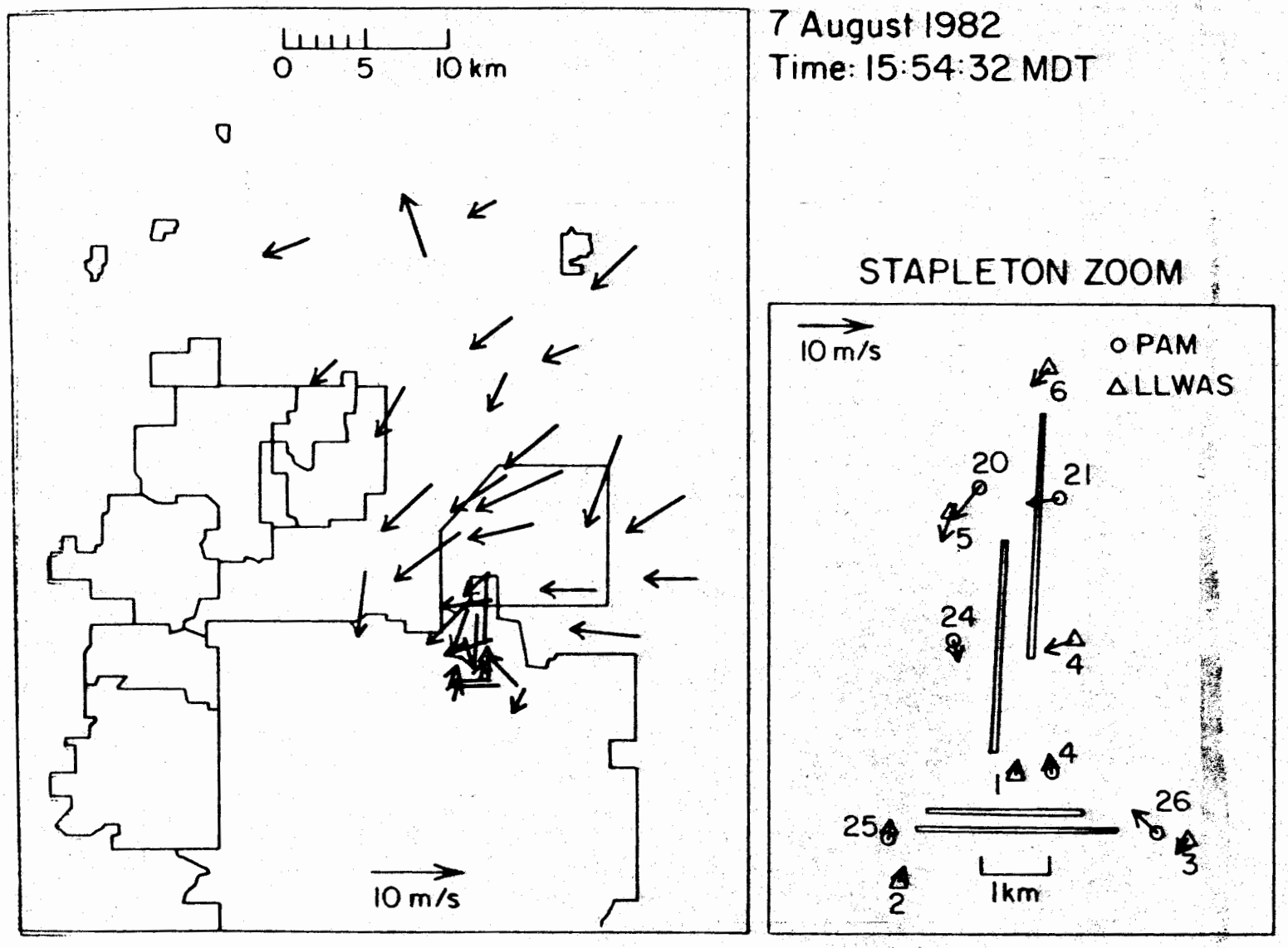

Figure 18g.2. Wind vectors on 7 August 1982 (~1554 MDT) showing weak convergence over the airport.

areal average. If any new value exceeded the average by 15 kts or greater, it was defined as a trigger. Note that this new algorithm is based upon a speed difference only, in contrast with the standard LLWAS algorithm which is based upon a vector difference. Hence we call alarms from this new algorithm magnitude alarms. The entire JAWS/LLWAS data set was processed in this manner. Triggers were then grouped together as alarms in the same way as the standard LLWAS triggers.

Figures 19a and 19b show daily histograms similar in form and scale to Figures 16 and 17. Notice that the distribution of alarms is greatly reduced by this new algorithm. In fact, when we compare the Fujita and Wakimoto (1983) microburst distribution, the original LLWAS alarm distribution, and this new alternative algorithm distribution, we can see that the new calculation produces results that are much closer to the microburst distribution. We can summarize the trigger and alarm algorithm variations as follows:

	LLWSAS (shear)	NEW (Magnitude) ALGORITHM
TRIGGERS	3907	179
ALARMS	631	80

Triggers were significantly reduced and yet the new algorithm identified significant events that occurred at the airport.

Figure 20 is an example of this algorithm processing a microburst event, using both LLWAS and new algorithms. Figure 21 is a histogram for all sites showing the distribution of all triggers by time of day using the new running-mean algorithm; and Figure 22 is a histogram of LLWAS alarms by number of triggers per alarm (groups of triggers). These data, derived from the new algorithm, are much more consistent in their various distributions when compared to Fujita and Wakimoto (1983) microburst distributions than was the original LLWAS alarm distribution seen in Figure 16. If the surface system density is increased sufficiently, this algorithm will be a good candidate to test for use with operational systems. However, we feel that even this obvious improvement represents a quick fix, and we would urge caution against using any new scheme too quickly. Such algorithms that preferentially detect one type of meteorological event (in this case microbursts), may not detect, or may even surpress other events (such as gust fronts). One concept for possible operational use of such algorithms is to operate several algorithm types in parallel and provide outputs that indicate the probable event type encountered after processing of combined algorithms.

6. USE OF LLWAS STATISTICS AS A GUIDE FOR MAINTENANCE AND SYSTEM EVALUATION

Data from the LLWAS can be applied so that the operation of the system can be "self checked." As indicated previously in Section 3.1 summaries of operations in the form of listings of communication failure statistics are presently collected for use by system technicians. In addition the maintenance problems and meteorological statistics can be addressed by using

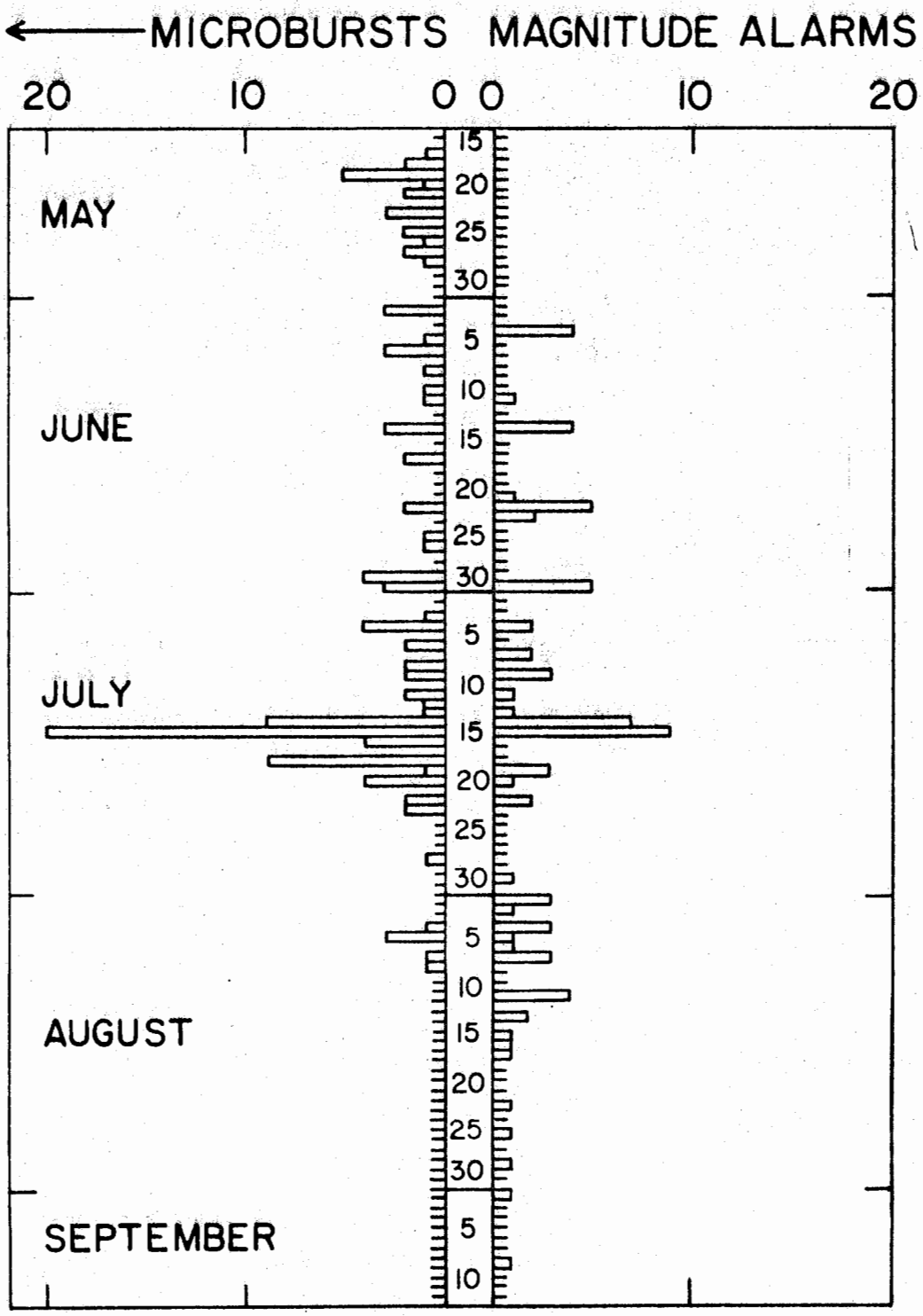

Figure 19a. Distribution of number of magnitude algorithm alarms by day during the period 20 May to 8 August (during which time the NCAR PAM was operating) compared with the distribution of number of microbursts by day as determined by Fujita and Wakimoto (1983) within 8 mi of the Stapleton runways.

