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NOAA Technical Memorandum ERL FSL-16

A SECOND EVALUATION OF AVIATION-IMPACT VARIABLES GENERATED BY LAPS

J.L. Mahoney
C. Hartsough
P.A. Miller
M.M. Cairns
R. J. Miller

Forecast Systems Laboratory
Boulder, Colorado
June 1995

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A SECOND EVALUATION OF AVIATION-IMPACT VARIABLES GENERATED BY LAPS

Jennifer Luppens Mahoney, Craig Hartsough, Patricia A. Miller
Mary M. Cairns, and Ronald J. Miller

ABSTRACT. This paper describes the second evaluation (E2) of aviation-impact variables (AIVs) derived from the Local Analysis and Prediction System (LAPS) analyses. This is part of an ongoing program at the Forecast Systems Laboratory (FSL), sponsored by the Federal Aviation Administration's Aviation Weather Research Program (AWRP). The evaluation was conducted from 22 February through 10 March 1992 using a verification dataset obtained from the Stormscale Operational and Research Meteorology-Fronts Experiment Systems Test (STORM-FEST). For verification purposes, LAPS produced analyses at specific station locations including; upper-air, surface, profiler, pilot report (PIREP) locations, and automated pilot report locations.

Overall, LAPS analyses of state-of-the-atmosphere variables (SAVs) and AIVs were within expected instrument errors, with a few exceptions. For example, a problem in the height calculation over the STORM-FEST domain was detected. This error was not apparent in the Colorado domain and will need further attention. On the other hand, the LAPS cloud analysis, which has been under development longer than many of the other AIV algorithms, produced good results when compared to the Surface Aviation Observations (SAOs). The LAPS precipitation analysis, based primarily on radar measurements, underanalyzed large precipitation amounts and overanalyzed small precipitation amounts. Since E2 was the first time icing and turbulence algorithms were tested for LAPS, the results can be considered baseline values.

1. INTRODUCTION

Most evaluations of numerical models and data assimilation systems are concerned with SAVs such as temperature, moisture, and winds. Although these variables are the basis for weather forecasting, it is often left to humans to interpret the output of SAVs and develop analyses and forecasts of AIVs such as ceilings, visibility, and precipitation type. FSL, part of the National Oceanic and Atmospheric Administration, is involved in an FAA-sponsored project aimed at developing gridded analyses and forecasts of AIVs from numerical models and analysis systems (Kraus 1993). The Aviation Division of FSL has created a Verification Program to evaluate the accuracy of the gridded systems and to assist in the development of the algorithms used to generate AIVs.

To date, five systems have been evaluated: the Mesoscale Analysis and Prediction System (MAPS), the Local Analysis and Prediction System (LAPS), the Colorado State University Regional Atmospheric Modeling System (CSU-RAMS), the MAPS Surface Analysis System (MSAS), and the National Centers for Environmental Prediction's Eta model. The LAPS analyses of SAVs and AIVs are presented in this document. See Cairns et al. (1994a and 1994b) for results from the MAPS and Eta models.

So far two verification exercises have been conducted, E1 and E2. E1, which occurred 1-10 April 1991, is described in general in Cairns (1992) and Cairns et al. (1993) and the datasets and verification methods are discussed in Miller and Cairns (1993). This exercise provided a baseline from which to build E2 which occurred 22 February-10 March 1992. The E2 domain covered portions of the STORM-FEST domain. To this point, E2 results for MAPS and Eta are completed.

2. SYSTEM DESCRIPTION

LAPS is designed to assimilate all available sources of real-time meteorological data and produce timely analyses of subsynoptic meteorological events. LAPS currently includes input data from SAOs, Automated Surface Observations (ASOS) sites, FSL's local surface mesonet (Pratte and Clark 1983), automated aircraft reports, satellite, WSR88D Doppler radars, and Wind Profiler Demonstration Network (WPDN) Doppler and acoustic radars. Surface and upper-air grids are produced from separate analysis systems once each hour on a regularly spaced grid with 10-km horizontal resolution. The upper-air system includes 21 layers at 50-mb vertical resolution. LAPS is being combined with a version of the CSU - RAMS model to produce forecasts of meteorological variables in the 0-12 h time range. However, only the LAPS analyses and the development of AIVs from the analyses are presented in this paper.

For this evaluation, the 1993 operational version of LAPS was rerun using data sources collected during the 1992 STORM-FEST experiment. Two different grid areas were produced: the Colorado LAPS domain, a 61 x 61 grid that covers most of Colorado and parts of the surrounding states and the STORM-FEST grid, a 91 x 127 grid, covering the main data collection area in the central United States. Analyses for both domains were generated from 23 February to 10 March 1992.

Many changes were made to the LAPS analyses for Exercise 2 that directly affect this verification. The changes include:

- The creation of a visibility field based on a Barnes (1964) analysis of surface visibility reports.
- The addition of a new method for calculating altimeter.
- The addition of RASS data to the LAPS temperature analysis to help improve the low-level temperature structure.
- The correction of a programming error in the LAPS humidity analysis.
- An improved LAPS cloud analysis, including; better use of infrared satellite data, better use of radar data especially below cloud base, and improved use of Atmospheric Weather Observing Stations (AWOS) that only report ceilings to 12000 ft. Also, visible satellite data were added to the analysis.
- The includion of the modified Smith-Feddes icing from Pat Haines (Haines et. al 1989) in the liquid water content analysis.
- The design of a crude turbulence algorithm as a first attempt to provide a turbulence analysis by LAPS.
- The addition of a new LAPS moisture analyses of precipitation type and amount.

3. VERIFICATION DATA

Although STORM-FEST occurred from 1 February through 15 March 1992, E2 covers only the period when the LAPS model ran, 22 February - 10 March, 1992. The main impetus for choosing the STORM-FEST period was to utilize the enhanced observation datasets which were available during this large experiment. Four primary observation data sources were selected for the verification data: SAO, upper-air (UPA) rawinsonde, vertical wind profiler (PRF), and pilot reports (PIREPS). Most of the raw observation data were obtained from the STORM-FEST field project office and those observations unavailable from STORM-FEST were obtained from FSL's Facility Division. Table 1 lists the SAVs and AIVs verified in the evaluation.

3.1. Surface Data

This section describes the verification data collection and quality control. For E2, 319 SAO stations, which manually recorded observations all day long, were selected for the surface verification dataset. Thirty-one of the 319 sites were not collected by STORM-FEST but were obtained from the FSL data archives. No special observations were used in the verification, only hourly observations. In addition to the manual SAOs, STORM-FEST collected automated observations within the STORM-FEST domain from AWOS, ASOS, and other automated networks (FSL Mesonet, NCAR PAM, High Plains Network, Illinois State Water Survey). With the exception of the ASOS sites, the automated observations were also used in the verification.

The SAO data obtained from STORM-FEST were already quality controlled. This was done by comparing the observations to analyses from MSAS (Miller and Benjamin 1992). Disagreements between the observations and analyses were flagged according to Table 2. Precipitation amounts were only checked for gross error limits. In addition, a manual quality control check was performed on selected observations, which verified and/or adjusted unlikely and questionable quality flags. For this verification, only "Good" or "Questionable" data were used; and it should be noted that only the individual value was declared to be bad, not the entire observation.

For the SAO data obtained from FSL, two quality control checks were performed on the observations. The first was a simple check to make sure values were within acceptable ranges (e.g., 50^{o} F < Temp < $+130^{o}$ F). For the second check, the time-series of the data were plotted and subjectively evaluated to detect any obvious errors. If a value of an observed element failed either check, it was declared as missing and no attempt was made to correct or reconstruct the value. As with the STORM-FEST data, only the value was declared to be bad, not the entire observation.

Although the SAOs contained nearly all parameters to be verified, two parameters were needed in the verification that were unavailable from the SAO data: precipitation amount and cloud-top height. For the automated sites, the precipitation amount data were included with the observation. For the manual SAOs, a separate database of precipitation data was obtained from STORM-FEST. Many SAO sites had collocated precipitation gauges, but some did not. An

Table 1. State-of-the-Atmosphere Variables (SAVs) and Aviation-Impact Variables (AIVs) Evaluated in Exercise 2

		VARIABLE	UNITS
SURFACE			
	SAVs		
		Altimeter	in. of mercury
		Temperature	^oF
		Dewpoint	^oF
		Wind Speed	kt
		Wind Direction	degrees
	AIVs		
		Cloud Bases	hundreds of ft.
		Cloud-Top Height	hundreds of ft.
		Cloud Amount	coded (e.g. CLR SCT)
		Ceiling	hundreds of ft.
		Visibility	miles
		Obstructions to Visibility	coded (e.g. H, K)
		Precipitation Occurrence	yes/no
		Precipitation Phase	coded (e.g. 1=liquid)
		Precipitation Type	coded (e.g. RW, S)
		Precipitation Amount	in./h or /3-h
RAWINSONDE			
	SAVs		
		Height	meters
		Temperature	^oC
		Dewpoint Temperature	^oC
		Wind Speed	kt
		Wind Direction	degrees
		Wind, U, V	ms^{-1}
PROFILER			
	SAVs		
		Wind, U, V	ms^{-1}
		Wind Speed	kt
		Wind Direction	degrees
		Vertical Wind	cms^{-1}
PIREPS/CITIES			
		Icing	yes/no
		Turbulence	yes/no

algorithm was written to select the gauges within 10 km of the SAO site to let the user subjectively decide which gauge was most representative. This decision was easily made by looking at the descriptive name of the rain gauge location. In those cases where a gauge was not selected, verification of precipitation amount was not performed for those sites. Of the 319 manual SAO sites, 220 (69%) had precipitation data. A total of 169 (53% of 319) of the precipitation sites were exactly collocated with a SAO site.

Table 2. Quality control thresholds for STORM-FEST surface observations

PARAMETER	UNLIKELY	QUESTIONABLE
	MAPS Variance	
Station Pressure	> 10.00 mb	> 3.00 mb
Sea Level Pressure	> 10.00 mb	> 3.00 mb
Calculated Sea Level Pressure	> 20.00 mb	> 6.00 mb
Dry Bulb Temperature	> 8.00 °C	> 5.00 °C
Dewpoint Temperature	> 8.00 °C	> 5.00 °C
Wind Speed	> 20.00 ms^{-1}	> 90.00 deg
	GROSS Limit	
Precipitation	> 75.00 mm hr^{-1}	> 25.00 mm hr^{-1}

All of the precipitation data were quality controlled by the STORM-FEST office. The thresholds used are given in Table 2. For this verification, only good values (i.e., not unlikely or questionable) were used.

Cloud-top heights were derived from satellite infrared brightness temperatures (T_B). The digital T_B data were examined in a 0.2° latitude by 0.2° longitude area centered over the SAO site. The coldest pixel was chosen for the cloud-top temperature which was then compared to the nearest (in time and space) sounding to obtain a cloud-top height. This method underestimates the cloud top for optically thin clouds. A "window" of 200 nmi and +/- 3 h was used to find the closest sounding. Finally, the cloud-top height was compared to the observed cloud bases at that station to ensure that it was above the highest cloud base. The cloud was required to have a default thickness of at least one reportable value (i.e., low clouds, 500 ft.; middle and high clouds, 1000 ft., U.S. Department of Commerce (1994)). If the cloud-top height could not be determined using the above method, the height was considered missing and was not used in the verification.

3.2. Rawinsonde Data

For E2, 104 rawinsonde stations were used in the verification. These included 74 NWS sites (including 3 in Alaska), nine Canadian sites, and 21 STORM-FEST sites (Central U.S. and West

Coast Picket Fence). All of these sites were available from the STORM-FEST office except for 32 NWS sites downwind (east and south) of the STORM-FEST domain, which were obtained from the FSL data archives.

The STORM-FEST data were interpolated to 10-mb levels, from the surface up to 100 mb. The NWS and Canadian sites launched at 0000 and 1200 UTC. Additionally, when an Intensive Observation Period (IOP) was declared, all sites launched every three hours. The other non-STORM-FEST NWS sites were available in the usual mandatory and significant level format, up to 100 mb at 0000 and 1200 UTC.

The STORM-FEST soundings were manually quality controlled by the STORM-FEST office by looking at each sounding on a skew-T chart. In addition, all soundings were compared to the NGM mandatory level gridpoint analyses. Values which disagreed with the NGM data by preset values were flagged as missing. These thresholds were taken from the MAPS quality control program (Miller and Benjamin 1991).

There has been much discussion about the accuracy of RAOB data, and in particular data from the moisture sensor at high levels. For a more complete review of the complications involved in using RAOB data for analysis, see Schwartz and Doswell (1991).

3.3. Profiler Data

Data from 30 wind profiler sites in the WPDN were available during STORM-FEST from the FSL data archives. Winds are reported every 250 m at 6-min intervals and combined into a 1-h average. The hourly averaged dataset was used for the verification data. Since profiler wind data are quality controlled before they are released, no additional checks were performed (Brewster and Schlatter 1986; Brewster 1989). The quality control method used by the WPDN during the STORM-FEST period occasionally failed to identify erroneous data, but more often incorrectly labeled good data as bad. Improvements to the quality control method were implemented in October 1993 (Miller et al. 1994).

3.4. Aircraft Reports

Two different sets of aircraft reports are used in the verification for icing and turbulence, voice PIREPS and Aeronautical Radio, Inc. (ARINC) Communications Addressing and Reporting Systems (ACARS). The voice PIREPS, obtained from the FSL data archives, was actually a merged database from two different circuits, FAA604 and DDS, that provided a more complete dataset. Only the turbulence and icing observation in the voice PIREPS were used. The ACARS data were obtained from United Airlines (UAL). In addition to the usual winds and temperature data, they included manual reports of turbulence, but not icing.

Note that all PIREPS were saved, even those that did not explicitly mention turbulence and/ or icing. Following are the naming conventions used for icing and turbulence reports.

Positive: report that event occurred.
Negative: PIREP explicitly states that event did not occur.

Null: PIREP does not include the icing and/or turbulence group. In other words, the event is not explicitly stated as positive or negative.

The rationale behind the Null PIREPS is that if the event was not explicitly stated in the report, then it probably did not occur. This assumption is not valid all the time, especially in the cases of light events (e.g., trace rime or light chop).

Determining the actual location of the PIREP is often not a straightforward process. PIREPS will often report their location as a route from one location to another (e.g., STL-PIA in table 3). In these cases, the midway point was used as the location of the PIREP. PIREPS will also report a range of flight levels, usually corresponding to the event they are reporting (e.g., MDT ICG BLO 100 or LGT TRB 250-290). In these cases, the PIREP is duplicated for every 1000 ft. between the range reported. Thus, a PIREP which reports turbulence between flight levels 250-290 would result in five turbulence reports at five levels.

PIREPS are used in two different ways for the verification of occurrence (not intensity) of icing and turbulence. In the first method, the gridded data are directly interpolated to the location of the PIREP (latitude, longitude, flight level, and time).

In the second method, approximately 20 cities (Table 3) were chosen because they displayed a high volume of air traffic. All PIREPS within 50 km around the city and with a time window +/- 1.5 h were interpolated to 1000-ft. flight levels creating a column of yes/no observations in 1000 ft. increments. For icing, these cities had high numbers of departures/arrivals, resulting in many low-level observations. For turbulence, the high-level (i.e., above flight level 240) traffic was used to determine the best cities. The proximity of the nearest rawinsonde station was also given consideration in the selection process, since part of the goal of this verification method was to obtain some ground truth observations of the SAVs (e.g., temperature and relative humidity for icing determination). This assisted in determining whether problems with the icing/turbulence diagnoses was from the LAPS system themselves or the algorithm. Results are not shown for the city verification method. The sample size for this method was inadaquate for a meaningful statistical comparison. However, this method is useful for a long-term study and will be used in the Real-Time Verification System (Mahoney et al. 1995, unpublished).

3.5. Instrument Precision

In any verification study, the raw observations that are being used as *truth* are assumed to be correct, after even minimum quality control has been applied. Although routine measurements of the atmospheric variables are often considered to be exact, there are known inaccuracies. Unfortunately, it is often difficult, if not impossible, to provide a standard against which a measurement can be verified. For example, if a rawinsonde reports a 500-mb temperature of -25°C, there is no other exact measurement by which we can judge the accuracy of the rawinsonde report. So, instrument precision is often described as the root mean square (RMS) difference between two identical collocated instruments. For example, two rawinsondes are attached to the same balloon, and the differences in their measurements are computed. Table 4 lists the surface and upper-air instrument RMS differences as defined by Hoehne (1980), NWS (1991a,b) and NOAA (1991). These numbers should be kept in mind when evaluating the

Table 3. Icing and Turbulence Cities

Icing Cities	Nearest RAOB site
Nashville (BNA)	At site
Washington/Dulles (IAD)	At site
Denver, CO (DEN)	At site
Salt Lake City, UT (SLC)	At site
Pittsburgh, PA (PIT)	At site
Seattle, WA (SEA)	Quillayute, WA (UIL, 177km)
Albuquerque, NM (ABQ)	At site
San Francisco, CA (SFO)	Oakland, CA (OAK, 20km)
San Diego, CA (SAN)	Miramar, CA (NKX, 13km)
Boston, MA (BOS)	Chatham, MA (CHH, 117km)
Bismarck, ND (BIS)	At site
Flint, MI (FNT)	At site
Dayton, OH (DAY)	At site
Kansas City, MO (MCI)	Topeka, KS (TOP, 82km)
Raleigh, NC (RDU)	Greensboro, NC (GSO, 107km)
Minneapolis, MN (MSP)	St. Cloud, MN (STC, 99km)
Saint Louis, MO (STL)	Peoria, IL (PIA, 221km)
Portland, OR (PDX)	Salem, OR (SLE, 81km)
Albany, NY (ALB)	At site
Chicago/Midway (MDW)	Peoria, IL (PIA, 203km)
Milwaukee, WI (MKE)	Green Bay, WI (GRB, 171km)
Omaha, NE (OMA)	N. Omaha, NE (OVN, 12km)
Turbulence	
Little Rock, AR (LIT)	At Site
Denver, CO (DEN)	At Site
Grand Junction, CO (GJT)	At Site
Tallahassee, FL (TLH)	At Site
Garden City, KS (GCK)	Dodge City, KS (DDC, 68 km)
Detroit, MI (DTW)	Flint, MI (FNT, 89 km)
Jackson, MS (JAN)	At Site
Kansas City, MO (MCI)	Topeka, KS (TOP, 82 km)
St. Louis, MO (STL)	Peoria, IL (PIA, 221 km)
Las Vegas, NV (LAS)	Desert Rock, NV (DRA, 96 km)
Albuquerque, NM (ABQ)	At Site
Greensboro, NC (GSO)	At Site
Dayton, OH (DAY)	At Site
Oklahoma City, OK (OKC)	Norman, OK (OUN, 22 km)
Pittsburgh, PA (PIT)	At Site
Charleston AFB, SC (CHS)	At Site
Rapid City, SD (RAP)	At Site
Nashville, TN (BNA)	At Site
Amarillo, TX (AMA)	At Site
El Paso, TX (ELP)	At site
Charleston, WV (CRW)	Huntington, WV (HTS, 82 km)

relative accuracy of numerical models and data assimilation systems. Even though a perfect analysis or forecast is the ultimate goal, it can hardly be assumed that an analysis or forecast error will be less than the precision of the verifying instrument. In addition, errors of representativeness (Daley 1991) due to the spacing of the observational data can affect the results.

Table 4. Instrument Root Mean Square Error (RMSE) Differences

UPPER AIR	
Pressure	2.0 mb
Temperature	0.54° C - 0.68° C
Relative Humidity	2.2%
Dewpoint Depression	2.7° C - 3.4° C
Height	15.3 m - 16.3 m
Wind Speed	6.0 kt
Wind Direction	14° at 10 kt, 2° at 120 kt
SURFACE	
Altimeter	0.02 in. Hg.
Temperature	1° C (1.8° F)
Dewpoint Temperature	from 1.1° F for Td > 32° F & T-Td < 11° F to 7.9° F for Td < 32° F & T-Td > 54° F
Wind Speed	2 kt or 5% (whichever is greater)
Wind Direction	5° for wind speed > 5kt
Ceiling	50 ft. up to 12,000 ft.
Precipitation	0.3 mm for 8-in. stick gauge, 0.02 in. for weighing gauge
Visibility	Subjective
Cloud Amount	Subjective

4. ANALYSES

4.1. Analysis Types

For verification purposes, LAPS analyses were rerun with the 1993 version of the system and interpolated to the observation locations described in Section 3. The number of data points that went into the verification of the STORM-FEST domain was a factor of 10 larger than the dataset used to verify the LAPS Colorado domain. The output was constructed to mirror the observational format. For example, if there is a low overcast cloud deck, observers cannot report any clouds above that deck because their vision is blocked by the low clouds. Although, LAPS can *see* cloud decks above a lower overcast deck, for the purposes of this exercise, these data were not verified.

In addition to the SAVs that were directly available from the LAPS grids, AIVs were also derived. In one case, LAPS did not yet have the capability to produce a particular AIV (e.g., obstructions to visibility) and thus was not evaluated on that parameter. Table 5 lists the SAVs and AIVs that were diagnosed by LAPS.

Table 5. SAVs and AIVs Provided by LAPS for Exercise 2

SURFACE	
Wind Direction	Yes
Wind Speed	Yes
Temperature	Yes
Dewpoint	Yes
Altimeter	Yes
Precipitation Occurrence	Yes
Precipitation Phase	Yes
Precipitation Type	Yes
Precipitation Amount	Yes
Visibility	Yes
Obstruction to Visibility	No
Ceiling	Yes
Cloud Heights	Yes
Cloud Amount	Yes
Cloud Top	Yes
RAWINSONDE	
Height	Yes
Temperature	Yes
Dewpoint	Yes
Wind Speed	Yes
Wind Direction	Yes
PROFILER	
U-Component	Yes
V-Component	Yes
W-Component	Yes
ICING	
Occurrence	Yes
TURBULENCE	
Occurrence	Yes

4.2. Areas and Frequencies

The verification area was defined by approximately 25-50°N and 65-130°W. LAPS produced analyses within its 2 grid regions: the Colorado domain and the STORM-FEST domain (see Section 2 for grid dimensions). Within the verification area, LAPS was required to interpolate the analyses to surface, upper-air, profiler, and PIREP locations. The LAPS model was rerun in an operational mode for 12 days between 0000 UTC 22 February and 0000 UTC 10 March 1992 and produced an analysis hourly.

4.3. Derivation of Aviation-Impact Variables

Numerical models and data assimilation systems analyze and forecast SAVs, such as winds, temperature, and moisture. Weather variables that affect aviation procedures (such as icing and turbulence) are typically not analyzed or forecast by the model and must be derived from the SAVs. Many methods can be used to derive these AIVs. A method currently used at NMC is the model output statistics (MOS) approach.

One of the main objectives of the verification exercise is to evaluate the accuracy not only of the analyses and forecasts but also of the AIV derivation methods. For E2, the LAPS modelers developed their own methods of AIV derivation. Appendix A provides a detailed description of the LAPS AIV derivations for E2.

5. RESULTS

Appendix B describes statistical measures used for this verification, while Appendix C lists a summary of LAPS verification statistics for SAVs and AIVs compared to upper air, profiler, surface, icing, and turbulence observations. The following subsections further discuss details of the LAPS evaluation. The reader is encouraged to tab Appendix C, as each section refers heavily to the statistics listed there.

When evaluating LAPS errors, keep in mind that LAPS blends many sources of data into a 10-km horizontal resolution. This procedure tends to smooth the extreme values of the SAVs and AIVs. In addition, the observation data used to verify the LAPS analyses is only one of many datasets that LAPS combines to produce its analyses. Therefore, the dataset used to verify the LAPS analysis is not independent of the data used to compute the analyses. However, the precision with which the LAPS analyses can match the observations is extremely valuable when the analyses are used as a background field for another model (e.g., RAMS). In some cases, however, LAPS cannot simultaneously match different types of data that may be inconsistent with each other.

A noteworthy consideration when comparing the LAPS Colorado domain with the STORM-FEST domain is that 17 observing stations were evaluated in the STORM-FEST domain that produced 26701 records, while the Colorado domain received data from only 4 observing stations that produced 1480 records. Therefore, the sample size for the STORM-FEST domain was considerably larger than the Colorado dataset.

5.1. Upper Air

Height. The mean errors for the LAPS height analyses are shown in Figs. 1 and 2. LAPS does a good job with its height analysis for the Colorado domain with only a 1 to 2 dm height bias below 400 mb, with a near zero bias above that level (Fig. 1). However, a large height bias of 3 to 4 dm is detected in the LAPS STORM-FEST domain (Fig. 2). This mean error may be the cause of an error in the LAPS surface adjustment algorithm that produces a height analysis that is 40 m too high. Since this study, improvements to the LAPS height algorithm have been implemented.

Temperature. LAPS does an excellent job with its temperature analysis for both domains, as seen in the temperature bias plots (Figs. 1 and 2). The biases are less than 1 degree and become slightly negative with height. A similar temperature bias was detected in the MAPS runs at upper levels (Cairns et. al 1994a). Since LAPS uses the MAPS temperature field as a first guess background, the MAPS errors could be affecting the LAPS analyses. Small biases evident in the lowest 50 mb may be due to the inability of the upper-air analyses to resolve boundary layer fluctuations.

The 850-mb scatterplot (Fig. 3) of the LAPS Colorado domain shows that a warm bias is associated with colder temperatures, since the regression line of the data is above the dashed (perfect) line for temperatures colder than 0^{o} C. This bias only exists in the LAPS analysis produced on the Colorado domain, possibly due to the more complicated mountainous terrain that exists in that domain. The small number of verifying observations, however, makes it difficult to draw any firm conclusions. Nearly a one to one correspondence between LAPS 850-mb temperature and the observed temperature (Fig. 4) exists in the STORM-FEST domain.

The freezing level is well analyzed by LAPS. The scatterplots (Figs. 5 and 6) for both domains indicate a tendency for LAPS to overanalyze the height of the freezing levels. This result may suggest that LAPS is mis-analyzing multiple freezing levels as was the case with the MAPS model (Cairns et al. 1994a).

Moisture. A moist bias, evident in Figs. 7 and 8, occurs between 850 and 500 mb in both the Colorado and STORM-FEST domains. This moist bias does not affect the cloud, ceiling or visibility computations, since they are derived independent of the moisture fields. The scatterplots for RH at 850-mb (Figs 9 and 10) indicate that the general trend is for LAPS to be too moist in dry cases and dry when the relative humidity approaches 100%. This error is more pronounced in the STORM-FEST domain.

Winds. Recall that RAOBs are not used directly in the LAPS analyses due to general lack of timeliness. LAPS has a tendency to underanalyze the wind speed at nearly all levels for both domains, as shown in the bias plots of Figs. 11 and 12. The greatest errors, excluding the error which occurs at 100 mb due to the upper boundary conditions in LAPS, are approximately 6 kt and occur below 800 mb. The magnitude of the error decreases with height to approximately 2

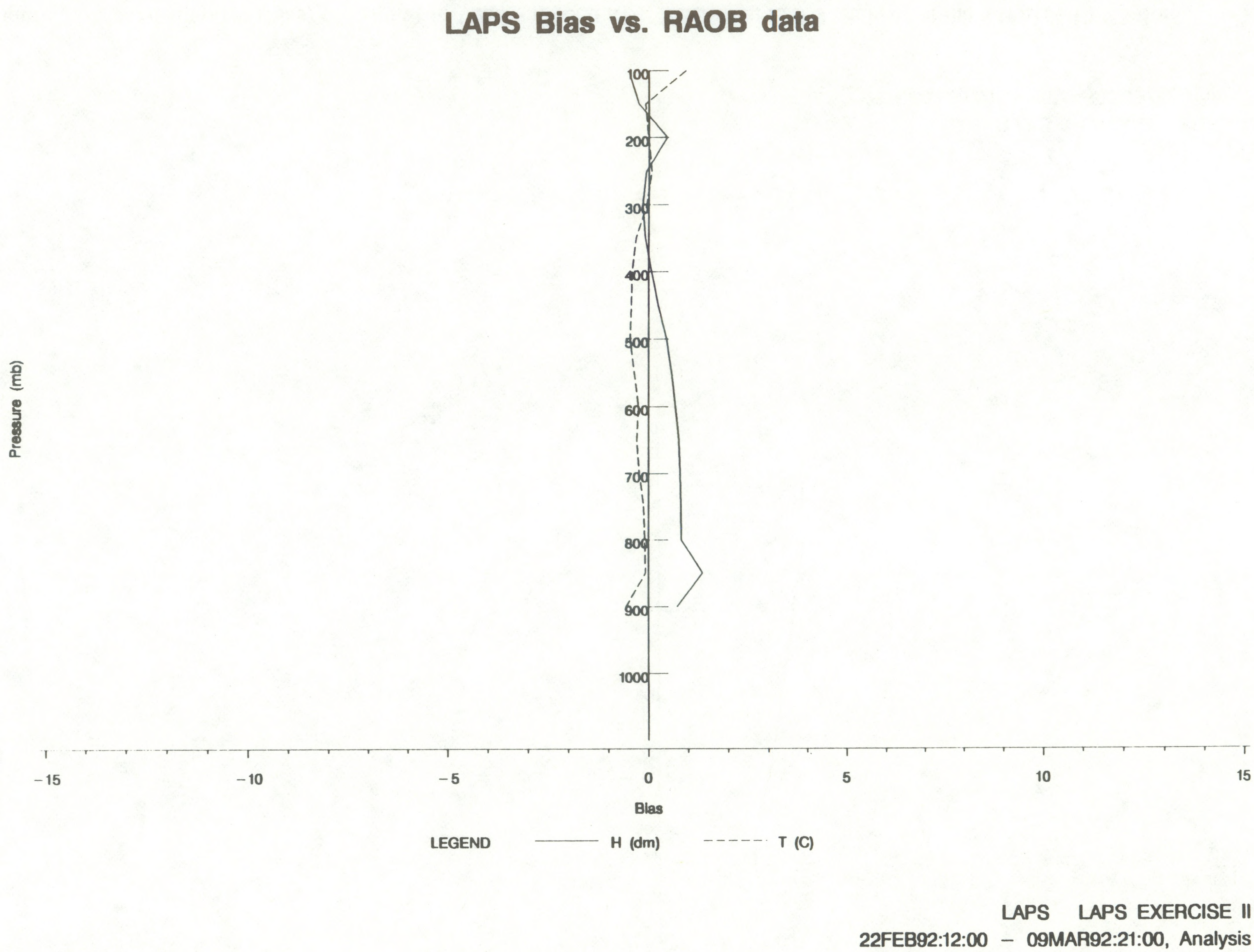

Figure 1. Mean error (bias) of height (dm) and temperature (C) between LAPS analysis of the Colorado domain and RAOBS.