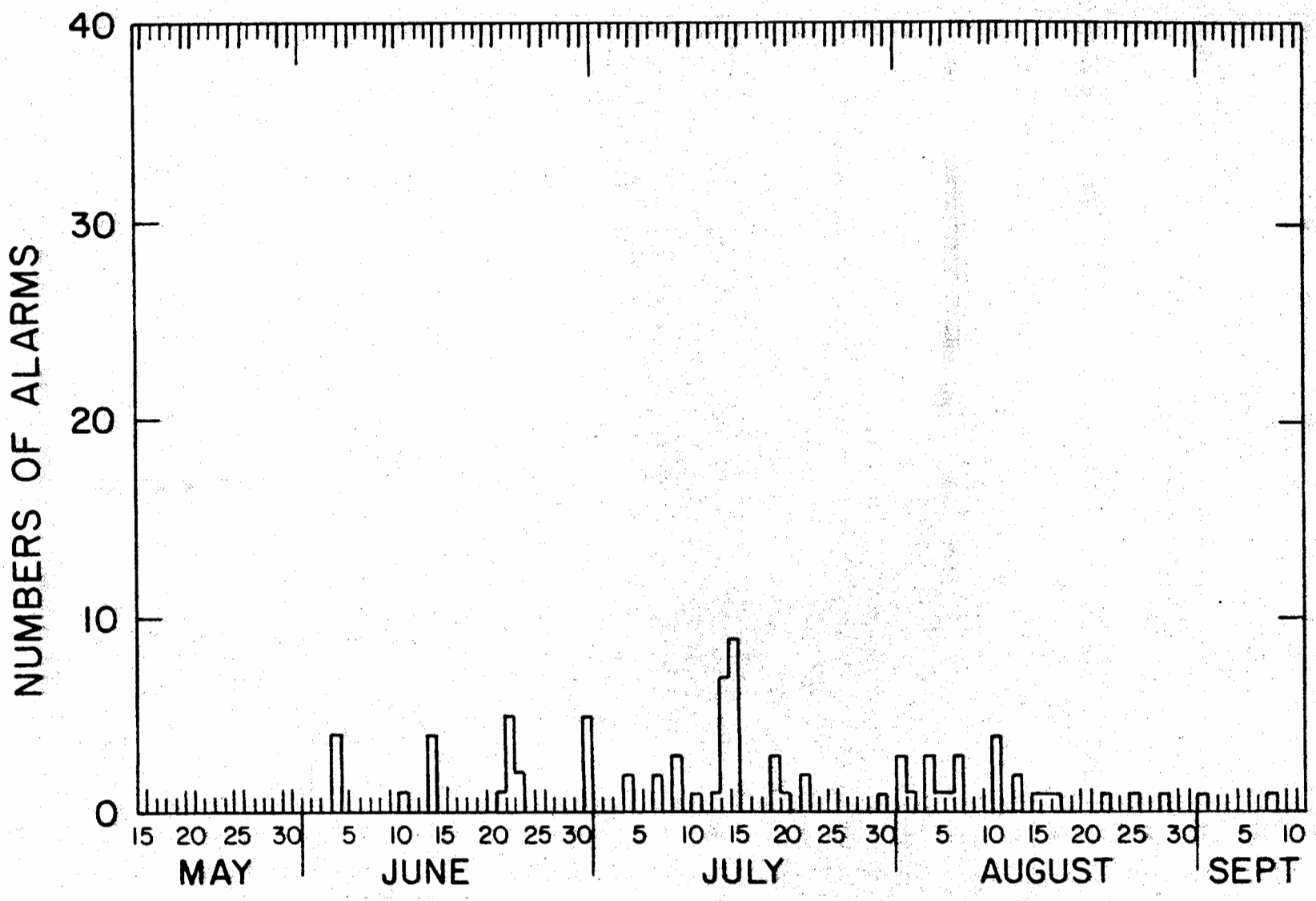

Figure 19b. Daily distribution of LLWAS alarms as calculated by the new running-mean algorithm.

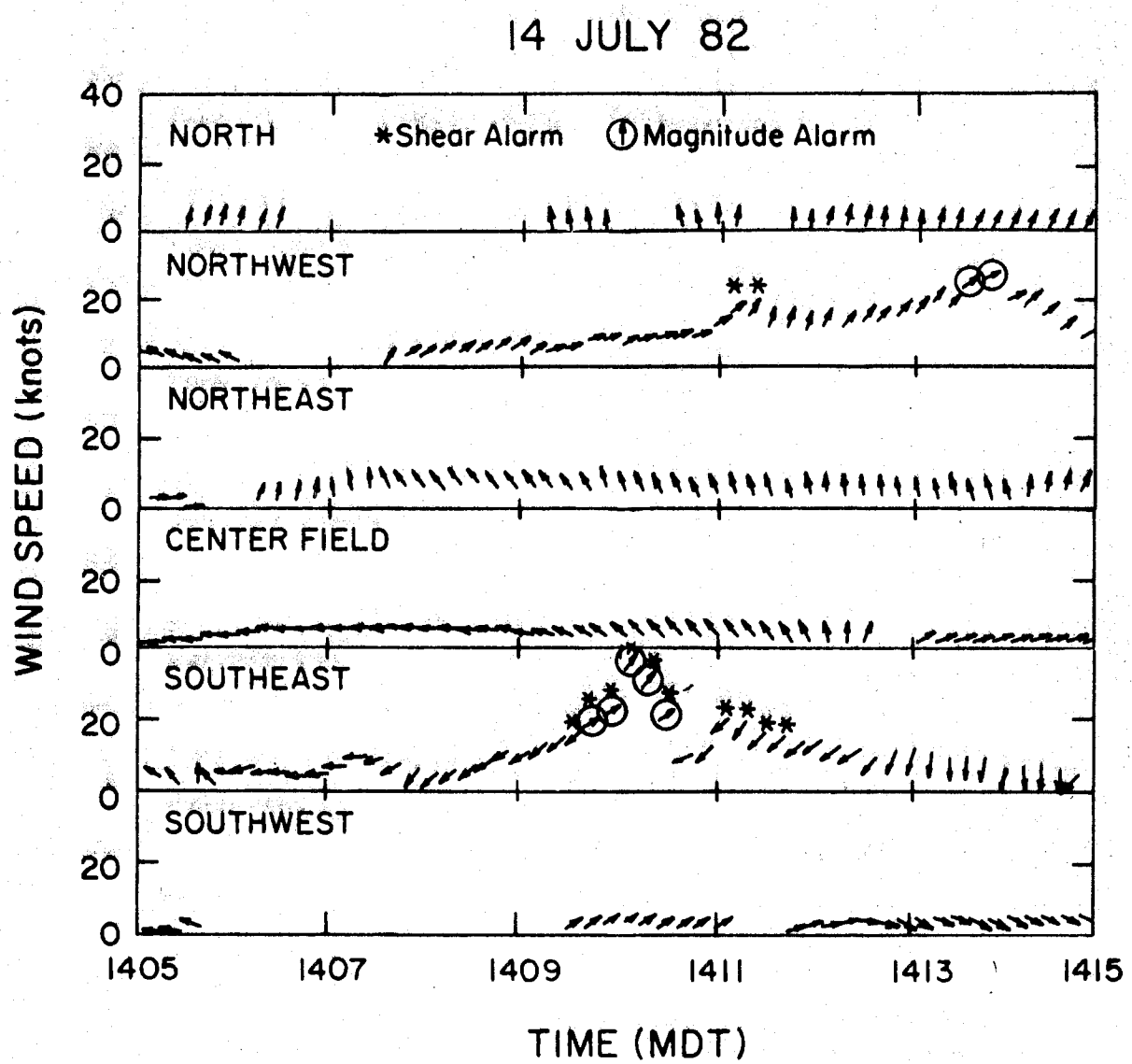

Figure 20. Example of LLWAS data for 14 July 1982 (1405 to 1415 MDT). Two versions of a running mean algorithm (shear and magnitude threshold) are shown.

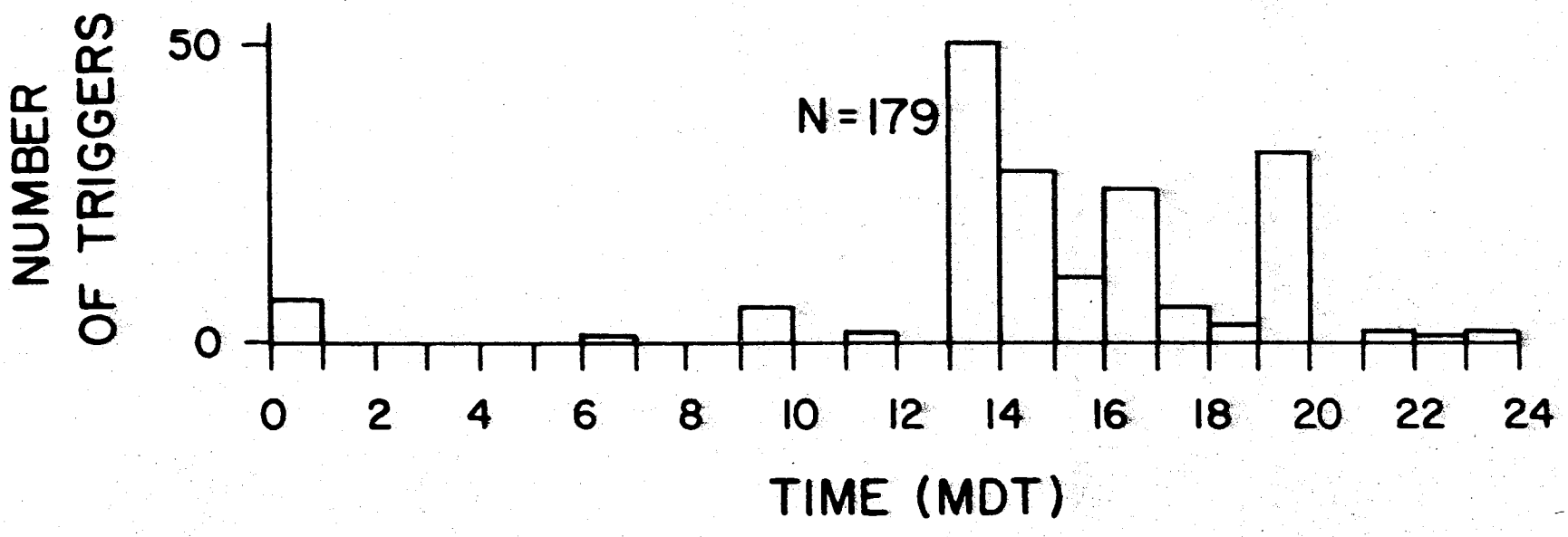

Figure 21. Histogram of LLWAS triggers for all sites, using the new running-mean algorithm.