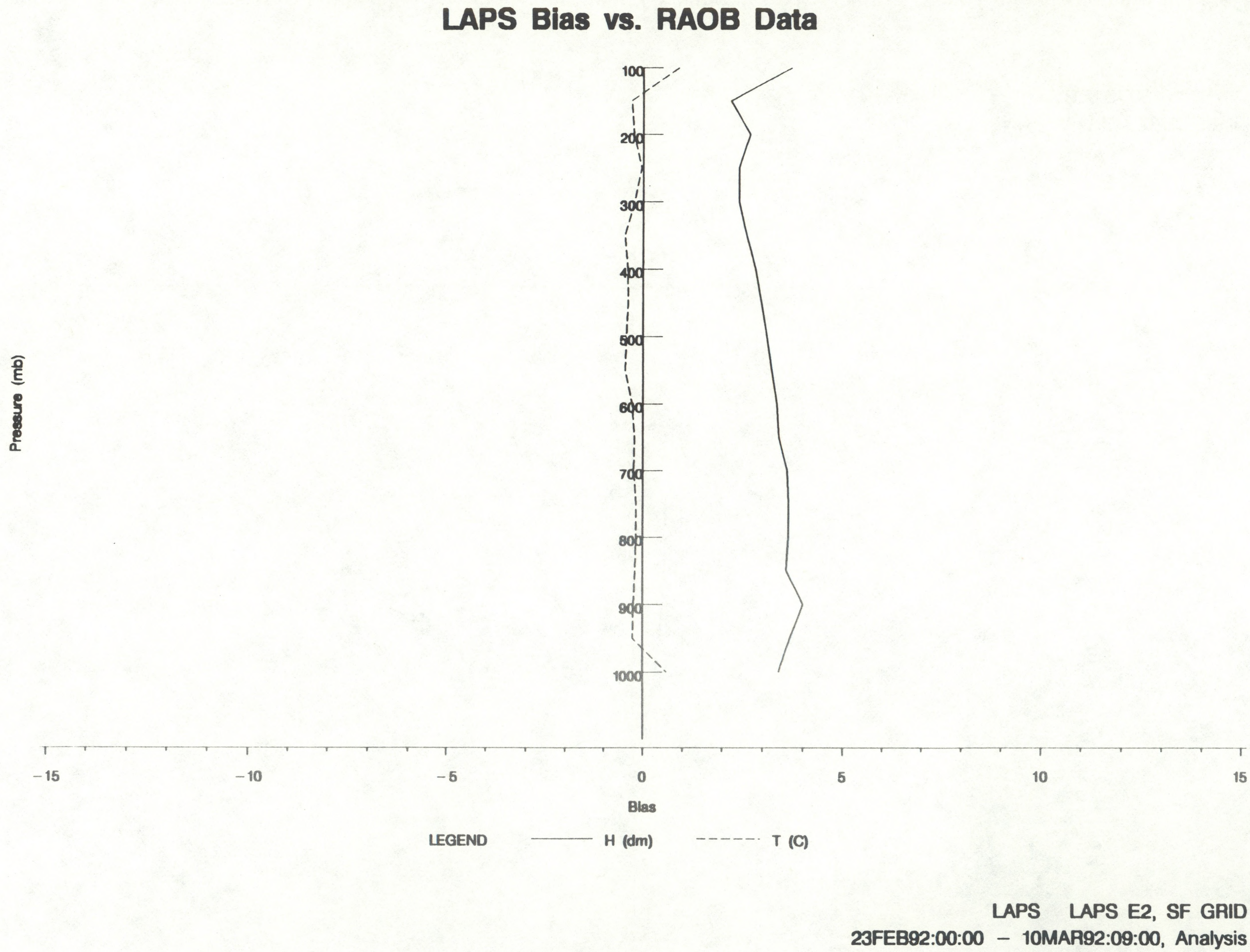

Figure 2. Mean error (bias) of height (dm) and temperature (C) between LAPS analysis of the STORM-FEST domain and RAOBS.

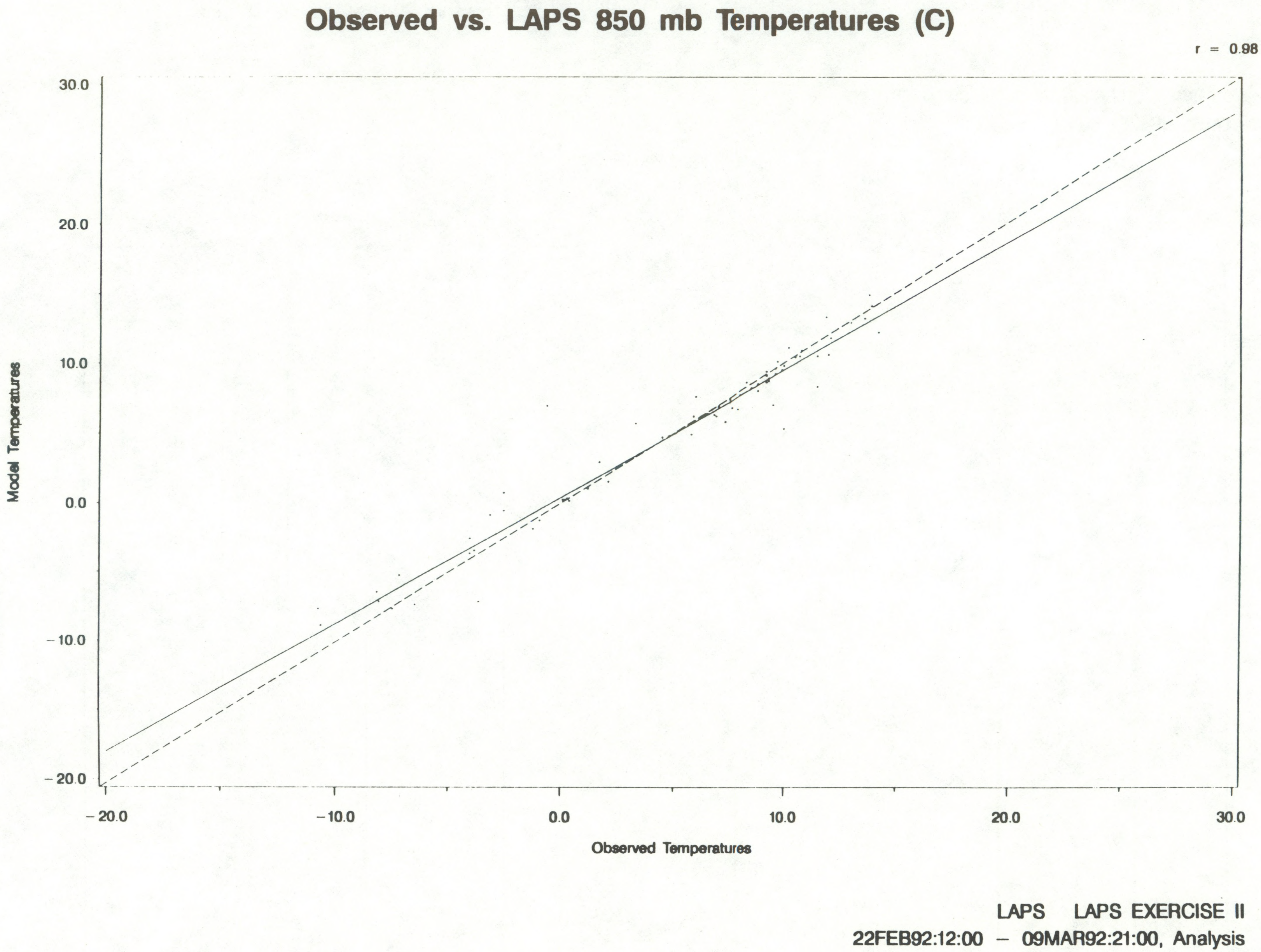

Figure 3. Scatterplot of observed 850 mb temperature versus LAPS analysis for the Colorado domain.

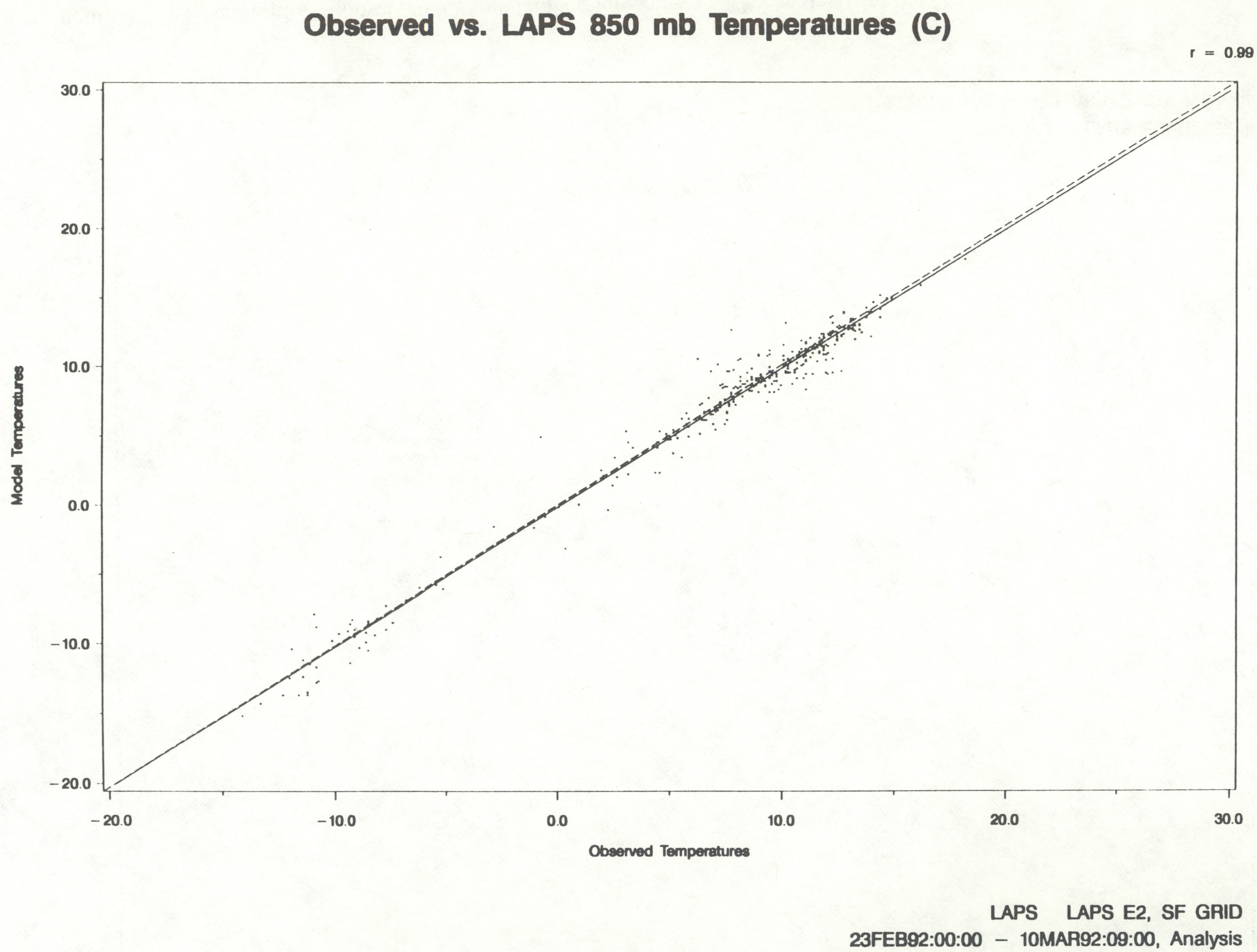

Figure 4. Scatterplot of observed 850 mb temperature versus LAPS analysis for the STORM-FEST domain.

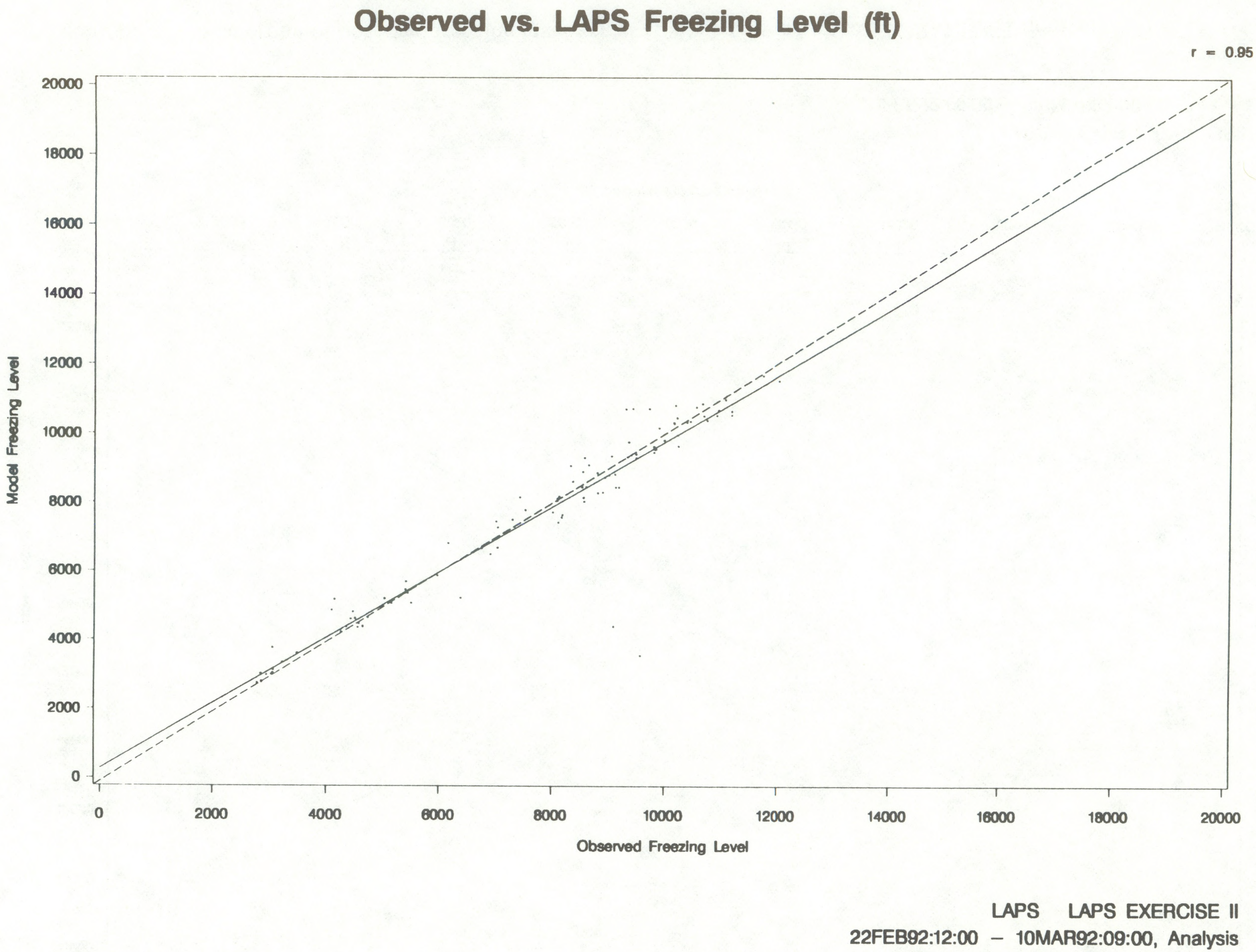

Figure 5. Scatterplot of observed freezing level versus LAPS analysis for the Colorado domain.

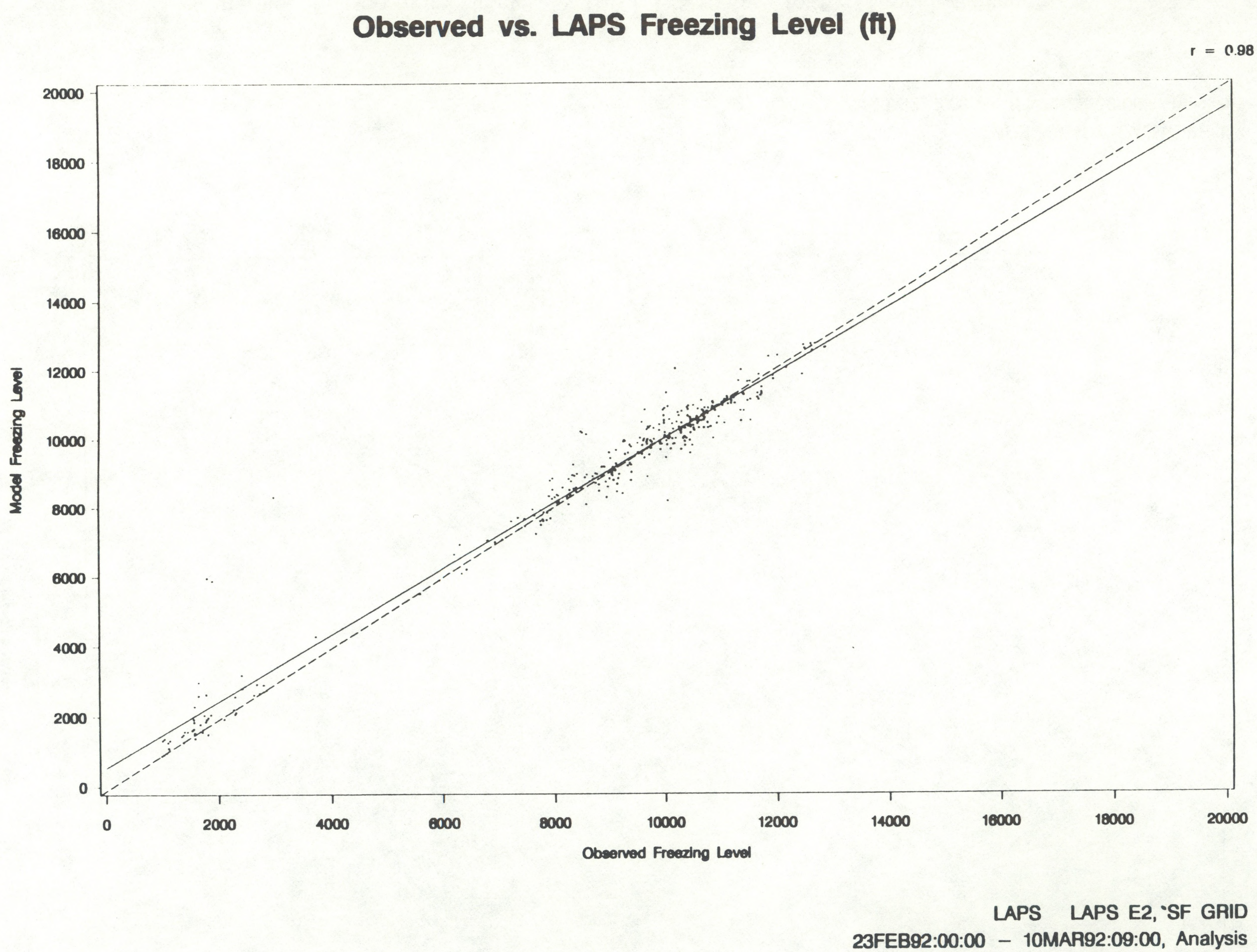

Figure 6. Scatterplot of observed freezing level versus LAPS analysis for the STORM-FEST domain.

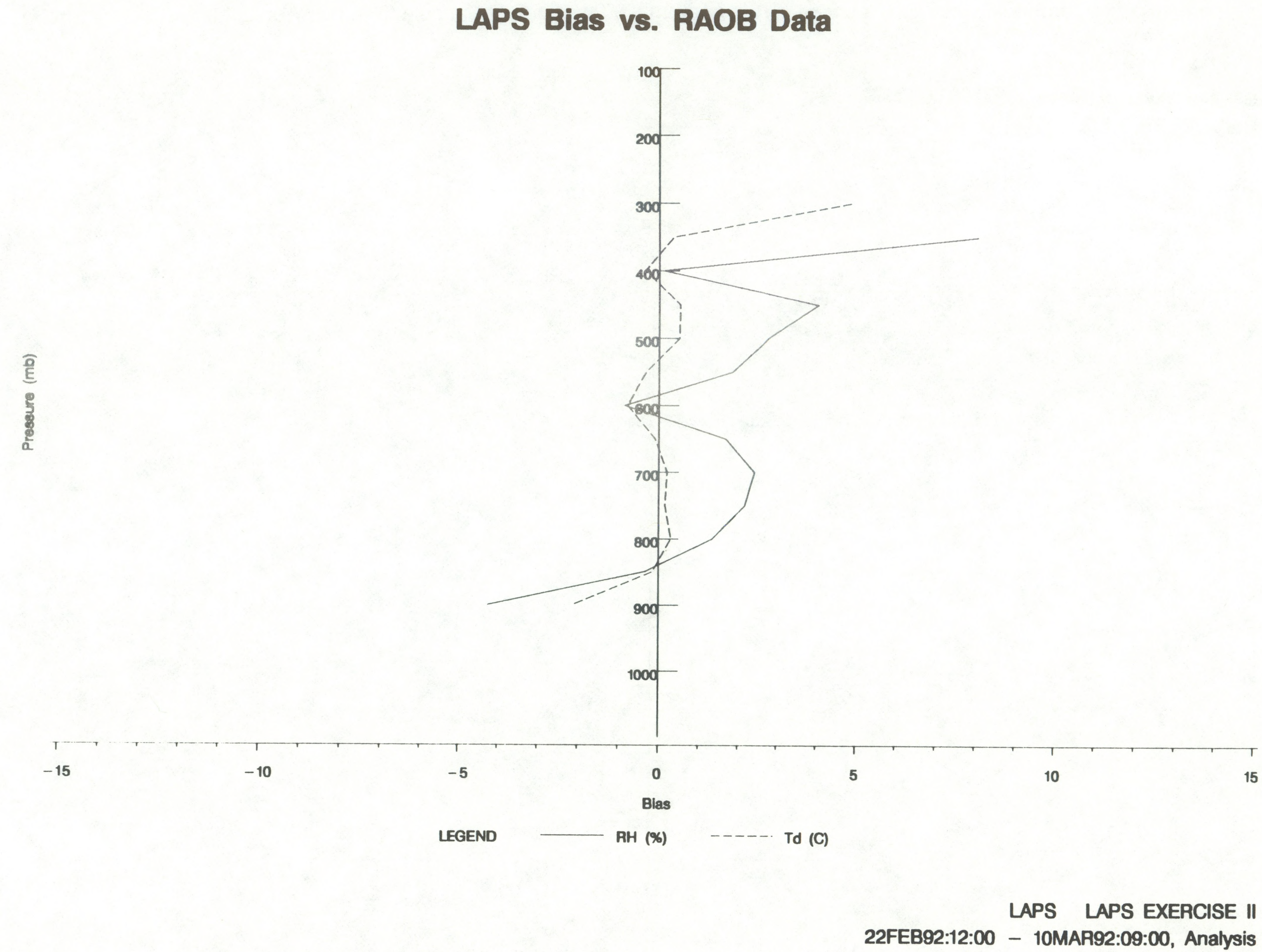

Figure 7. Mean error (bias) of dewpoint (C) and relative humidity (%) between LAPS analysis of the Colorado domain and RAOBS.

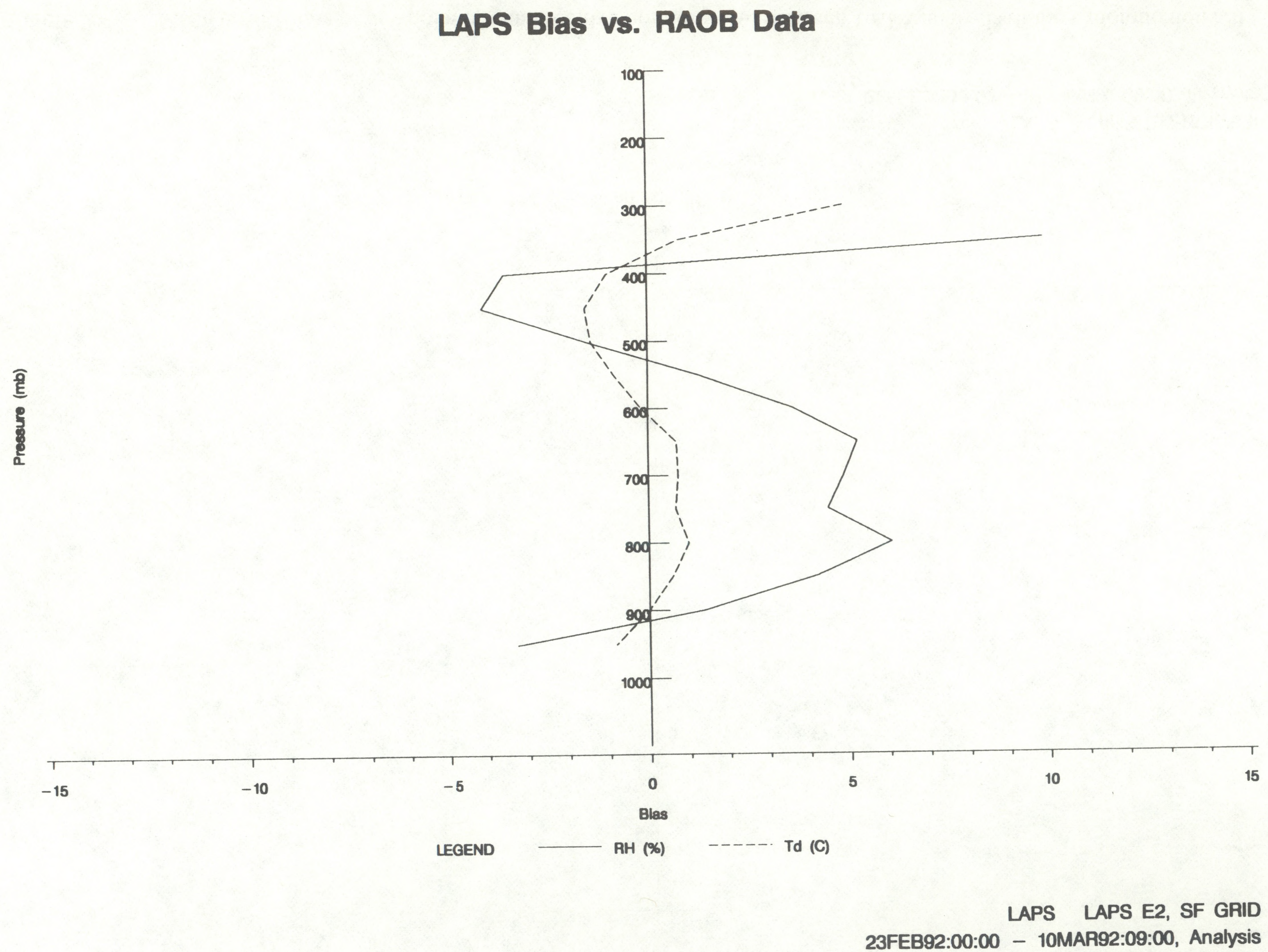

Figure 8. Mean error (bias) of dewpoint (C) and relative humidity (%) between LAPS analysis of the STORM-FEST domain and RAOBS.

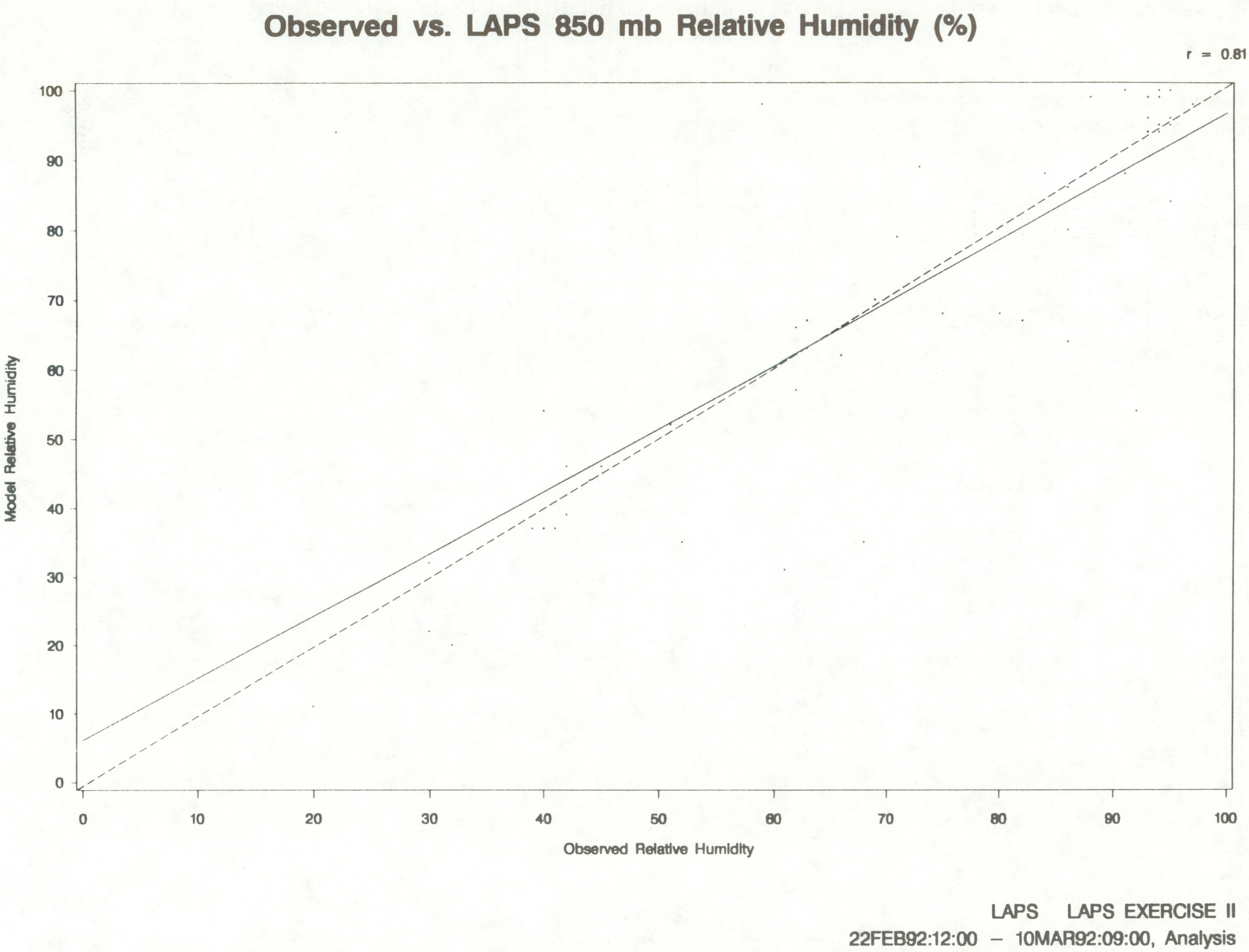

Figure 9. Scatterplot of observed 850 mb relative humidity (%) versus LAPS analysis for the Colorado domain.

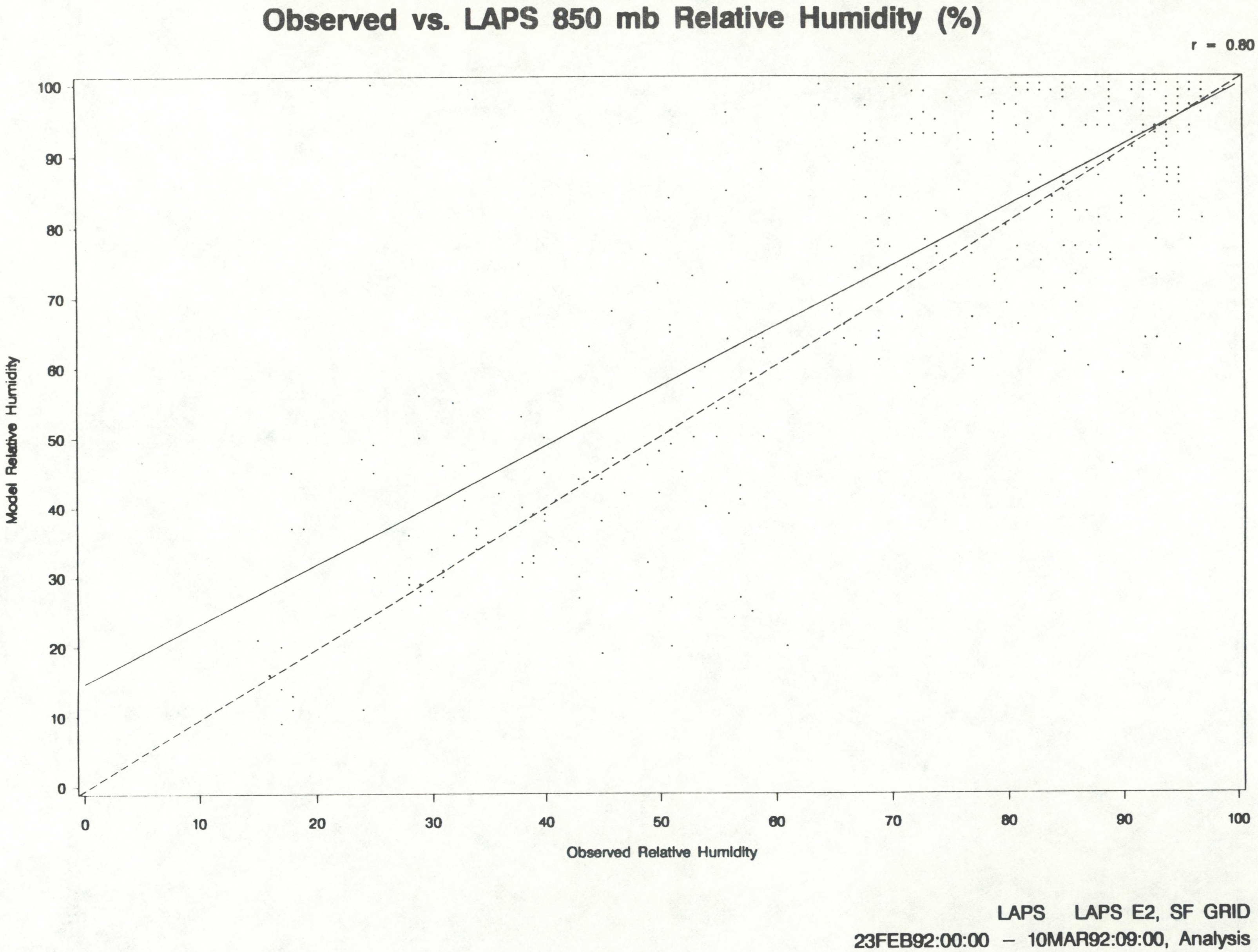

Figure 10. Scatterplot of observed 850 mb relative humidity (%) versus LAPS analysis for the STORM-FEST domain.

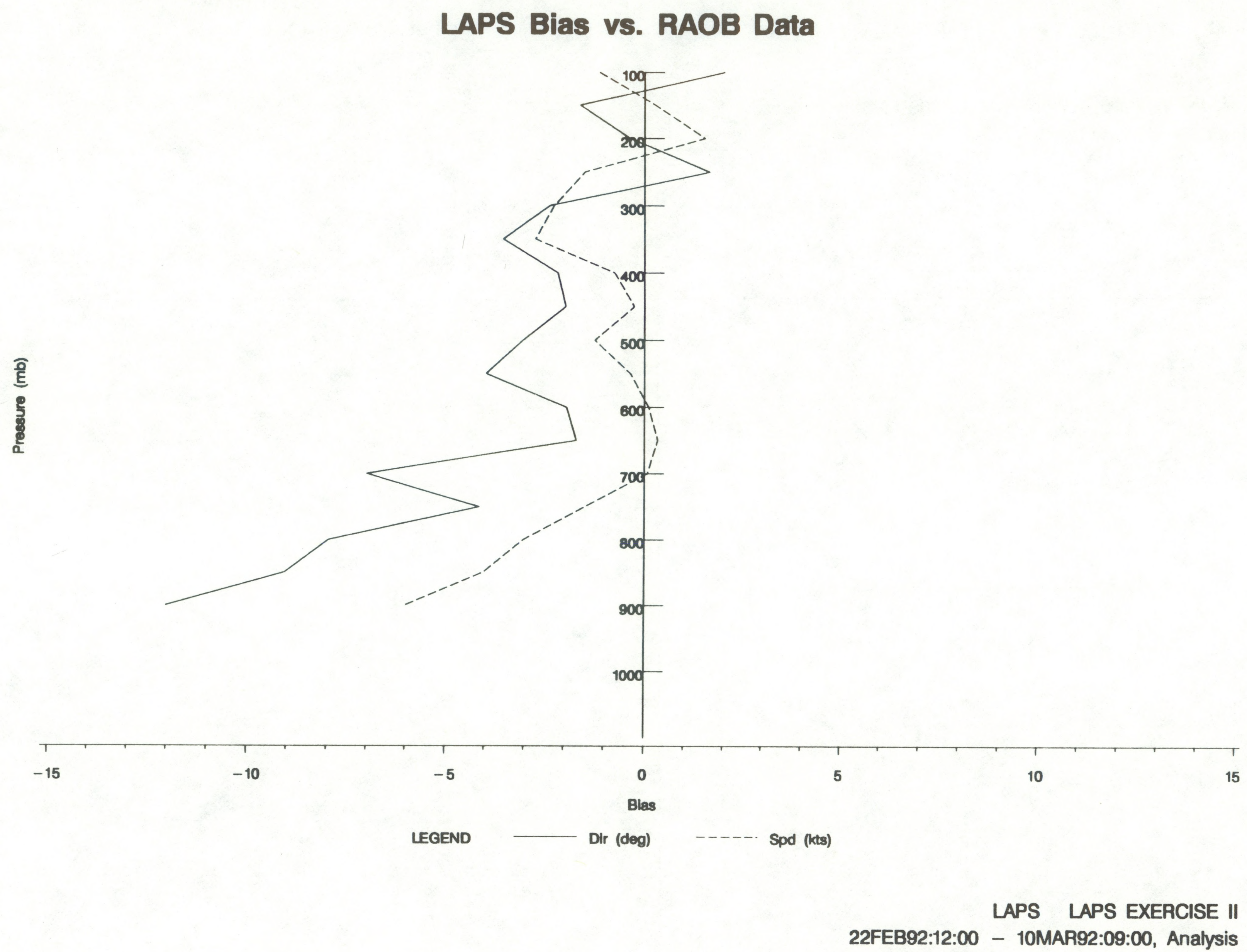

Figure 11. Mean error (bias) of wind direction (deg) and speed (kts) between LAPS analysis of the Colorado domain and RAOBS.

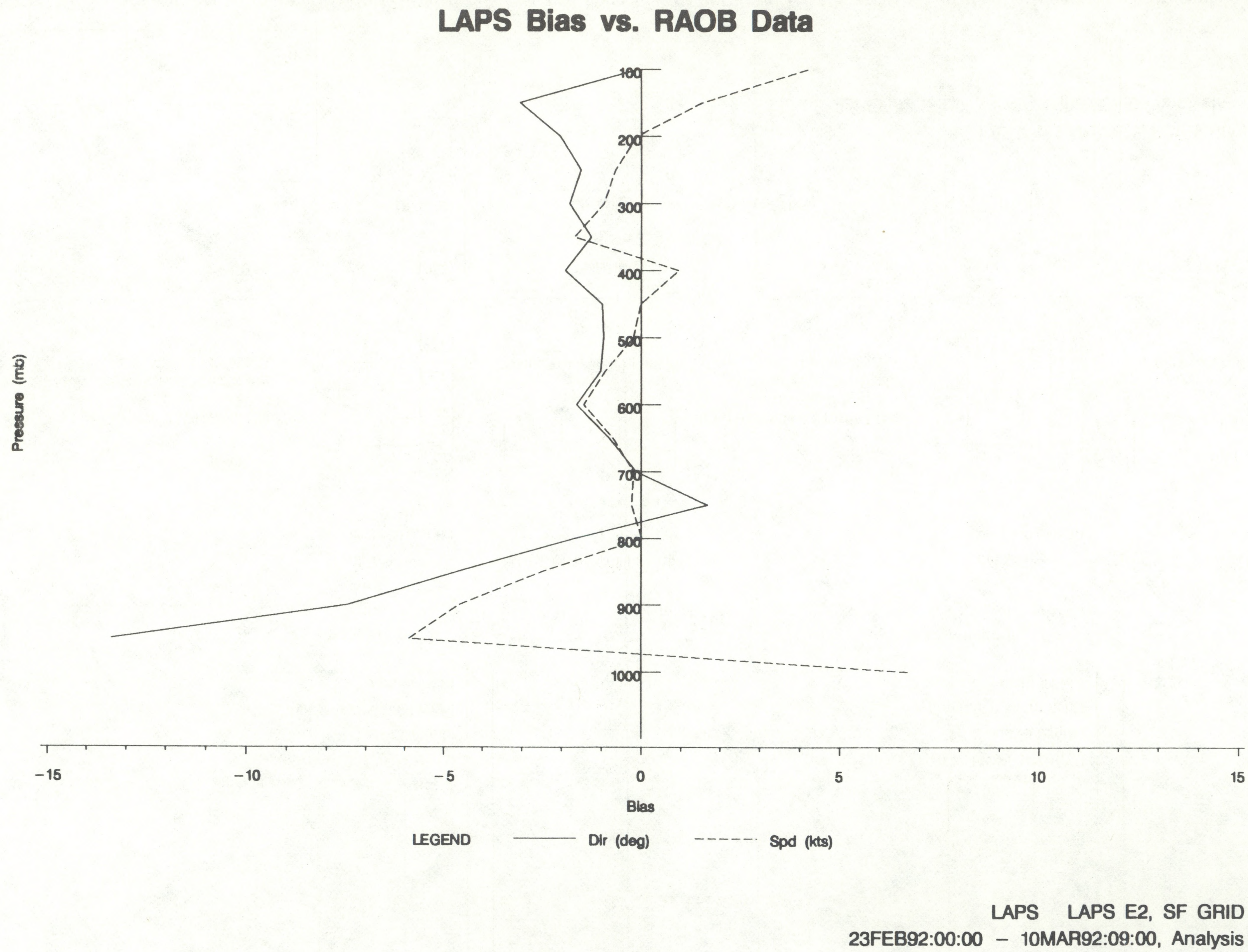

Figure 12. Mean error (bias) of wind direction (deg) and speed (kts) between LAPS analysis of the STORM-FEST domain and RAOBS.

kt and remains slightly negative at mid- to upper-levels. This error is more evident in the 850-mb scatterplots for both domains (Figs. 13 and 14). At this level, LAPS has a tendency to underanalyze wind speeds greater than 15 kt and overanalyze speeds less than 10 kt.

Additional analysis was done to investigate the large bias in the low-level wind field. A bar chart of 950-mb wind speed errors (Fig. 15) shows a 4-6 kt negative bias, since the errors are evenly distributed about -5 instead of 0. However, this bias is amplified by the larger errors produced in only a few cases. Further investigation of these cases revealed that many of the errors occurred at stations located in the central U.S. during 4 March and 8-10 March 1992. During these periods, strong cyclogenesis occurred over the central U.S. More specifically, the low-level jet was underanalyzed by the LAPS model in these cases. An example of this occurred in Stephenville TX (SEP) on 1200 UTC 9 March 1992 (Fig. 16). At this time, a 19-kt low-level jet was observed below 900 mb at SEP. LAPS analyzed a 10-kt wind at this level, thus significantly underanalyzing the low-level jet. In another instance, LAPS underanalyzed the low-level jet in Omaha, NE (OVN) (Fig. 17) at 1200 UTC 9 March 1992 by 10 kt.

The RMSVEs are quite significant with values between 5 and 6 m s^{-1} in both of the LAPS domains (Figs. 18 and 19). However, the most significant errors occur at 850 mb and 200 mb in the LAPS STORM-FEST domain. These results are consistent with the location of the low-level and upper-level jet streams. Since the RMSVE gives greater weight to larger errors, this would suggest that the larger errors at these two levels are associated with the few cases where the low-level jet stream and upper-level jet stream were especially strong (i.e. during the cyclogenesis cases), as was discussed in the previous paragraph.

5.2. Profiler

Winds. The RMSVEs for the profiler winds (Figs. 20 and 21) are smaller than for the RAOB winds (refer back to Figs. 18 and 19). This is due to the inclusion of the profiler observations in LAPS wind analysis, while RAOB data are excluded in the analysis. For both domains, the errors in the analyses are typically less than 4 m s^{-1} from just above the surface to 11 km. Above the 11 km height, the wind error begins to increase; this is again consistent with the location of the upper-level jet stream. The errors above 15 km are questionable, and are thought to be caused by either inaccurate profiler winds (not caught by the quality control procedures) or inaccurate analyses resulting from the coarse vertical resolution of LAPS near the tropopause. Additional analysis errors may be caused by the fact that 15 km AGL is often above the top of the LAPS analyses, causing extrapolation, not interpolation, techniques to be used to calculate the analysis-minus-observation differences. Similar errors above 15 km were obtainted in both the MAPS and Eta studies (Cairns et al. 1994a and b).

Plots of wind bias for both domains (Figs. 22 and 23) show that there is a tendency for negative bias in both the wind speed and direction below 3 km. The errors are consistent with the mean errors noted in the RAOB plots, but considerably smaller in magnitude. The mean errors above this level are similar to those detected by MAPS (Cairns et al. 1994a).

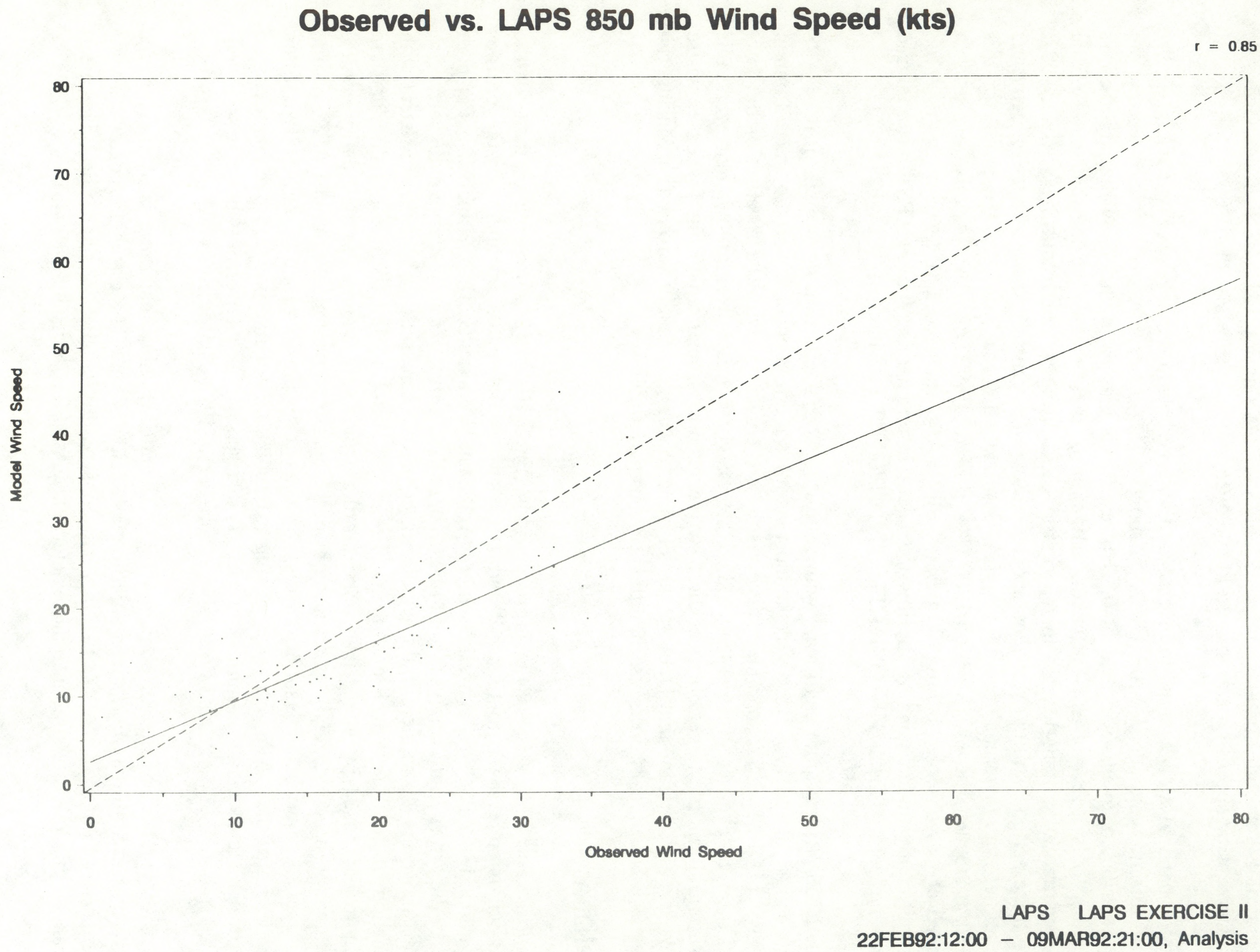

Figure 13. Scatterplot of observed 850 mb wind speed and LAPS analysis for the Colorado domain.

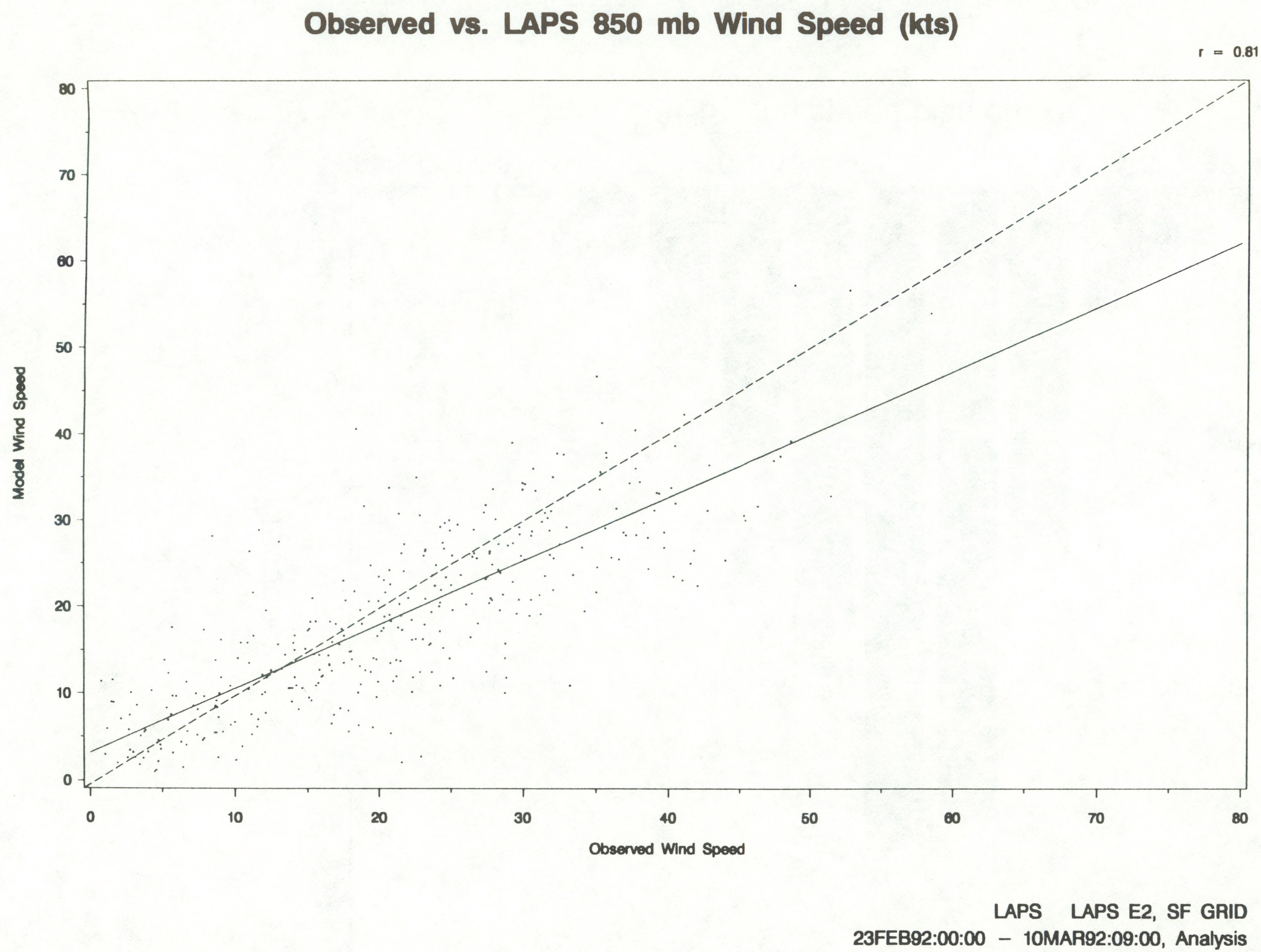

Figure 14. Scatterplot of observed 850 mb wind speed and LAPS analysis for the STORM-FEST domain.

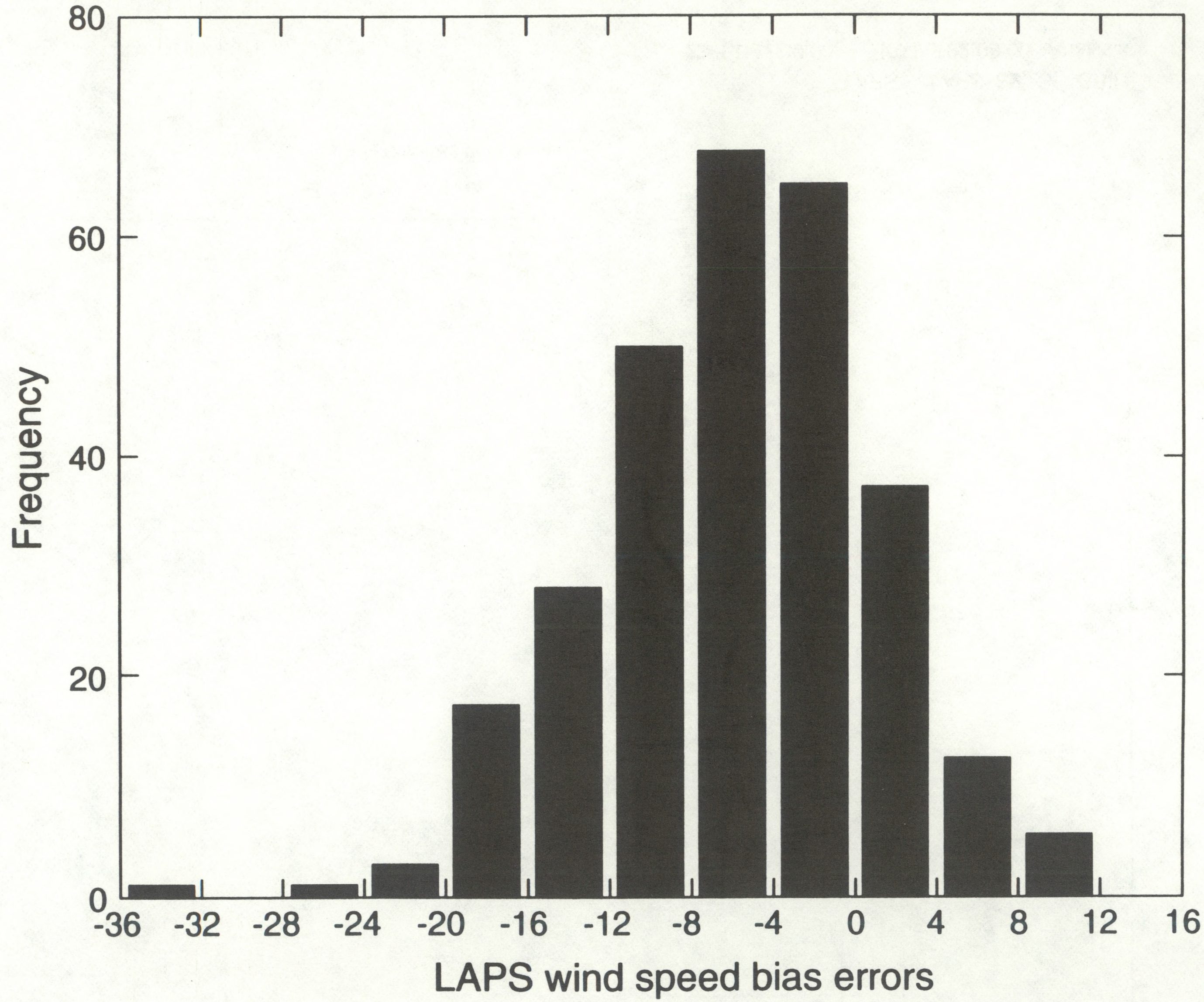

Figure 15. Distribution of 950 mb wind speed bias errors for LAPS analysis for the STORM-FEST domain.

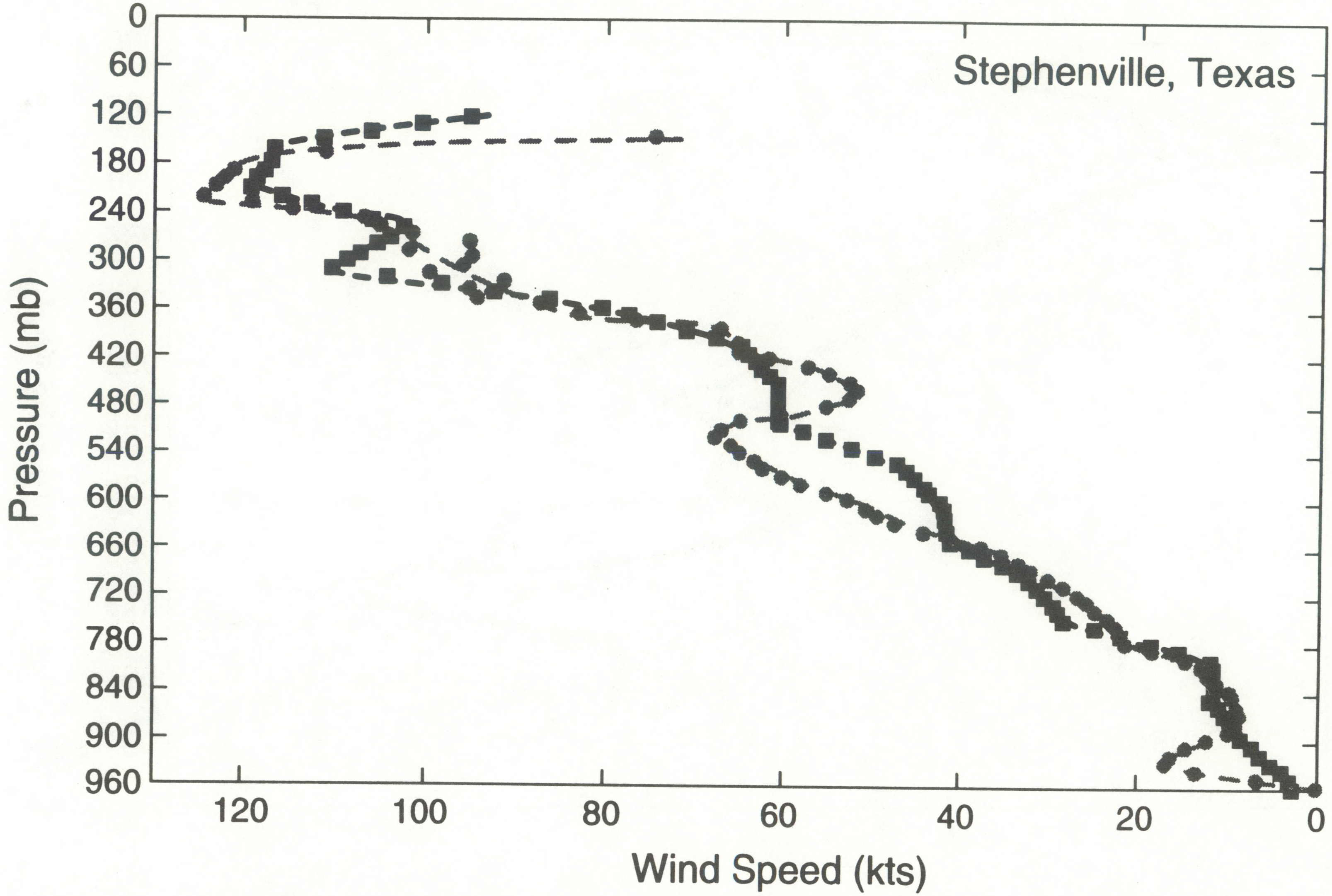

Figure 16. Plot of wind speed for RAOBS (black line) and LAPS (gray line) analysis for Stephenville, TX (SEP), at 1200 UTC 9 March 1992

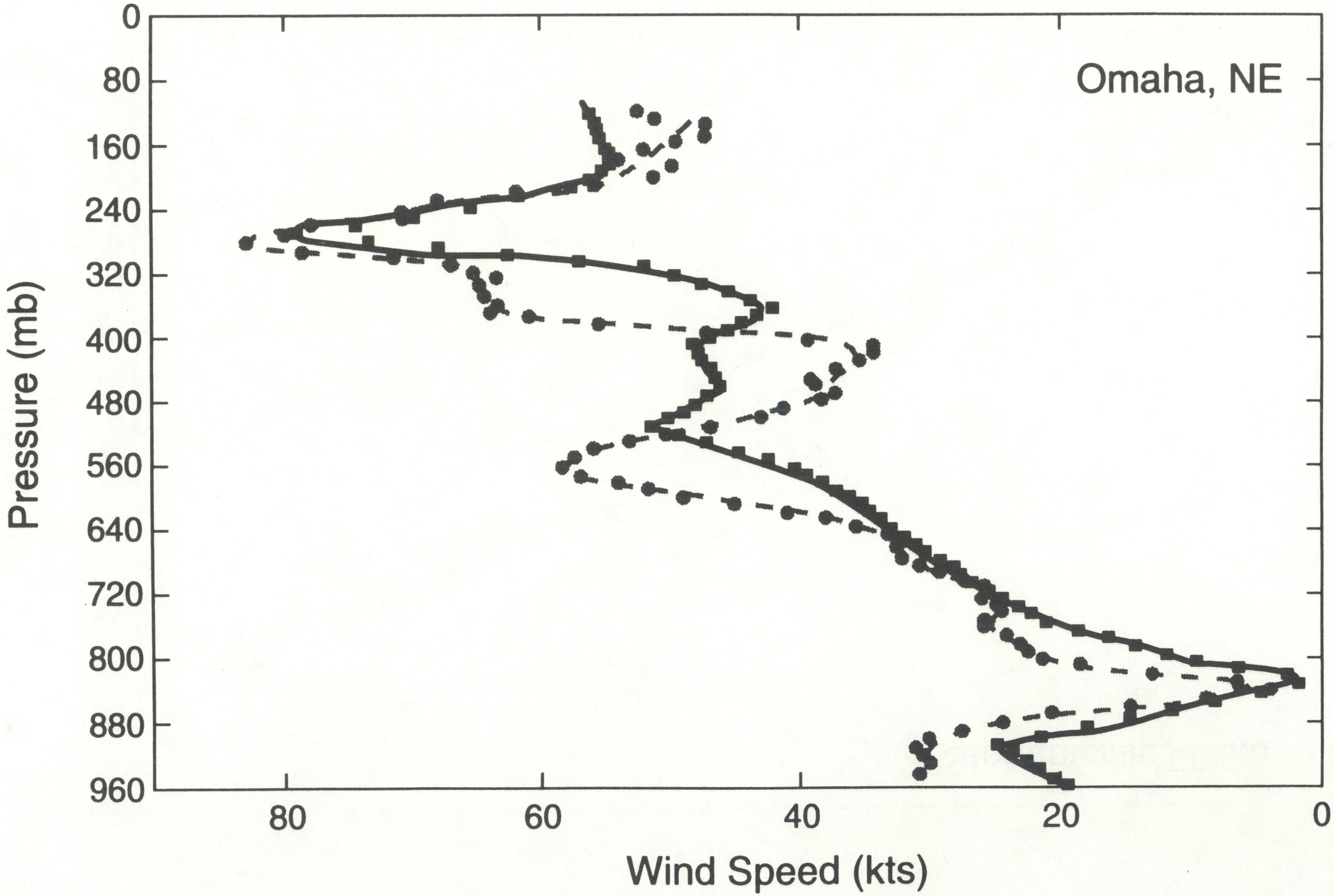

Figure 17. Plot of wind speed for RAOBS (black line) and LAPS (gray line) analysis for Omaha, NE (OVN), at 1200 UTC 9 March 1992.