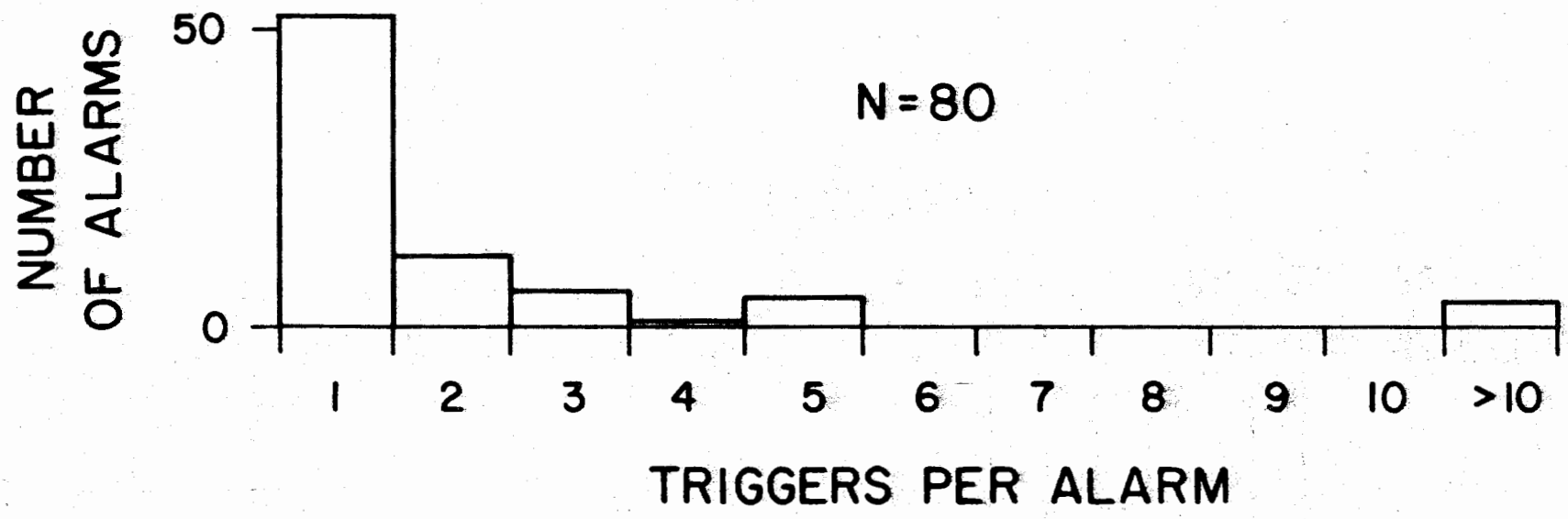

Figure 22. Histogram of LLWAS alarms by number of triggers per alarm (groups of triggers) using the new running-mean algorithm.

internal tests to determine the system integrity and local properties such as (1) detection of wind speed measurment errors, (2) detection of wind direction measurement errors, (3) analysis of bad data points, (4) identification of anemometer siting effects and problems, and (5) development of wind statistics depicting local meteorology. Following sections provide details and examples of these.

We recommend that the capabilities outlined in Sections 6.1, 6.2, and 6.3 be applied as a part of a daily maintenance routine. The LLWAS miniprocessor could provide similar summary data on a daily basis. Other statistics (outlined in Sections 6.4 and 6.5) dealing with siting problems or meteorological phenomena are more appropriate for analysis by some central facility.

6.1 Detection of Errors in the Measurement of Wind Speed

A histogram showing the distribution of wind speed for each anemometer site of an LLWAS system (e.g., Fig. 4) can detect problems with a wind sensor. Slow deterioration of an anemometer bearing (although not causing a complete lack of sensor response) could be detected by inspection of site statistics. The degraded response of the anemometer at the north LLWAS site during the JAWS experiment is evident when Figures 4 and 23 are inspected.

6.2 Detection of Errors in the Measurement of Wind Direction

An anemometer could develop errors in measuring wind direction because of mechanical or electronic problems. The statistics of the direction measurements of a site compared with the centerfield can indicate such systematic direction errors in a vivid manner. These comparisons can be especially useful when a large-scale flow (which can be expected to produce relatively uniform winds spatially) has occurred over a 24 h period. An example of a useful display of directional data is shown in Figure 24. An x,y array was created for the southwest and centerfield sites using bins of wind direction in 15° increments. The number of measurements (z values) falling in each bin can be counted with little impact on microprocessor memory. The final x,y,z array of data can be fed to a line printer. On 2 August 1982 a wide range of wind directions occurred. Figure 24 shows that the counts cluster near a diagonal (indicating agreement between the southwest and centerfield wind directions). A consistent offset from the diagonal would indicate an equipment or terrain obstruction problem.

6.3 Analysis of Bad Data Points Typically Arising from Transmission Errors

Listing of bad data points by site as a function of time of day could permit identification of the source of the problem. Also there would be a clear indication of the impact of these problems upon system operations. Inspection of the data shown in Figure 4 shows that there were great differences in the numbers of bad data points obtained from the various LLWAS sites during the JAWS experiment. For example the northeast and north sites each had over 2000 bad data intervals while the total for the other three sites was less than 100 bad points. Radio interference problems or marginal transmission paths could be the sources of these bad data at certain times of day.

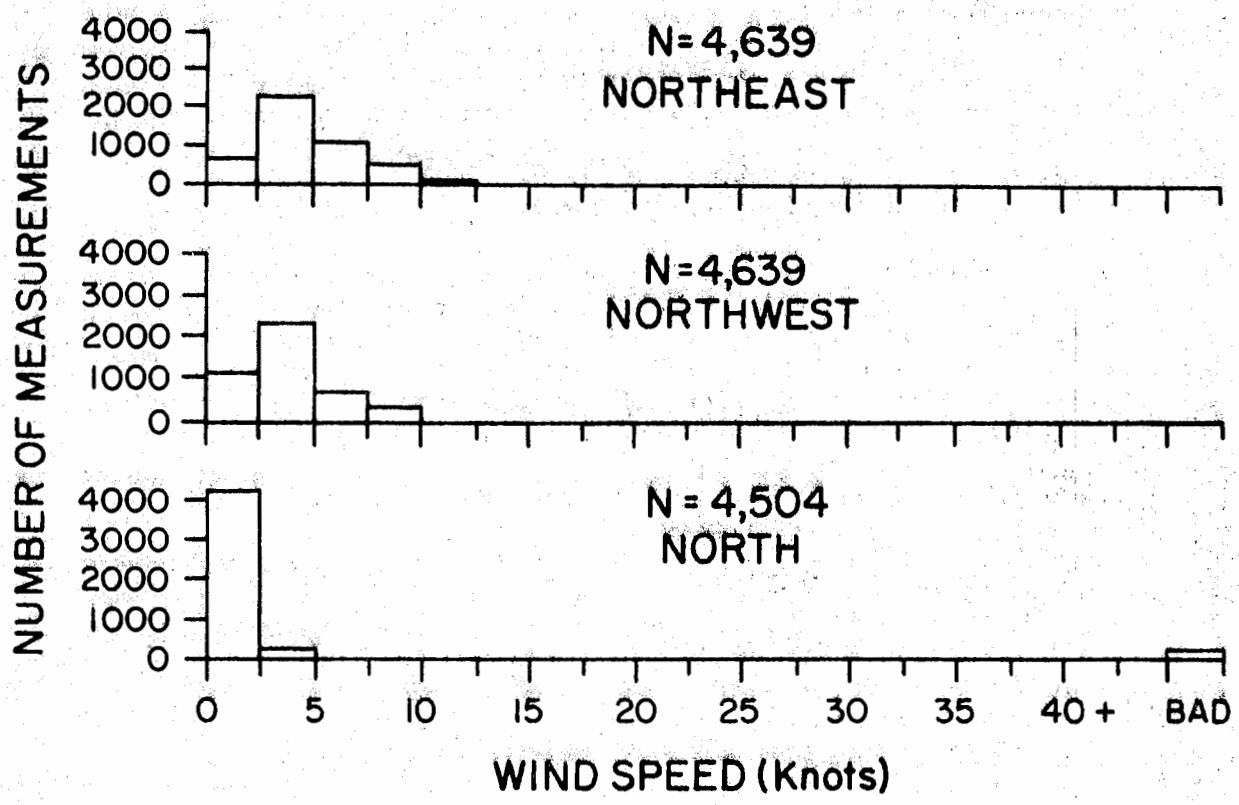

Figure 23. Histogram of LLWAS wind speed data for 3 July 1982 (0715-2359 MDT) comparing three sites. The low-sensitivity problem with the north site becomes quite evident.

SOUTH WEST SITE DIRECTION	CENTER FIELD DIRECTION																							
	0-14	15-29	30-44	45-59	60-74	75-89	90-104	105-119	120-134	135-149	150-164	165-179	180-194	195-209	210-224	225-239	240-254	255-269	270-284	285-299	300-314	315-329	330-344	345-359
0 TO 14	258	49	72	37	6	2	0	0	0	0	0	0	0	0	0	2	19	1	0	0	3	9	48	95
15 TO 29	91	47	60	24	7	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	30
30 TO 44	46	48	78	32	24	13	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	10
45 TO 59	6	36	43	27	33	27	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	6
60 TO 74	53	21	22	6	25	92	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	17
75 TO 89	18	5	16	8	14	30	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
90 TO 104	5	5	8	6	0	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
105 TO 119	2	0	1	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120 TO 134	1	0	1	2	0	3	0	0	5	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0
135 TO 149	2	0	0	0	0	3	6	7	14	40	18	0	0	0	0	0	0	0	0	0	0	0	0	0
150 TO 164	0	0	0	0	3	6	15	3	16	54	263	147	23	0	0	0	0	0	0	0	0	0	0	0
165 TO 179	0	0	0	0	6	4	2	2	2	5	187	776	175	1	0	0	0	0	0	0	0	0	0	0
180 TO 194	0	0	0	1	3	0	0	0	0	0	7	376	153	22	0	0	0	0	0	0	0	0	0	0
195 TO 209	2	0	0	0	0	0	0	0	0	0	0	1	51	83	7	0	1	0	0	0	0	0	0	0
210 TO 224	0	0	0	1	0	0	0	0	0	0	0	0	0	21	5	6	5	7	3	3	3	13	1	0
225 TO 239	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	18	4	0	5	8	11	0
240 TO 254	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	20	33	15	1	15	0	1	0
255 TO 269	26	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	8	20	23	10	0	0
270 TO 284	3	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	19	8	72	5	7
285 TO 299	8	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	79	159	39	42
300 TO 314	52	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	133	272	78	51
315 TO 329	45	18	10	8	7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	53	204	128	42
330 TO 344	107	29	5	19	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	59	164	93
345 TO 359	93	64	19	18	1	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	53	53

Figure 24. Centerfield direction compared with the southwest site direction for the period 0000 to 2314 MDT on 2 August 1982. A consistent off-diagonal grouping of measurements would indicate a systematic wind direction problem.