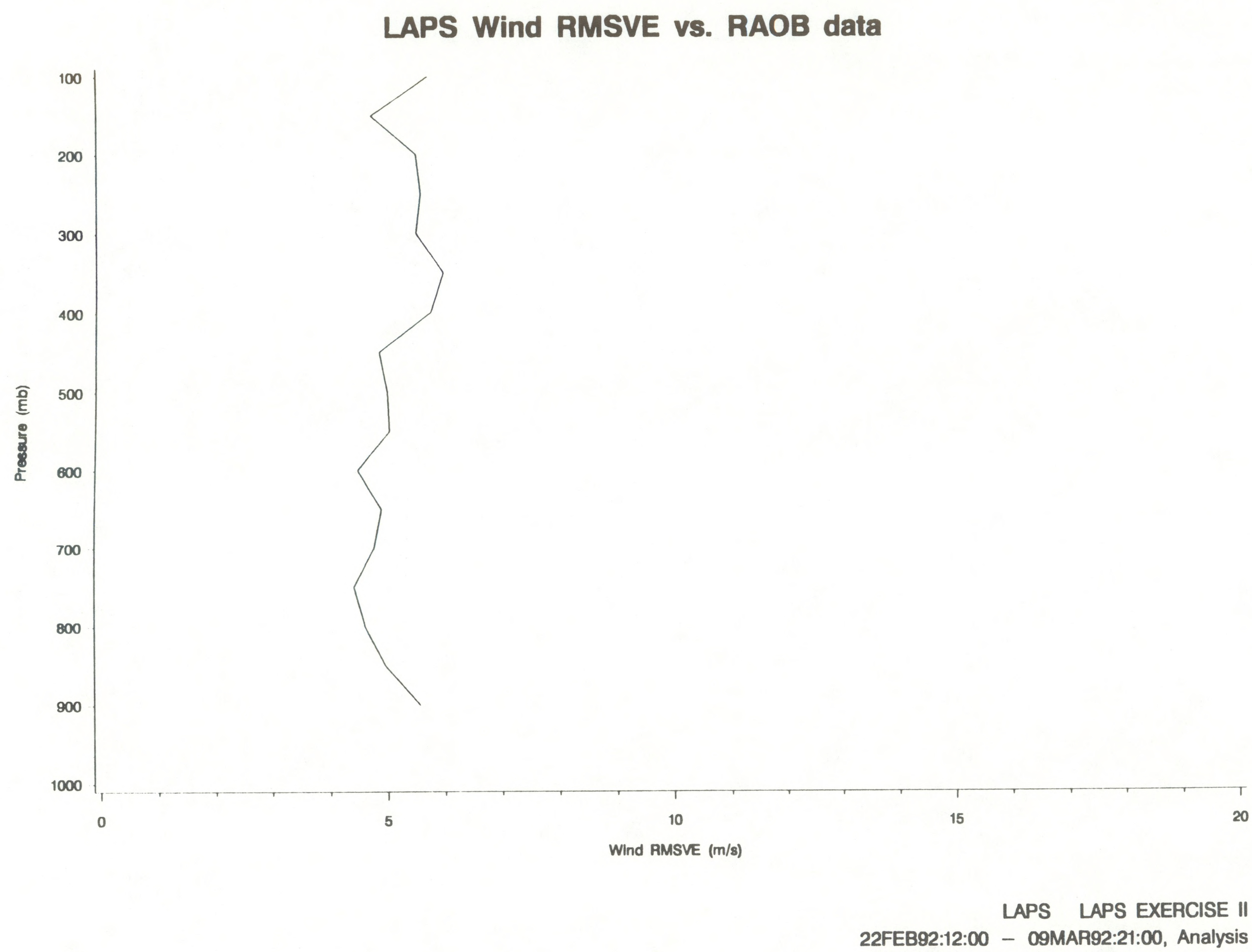

Figure 18. Root mean square vector error (RMSVE) for observations and LAPS analysis of the Colorado domain.

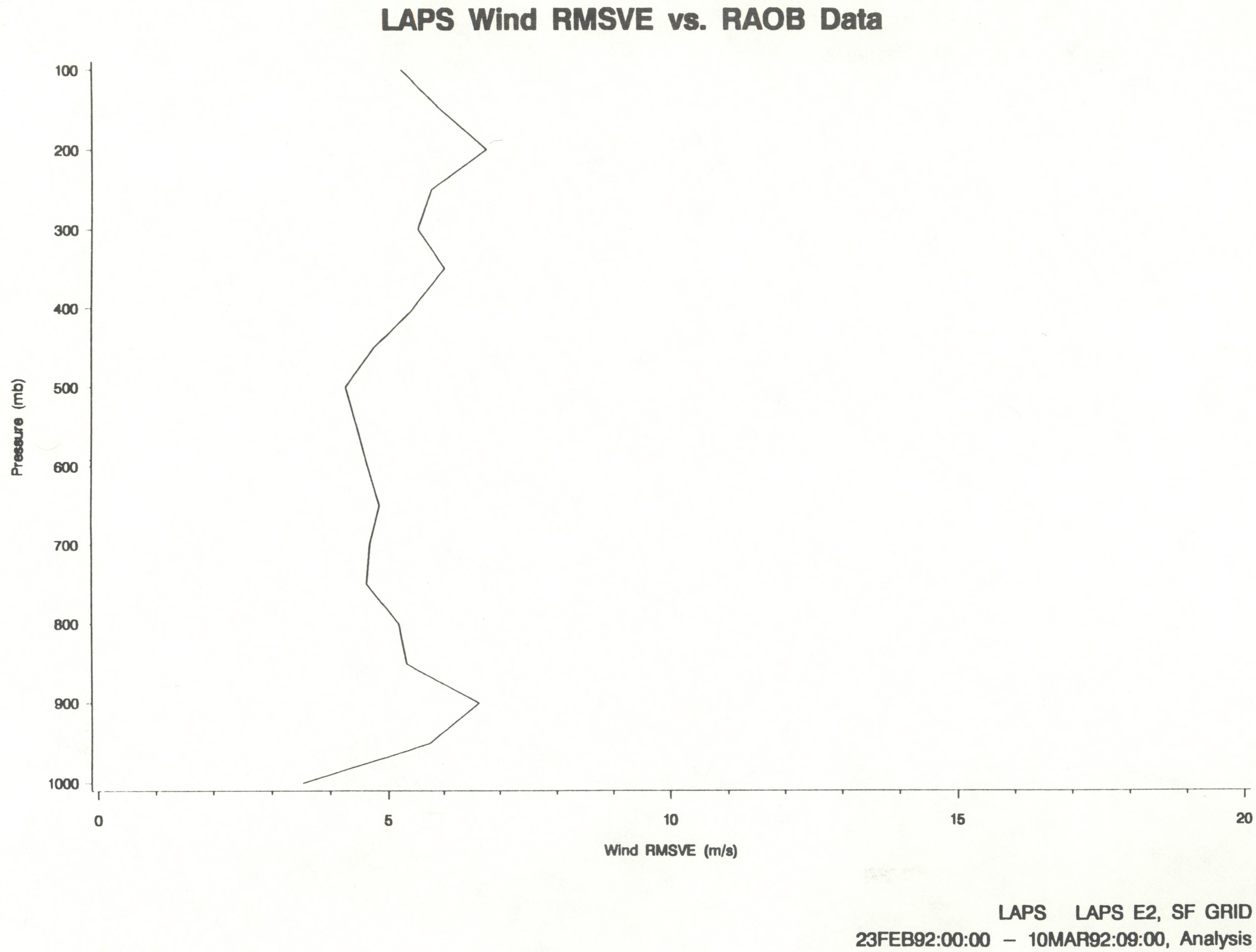

Figure 19. Root mean square vector error (RMSVE) for observations and LAPS analysis of the STORM-FEST domain.

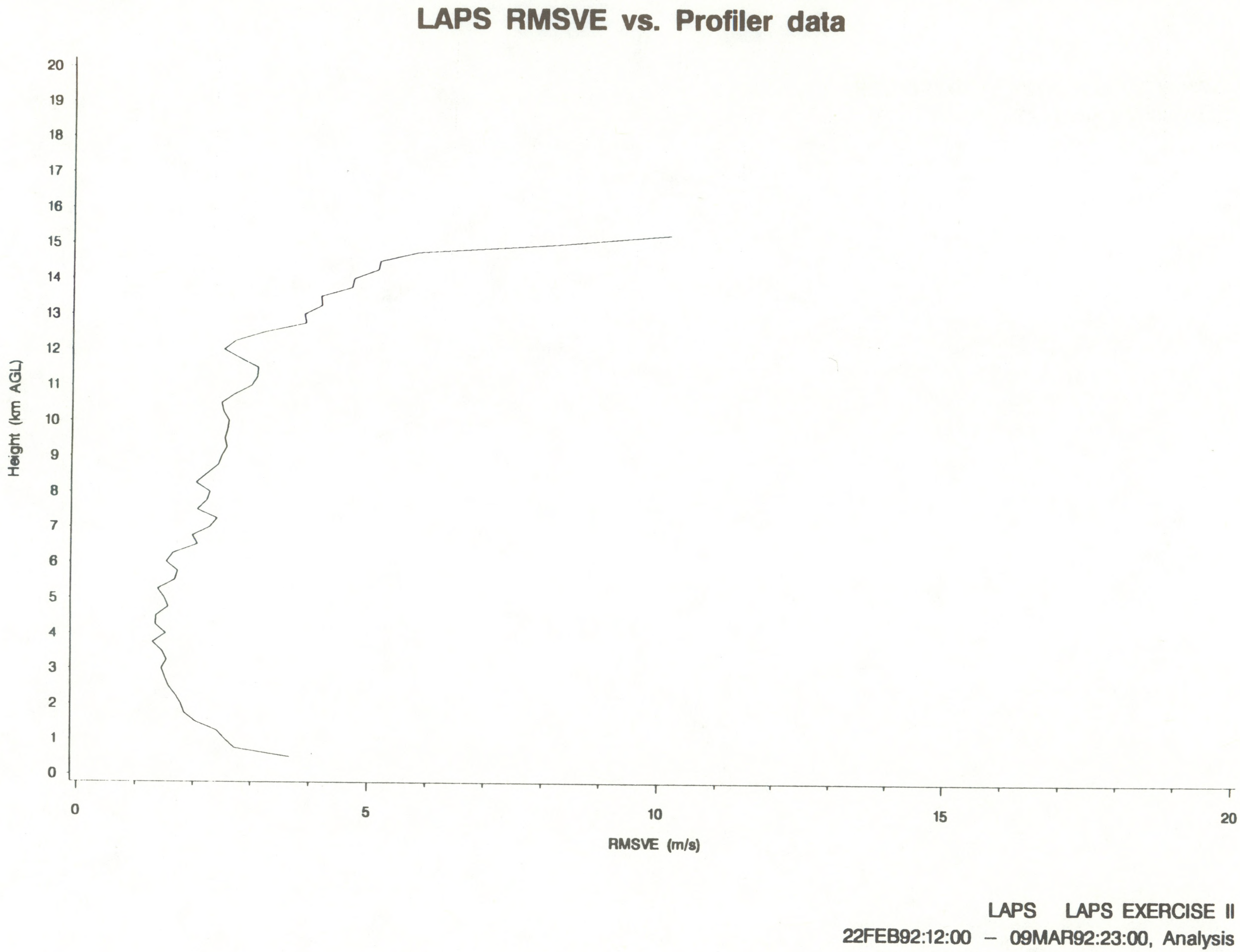

Figure 20. Root mean square vector error (RMSVE) for profiler data and LAPS analysis of the Colorado domain.

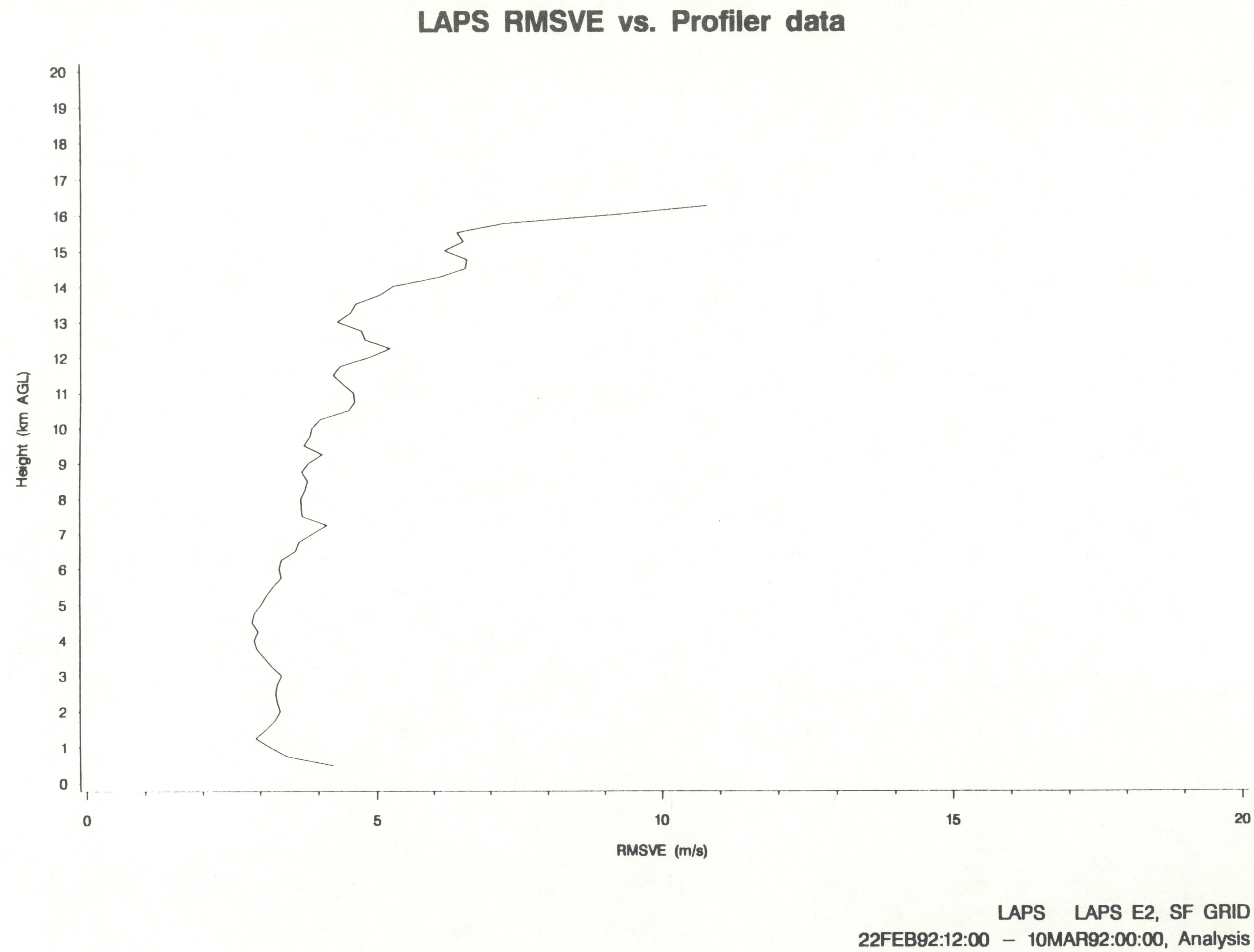

Figure 21. Root mean square vector error (RMSVE) for profiler data and LAPS analysis of the STORM-FEST domain.

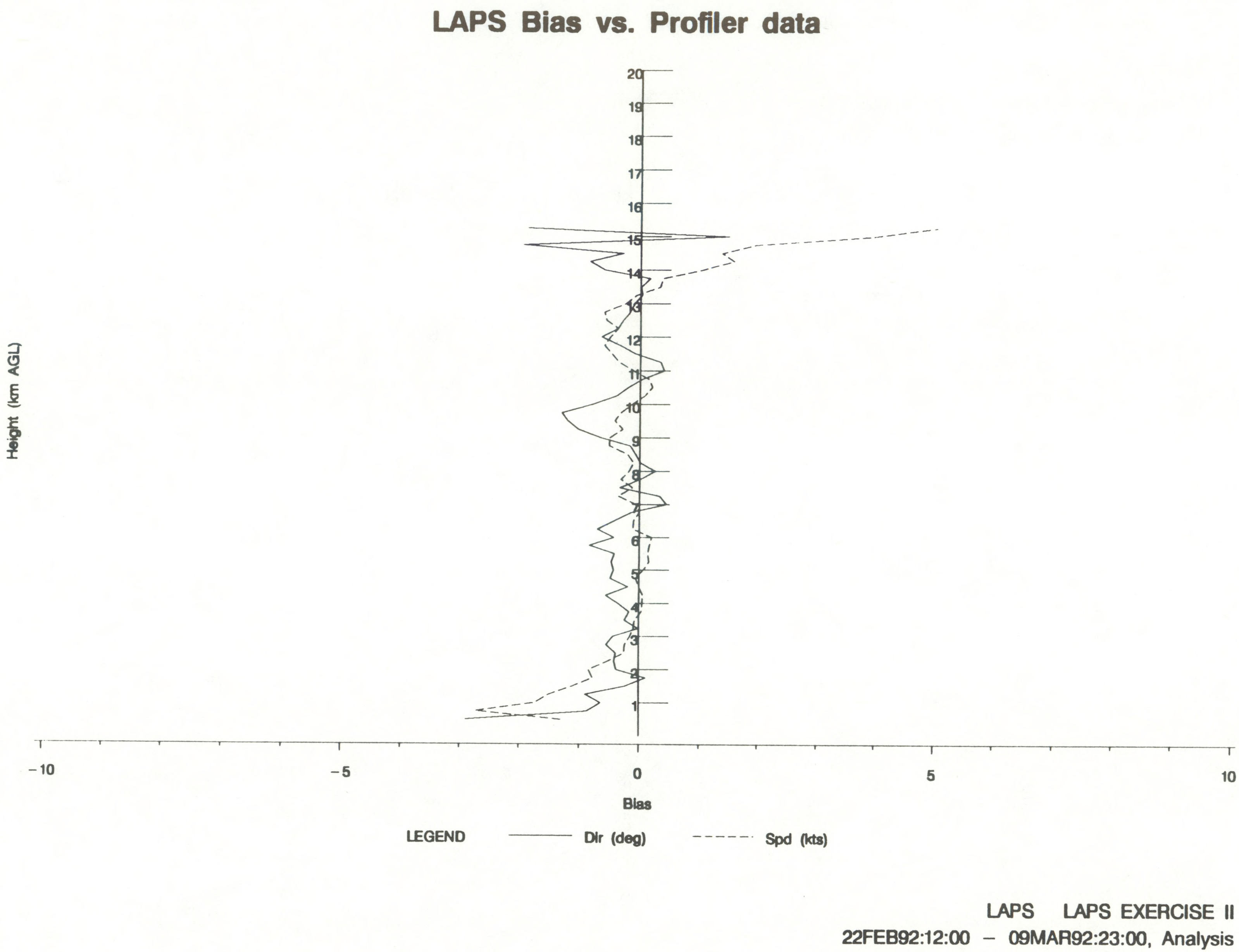

Figure 22. Mean error (bias) of wind direction (deg) and speed (kts) between profiler data and LAPS analysis of the Colorado domain.

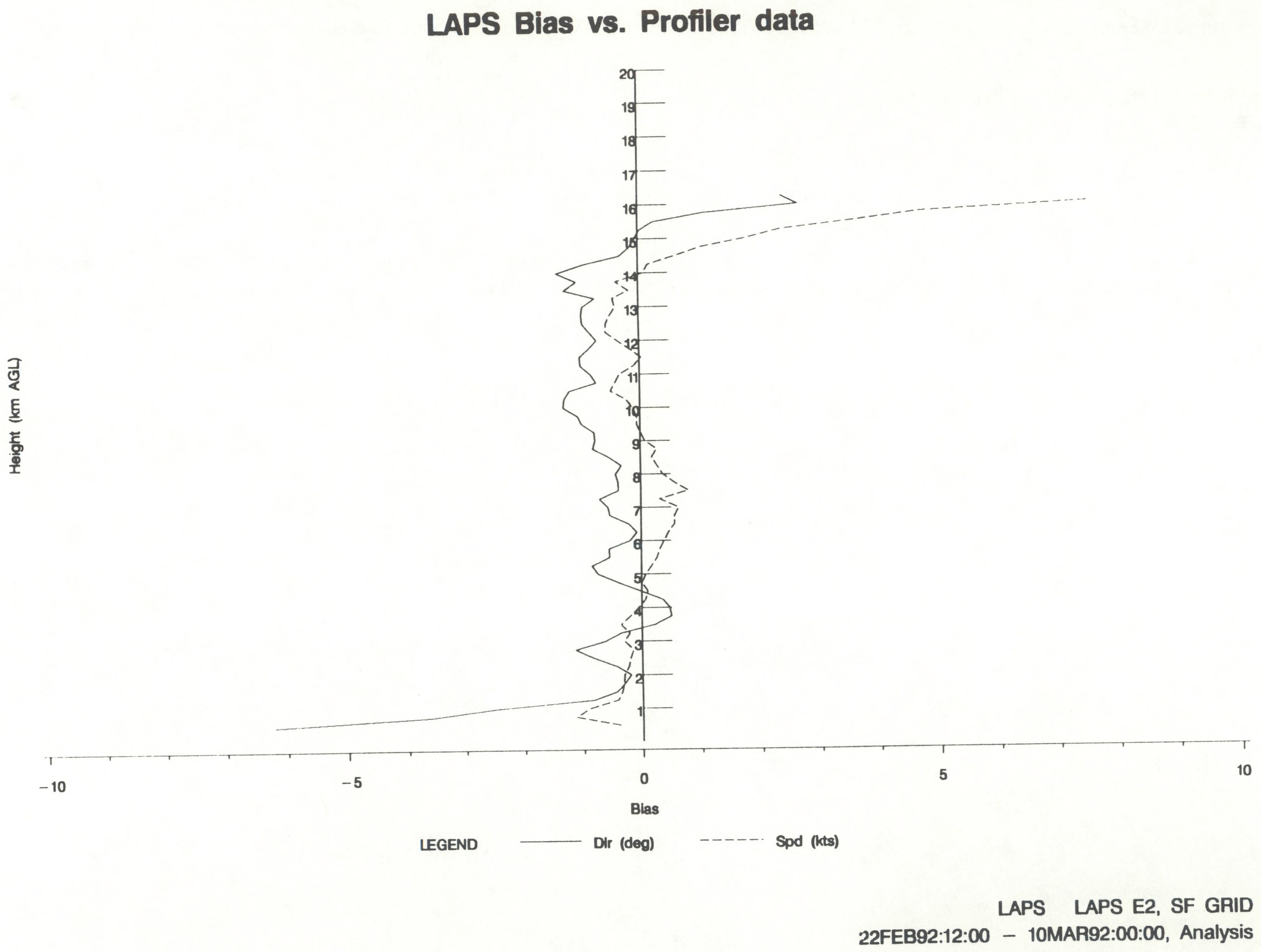

Figure 23. Mean error (bias) of wind direction (deg) and speed (kts) between profiler data and LAPS analysis of the STORM-FEST domain.

5.3 Surface

Note, the surface observations used to verify LAPS results were often included in the LAPS surface analyses. Therefore, the results from the LAPS analyses are not independent of the data used to verify them. Nevertheless, the small statistical errors in many of the results reflect the ability for the LAPS surface analysis system to closely match the observations. Therefore, these analyses (which closely resembles the observed field of data) can then be used to initialize other models.

Altimeter. The altimeter errors for the Colorado and STORM-FEST domains are quite small with MAEs of .02 in and .01 in, respectively. The bias is near zero in both cases (Appendix C).

Temperature. For both domains, LAPS analyzes surface temperatures slightly warmer than the observations for temperatures less than 40° F, while for tempertures greater than 50° F, the analyzed temperatures are somewhat cooler as indicated by the position of the regression line in the scatterplots (Figs. 24 and 25). The overall scatter in this field is very small with a correlation coefficient of 0.98 for both domains. The same results are visible in the box plots (Figs. 26 and 27). The LAPS analysis method uses nearby observations, the previous hour's analysis, satellite data, and the effects of the local terrain to estimate the surface temperature. In some cases, use of the previous hour's grid as the background field may cause the analysis to be too slow to warm (or cool).

Moisture. As seen in the RAOB data, LAPS analysis is slightly too moist for lower observed dewpoints This is evident in both the scatterplots for Colorado and STORM-FEST domains (Figs. 28 and 29).

The LAPS surface relative humidity (RH) distribution compares well with the distribution of observed RH with some visible scatter in the results (Figs. 30 and 31). The scatterplots show interesting behavior when the observed RH exceeds roughly 50%. The amount of scatter increases at that point, particularly in cases where LAPS computes nearly 100% RH. Analysis errors in the Colorado domain are known to be caused, in part, by errors in the FSL mesonet humidity sensors (which are ingested into the LAPS analysis) and by errors introduced by the complicated moisture transformations performed in LAPS. For example, LAPS uses temperature and pressure to get the dewpoint from the mesonet RH and then uses the dewpoint to get the RH for the analysis.

Wind. In general, LAPS underanalyzes the surface wind speed for speeds greater than 5 kt, although the analysis for the STORM-FEST domain was significantly better than that for the Colorado domain. This result is clearly evident in the box plots (Figs. 32 and 33). The strong winds

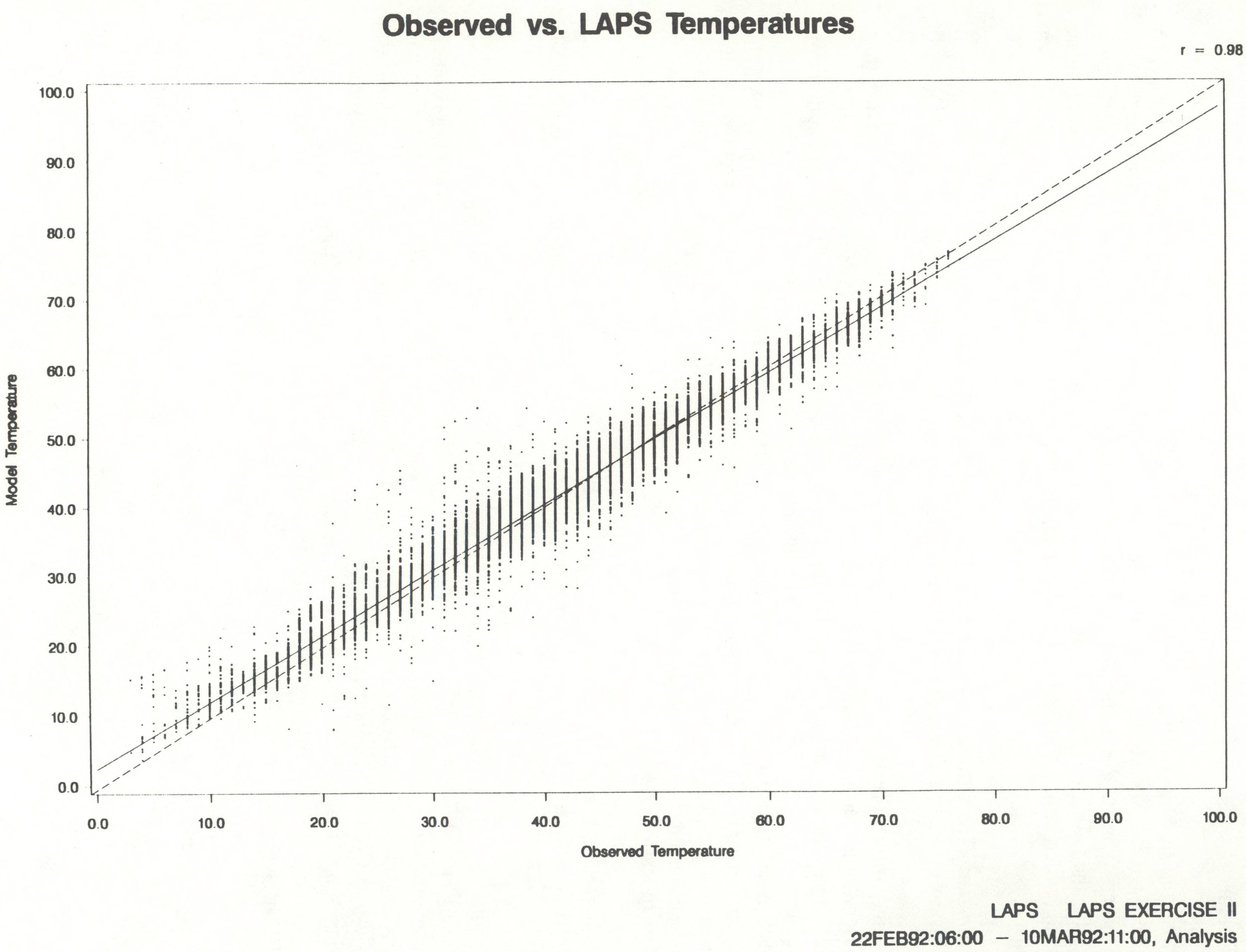

Figure 24. Scatterplot of observed temperature (F) versus LAPS analysis of the Colorado domain temperature.

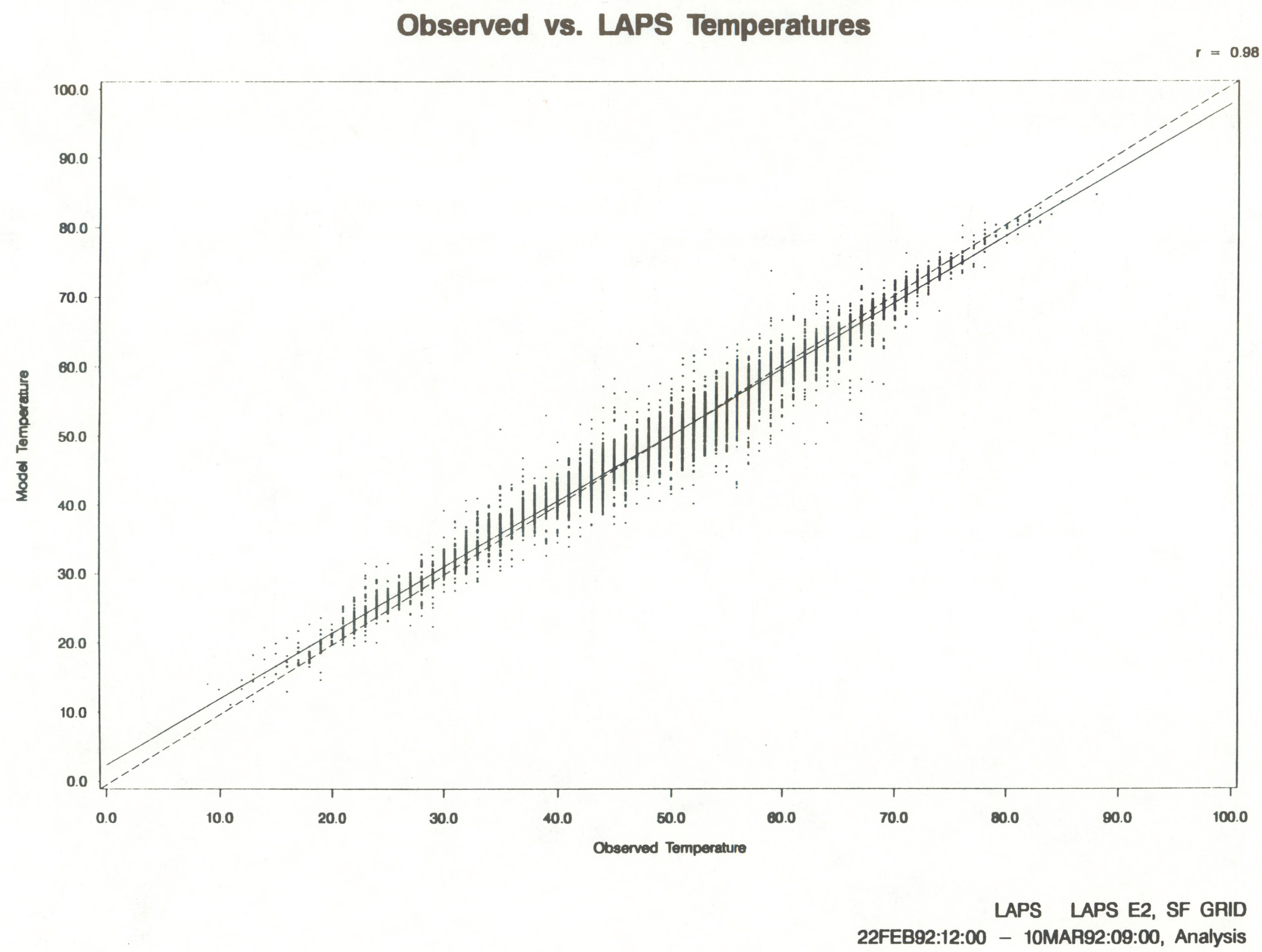

Figure 25. Scatterplot of observed temperature (F) versus LAPS analysis of the STORM-FEST domain temperature.

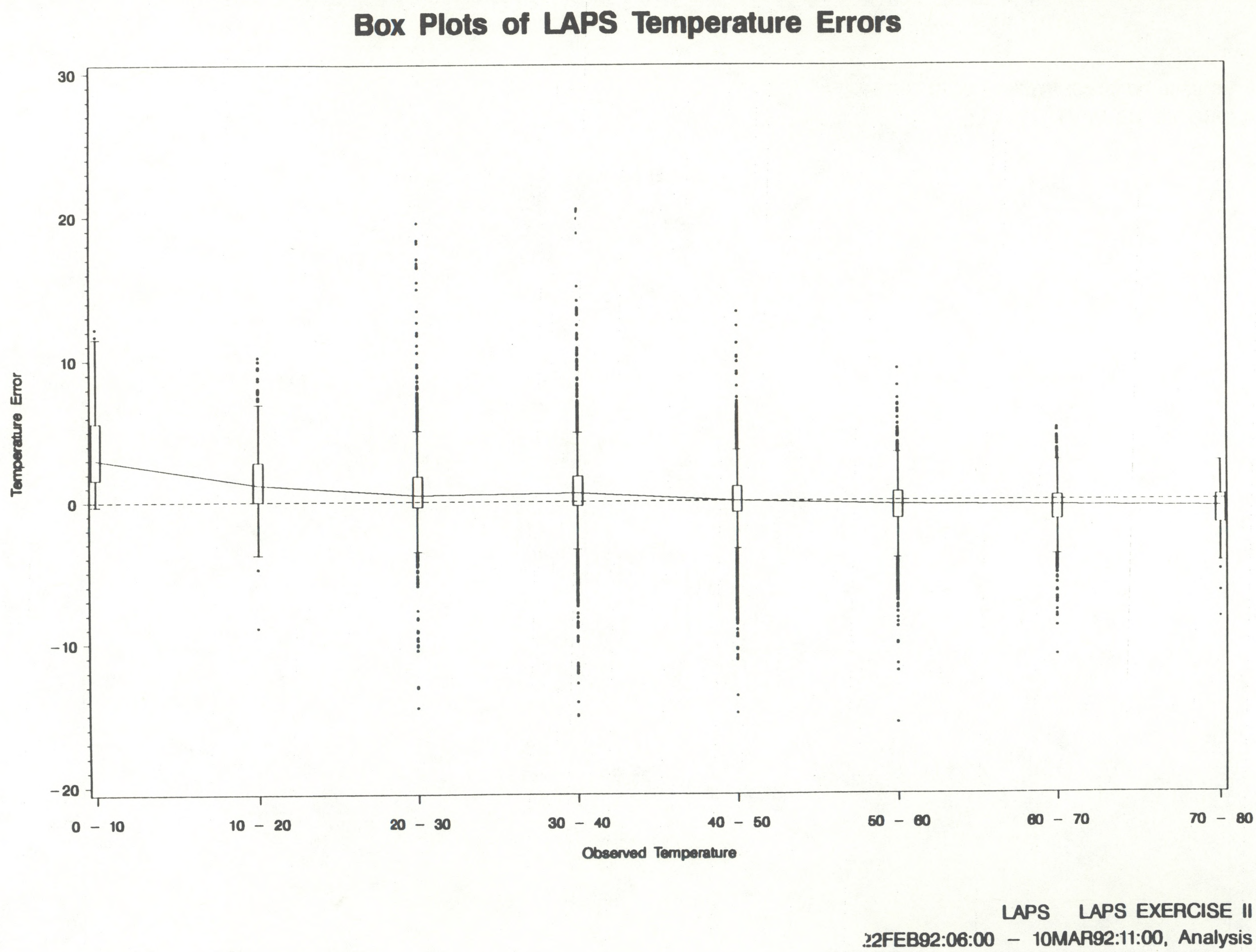

Figure 26. Box plots of observed temperature (F) versus LAPS analysis of the Colorado domain temperature errors.

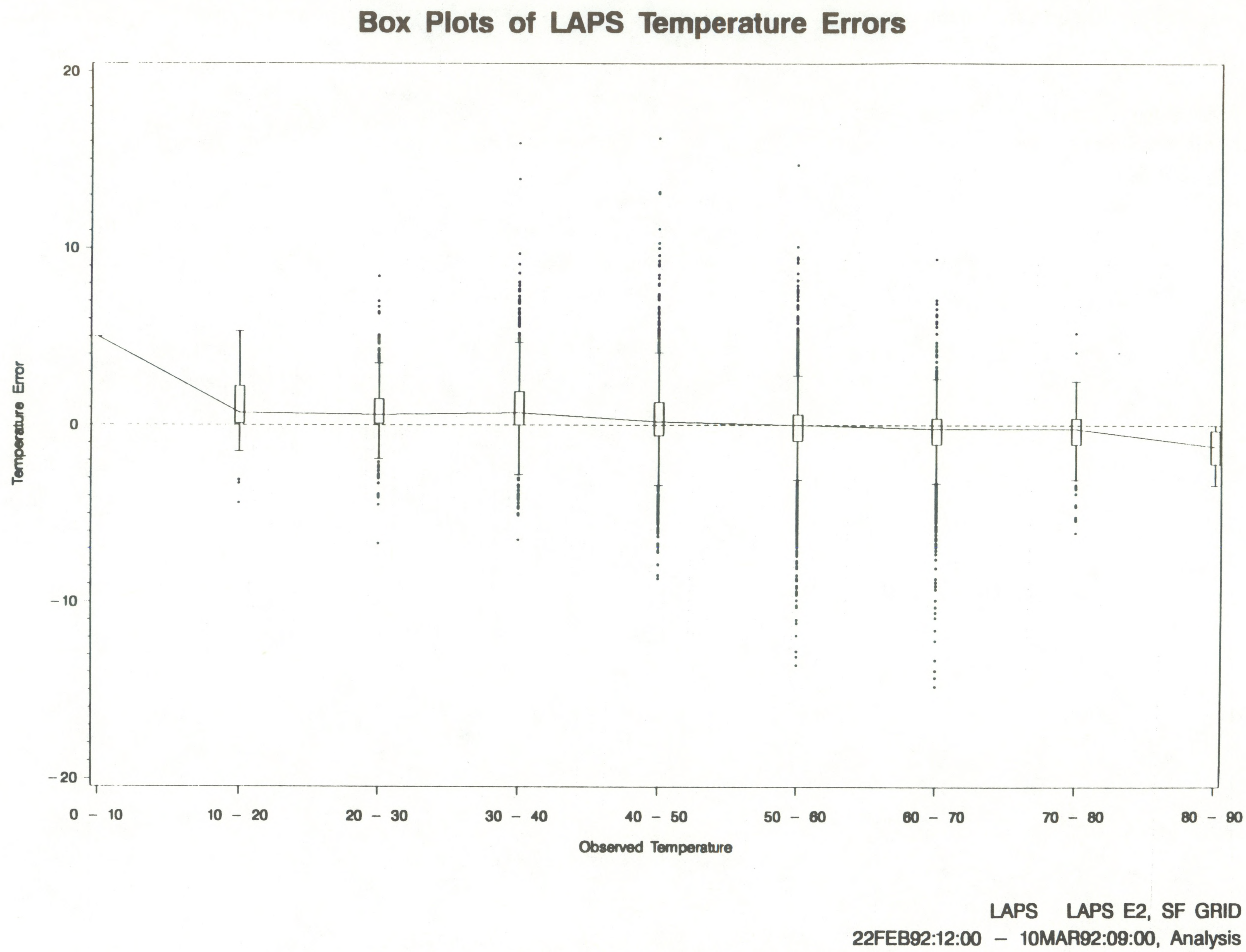

Figure 27. Box plots of observed temperature (F) versus LAPS analysis of the STORM-FEST domain temperature errors.

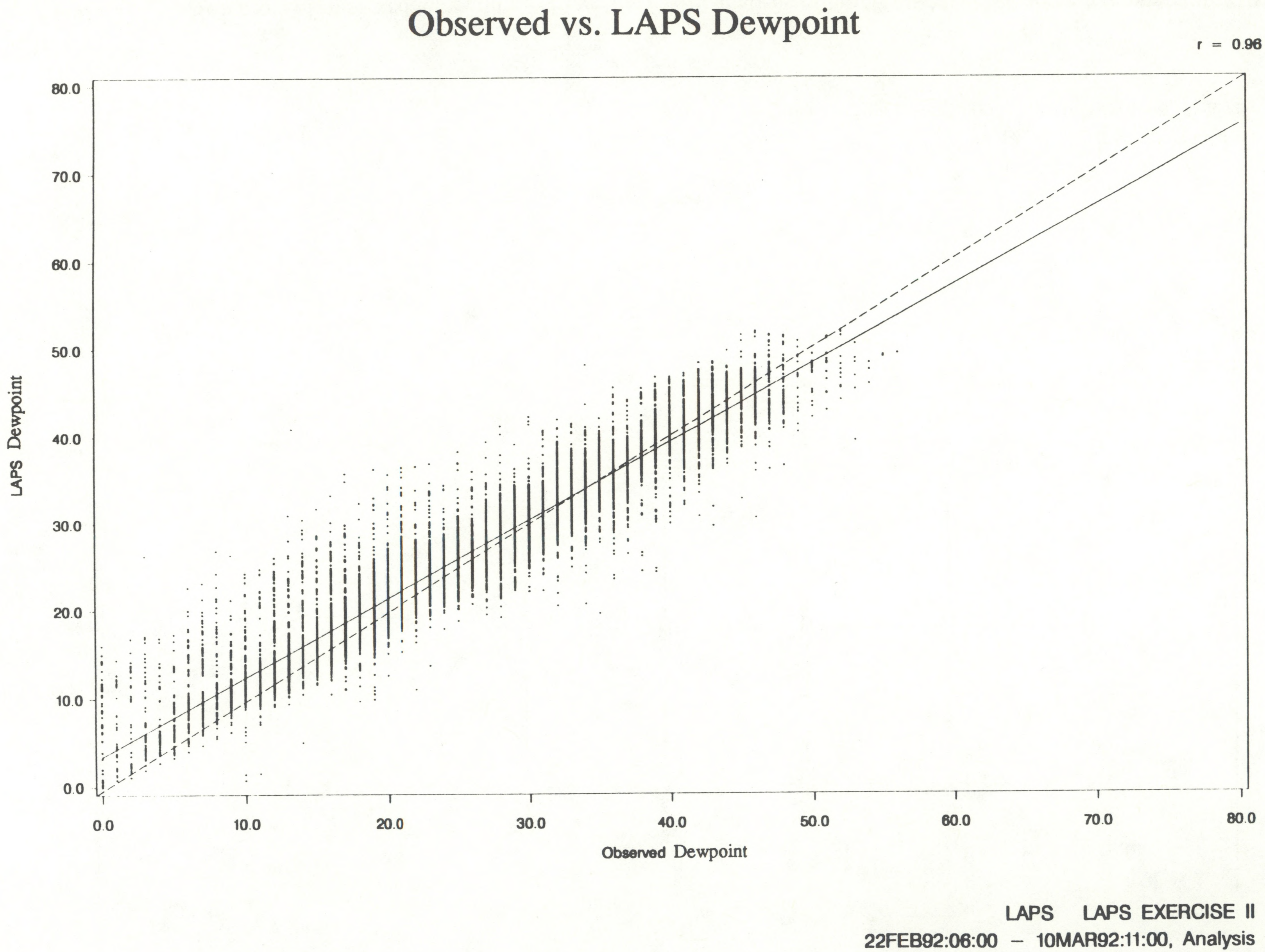

Figure 28. Scatterplot of observed dewpoint (F) versus LAPS analysis of the Colorado domain dewpoint.

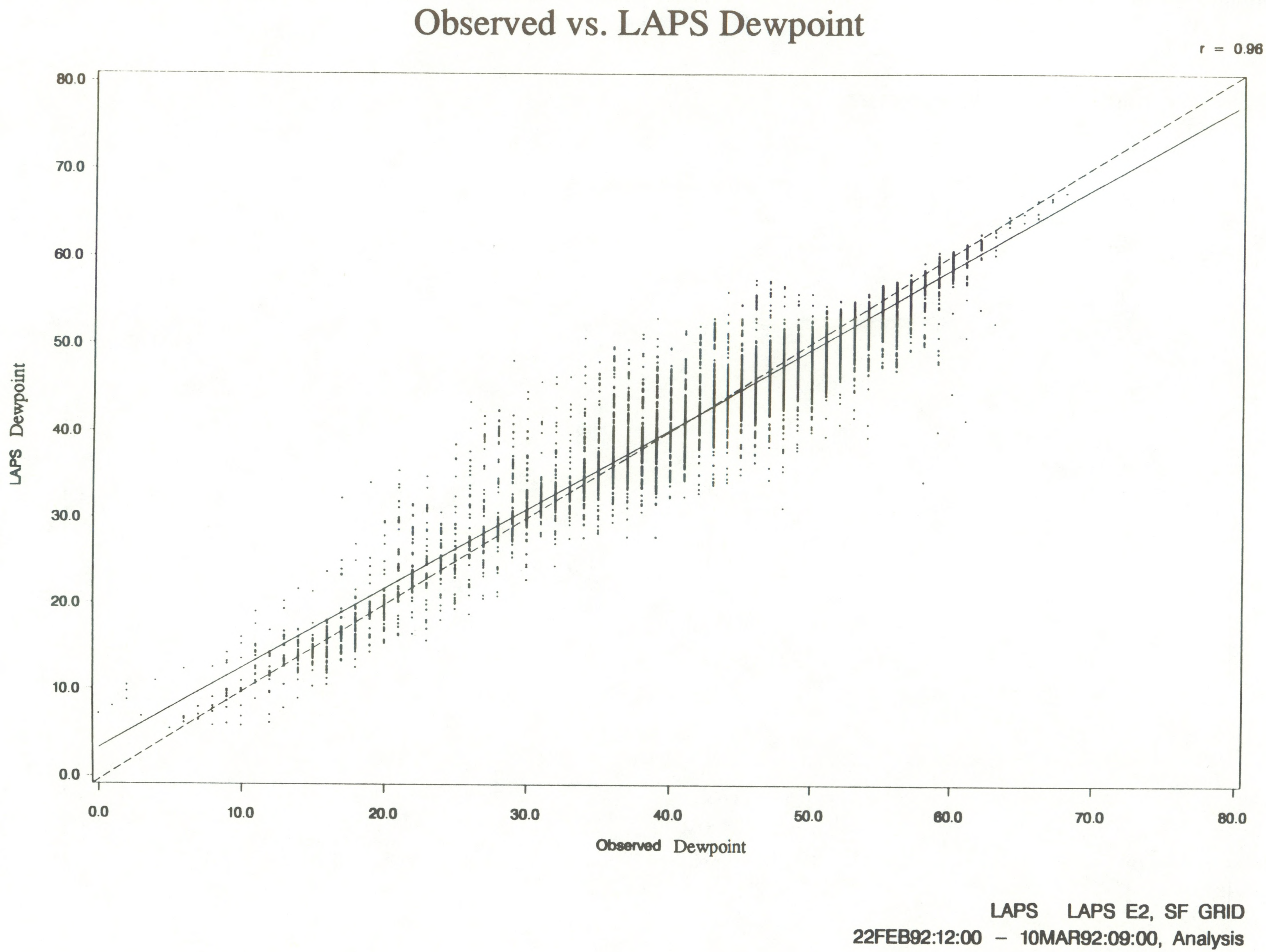

Figure 29. Scatterplot of observed dewpoint (F) versus LAPS analysis of the STORM-FEST domain dewpoint.

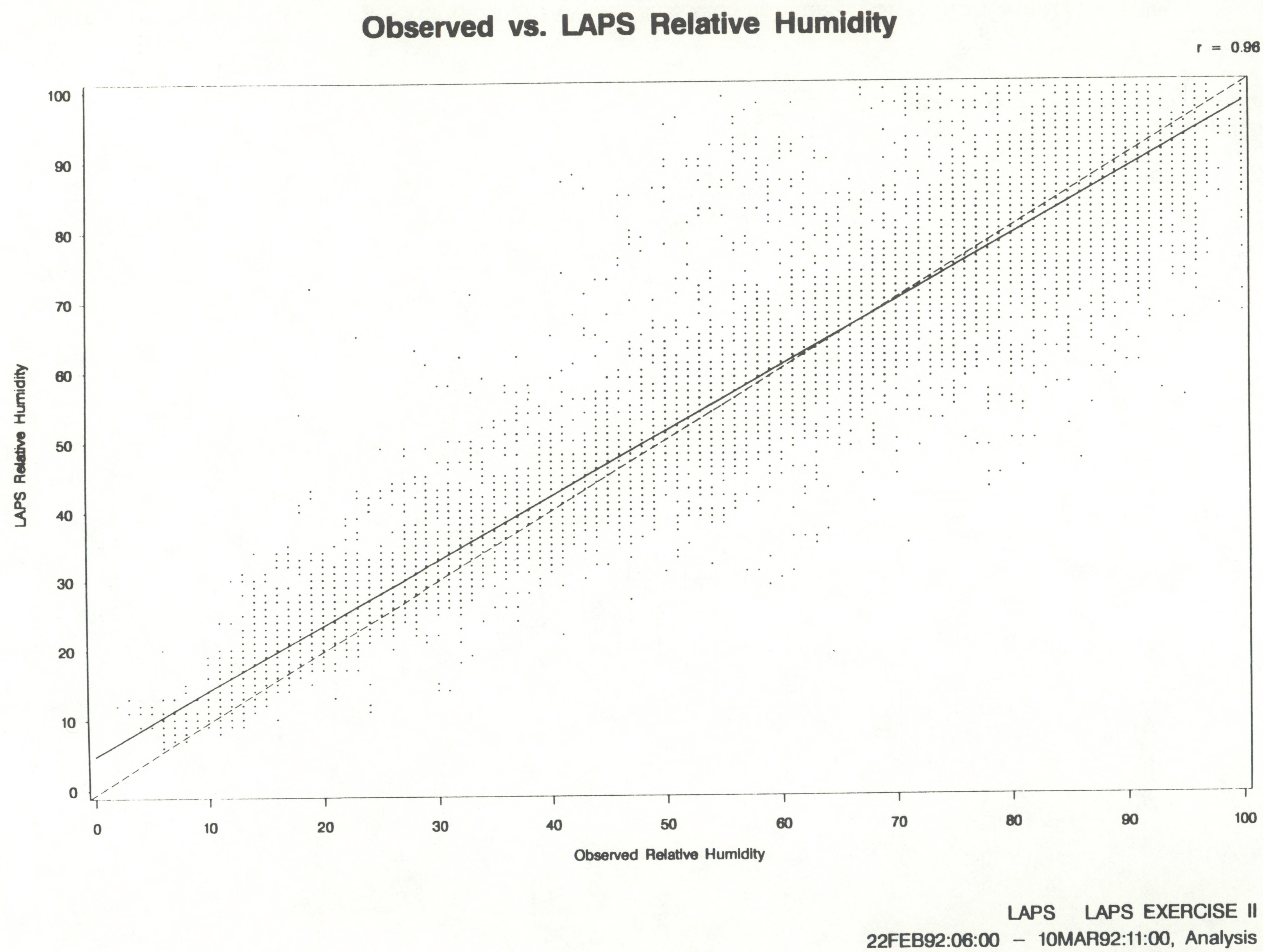

Figure 30. Scatterplot of observed relative humidity (%) versus LAPS analysis of the Colorado domain relative humidity.

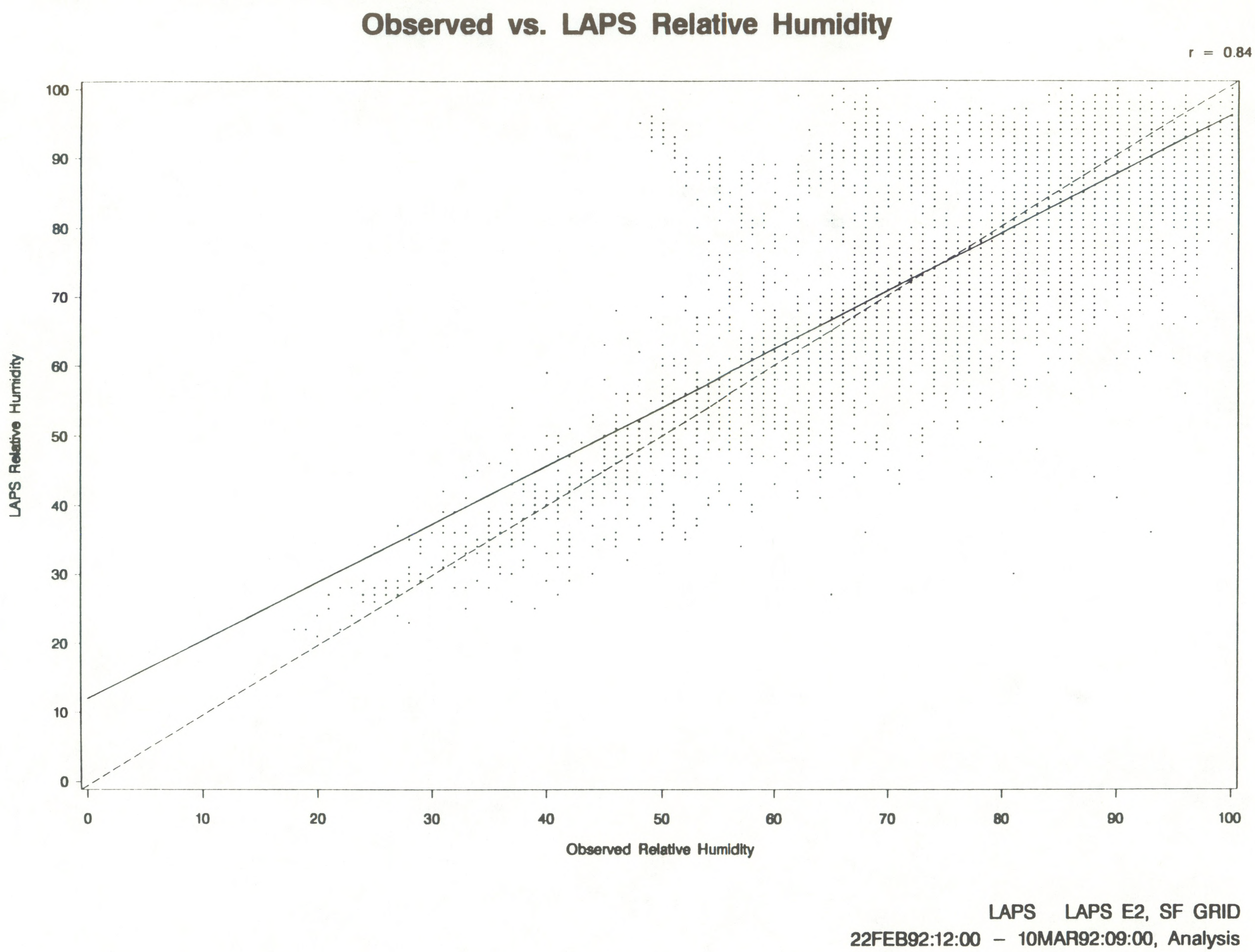

Figure 31. Scatterplot of observed relative humidity (%) versus LAPS analysis of the STORM-FEST domain relative humidity.

Box Plots of LAPS Wind Speed Errors

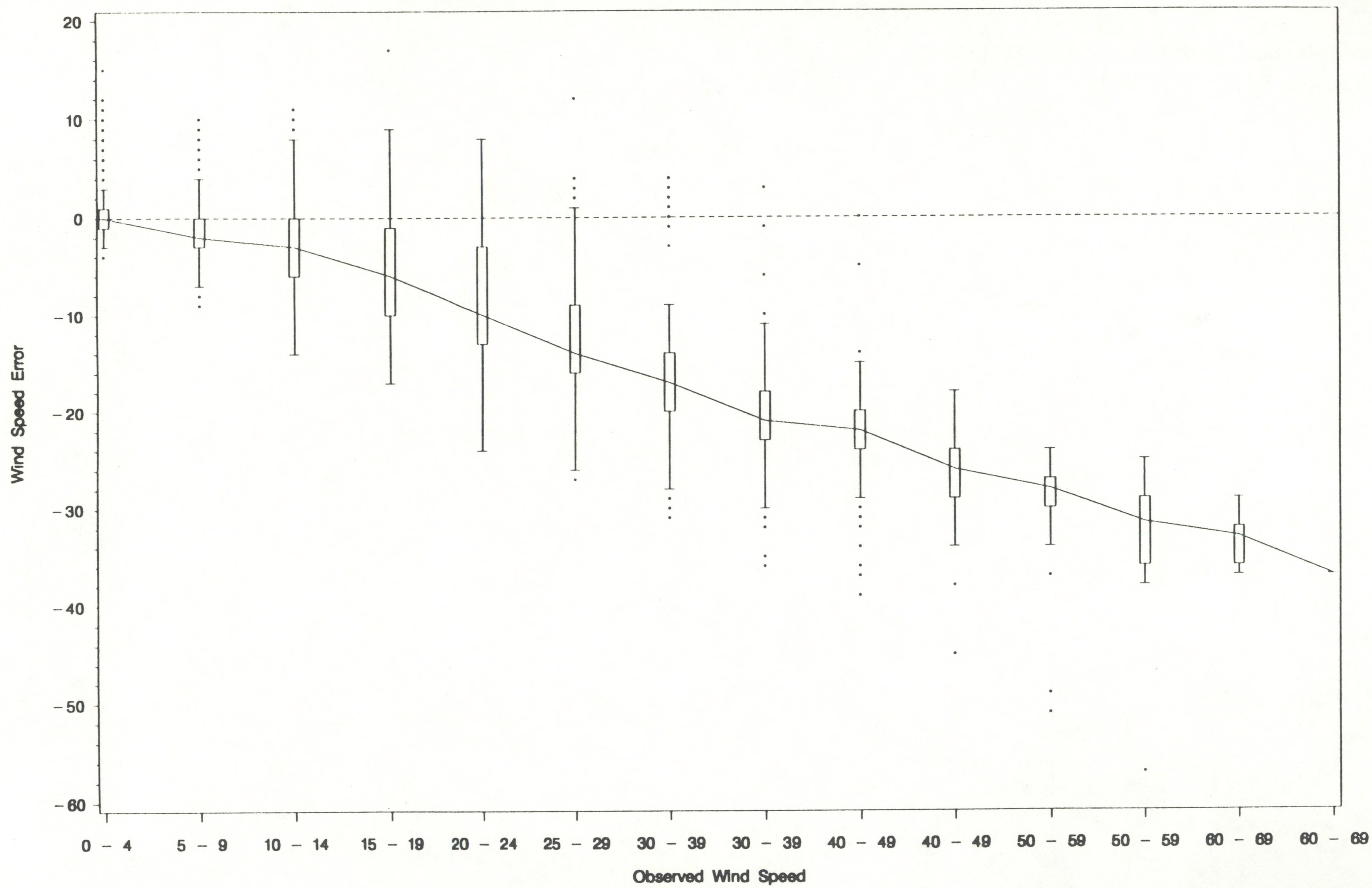

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Figure 32. Box plots of observed wind speed (kts) versus LAPS analysis of the Colorado domain wind speed errors.