6.4 Identification of Location or Terrain Problems

Comparisons between the various sites using wind direction and speed statistics can identify a variety of siting problems. A combination of time-of-day histograms (Fig. 10) and studies of the mean wind speeds and directions under different conditions can indicate problems related to runway proximity or local terrain features. In this way the frequencies of local disturbances such as wake vortex impacts or drainage flows can be compared for the various sites. Consideration of statistics comparing wind speed and direction data can also indicate conditions when local winds are underestimated by the influences of local buildings or vegetation. Figure 25 is an example of a display that could be used to study siting effects.

In this display the x values are the centerfield wind direction in 15° increments. The y values are the difference in wind speed between the southwest and centerfield sites. The number of measurements falling in each bin are counted and the x,y,z array is presented in Figure 25 for 2 August 82. For large-scale flows the values should be distributed symmetrically about the center line (zero difference). A consistent bias with the centerfield wind speeds consistently above or below the site values would indicate an equipment calibration problem. If such consistent differences occurred only for a range of directions, terrain effects are the probable cause.

6.5 Development of Wind Statistics Depicting Local Meteorology

The statistics of the meteorological processes influencing a given airport can be invaluable for operational planning. Specifically, the time-of-year and time-of-day statistics of wind shears above some threshold level for an airport could be used as a basis for scheduling hours of peak activity. Certainly, cautionary information could be provided to pilots concerning times when heightened awareness is indicated. Examples of meteorological processes that could be specified using data recorded on LLWAS systems are:

- sea breezes
- nocturnal drainage flows
- frontal passages
- time-of-day wind shear extreme statistics
- microbursts
- thunderstorm gust fronts.

In addition more representative data on airport mean wind speed and direction could be provided as a function of time of year.

7. LIMITATIONS OF THE SYSTEM

The following are limitations of the system:

(1) LLWAS is clearly a surface-wind measurement system: horizontal winds above the sensors are not detected. This may not be a significant problem in

SOUTH WEST TO CENTER DIFFERENCE (KNOTS)	CENTER FIELD DIRECTION																							
	0-14	15-29	30-44	45-59	60-74	75-89	90-104	105-119	120-134	135-149	150-164	165-179	180-194	195-209	210-224	225-239	240-254	255-269	270-284	285-299	300-314	315-329	330-344	345-359
-23 TO -24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-21 TO -22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-19 TO -20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-17 TO -18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-15 TO -16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-13 TO -14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
-11 TO -12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	7	0	0
-9 TO -10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	35	0	0
-7 TO -8	0	0	0	3	2	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	42	75	1	0
-5 TO -6	6	5	5	14	14	6	0	0	0	3	12	5	0	8	0	0	6	6	3	0	57	73	9	3
-3 TO -4	20	23	21	18	7	19	9	5	10	32	46	174	0	57	3	2	11	6	8	4	70	165	92	63
-1 TO -2	102	61	81	29	19	23	4	1	9	36	161	472	67	33	8	8	19	24	9	22	78	321	213	128
0 TO 0	205	45	50	20	12	7	19	0	0	12	121	269	102	15	1	8	12	12	11	12	29	84	84	73
1 TO 2	240	75	79	42	39	65	32	4	7	18	114	322	165	11	0	0	6	20	8	10	26	44	119	116
3 TO 4	187	65	59	37	16	78	5	2	11	12	21	54	54	3	0	0	0	0	0	0	0	6	36	56
5 TO 6	45	41	27	19	15	27	0	0	0	1	0	4	11	0	0	0	0	0	0	0	0	1	1	7
7 TO 8	23	13	11	8	5	2	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
9 TO 10	5	1	9	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 TO 12	0	0	1	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13 TO 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15 TO 16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17 TO 18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19 TO 20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21 TO 22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23 TO 24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 25. Wind speed difference between the southwest and centerfield site as a function of direction measured at the centerfield site. These data are shown for several wind regimes. Siting problems or localized flows would show as a deviation from a symmetrical distribution centered at 0 kts difference.

a gust front or sea breeze front situation, but it is a serious limitation when there are strong wind shears that are not present at the surface, as in many frontal and low-level jet situations.

(2) LLWAS has temporal and spatial resolution limitations which may present serious problems for the detection of the smaller scale events. Appendix A (Bedard and McCarthy, 1984) describes a case study documenting the small time and spatial scales that can occur. The distances between anemometers are a measure of the scale of event which can be detected with confidence. The average spacing between the centerfield and the boundary sites is about 3 km for a typical LLWAS. Because of the averaging done at the centerfield, short-lived microbursts may not be detected there; consequently the effective wind shear resolution for short-lived microbursts is greater than 3 km and perhaps more nearly 6 km. Although a brief gust at the centerfield will be registered as a gust (if it is of sufficient magnitude), abrupt wind-shift lines may be flagged with a delay as a shear alert by the centerfield anemometer. Therefore, although effective for gust fronts, the spatial resolution scale is not appropriate for the detection of microbursts, which can occur on scales of 1 to 3 km (Wilson and Roberts, 1983). Likewise, the temporal resolution is compromised by the long averaging at the centerfield site; a brief high wind encounter at centerfield would not be identified unless it were of large enough magnitude. This effectively eliminates the centerfield site as a high-resolution wind shear sensor. However, decreasing the centerfield averaging time would of necessity result in larger and more rapid variations, increasing the probability of false alarms. Compensation might be achieved by increasing the threshold value at the expense of missing some events, or by revisions of the overall detection algorithm strategy.

An alternate approach would be to create another analysis path using the centerfield data while retaining the averaging system now in use. The 8-10 s grab samples from the centerfield sensor could be compared with the running average in the same manner as the outlying sites. In this way the spatial and time resolution can be improved with no hardware changes required. This would seem a desirable first step in improving the LLWAS. Since events can appear over time scales shorter than 30 s, failure to detect an event over one or two scans or failure to apply the information can be critical to operations.

(3) Surface wind events outside of the 3 km radius of the airport are not sensed, which represents a possible deficiency if an aircraft low altitude encounter with wind shear were to occur outside of this radius.

(4) Vertical motions are not sensed directly; only horizontal ones, which may have been initiated by downdrafts, are sensed. There is no warning provided of descending downdrafts. Although the resulting outflows may be detected, the hazard may already have been present for tens of seconds or even minutes. For example, a descending downdraft produces divergence near the surface when the downward moving air has moved to within about one diameter's scale length of the surface of the Earth. Thus, downburst vertical speeds from smaller scale downbursts can be expected to occur closer to the surface than larger scale downflows. In addition if an anemometer is located directly beneath a downflow (at or near the stagnation point), no horizontal flows may be detected unless the system is translating.

(5) LLWAS does not directly measure the wind along the flight paths, and thus can report events not traversed by an aircraft, which the pilot could perceive as a false alarm.

(6) Although downdrafts are converted to horizontal winds near the surface, the diverging horizontal flows often may not occur at or near surface sensors because of a variety of meteorological factors, such as shallow temperature inversions close to the surface.

8. PRELIMINARY RECOMMENDATIONS REGARDING THE LLWAS

The LLWAS is a useful system, particularly for the detection of certain wind shear situations such as gust fronts, frontal passages, and sea-breeze fronts, which have dimensions of many kilometers, have durations of tens of minutes or more, and travel across the ground. With modifications that improve the spatial resolution and time resolutions of the surface wind measurements, the LLWAS should be capable of detecting a high fraction of the dangerous wind shear conditions in the vicinity of airports including microbursts that have reached the surface. Such an investigation of upgrading of the LLWAS has been initiated by the FAA.

Figure 26 is a schematic view of the various stages of a microburst. Microbursts typically take longer than 2 minutes to descend from the source region (near cloud base) to the surface. At the lower portions of the descending region (<300 meters) the microburst flows can pose a hazard to aircraft since divergence causes a horizontal area of increasing/decreasing lift to rapidly evolve as the Earth's surface is approached. At the base of the descending region the flows have not reached the surface and therefore are not detectable by anemometers. As the system continues to descend strong winds will typically occur at the Earth's surface outside of the stagnation region. Although anemometers can readily detect this area of high winds, they provide no advance warning. Therefore, remote sensing techniques must be developed and installed to detect the microburst in the generation and descending stages, where negligible horizontal components occur. Such techniques using Doppler radar for providing earlier warnings of the impending microburst hazard are currently being developed (Roberts and Wilson, 1984). At the present time, Doppler radars are most successful in detecting microbursts during the hazardous, diverging stage. There is a great need to continue the development of remote sensing techniques to provide earlier warnings.

The LLWAS is the only currently available system for detecting wind shear on a regular basis. It is recommended that the LLWAS system be substantially improved and these improvements installed in existing LLWAS systems at all major airports. In any future installations consideration should be given to ensure that the system can be adapted or retrofitted to permit the integration of improvements in hardware, software, and recording capabilities. Every effort should be made to assess and improve its performance. Possible approaches include, but are not limited to, the following:

(1) Examine signal processing techniques from simple approaches to an exhaustive re-examination of sampling theory concepts. Consider the application of alternate algorithms such as the one described in this report that is sensitive to wind magnitude changes.