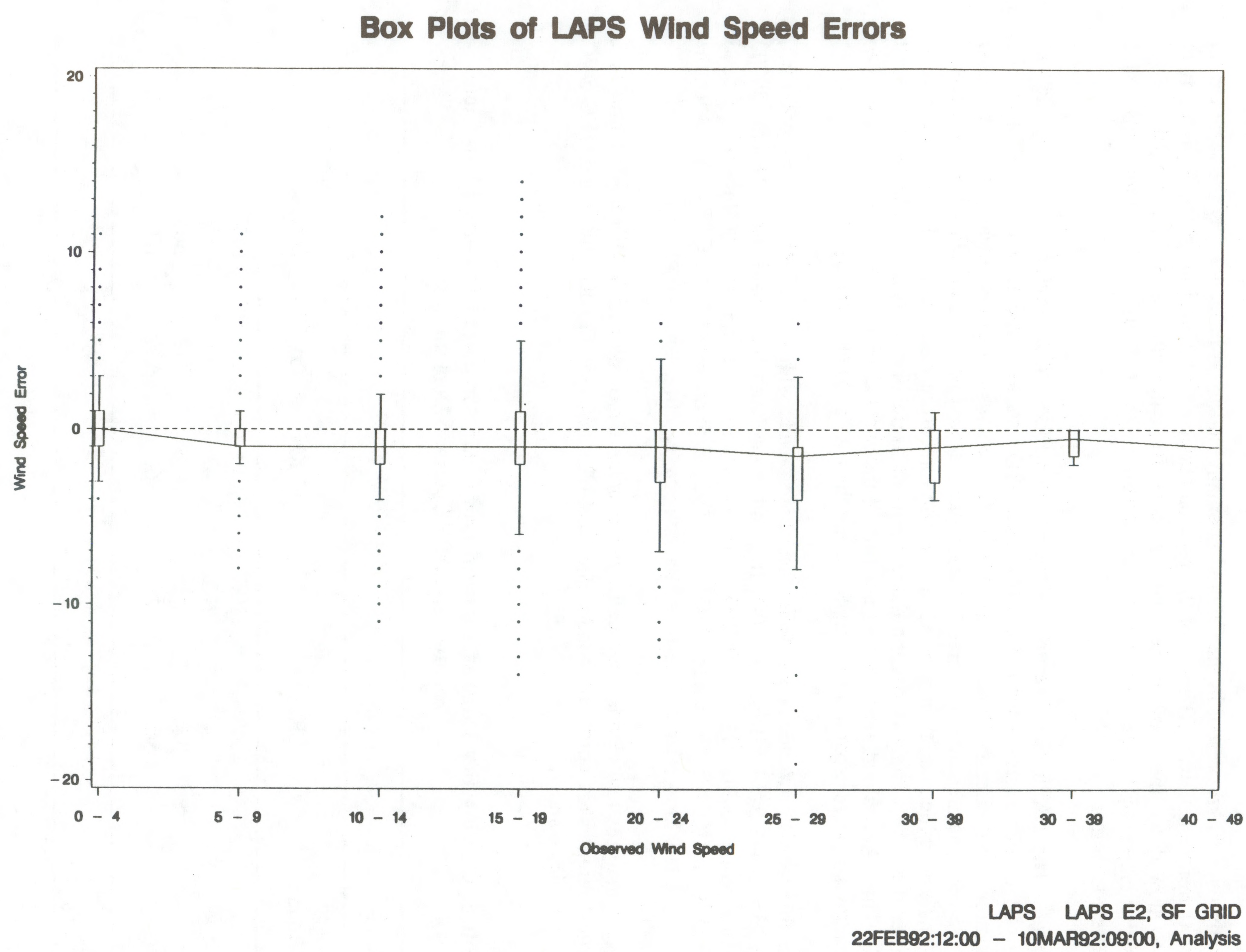

Figure 33. Box plots of observed wind speed (kts) versus LAPS analysis of the STORM-FEST domain wind speed errors.

(generally over 40 kt) present in the Colorado domain tend to be influenced by the local terrain and are therefore isolated. The use of the previous hour's LAPS grid as the background field tends to slow down the wind in the analysis as do frictional effects. In addition, the LAPS analysis attempts to balance the wind and pressure field (Albers 1992), which may also introduce some error.

Cloud. The LAPS cloud results reflect the integration of several data sources, such as hourly surface observations from the SAOs and ASOS stations, radar, and satellite data, and observations from aircraft (Albers et al. 1994). The analysis may not always favor the SAO when the other data sources disagree. These data are used to diagnose clouds and produce a LAPS analysis, which can then be used to initialize forecast models, such as RAMS. Therefore, the better the LAPS analysis fits the data, the more useful the analysis will be to a forecast model. The LAPS cloud analysis was not part of the surface analysis system in this exercise; verification data were produced by postprocessing the LAPS 3D cloud analysis.

For this report, low clouds are defined as those clouds with a base below 2 km (6500 ft.), middle clouds are 2-6 km (6500 - 20000 ft.), and high clouds have bases above 6 km (20000 ft.). For cloud amounts: 1) clear (CLR) < 0.1 cloud cover; 2) scattered (SCT) = 0.1 - 0.5; 3) broken (BKN) = 0.6 - 0.9; 4) overcast (OVC) > 0.9; and 5) obscured (X or OBSCD) is when the sky is completely hidden by surface-based phenomena (e.g. fog, rain, snow).

LAPS analyzes low clouds very well. For both the Colorado and STORM-FEST domains, the largest samples are correctly found in the CLR-CLR, SCT-SCT, BKN-BKN and OVC-OVC boxes in Tables 6 and 7.

Table 6. Contingency Table of Analyzed Low Cloud Amount by Observed Low Cloud Amount for LAPS Colorado Domain

	Observed Low Clouds				
Diagnosed Low Clouds	CLR	SCT	BKN	OVC	Total
CLR	**1300**	106	10	1	1417
SCT	25	**203**	47	17	292
BKN	32	82	**198**	249	561
OVC	56	28	60	**529**	673
Total	1413	419	315	796	2943

Table 7. Contingency Table of Analyzed Low Cloud Amount by Observed Low Cloud Amount for LAPS STORM-FEST Domain

Diagnosed Low Clouds	Observed Low Clouds: CLR	SCT	BKN	OVC	Total
CLR	**703**	89	15	26	833
SCT	20	**250**	38	4	312
BKN	33	106	**288**	284	711
OVC	81	59	110	**723**	973
Total	837	504	451	1037	2829

However, when a BKN layer of clouds was observed, LAPS analyzed 110 (24%) of the 451 cases as OVC in the STORM-FEST domain. On the other hand, in the Colorado domain, LAPS analyzed 249 (30%) of the 796 OVC cloud layers as BKN cloud layers. These results suggest that LAPS has some difficulty distinguishing between BKN and OVC cloud layers.

When low, middle and high clouds were considered together, LAPS did an excellent job analyzing the CLR-CLR and OVC-OVC cloud categories, as shown in Figs. 34 and 35. LAPS analyzed 80% of the CLR-CLR and 66% of the OVC-OVC correctly for the Colorado domain and 71% and 80% respectively for the STORM-FEST domain. However, LAPS still has some problems discerning between middle categories, such as SCT and BKN cloud layers.

Ceiling and visibility were verified according to the standard categories used in aircraft operations (Table 8).

Table 8. Ceiling and Visibility Categories

Flight Rules	Ceiling (ft.)	Visibility (mi)
Visual Flight Rules (VFR)	$3000 \leq cig$	$5 < vis$
Marginal Visual Flight Rules (MVFR)	$1000 \leq cig < 3000$	$3 \leq vis \leq 5$
Instrument Flight Rules (IFR)	$500 \leq cig < 1000$	$1 \leq vis < 3$
Low Instrument Flight Rules (LIFR)	$500 > cig$	$1 > vis$

LAPS has a good diagnosis of the ceiling height in the analysis data, with a small bias and near-zero log score (Appendix C). The probability of detection (POD) for IFR ceilings in the operation domain was 56% and 68% for the STORM-FEST domain. It is apparent from the scatterplots (Figs. 36 and 37) that LAPS produces a ceiling height analysis that is too high for low ceilings and too low for high ceilings. The coarse vertical resolution is suspected to

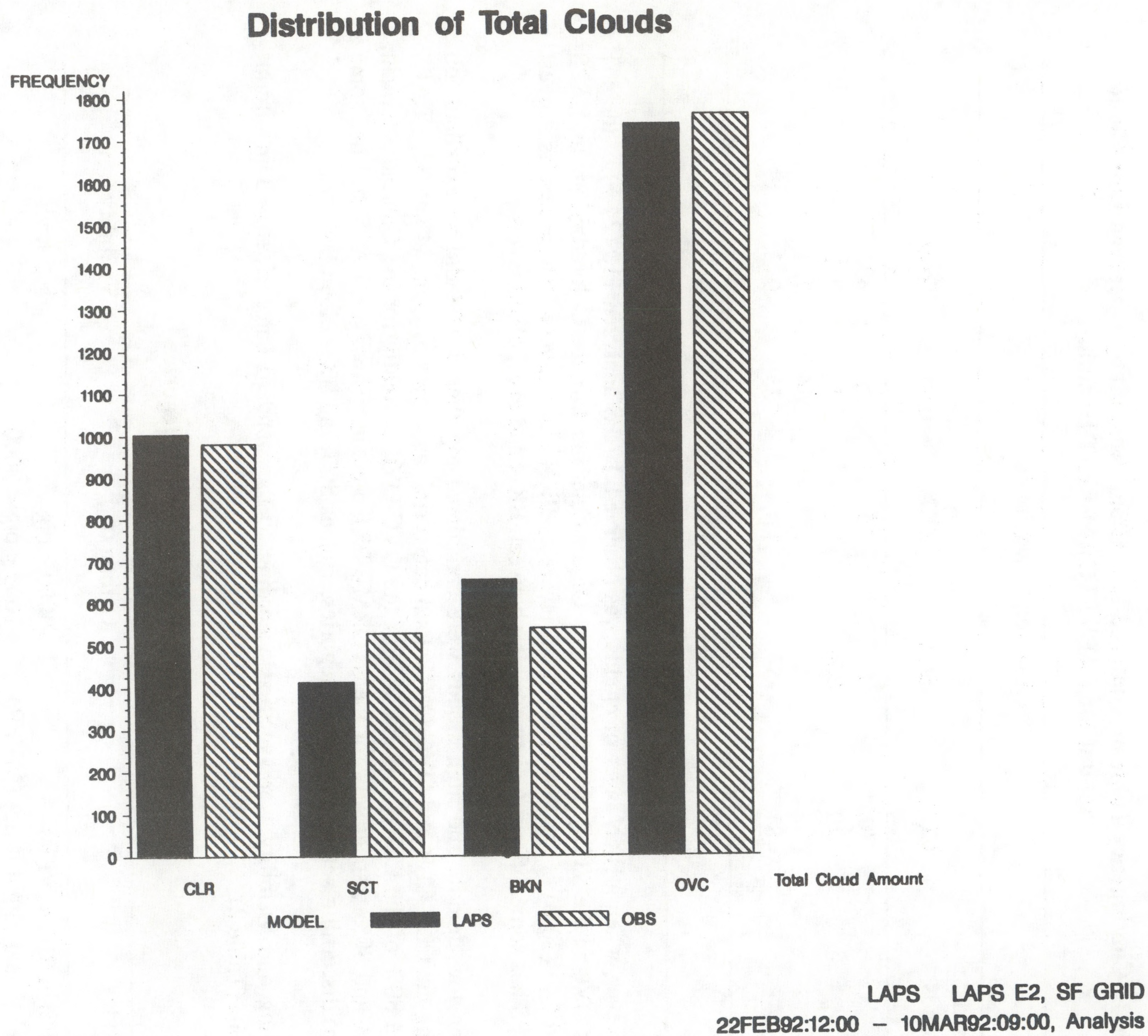

Figure 34. Distribution of observed total clouds versus LAPS analysis of the Colorado domain total clouds.

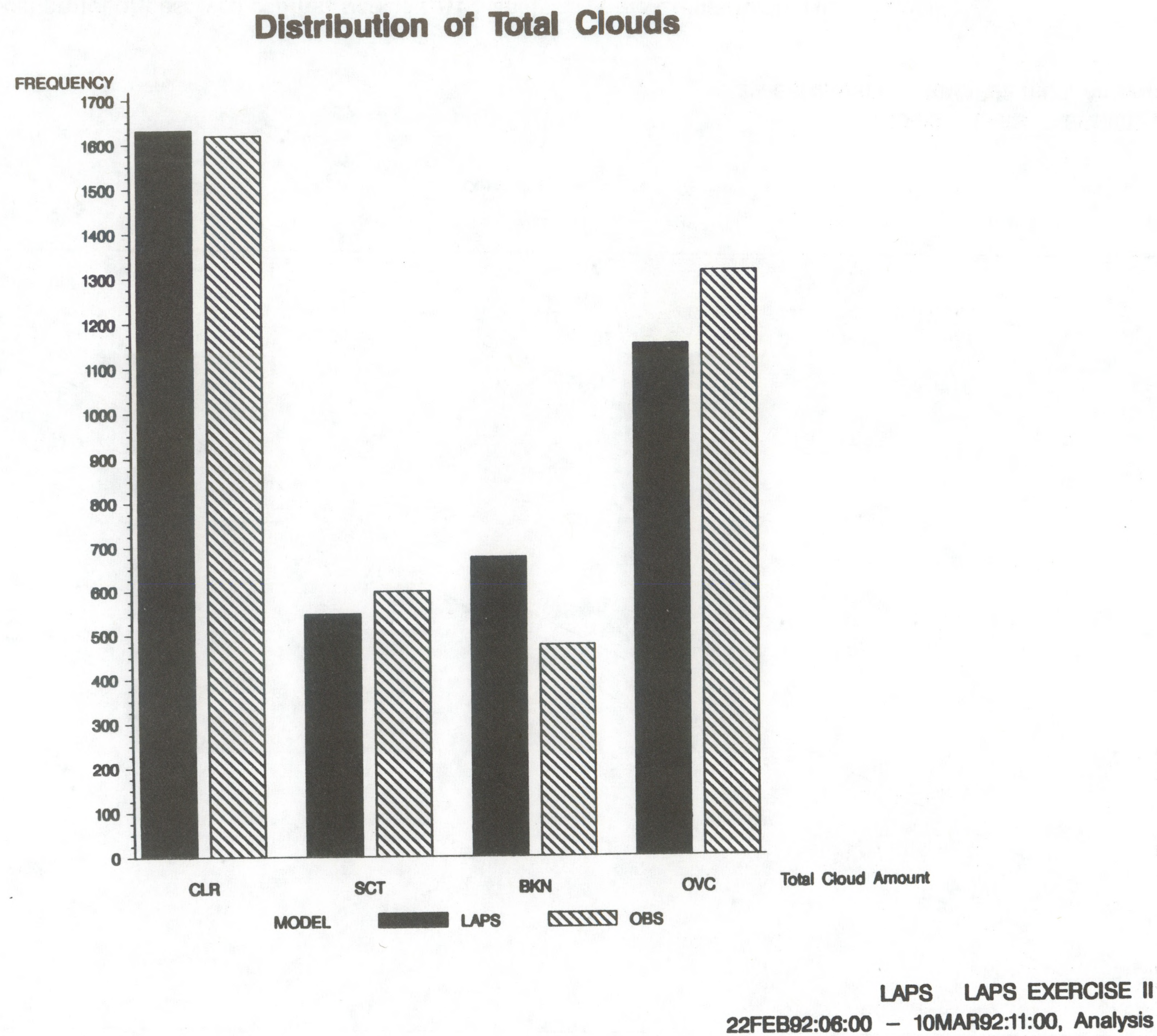

Figure 35. Distribution of observed total clouds versus LAPS analysis of the STORM-FEST domain total clouds.

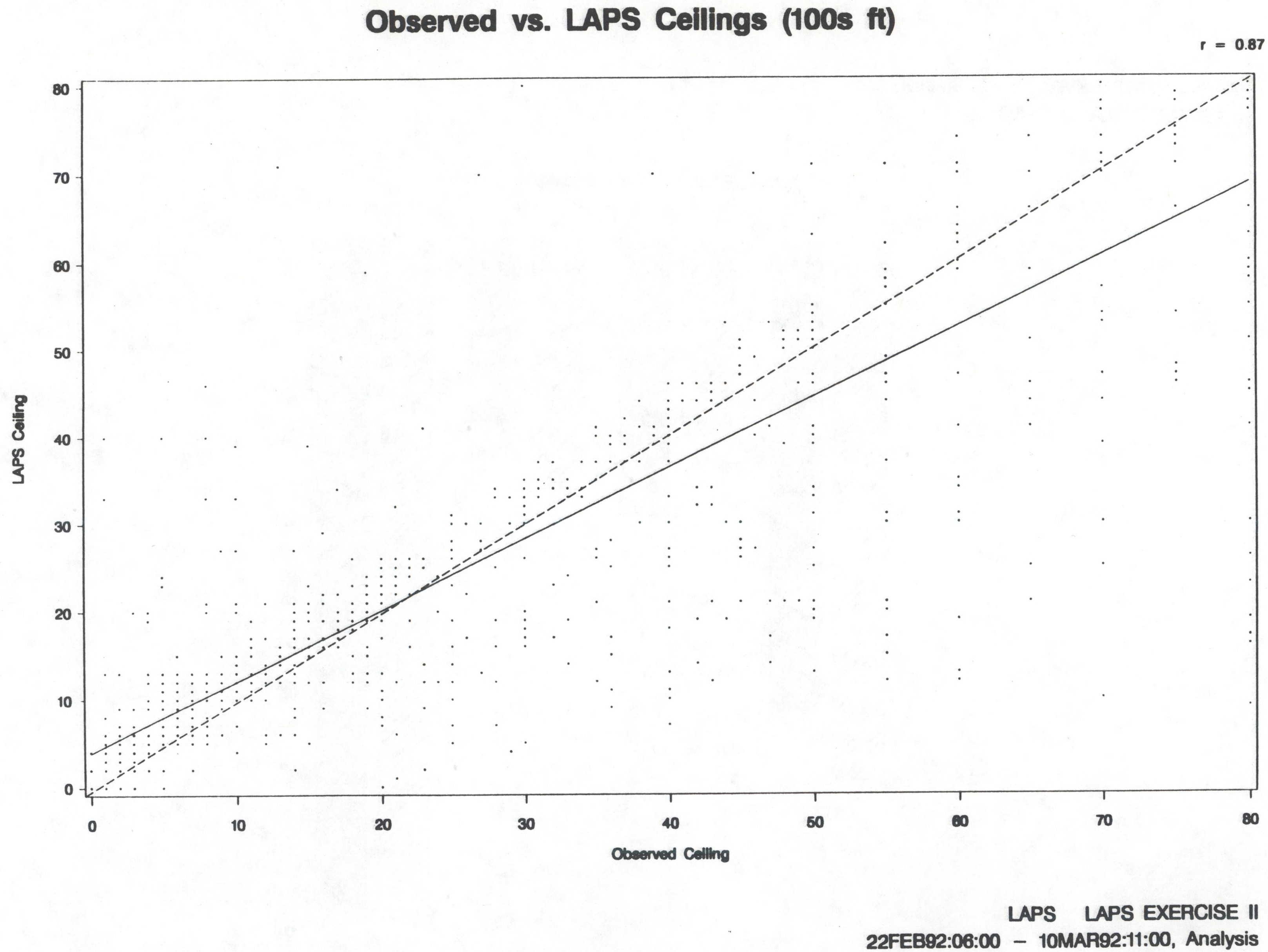

Figure 36. Scatterplot of observed ceilings versus LAPS analysis of the Colorado domain ceilings.

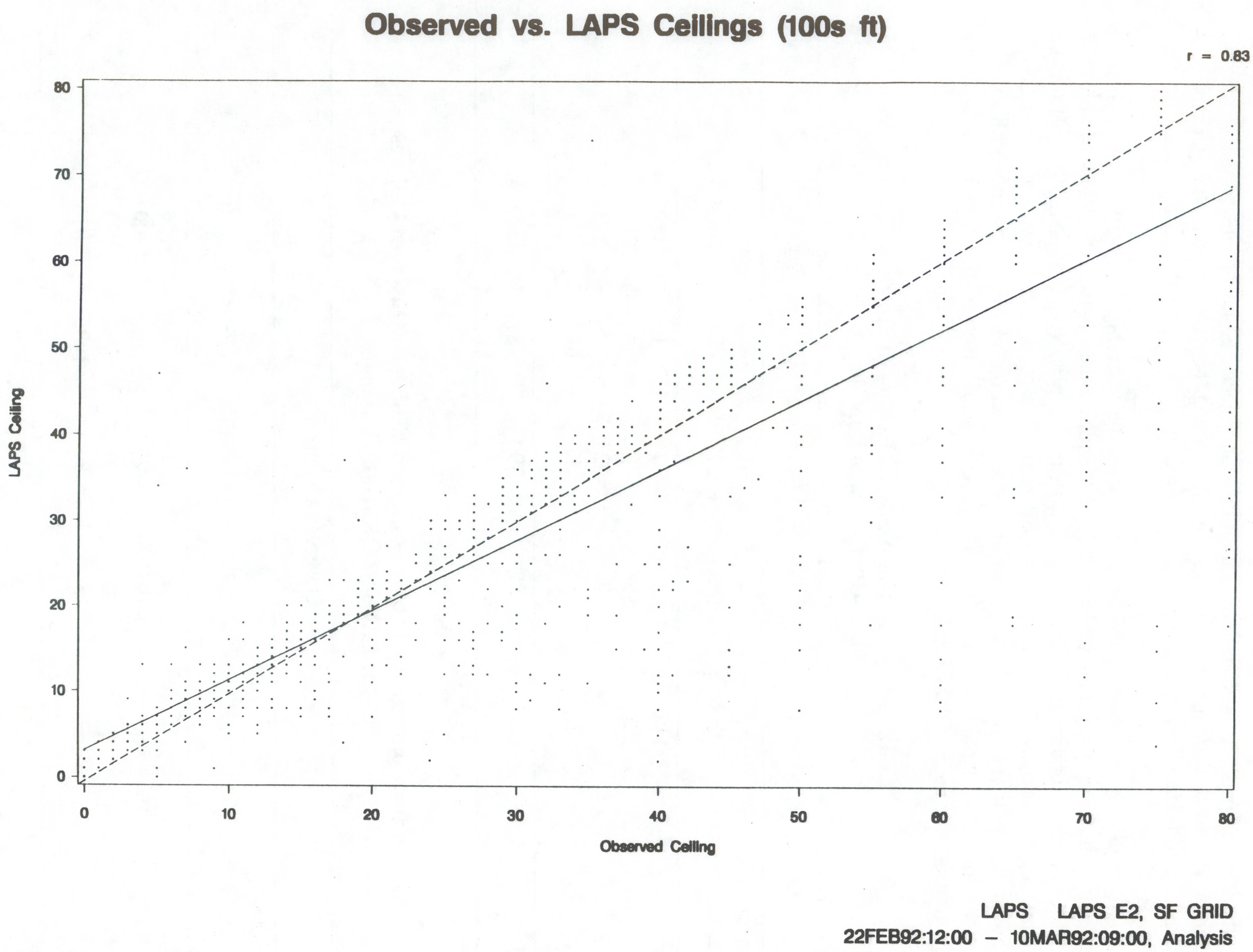

Figure 37. Scatterplot of observed ceilings versus LAPS analysis of the STORM-FEST domain ceilings.

cause these descrepencies. On the other hand, the contingency tables (Tables 9 and 10) for the two domains show that the highest numbers are found along the diagonal, which suggests that in most cases, LAPS identifies the correct ceiling categories.

Visibility. Since the LAPS visibility analysis uses the verifying observations to produce its analysis, it is not surprising that LAPS correctly identified the majority of VFR, MVFR, IFR and LIFR visibility conditions as shown in the distribution plots (Figs. 38 and 39). However, distinguishing between MVFR and IFR or VFR remains a most troubling problem for LAPS. As shown in Table 11 and 12, when MVFR was observed, LAPS analyzed VFR or IFR conditions for the Colorado domains 48% of the time, while 30% of the time LAPS analyzed VFR conditions for the STORM-FEST domain.

Table 9. Contingency Table of Analyzed Ceiling by Observed Ceilings for LAPS Colorado Domain

	Observed Ceilings				
Diagnosed Ceilings	LIFR	IFR	MVFR	VFR	Total
LIFR	**112**	3	7	1	123
IFR	72	**106**	25	4	207
MVFR	11	74	**321**	95	501
VFR	2	5	37	**687**	731
Total	197	188	390	787	1562

Table 10. Contingency Table of Analyzed Ceiling by Observed Ceilings for LAPS STORM-FEST Domain

	Observed Ceilings				
Diagnosed Ceilings	LIFR	IFR	MVFR	VFR	Total
LIFR	**145**	7	2	2	156
IFR	66	**195**	23	16	300
MVFR	1	81	**506**	95	683
VFR	3	3	35	**1035**	1076
Total	215	286	566	1148	2215

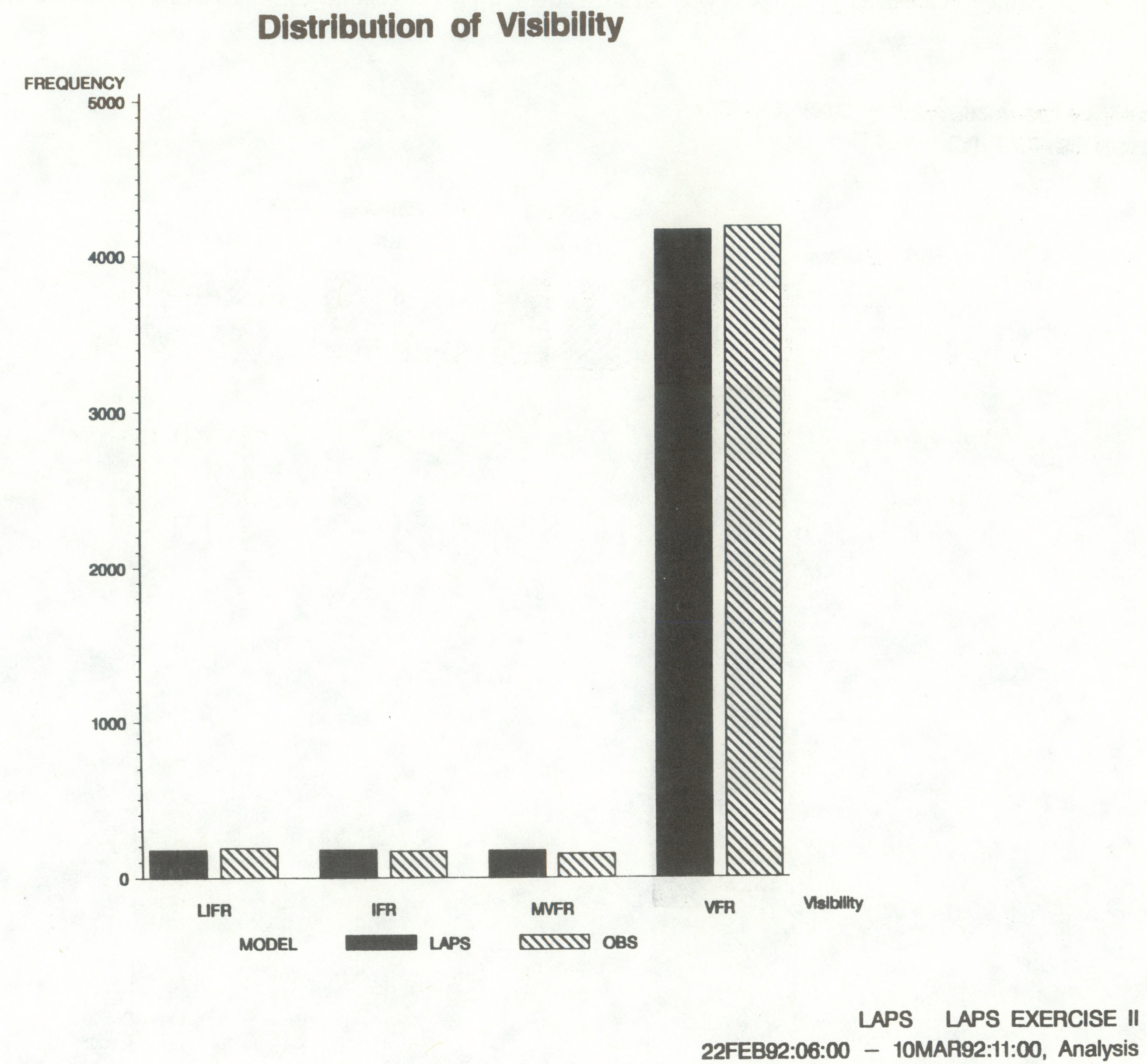

Figure 38. Distribution of observed visibility versus LAPS analysis of the Colorado domain visibility.

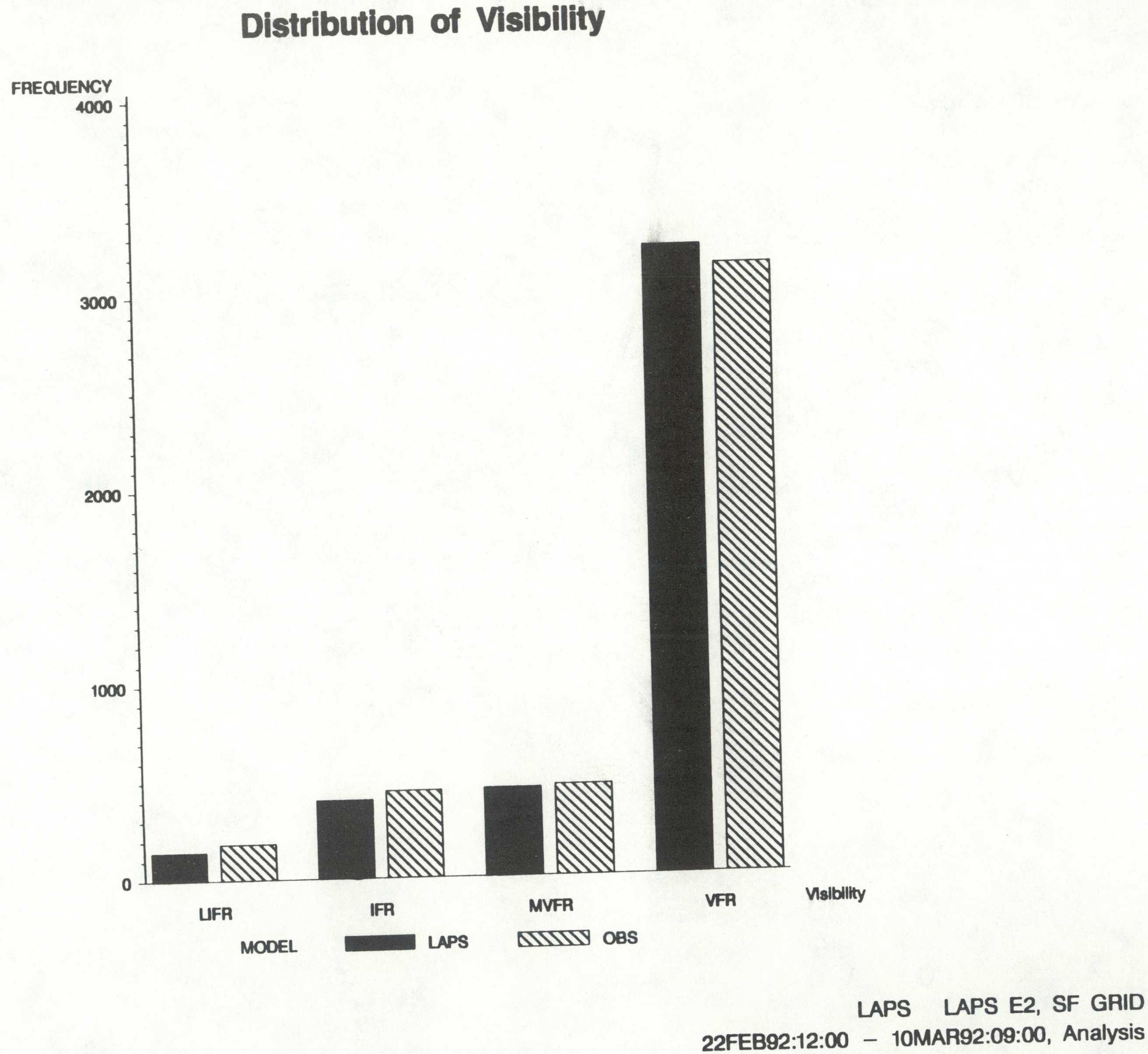

Figure 39. Distribution of observed visibility versus LAPS analysis of the STORM-FEST domain visibility.

Table 11. Contingency Table of Analyzed Visibility by Observed Visibility for LAPS Colorado Domain

Diagnosed Visibility	Observed Visibility LIFR	IFR	MVFR	VFR	Total
LIFR	**151**	13	7	7	178
IFR	20	**102**	24	30	176
MVFR	3	45	**69**	54	171
VFR	16	6	48	**4085**	4155
Total	190	166	148	4176	4680

Table 12. Contingency Table of Analyzed Visibility by Observed Visibility for LAPS STORM-FEST Domain

Diagnosed Visibility	Observed Visibility LIFR	IFR	MVFR	VFR	Total
LIFR	**123**	18	1	2	144
IFR	52	**310**	37	2	401
MVFR	0	109	**282**	60	451
VFR	8	9	143	**3068**	3228
Total	183	446	463	3132	4224

Precipitation. Precipitation analyses are not directly computed by the LAPS surface analysis system, but are instead computed using the postprocessing procedures described in Appendix A. The resulting precipitation grids are quite accurate, producing small errors with a near-zero bias (Appendix C). It should be noted, however, that these statistics are weighted by the large number of nonprecipitation cases (only 6% of the 8716 cases had non-zero 1-h precipitation accumulations for the STORM-FEST domain). Scatterplots (Figs. 40 and 41) show that LAPS consistently underanalyzes precipitation amounts greater than 0.05 in., a pattern that is most likely caused by the use of radar data in the LAPS procedures. Radars report area

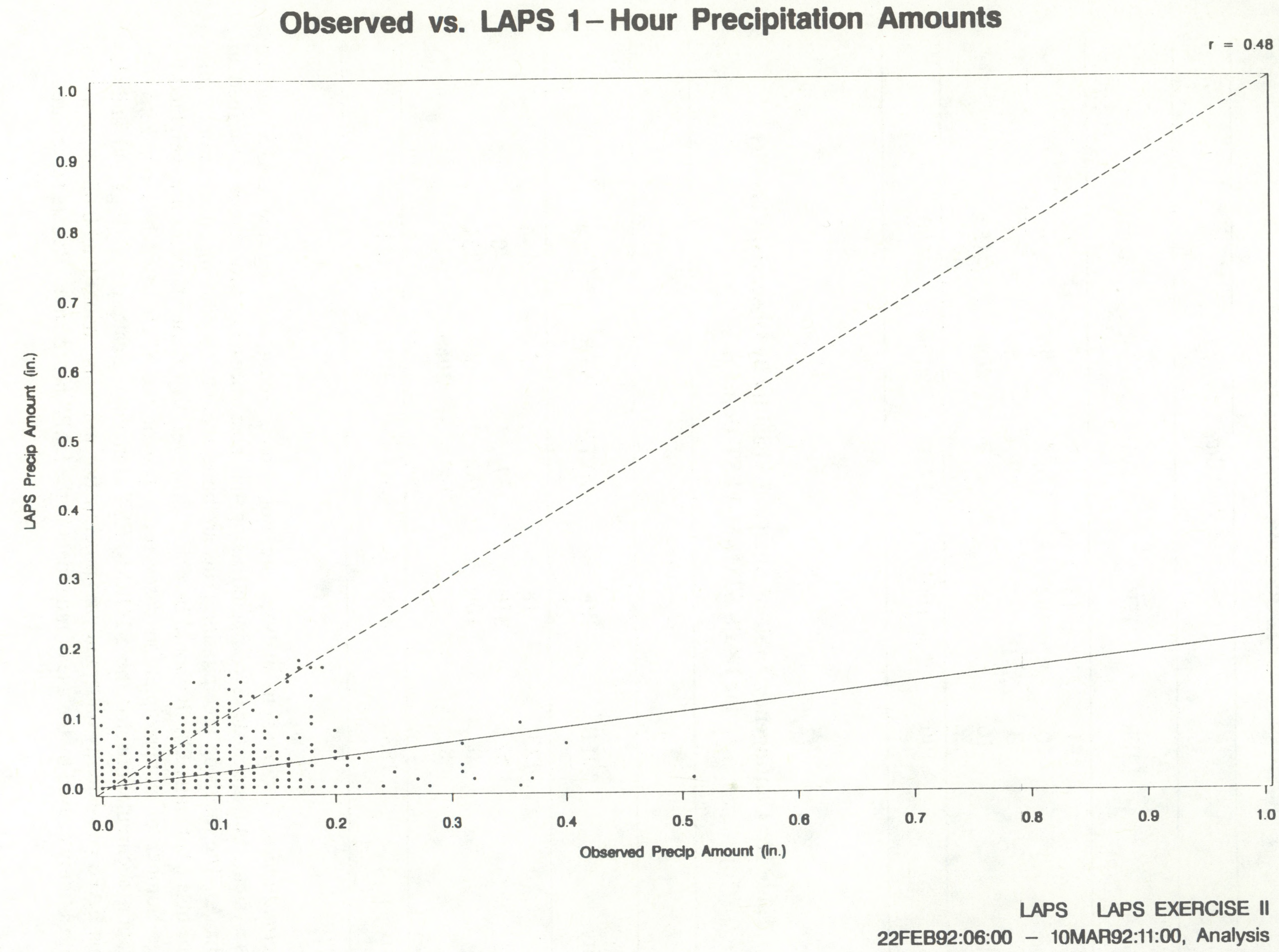

Figure 40. Scatterplot of observed 1-h precipitation amounts versus LAPS Colorado domain 1-h precipitation amounts.

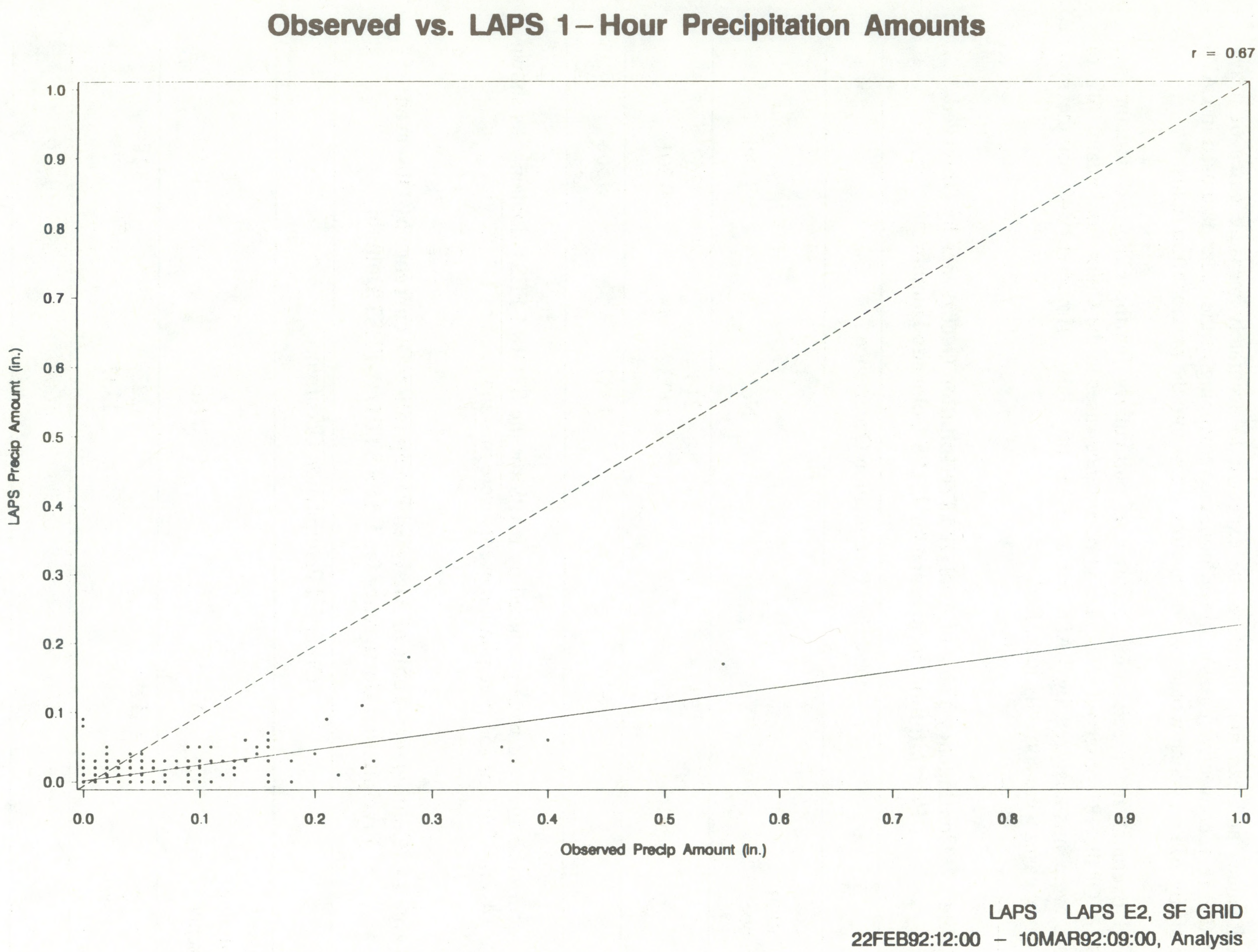

Figure 41. Scatterplot of observed 1-h precipitation amounts versus LAPS STORM-FEST domain 1-h precipitation amounts.

averaged values and can not, therefore, be expected to accurately measure cases of heavy precipitation (e.g. convective cases). In addition, the remapping of the radar data used in LAPS may be off by 20 km, which would introduce more errors into the precipitation fields.

LAPS overanalyzed precipitation occurrence, particularly for the Colorado domain (see Table 13). Of the 181 observed precipitation occurrence cases in the Colorado domain, 70% of the cases were mis-analyzed by LAPS for an FAR of 0.801. However, 84% of the non-precipitation cases were correctly identified.

Table 13. Contingency Table of Analyzed Precipitation Occurrence by Observed Precipitation Occurrence for LAPS Colorado Domain

	Observed Precipitation Occurrence		
Diagnosed Precipitation Occurrence	Yes	No	Total
Yes	**53**	214	267
No	128	**1173**	1301
Total	181	1387	1568

Better occurrence analyses were produced by LAPS for the STORM-FEST domain. As shown in Table 14, only 24% of 156 precipitation events were mis-analyzed by LAPS.

Table 14. Contingency Table of Analyzed Precipitation Occurrence by Observed Precipitation Occurrence for LAPS STROM-FEST Domain

	Observed Precipitation Occurrence		
Diagnosed Precipitation Occurrence	Yes	No	Total
Yes	**118**	223	341
No	38	**1337**	1375
Total	156	1560	1716

When considering only cases where precipitation was observed, LAPS was able to discern between liquid and frozen precipitation quite well. For example, the LAPS Colorado domain correctly identified 32 precipitation cases as liquid and 14 of the 18 cases as frozen (Table 15), while in the STORM-FEST domain LAPS identified the 106 liquid cases and the 9 frozen cases correctly (Table 16). On the other hand, when no precipitation was observed, LAPS analyzed no precipitation 84 and 85% of the time for the Colorado and STORM-FEST domains, repespectively.

Table 15. Contingency Table of Analyzed Precipitation Phase by Observed Precipitation Phase for LAPS Colorado Domain

	Observed Precipitation Phase			
Diagnosed Precipitation Phase	None	Liquid	Frozen	Total
None	**1173**	77	50	1300
Liquid	155	**32**	4	191
Frozen	56	0	**14**	70
Total	1384	109	68	1561

Table 16. Contingency Table of Analyzed Precipitation Phase by Observed Precipitation Phase for LAPS STORM-FEST Domain

	Observed Precipitation Phase			
Diagnosed Precipitation Phase	None	Liquid	Frozen	Total
None	**1337**	30	8	1375
Liquid	219	**106**	0	325
Frozen	3	0	**9**	12
Total	1559	136	17	1712

5.4. Turbulence

Statistics were generated using one algorithm available from LAPS. This calculation is based solely on the Richardson number, as described in Appendix A. Tests were conducted to determine a turbulence scaling value for this exercise. Thus, values greater than zero are representative of turbulent conditions.

PIREPS at city locations and PIREP locations were used as the verification dataset for this exercise (see Section 4). However, due to the small sample size of PIREPS at city locations, those results are not presented here. The sample sizes at PIREP locations are also small, particularly for the MDT-SVR and SVR cases, however, these results can be used to detect analysis trends and are presented.

Plots of POD*yes* and POD*no* by 5000 ft. layers for LAPS analyses for both domains are shown in Figs. 42 and 43. For a threshold greater than zero, POD*yes* is greater than 0.8 between 5000 and 20000 ft. This value drops off with height in the Colorado domain, but remains high in the STORM-FEST domain. Despite these favorable results, the POD*no* values are quite small for both domains and generally remain below 0.4, indicating that LAPS is probably overanalyzing the occurrence of turbulence.

Distribution plots of turbulence by observed intensity (Figs. 44 and 45) also indicate a PODyes value greater than 0.8 for all intensity categories.

A better understanding of the usefulness of the algorithm can be seen in Table 17 of analyzed turbulence occurrence versus observed turbulence for the STORM-FEST domain only (similar results were apparent in the Colorado domain, but are not shown here).

Table 17. Contingency Table of Analyzed Turbulence Occurrence by Observed Turbulence Occurrence for the LAPS STORM-FEST grid

Diagnosed Turbulence	Observed Turbulence		
	Yes	No	Total
Yes	864	346	1210
No	166	199	365
Total	1030	545	1575

When turbulence was observed, LAPS did an excellent job detecting these cases. For instance, LAPS accurately analyzed cases with turbulence 83% of the time. However, when no turbulence was explicitly stated in the PIREP, LAPS misanalyzed those cases 63% of the time. Therefore, 76% of the time (whether turbulence is observed or not), LAPS analyzed cases with turbulence.

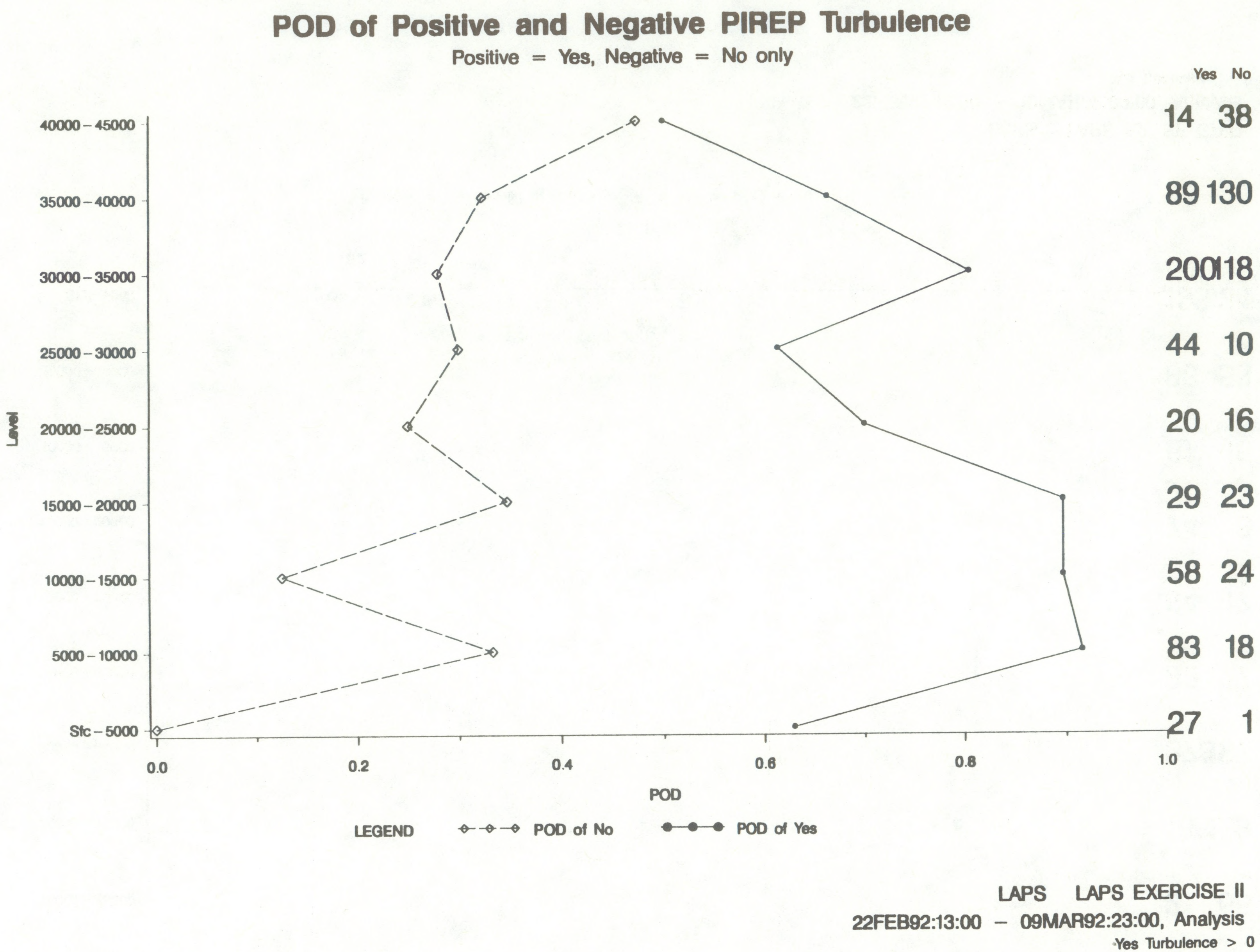

Figure 42. Plot of probability of detection (POD) for observed turbulence versus LAPS turbulence for the Colorado domain.

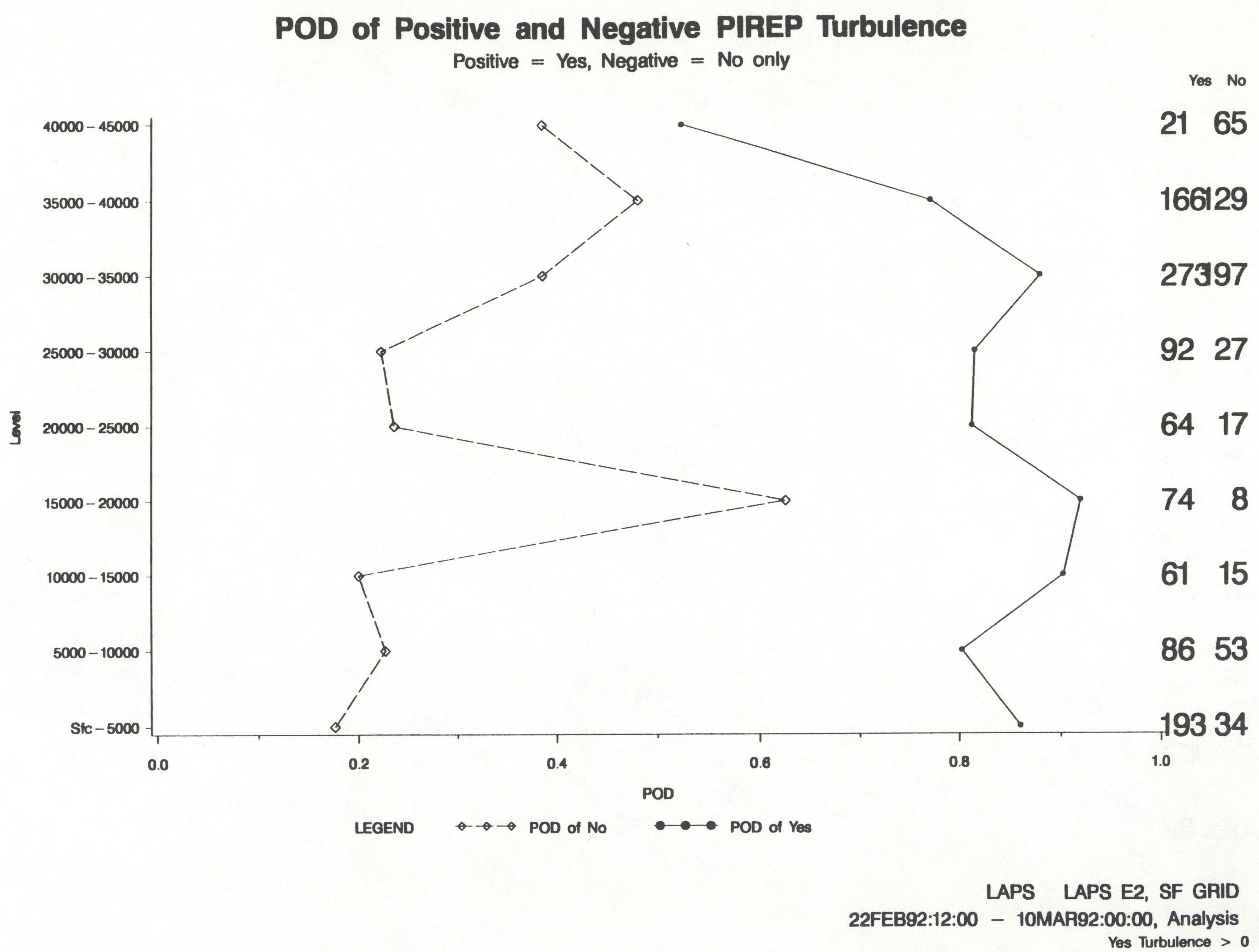

Figure 43. Plot of probability of detection (POD) for observed turbulence versus LAPS turbulence for the STORM-FEST domain.

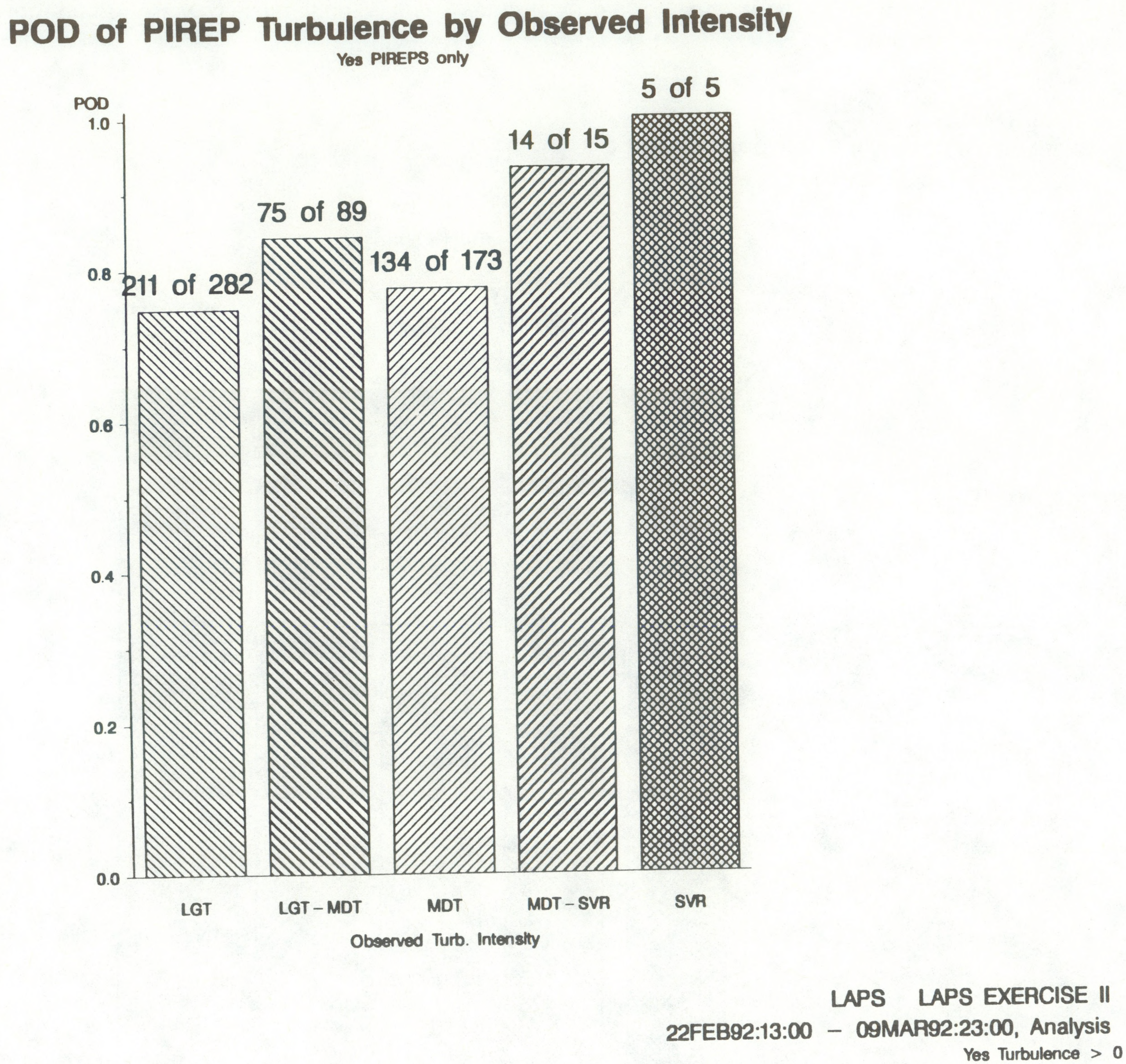

Figure 44. Distribution of observed turbulence intensity versus LAPS turbulence intensity for the Colorado domain.

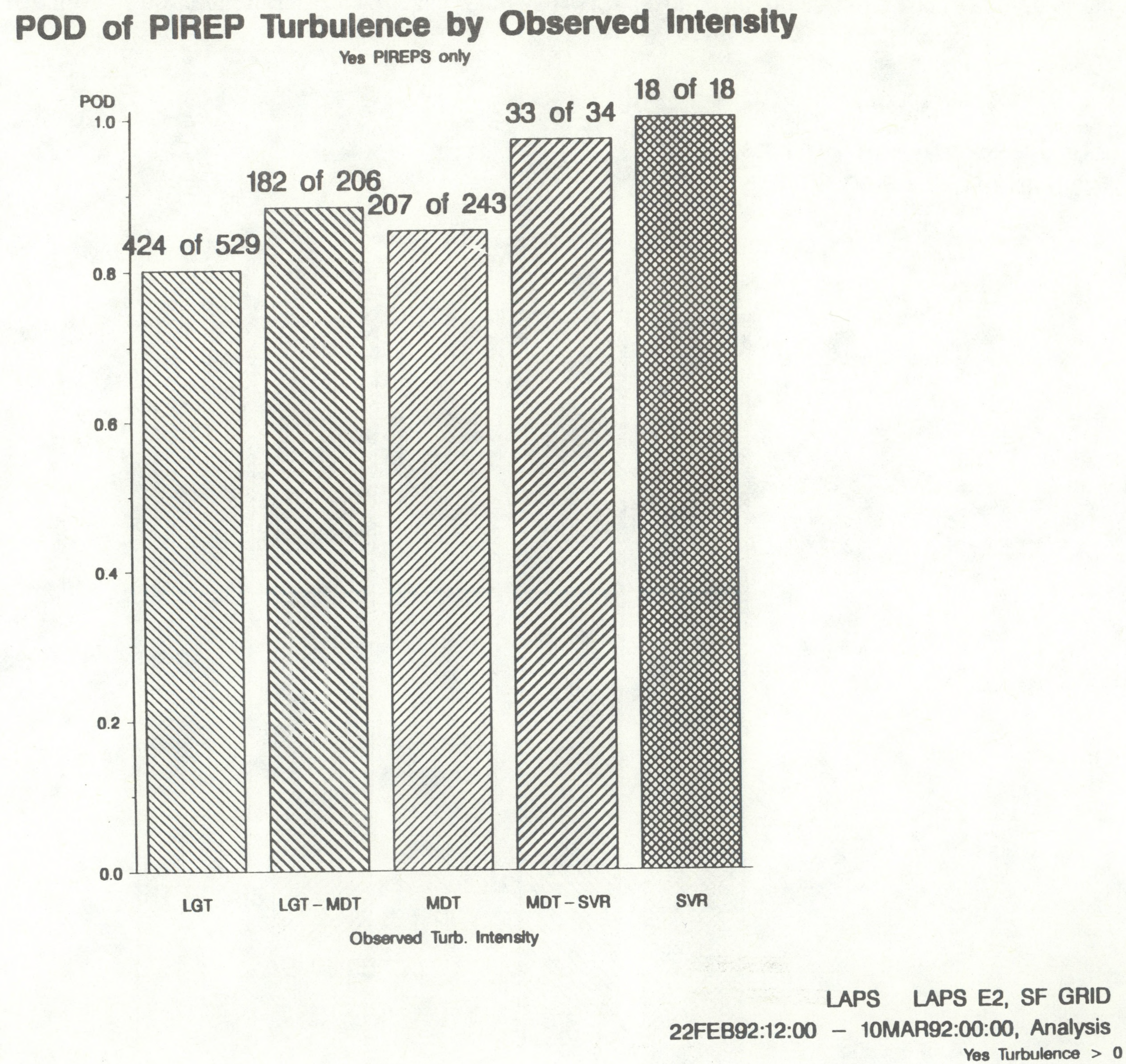

Figure 45. Distribution of observed turbulence intensity versus LAPS turbulence intensity for the STORM-FEST domain.

5.5. Icing

The LAPS analysis uses the modified form of the Smith-Feddes algorithm to determine icing severity. The icing index ranges from 0 to 6, but all index values greater than 0 are considered positive for icing in this report and are explained in Appendix A. The verification of the LAPS icing index is hampered somewhat in this study, due to the low number of PIREPS reporting *no* icing. However, some conclusions can still be drawn.

The plots of POD*yes* and POD*no* by 5000-ft layers for both domains are shown in Figs. 46 and 47. For a LAPS threshold of zero (which takes into account all icing cases, excluding the null cases) the POD*no* values are greater than 0.8 from the surface to 9000 ft and then drop off dramatically with height above that, although these numbers may be deceiving due to the small number of cases. The best POD*yes* values are above 12000 ft.