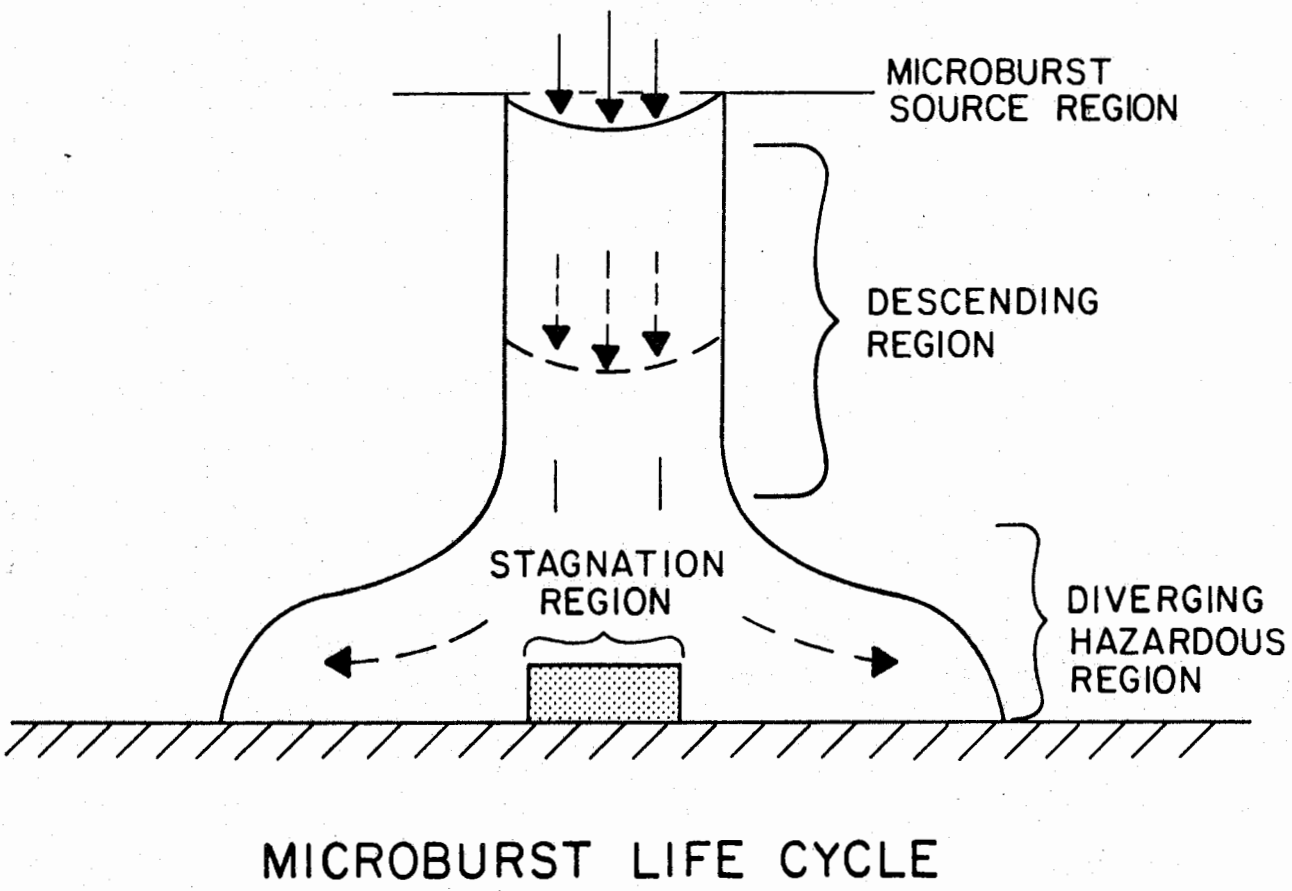

Figure 26. Schematic view of the various stages of a microburst.

(2) Investigate the benefits that might be derived by increasing the number of sensors and reducing the spacing between them. Methods should be used to increase the effectiveness of the centerfield anemometer as suggested in Section 2.1. Figure 26 shows the influence of the centerfield averaging. In this figure higher time resolution data measured on the SE site on 14 July 1982 is used to illustrate the impact of centerfield 15 scan averaging on an impulsive microburst wind surge. The original data at approximately 11 s intervals was processed with a 15 scan averaging to simulate the centerfield response. The original data and the averaged data both appear in Figure 27. The largest wind speed passed through the filter is smaller by a factor of two than the original time series. The appearance of the wind maximum is also delayed by about one minute in this simulation.

(3) Analyze and revise the current method for displaying wind data. It is technically feasible to provide this information directly to pilots. Use of a computer synthesized voice system should be examined. In fact, we have tested the concept of passing data from a LLWAS wind shear file to a voice synthesizer. Data processed in this manner showed vividly the advantages of the prompt and accurate information transfer. Controllers could also be relieved of the unnecessary burden of transferring this information.

(4) Analyze and revise, if appropriate, the current criteria for issuing a wind shear warning. For example, the use of one threshold for issuing a caution and a second, higher threshold for issuing a warning would help ensure that warnings were heeded.

(5) Further study the use of complementary sensors to augment wind shear information yielded by the LLWAS.

(6) Record and analyze wind measurements by the LLWSAS installations nationwide to obtain climatic properties of ground-based wind shear. We strongly recommend this improvement. Not only could the climatology of low-altitude wind shear be obtained, but routine, long-term batch statistics would vastly improve ongoing maintenance as described in Section 6. A forthcoming report based upon the results of detailed case studies of wind shear events during the JAWS Project will provide recommendations for further research and detail additional areas in which the LLWAS can be improved.

9. ACKNOWLEDGMENTS

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The recording and processing of the LLWAS data during JAWS was made possible by of the assistance of several individuals. Frank Coons is

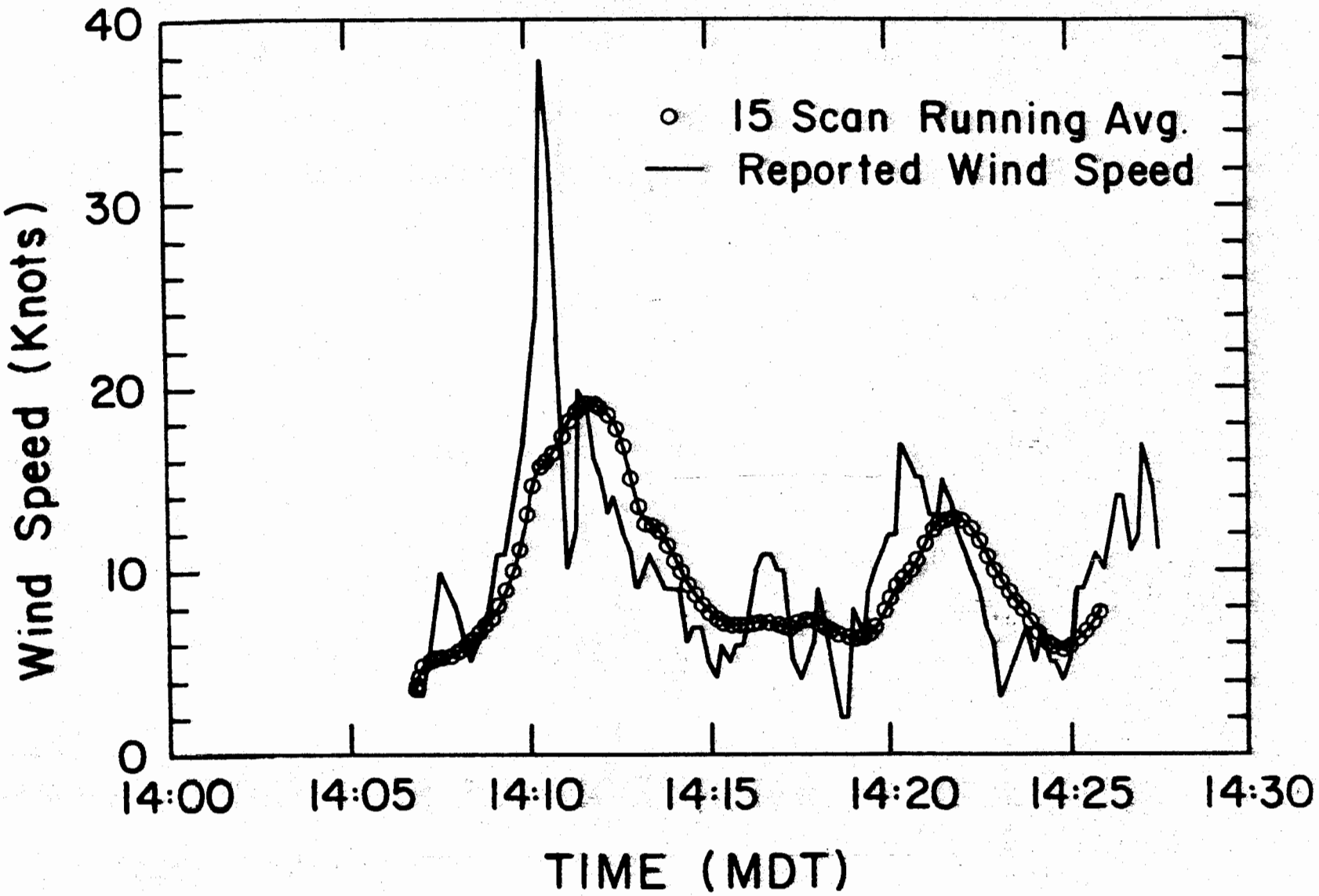

Figure 27. Wind data for the southeast site for a microburst event on 14 July 1982, was reprocessed using a 15-scan average. This comparison shows the great influence of the centerfield averaging in preventing the detection of short-lived microbursts.

acknowledged for making it possible for LLWAS system data to be recorded during the JAWS experiment. The special software and hardware required for recording the LLWAS data without distrupting operations was provided by E. Schlatter of the FAA Technical Center at Atlantic City, N.J. The system was installed, maintained, and operated by FAA personnel at Stapleton Airport. We are particularly grateful to J. Sly. The extensive software for processing recorded data from the LLWAS was produced at NOAA's Wave Propagation Laboratory by D. Simms. We also thank D. Rebhun and F. Melewicz of the FAA for helpful comments on the manuscript.

10. REFERENCES

Bedard, A. J., Jr. (1982): Sources and detection of atmospheric windshear. AIAA J. 20, no. 7, 940-945.

Bedard, A. J., Jr., and J. McCarthy (1984): A case study illustrating time scales and operational responses for a wind shear episode during the JAWS Project. Published Manuscript AIAA-84-0351, 22nd Aerospace Sciences Meeting, Jan. 9-12, 1984, Reno, Nev., American Institute of Aeronautics and Astronautics, N.Y. N.Y., 8 pp.

Bedard, A. J. Jr., F. H. Merrem, D. Simms, and M. M. Cairns (1979): A thunderstorm gust-front detection system: Part I System operation and significant case studies; Part II Statistical results. Federal Aviation Administration Report FAA-RD-79-55, 130 pp.

Brock, F. V., and P. K. Govind (1977): Portable Automated Mesonet in operation. J. Appl. Meteor., 16, 299-310.

Caracena, F., J. McCarthy, and J. A. Flueck (1983): Forecasting the likelihood of microbursts along the Front Range of Colorado. Preprints, 13th Conf. on Severe Local Storms, 17-20 Oct., Tulsa, Okla., Amer. Meteor. Soc.

Frost, W., H. Chang, J. McCarthy, and K. Elmore (1983): Aircraft performance in a JAWS microburst. Preprints, 21st Radar Meteor. Conf., Edmonton, Ala., Canada, 19-23 Sept., Amer. Meteor. Soc., 630-637.

Fujita, T. T. (1981): Tornadoes and downbursts in the context of generalized planetary scale. J. Atmos. Sci., 38, 1512-1534.

Fujita, T. T. (1983): Analysis of storm-cell hazards to aviation as related to terminal Doppler radar siting and update rate. Satellite Mesometeorological Research Project Research paper 204 Published by Dept. of Geophysical Sciences, University of Chicago, Dec. 1983.

Fujita, T. T., and H. R. Byers (1977): Spearhead echo and downburst in the crash of an airliner. Mon. Wea. Rev., 105, 129-146.

Fujita, T. T., and F. Caracena (1977): An analysis of three weather-related aircraft accidents. Bull. Amer. Meteor. Soc., 58, 1164-1181.

Fujita, T. T., and R. Wakimoto (1983): A microburst in JAWS depicted by Doppler radars, PAM, and aerial photographs. Preprints 21st Radar Meteor. Conf., Edmonton, Ala., Canada, 19-23 Sept., Amer. Meteor. Soc., 638-645.

Goff, R. C., J. T. Lee, and E. A. Brandes (1977): Gust front analytical study. Federal Aviation Administration Technical Report No. FAA-RD-77-119, Dec. 1977.

Goff, R. C. (1980): The low-level wind shear alert system (LLWSAS). Federal Aviation Administration Report FAA-RD-80-45, 120 pp.

JAWS (1982): Field Operations Plan 1982. Available from the JAWS Project Office at NCAR, Boulder, Colo.

JAWS (1983): The JAWS Project Operations Summary 1982. Available from the JAWS Project Office at NCAR, Boulder, Colo.

Kessinger, C., M. Hjelmfelt, and J. Wilson (1983): Low-level microburst wind structure using Doppler radar and PAM data. Preprints 21st Radar Meteor. Conf., Edmonton, Ala., Canada, 19-23 Sept., Amer. Meteor. Soc., 609-615.

Lee, J. T., J. Stokes, Y. Sasaki, and T. Baxter (1978): Thunderstorm gust fronts--observations and modeling. FAA Technical Report No. FAA-RD-78-145, Dec. 1978.

McCarthy, J., J. W. Wilson, and T. T. Fujita (1982): The Joint Airport Weather Studies Project. Bull. Amer. Meteor. Soc., 63, 15-22.

McCarthy, J., R. Roberts, and W. Schreiber (1983): JAWS data collection, analysis highlights, and microburst statistics. Preprints, 21st Radar Meteor. Conf., Edmonton, Ala., Canada, 19-23 Sept., Amer. Meteor. Soc., 596-601.

Roberts, R. D., and J. W. Wilson (1984): Precipitation and kinematic structure of microburst producing storms. Preprints, 22nd Radar Meteor. Conf., Zurich, Switzerland, 10-13 Sept. Amer. Meteor. Soc., 71-76.

Townsend, J. W., Jr. (1983): Low altitude wind shear and its hazard to aviation. Report of the Committee on Low-Altitude Wind Shear and its Hazard to Aviation. National Academy Press, Washington D.C., issue 10, 836 pp.

Wilson, J. W., and R. D. Roberts (1983): Evaluation of Doppler radar for airport wind shear detection. Preprints, 21st Radar Meteor. Conf., Edmonton, Ala., Canada, 19-23 Sept., Amer. Meteor. Soc., 616-623.

APPENDIX

AIAA-84-0351, 22nd Aerospace Sciences Meeting, Jan. 9-12, 1984. Reno, Nevada, American Institue of Aeronautics and Astronautics, NY, NY.

A CASE STUDY ILLUSTRATING TIME SCALES AND OPERATIONAL RESPONSES FOR A WIND SHEAR EPISODE DURING THE JAWS PROJECT

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Abstract

A microburst event on 14 July 1983 illustrates the short time scales involved in responding to this type of wind shear. The event also illustrates how a controller used information from several sources in helping a number of aircraft avoid a dangerous wind shear situation. We discuss the implications of this event for the design of future wind shear detection systems and we relate these observations to data obtained during the JAWS experiment.

Introduction

On 14 July 1982 during the Joint Airport Weather Studies Experiment (JAWS) (McCarthy et al., 1982[1]), a series of aircraft problems related to wind shear occurred during a 20 minute interval from about 1400 to 1420 MDT. We use this case to illustrate the operation of the Low Level Wind Shear Alert System (LLWSAS) as well as to illustrate the small spatial and temporal scales characterizing some microbursts.

Fortunately, during this interval the communication tapes for air traffic control were transcribed by the Transportation Systems Center as part of a special study. The Automatic Terminal Information Service (ATIS) recordings were also available because of this study. Thus, we are able to reconstruct the operational sequence of events during this wind shear episode and emphasize both the time scales involved and the interplay between the meteorology, aircraft, and the aircraft control system. This summary indicates the need for quick response systems at every level when encountering a microburst hazard (detection, dissemination, and aircraft response).

Wind Shear Event of 14 July 1982 Measured by Surface Sensors

The LLWSAS functioning as a component of the JAWS experiment (Bedard et al.[2]) detected an abrupt windshear event on 14 July 1982. The Portable Automated Mesonet (PAM) of the National Center for Atmospheric Research (Brock and Govind[3]) operated in a region including the airport and also provided data. Figures 1, 2, and 3 summarize these data and provide information on the locations of the measuring sites relative to the airport.

Figures 1a, 1b, and 1c depict wind speed and direction information obtained by the LLWSAS for three intervals (1405-1415 MDT), 1415-1425 MDT, and 1425-1435 MDT). Figures 2 and 3 present data from both the LLWSAS and PAM arrays at the times of the peak wind surges for the southeast LLWSAS site (~14:10) and the peak wind gust measured at the nearest PAM site (14:12:26). There was no evidence of the disturbance at any other measurement site although some sensors were within 3 km. The peak wind aurge measured at the PAM site lagged the LLWSAS measurement time by more than 1-min. This delay could have been caused by advection or some physical process causing the leading edge of the microburst to be not represented at the PAM site. The time delay (>60 s) involved with a separation distance of ~1/2 km or with siting effects is important compared with the operational times involved with this partacular microburst. Also, if the microburst had occurred in a different area of the airport it could easily have gone undetected as a significant event.

Table 1 summarizes important portions of pilot/controller communications for the period between 1407 and 1415 MDT. There were three go arounds in less than 10 min; one aircraft (F244) had to go almost to takeoff power. In our view, this situation was well handled by the pilots and local control. Information concerning windshear encountered by the pilots and detected by the LLWSAS was communicated promptly. A microburst apparently occurred just to the east of the east-west runway and was encountered by an aircraft on approach during the time the wind surge was first evident on the LLWSAS (1409:54). Although the LLWSAS provided at most seconds of warning in this instance, subsequent LLWSAS information provided valuable guidance concerning conditions around the E-W runway. The southeast LLWSAS site did provide information at a critical juncture concerning a 38 kt wind, which guided flight A17 in making a decision to go around. However, the wind shear danger was first reported by the pilot of flight F244. At about 1414 a region of blowing dust was noted. Pilots and control used all available information in this situation.

Another aspect of the operational communication system is illustrated in Table 2. Transcripts from the ATIS communication tapes broadcast before and after this series of windshear problems do not warn of the meteorological windshear hazards being encountered in the terminal area.

The message previous to those appearing in Table 2 was at 1350 MST. The winds described in message KILO (1406 MST) just prior to the event do not agree with those recorded by the LLWSAS. At the time of the message the LLWSAS centerfield winds were 089 at 4 kt. No significant gusts were measured during the previous 15 min at any LLWSAS site. The reason is that an additional anemometer

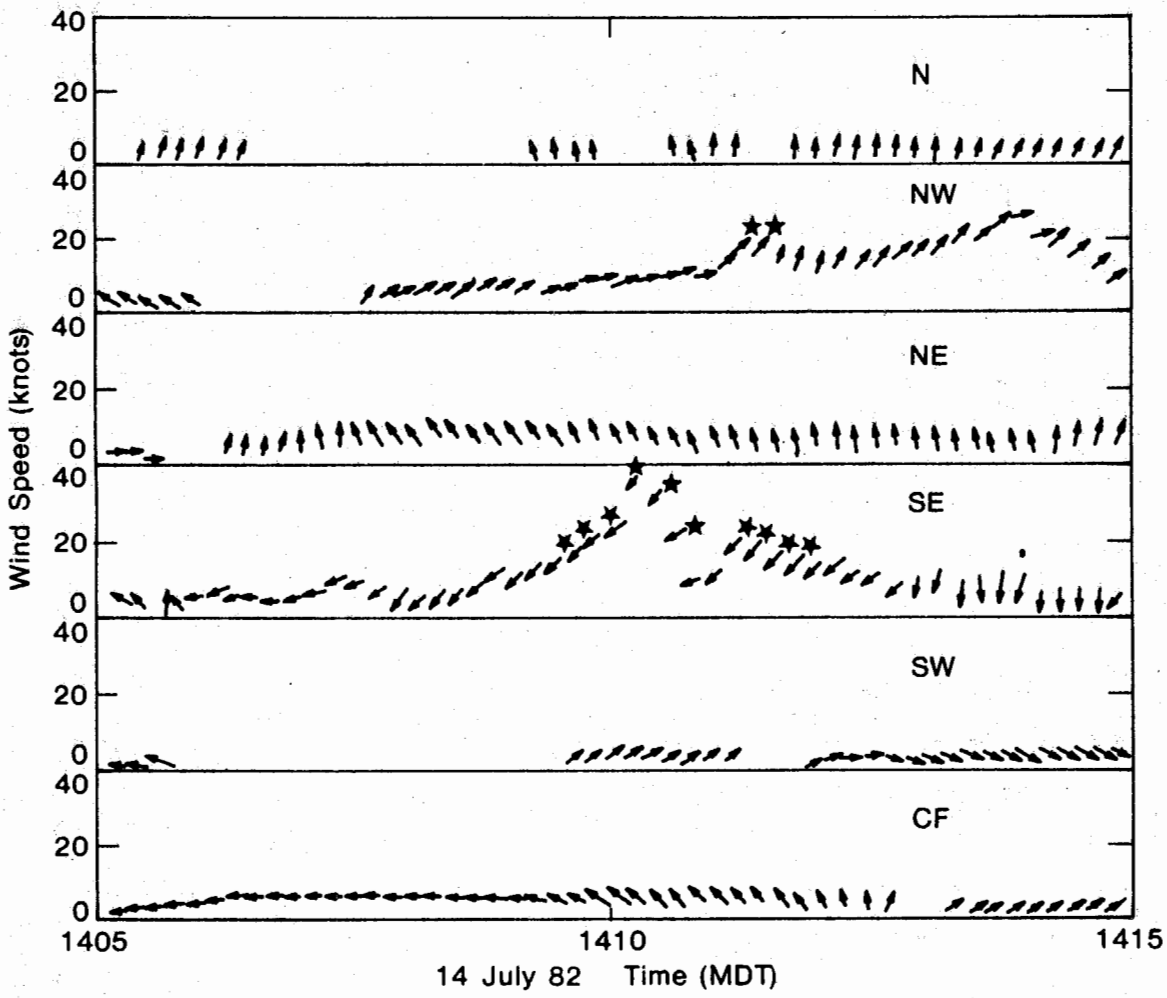

Figure 1a. Wind speed and direction measurements for the LLWSAS system at approx. 11 s intervals from 1405 to 1415 MST. The origin of each arrow indicates the wind speed. An arrow pointing towards the top of the page indicates a wind from south to north. A * indicates a value exceeding 15 knot vector difference between the centerfield and outlying site. An audible alarm occurs in the tower when the threshold is exceeded.

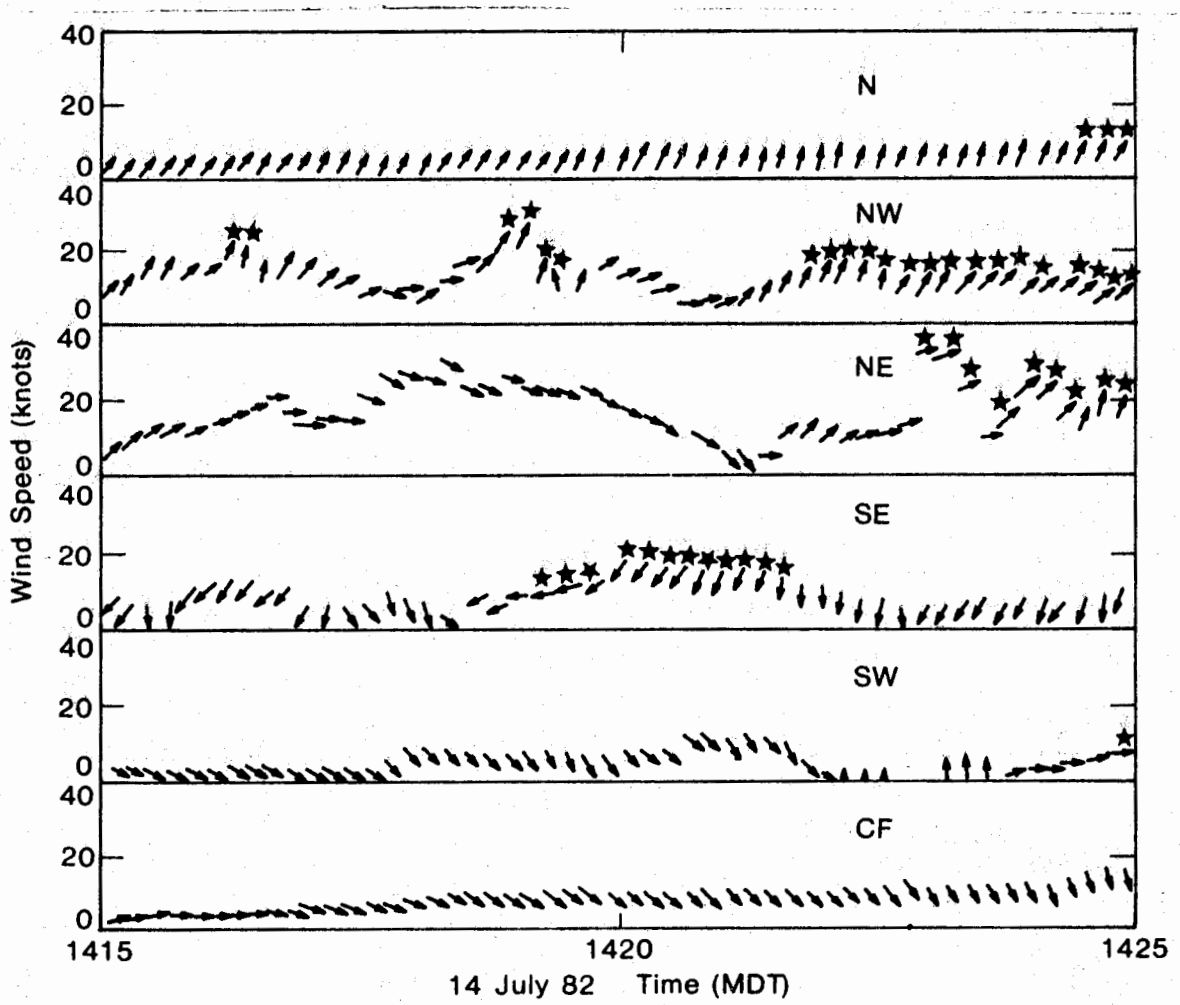

Figure 1b. Wind speed and direction measurements for the LLWSAS system at approx. 11 s intervals from 1415 to 1425 MST. The origin of each arrow indicates the wind speed. An arrow pointing towards the top of the page indicates a wind from south to north. A * indicates a value exceeding 15 knot vector difference between the centerfield and outlying site. An audible alarm occurs in the tower when the threshold is exceeded.

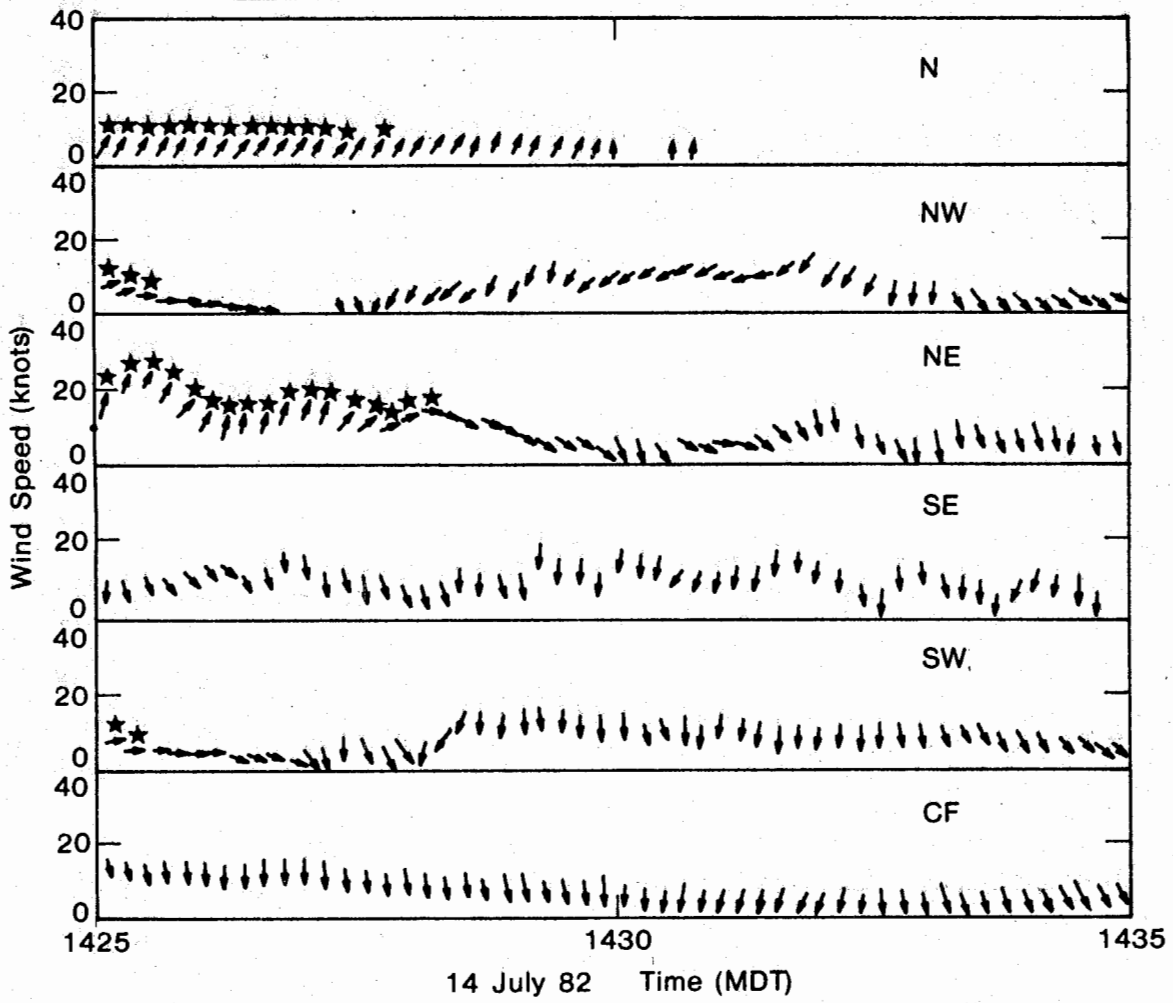

Figure 1c. Wind speed and direction measurements for the LLWSAS system at approx. 11 s intervals from 1425 to 1435 MST. The origin of each arrow indicates the wind speed. An arrow pointing towards the top of the page indicates a wind from south to north. A * indicates a value exceeding 15 know vector difference between the centerfield and outlying site. An audible alarm occurs in the tower when the threshold is exceeded.

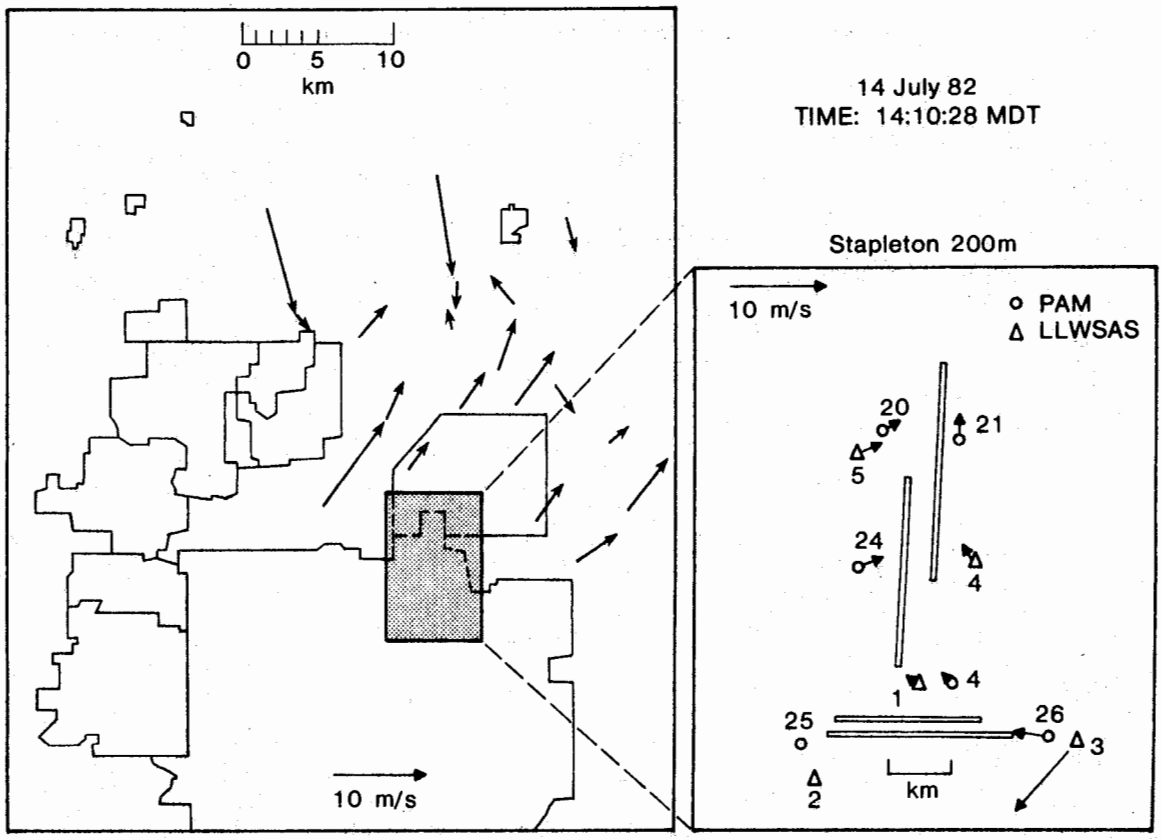

Figure 2. Wind vector information for the LLWSAS and PAM surface sites at 14:10:38 MDT.

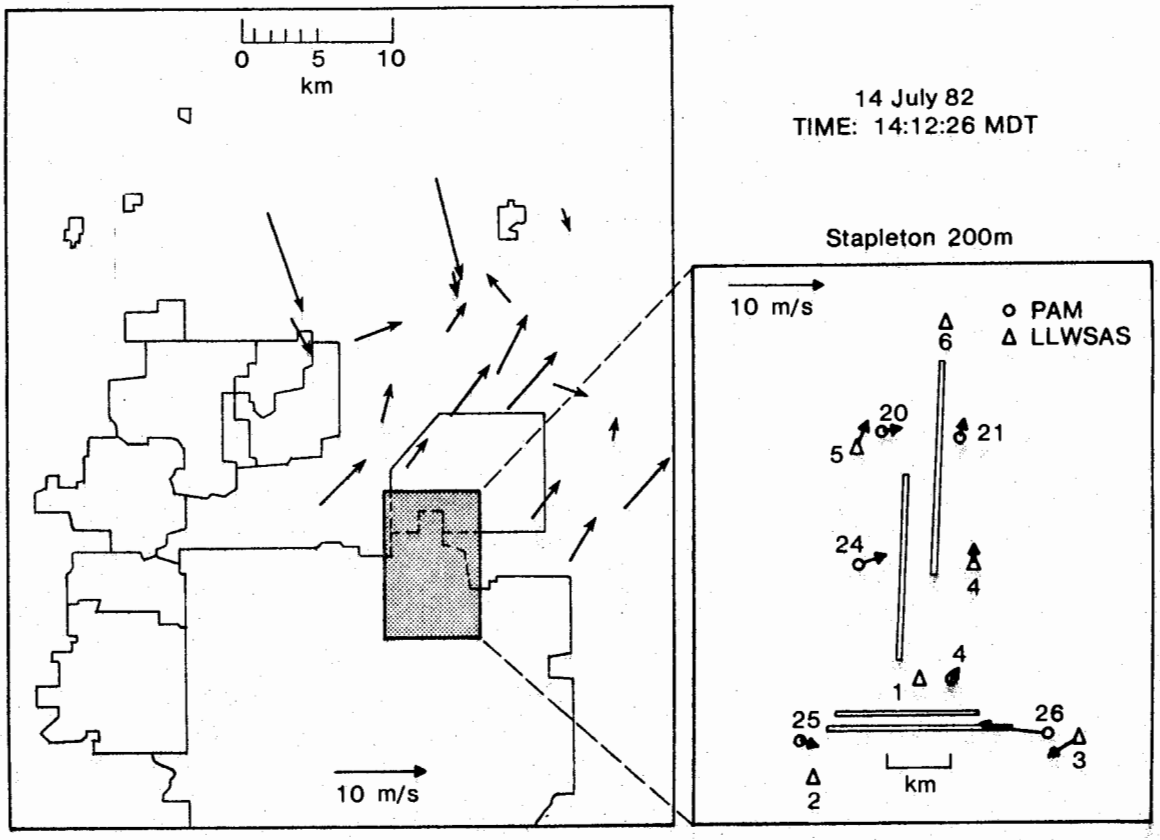

Figure 3. Wind vector information for the LLWSAS and PAM surface sites at 14:12:26 MDT.

Table 1. Pilot/controller communications between 1407 and 1415 MDT

Local Control # 2 (E-W) P = Pilot C - Controller

Time (MDT) h	min	s	Flight	Details	SE site LLWSAS winds	Alarm (A)
14	07	50	[F244]	C - wind calm	072 @ 9 kt	
14	09	10	[A17]	C - wind calm	067 @ 11 kt	
14	09	54			054 @ 17 kt	(A)
14	10	00	[F244]	P - quite a shear @ 300 ft C - plus or minus P - minus		
			[A17]	C - wind shear reported loss of air speed at 300 feet P - copy		
			[F244]	P - going around C - how much did you lose? P - had to go almost to take off power to catch it		
14	10	28			040 @ 38 kt	(A)
14	10	40	[A17]	P - wind check C - CF wind 130° @ 4 and EW wind where you are 040 @ 38 P - we are going to have to go around	039 @ 33 kt	(A)
14	11	20	[A17]	P - we are going to have to get a stabilized wind to land C - worst one we got is out there on the east-right now it is down to 070 @ 10	046 @ 12 kt	(A)
			[F244]	P - we are going to try it again. We would like to have a - ??? - this time and give you an idea where it is		
14	11	30	[UA463]	C - CF wind 150 @ 4, EW wind 050 @ 20 want to try it or go around? P - 20 knots, no we can't do that		
14	12	37			057 @ 11 kt	(A)
14	14	20	?	C - F244 got some pretty good dust about 2 out; you can probably see it; right here it is showing 300 @ 4 CF and E-W 010 @ 9 knots		
			[F244]	P - Thats what got us awhile ago C - Think so; about time you reported it, I got it here; it got up to 38 knots real quick P - We had to go to takeoff to stop that sinker		

Dashed line indicates that continuous LLWSAS alarms for the SE site appeared in the control tower between 09 min 54 s and 12 min 37 s.

Table 2. Transcripts from the Air Traffic Information System Messages

1406 MDT	Stapleton arrival information KILO 2006 Greenwich weather VFR temperature 87, wind 360 at 14 gusts to 25, altimeter 29.99. Expect profile descent vectors for visual approach. Landing runways 35L 35R VFR. Arrivals landing Stapleton contact approach north 120.5 south 120.8 for TCA clearance. Advise you have KILO.
1654 MDT	Stapleton arrival information LIMA 1054 Greenwich weather VFR temperature 84, wind 360 at 16, altimeter 30.00. Expect profile to clear vectors approach runway 35 VFR. Arrivals landing at Stapleton contact approach north 120.5, south 120.8 for TCA clearance. Advise you have LIMA.

located near the north LLWSAS site is used with an analog readout in preparing ATIS messages. This non LLWSAS anemometer is preferred by controllers because of its "faster update rate". The preference for use of this independent anemometer may also reflect the fact that the north LLWSAS site had instrument problems which caused it to read low (Bedard et al.[2]). These transcripts indicate that the ATIS is not presently configured to respond to rapidly changing systems such as microbursts, and times of increased work loads do not permit manual up-dating to ensure that current information is available. We direct these critical remarks towards the basic capabilities of the present ATIS system which require time for an operator to initialize. It is technically feasible to make a large segment of the ATIS message automatic either through the use of a voice synthesizer and/or a data link with graphics display. Designs for the Automated Weather Observing System (AWOS), now being tested for small, unmanned airports use voice synthesizers to update messages essentially in real time. Similar technology should be applied to update ATIS information transfer capabilities.

Summary

The microburst occurring off the east end of the E-W runway at Stapleton International Airport on 14 July 1982 provides guidance concerning the temporal and spatial scales required for providing detection and warning. The important features of the microburst and associated operational responses are the following:

(a) The lifetime of the gust surge at the SE LLWSAS site was about 60 s; the surge evolved at the surface site in less than 30 s.

(b) The peak gust measured at the closest PAM station, located less than about 1/2 km from the SE LLWSAS, lagged the SE LLWSAS station by more than 60 s indicating the importance of advection time or physical processes delaying the appearance of the gust surge.

(c) The microburst was not detected at any other surface sites, although several sites were less than 3 km from the SE LLWSAS site. Thus, the microburst could easily have occurred within the LLWSAS array and gone undetected.

(d) Three go arounds on the E-W approach occurred within 10 min, all associated with strong shear to the east of the runway. This series of events underlines the value of executing go arounds during potentially dangerous wind shear situations.

(e) The use of pilot reports, LLWSAS measurements of shear, and visible indications (blowing dust) helped aircraft avoid the region of dangerous shear.

(f) The fact that the ATIS tapes made no mention of the hazardous conditions indicates the need for upgrading the system to provide more current information.

(g) There is a need to use clear terminology in making pilot reports. The recommended method for wind shear reporting is to state the loss or gain of airspeed, the altitude at which it occurred, and the location and type of aircraft. Such pilot reports can be critical to helping following aircraft avoid dangerous wind shear.

Windshear detection systems, either improved LLWSAS or remote sensing approaches, need to provide for rapid distribution of hazard information. This case study describing an evolving system and associated aircraft problems indicates that time scales of 10's of seconds can be critical to operations. There is a great need to determine if there exists precursor information (which would, e.g., permit Doppler radar detection of a downburst at or near cloud base). Fujita and Wakimoto[4] suggest that upper level circulations may be associated with downbursts. Existing data bases should be carefully examined (e.g., analysis of the JAWS data base is now proceeding), to detect correlations between downbursts and the preceding meteorological conditions.

Acknowledgments

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References

1. McCarthy, J., J. W. Wilson, and T. T. Fujita (1982): The Joint Airport Weather Studies Project. Bull. Amer. Meteorol. Soc., 63, 15-22.

2. Bedard, A. J., Jr., J. McCarthy, and T. Lefebvre (1983): Statistics from the operation of the Low-Level Wind Shear Alert System (LLWSAS) during the JAWS project at NCAR. Report to the Federal Aviation Administration and to the National Aeronautics and Space Administration now in progress.

3. Brock, F. V., and P. K. Govind, (1977): Portable Automated Mesonet in operation. J. Appl. Meteorol., 16, 299-310.

4. Fujita, T. T., and R. M. Wakimoto (1983): JAWS microbursts revealed by triple-Doppler radar, aircraft, and PAM data. Thirteenth Conference on Severe Local Storms, Oct. 17-20, 1983, Tulsa, Okla., Amer. Meteorol. Soc., Boston, Mass., 97-100.