The distribution of LAPS icing versus observed intensity (Figs. 48 and 49) indicates that LAPS is best at diagnosing MDT-SVR in the Colorado domain and MDT icing in the STORM-FEST domain. LAPS does poorly detecting the observed SVR cases, correctly analyzing icing only one-third of the time. However, these results can be effected by the small PIREP sample size.

6. CONCLUDING REMARKS

A second evaluation of aviation-impact variables derived from LAPS analyses was conducted from 23 February to 10 March 1992. Overall, LAPS analyses of SAVs and AIVs were within expected instrument errors, with a few exceptions. For example, a problem in the height calculation over the STORM-FEST domain was detected. This error was not apparent in the Colorado domain and will need further attention. On the other hand, the LAPS cloud analysis, which has been under development longer than many of the other AIV algorithms and produced good results when compared to the SAO observations. The LAPS precipitation analyses, which is based solely on radar measurements, underanalyzed large precipitation amounts and overanalyzed small precipitation amounts. The LAPS icing and turbulence algorithms were used as a baseline for E2, since E2 was the first time icing and turbulence were tested. Additional research is required to develop these algorithms.

LAPS analyses are well within expected errors and can be useful for both analyses and diagnostics, as well as background fields used to initialize local models. A real-time verification system is being developed in the Aviation Division of FSL so that development and verification of the LAPS algorithms (as well as output from many other models) can continue.

7. ACKNOWLEDGMENTS

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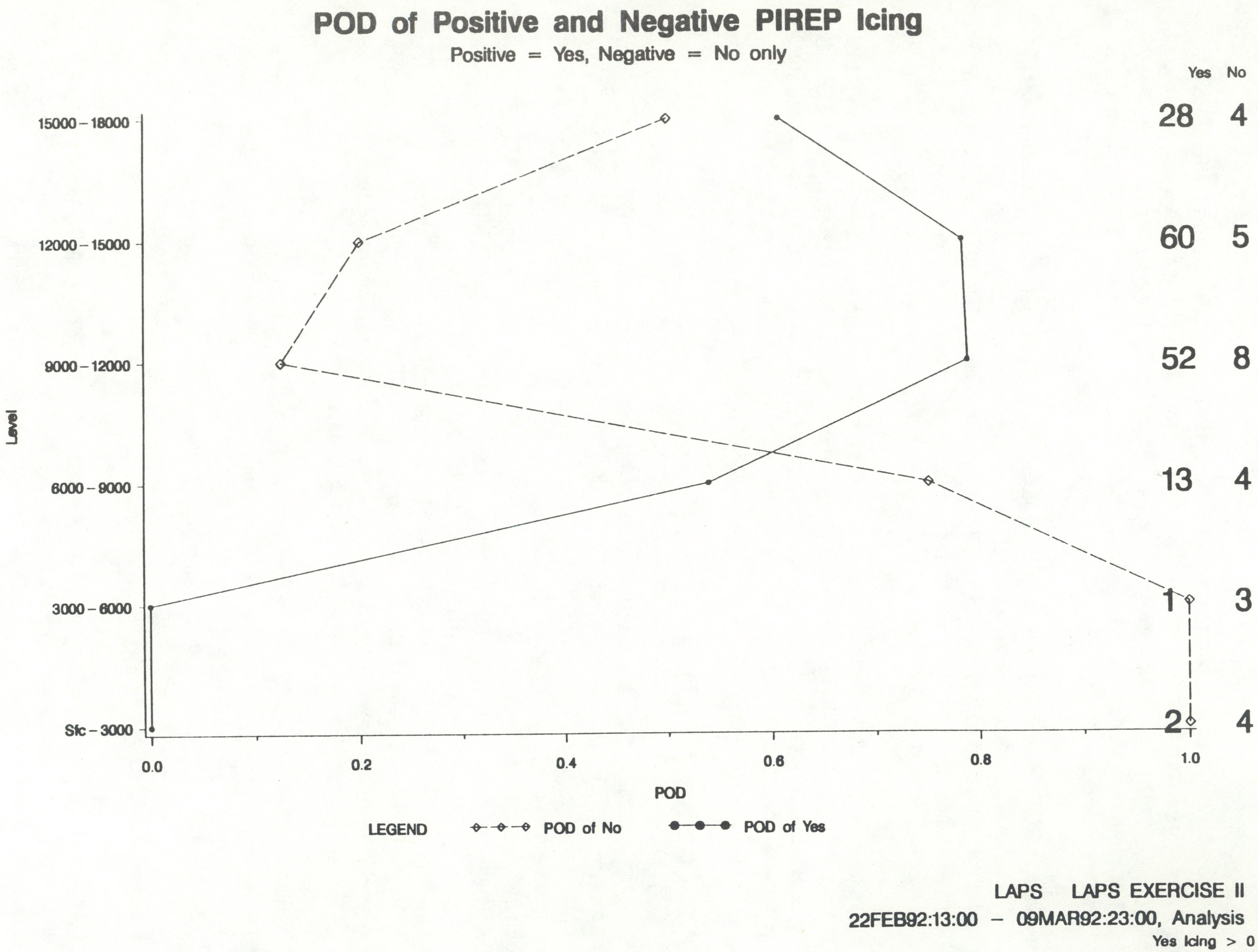

Figure 46. Plot of probability of detection (POD) for observed icing versus LAPS icing for the Colorado domain.

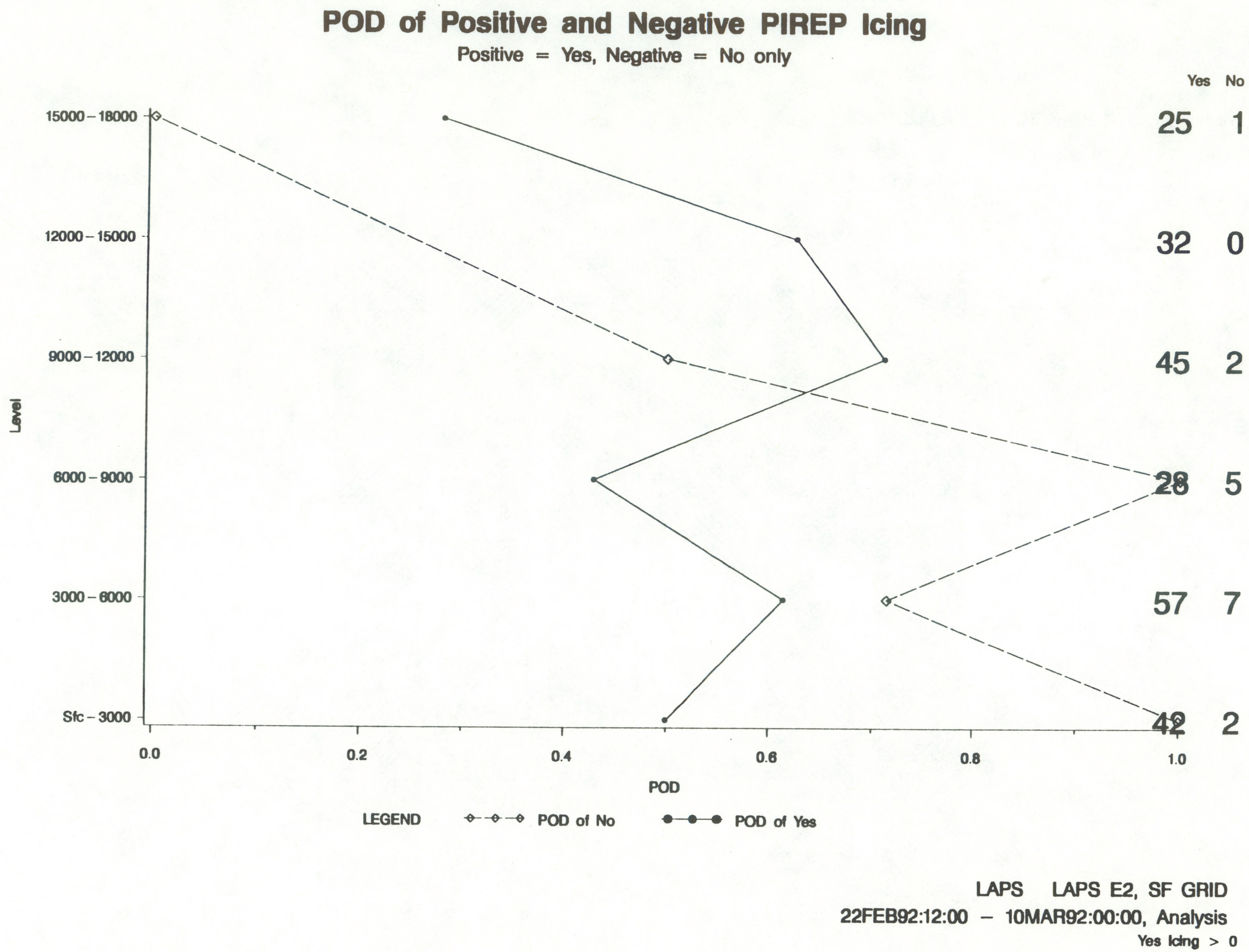

Figure 47. Plot of probability of detection (POD) for observed icing versus LAPS icing for the STORM-FEST domain.

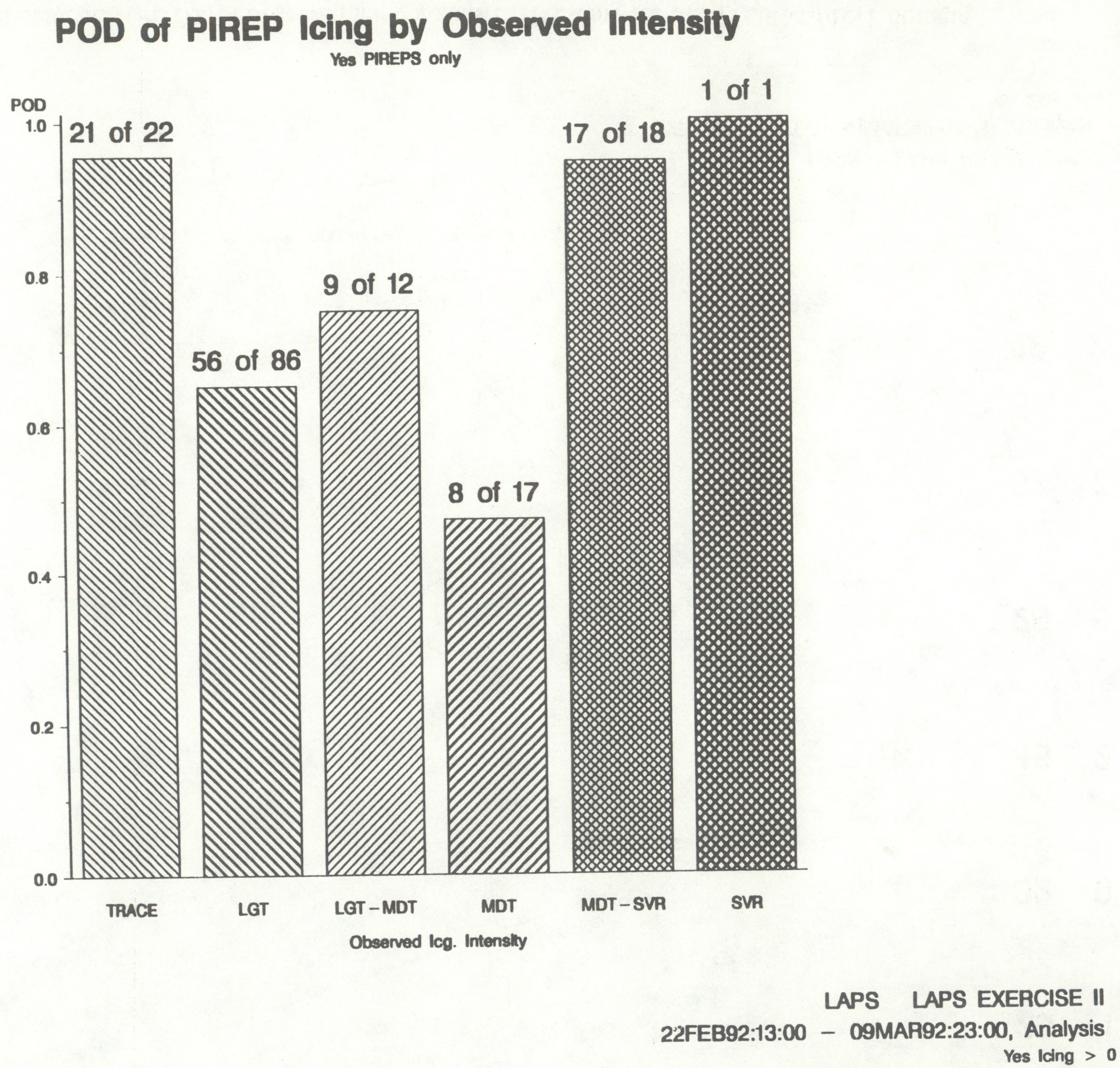

Figure 48. Distribution of observed icing intensity versus LAPS icing intensity for the Colorado domain.

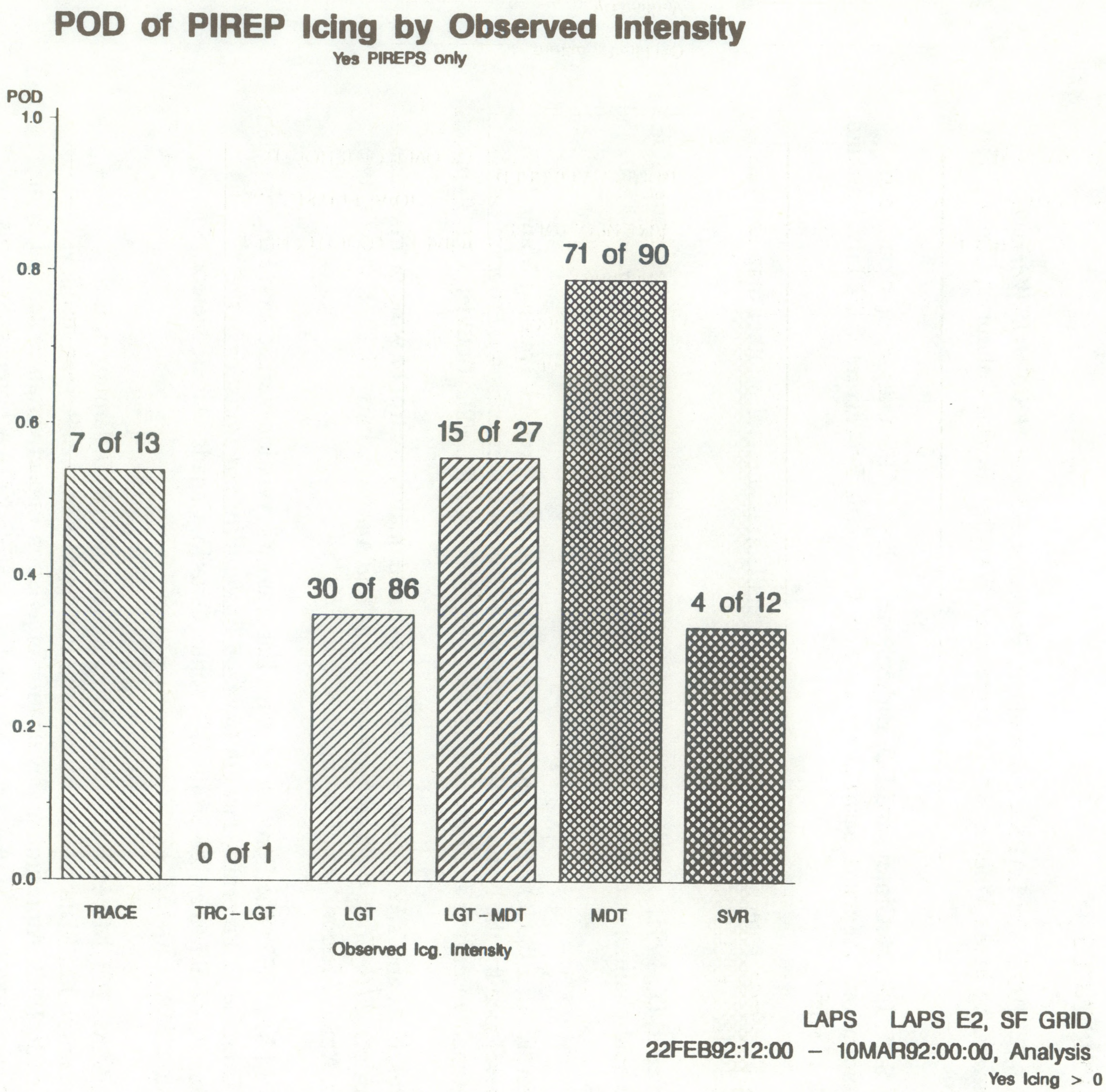

Figure 49. Distribution of observed icing intensity versus LAPS icing intensity for the STORM-FEST domain.

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APPENDIX A

DIAGNOSING SAVS AND AIVS IN LAPS

SAVs

Surface Grids

Surface grids, produced by the LAPS surface analysis system (McGinley et al. 1991), incorporate the previous LAPS analysis as a background field along with SAO and mesonet data from hourly observations. Each variable is then analyzed using the Barnes interpolation scheme. In cases where the terrain influences the temperature and dewpoint, the differences between the surface temperature at the surface station and an estimated surface temperature from MAPS (the estimated surface MAPS temperature is derived from extrapolation of the 700-mb MAPS temperature to the surface using the dry adiabatic lapse rate) are analyzed by the Barnes analysis scheme to produce a gridded field of surface temperature differences. Along with that procedure, a gridded field of surface temperature values are estimated using the MAPS 700-mb temperatures and extrapolating those to the surface and again applying the Barnes analysis scheme. From there, the difference values are added to these estimated surface temperature values. This method eliminates wild swings in the temperature values that may be introduced from the terrain influences. After the surface temperature field is produced, satellite data are incorporated into the surface analysis using a method known as Horizontal Shape Matching (Birkenheuer 1991). This technique uses the gradient information of the satellite data to better interpolate between known surface data values.

Upper-Air Grids

Upper-air grids are generated using MAPS analyses and forecasts as a background and incorporating new observations. Profiler, satellite, radar, and surface data are used to compute the new fields. Rawinsonde data are not directly used, although they influence the fields indirectly (and in a delayed manner) through the MAPS background. A detailed description of the LAPS analysis can be found in McGinley et al. (1991).

AIVs

Altimeter

Altimeter was derived from reducing the LAPS 1500-m pressure to station pressure. The station pressure was then converted to altimeter values. The nature of the errors, in this case, was mainly due to the smoothing procedure which is applied to the analysis.

Precipitation Type

Precipitation type is calculated using input radar reflectivity and wet-bulb temperature (from the LAPS three-dimensional temperature and humidity fields). Categories of precipitation type are: none, rain, snow, freezing rain, sleet, and hail. Vertical grid columns are analyzed from top to bottom, tracing the amount and type of precipitate as it falls through the column. Precipitate begins as snow, but can melt and possibly refreeze to form rain or freezing rain. Radar reflectivity greater than 45 dBZ is a threshold for hail. More details on the LAPS precipitation typing algorithm can be found in Albers et al., 1994.

Visibility

LAPS ingests visibility data from SAOs only (no mesonet data) and computes the log (visibility) to give more importance to lower visibilities. These results are then analyzed by the Barnes analysis scheme to produce a smoothed field.

Cloud Ceiling

Cloud ceilings are determined during the calculation of cloud levels and heights. A profile of cloud amounts is determined from the three dimensional LAPS cloud field (Albers 1992) by averaging the points surrounding the SAO location. Up to 25 points are averaged so that cloud information from roughly 20 km in any direction is included, as would be the case for a typical observer's view. As the cloud layers are being diagnosed from the cloud amount profile, the location at which the total cloud cover reaches the BKN category is computed. The height of this cloud base is given as the cloud ceiling.

Turbulence

The LAPS turbulence calculation is simply a scaled inverse Richardson number, with the stability and wind shear determined from the LAPS three-dimensional wind and temperature fields. The actual values for the index are

$$\text{Turbulence Index} = (50/Ri),$$

where the scaling is a subjective value based on typical Richardson numbers analyzed by LAPS. The object is to have typical Turbulence Index numbers in the range of 0-10. Richardson numbers in LAPS rarely are diagnosed less than about 5.0, due to the 10-km resolution.

Icing

The LAPS icing algorithm is based on a determination of supercooled liquid water within the LAPS domain, using an adaptation of the Smith-Feddes model (Haines et al. 1989). The calculation is dependent on the LAPS three-dimensional cloud and temperature fields (Albers 1992), as well as the input radar reflectivity data.

APPENDIX B

SUMMARY OF STATISTICAL MEASURES

A multitude of statistical measures are available for the description of a set of data. Among the most commonly used measures for meteorological verification are the bias or mean error, mean absolute error, root mean square error, percent correct, probability of detection, false alarm rate, critical success index, true skill statistic, and the Heidke skill score.

The bias, mean absolute error, and root mean square error are easily defined using Fi as the forecasts, Oi as the observations, and n as the number of forecast/observation pairs. The rest of the measures discussed here are formulated based on a contingency table. For complete descriptions, see Panofsky and Brier (1963), Stanski et al. (1989), Murphy et al. (1989), Doswell and Flueck (1989), and Doswell et al. (1990). Table 18 provides a quick reference for interpreting the verification measures.

Table 18. Quick Reference for Interpreting Verification Measures

Verification Measure	Range	"Best" Score
Bias or Mean Error (ME)	-00 to +00	0.0
Mean Absolute Error (MAE)	0.0 to +00	0.0
Root Mean Square Error (RMSE)	MAE to +00	0.0
Percent Correct	0% to 100%	100%
Probability of Detection (POD)	0.0 to 1.0	1.0
False Alarm Rate (FAR)	0.0 to 1.0	0.0
Critical Success Index (CSI)	0.0 to 1.0	1.0
True Skill Statistic (TSS)	-1.0 to 1.0	1.0
Heidke Skill Score (HSS)	-1.0 to 1.0	1.0
Log Score	-00 to +00	0.0

Bias or Mean Error

The bias, or mean (algebraic) error (ME), indicates the average direction of the deviation of the forecasts from the observed values. The bias is defined as

$$\text{Bias} = \text{ME} = (1/n) \sum_{i=1}^{n} (F_i - O_I)$$

A positive bias indicates that the forecast exceeds the observed value on the average (overforecasting), and a negative bias corresponds to a forecast below the observed value on the average (underforecasting). Also, for all arithmetic errors in this memorandum, the subtraction is always performed as model minus observation. For example, a positive arithmetic temperature error means that the model was too warm. The bias range is from $-\infty$ to $+\infty$; a value of zero is desired.

Mean Absolute Error

The mean absolute error (MAE) is a linear score that calculates the average magnitude of the error. The MAE is defined as

$$\text{MAE} = \left(\frac{1}{n}\right) \sum_{i=1}^{n} \left|F_i - O_i\right|$$

The MAE range is from 0 to ì; a MAE of 0 is desired.

Root Mean Square Error

The root mean square error (RMSE) is commonly used in meteorology. The RMSE is a quadratic score that gives the average magnitude of the errors, and is defined as

$$\text{RMSE} = \left[\left(\frac{1}{n}\right) \sum_{i=1}^{n} (F_i - O_i)^2\right]^{\frac{1}{2}}$$

The RMSE gives more weight to large errors than to small errors in the average, and is useful when large errors are undesirable. Values for RMSE range from the MAE to 1, and values close to the MAE (or zero) are desired.

The root mean square vector error (RMSVE) is similar, and is designed for evaluating magnitude and directional errors of the wind. RMSVE is defined as where u and v are the components of the wind, and as before f and o denote forecast and observed, respectively.

$$\text{RMSVE} = \left(\left(\frac{1}{n}\right) \sum_{i=1}^{n} (u_{fi} - u_{oi})^2 + (v_{fi} - v_{oi})^2\right)^{1/2}$$

Percent Correct

Percent correct is just that -- the percentage of correctly forecast events. In a contingency table, this refers to the numbers added along the diagonal (or correct forecasts) divided by the total number of events. Percent correct can be overwhelmed by large numbers in categories that are not of interest (e.g., forecasts of the null event). The values range from 0% to 100%; 100% represents a desired value.

Probability of Detection

The probability of detection (POD), or prefigurance, is calculated from a contingency table. It is defined as the number of correct forecasts divided by the number observed in each category. In other words, it is the percentage of events that occurred that were correctly forecast. It is a measure of the ability to correctly forecast a particular category. The POD ranges from 0.0 to 1.0, and 1.0 represents a desired forecast of the category. POD often is presented as a percentage (100 x POD).

For icing and turbulence POD is defined as;

$$\text{PODy} = (YY) / (YY + NY)$$

$$\text{PODn} = (NN) / (NN + YN)$$

These categories include, for example, "Yes" PIREPS that are associated wtih a "Yes" forecast (YY); "Yes" PIREPS associated wtih a "No" forecast (NY); "No PIREPS associated wtih a "Yes" forecast (YN); and "No" PIREPS that are associated with a "No" forecast (NN).

False Alarm Rate

The false alarm ratio (FAR), or postagreement, is defined as the number of incorrect forecasts divided by the total number of forecasts for each category. That is, it is the percent of forecasts that did not verify for each category. The FAR ranges from 0.0 to 1.0; a FAR of 0.0 is desirable. FAR often is presented as a percentage (100 x FAR).

Critical Success Index

The critical success index (CSI), or threat score, is defined as the number of correct forecasts for a given category divided by the number of cases forecast and/or observed for that category. The range is from 0.0 to 1.0, and values close to 1.0 are desired. The CSI is sensitive to both false alarms and missed events, and therefore is more sensitive in situations where rare events are involved. However, it gives no credit for correct forecasts of the null event.

True Skill Statistic

The true skill statistic (TSS) compares the number of correct forecasts, minus those attributable to random guessing, to a hypothetical set of perfect forecasts. It ranges from -1.0 to 1.0, and a score of 1.0 is desired. The TSS attempts to measure the skill of a forecast against what one would obtain if the forecast were merely a random guess. It also gives credit for the correct forecast of a null event, unlike the CSI. However, in cases where the null event dominates (e.g., tornadoes, thunderstorms), the TSS approaches the POD. This means that the TSS is vulnerable to hedging in rare event forecasts; if uncertain, the forecaster will score better by forecasting the null event. Another disadvantage of the TSS is that it is a complicated calculation when there are more than two categories

Heidke Skill Score

Similar to the TSS, the Heidke skill score (HSS) attempts to remove any artificial skill due to pure chance, while still giving credit for correctly forecasting the null event. However, the HSS does not have the same problems as the TSS, because it does not encourage hedging and is easily calculated for a multiple category situation. It also ranges from -1.0 to 1.0, and 1.0 represents a perfect score. The HSS is always equal to or that it is giving credit for correct null event forecasts. It also is possible to use other standards of reference (e.g., persistence, climatology) with the HSS. For these reasons, the HSS is considered to be one of the best skill scores.

Log Score

For some verifications, it is more reasonable to weight the score based on the importance of a forecast. For example, when forecasting ceilings, it is obvious that a 2,000 ft error when the observed ceiling is 10,000 ft is not critical as when the observed ceiling is 500 ft. Thus, the log score was designed to give more credit (punishment) to good (bad) forecasts made at the more important thresholds of IFR weather.

The score is defined as:

$$\text{Log Score} = \left(\frac{1}{n}\right) \sum_{i=1}^{n} \log\left((F_i) / (O_i) \right)$$

Since the score uses the logarithm of the ration of forecast to observed, the same score results for a forecast (observation) of 12,000 (10,000) and for a forecast (observation) of 1,200 (1,000). Note that in the first case, the arithmetic error is 2,000 ft, while in the second case the error is 200 ft. The Log Score uses an arithmetic (rather than absolute) mean, which allows for both positive (forecast > observation) and negative (forecast < observation) situations. The desired score is 0.

APPENDIX C

LIST OF STATISTICAL RESULTS

List of Statistical Results

	Colorado Domain	STORM-FEST Domain
UPPER AIR		
Height (dm)		
850 mb ME	1.17	3.59
850 mb MAE	2.37	4.33
850 mb RMSE	2.84	5.18
850 mb N	83	365
500 mb ME	0.23	3.11
500 mb MAE	2.17	4.02
500 mb RMSE	2.58	4.88
500 mb N	105	323
250 mb ME	-0.33	2.39
250 mb MAE	2.46	3.86
250 mb RMSE	3.08	4.80
250 mb N	100	320
Temperature (C)		
850 mb ME	-0.11	-0.18
850 mb MAE	0.83	0.72
850 mb RMSE	1.26	1.06

List of Statistical Results

	Colorado Domain	STORM-FEST Domain
850 mb N	79	367
500 mb ME	-0.47	-0.42
500 mb MAE	0.69	0.62
500 mb RMSE	0.95	0.82
500 mb N	105	323
250 mb ME	0.08	-0.04
250 mb MAE	0.75	0.67
250 mb RMSE	1.10	0.96
250 mb N	100	323
Relative Humidity (%)		
850 mb ME	-0.34	4.20
850 mb MAE	9.19	11.11
850 mb RMSE	15.72	16.27
850 mb N	52	362
500 mb ME	2.75	-1.53
500 mb MAE	14.99	16.34
500 mb RMSE	20.66	22.58
500 mb N	102	317
Wind Speed (kt)		

List of Statistical Results		
	Colorado Domain	STORM-FEST Domain
850 mb ME	-4.02	-2.40
850 mb MAE	5.91	5.61
850 mb RMSE	7.22	7.28
850 mb RMSVE	5.00	5.32
850 mb N	75	352
500 mb ME	-1.23	-0.19
500 mb MAE	4.49	4.47
500 mb RMSE	5.72	5.71
500 mb RMSVE	4.84	4.27
500 mb N	101	326
250 mb ME	-1.48	-0.65
250 mb MAE	5.70	5.60
250 mb RMSE	7.72	7.20
250 mb RMSVE	5.61	5.77
250 mb N	96	318
Max Wind Level (ft) Observed Winds ≥ 50 kts		
ME	127.139	-134.839
MAE	1980.63	2605.27
RMSE	3596.87	4554.51
N	72	341

List of Statistical Results	Colorado Domain	STORM-FEST Domain
Max Wind (kt) Observed winds ≥ 50 kt		
ME	-7.017	-8.95
MAE	8.02	10.94
RMSE	10.09	18.82
N	72	352
Freezing Level (ft)		
ME	-116.07	79.55
MAE	402.53	335.28
RMSE	850.43	593.11
N	107	346
Tropopause Height (ft)		
ME	228.90	129.19
MAE	1512.28	1445.46
RMSE	1861.04	1944.55
N	99	258
PROFILER		
Direction (deg)		
1000m ME	-0.56	-2.39
1000 m MAE	6.12	9.23
1000 m RMS	10.76	16.54

List of Statistical Results		
	Colorado Domain	STORM-FEST Domain
1000 m N	571	1255
5000 m ME	-0.43	-0.51
5000 m MAE	3.28	5.82
5000 m RMS	4.49	9.09
5000 m N	635	1650
10000 m ME	-0.67	-1.17
10000 m MAE	4.96	3.81
10000 m RMS	7.21	6.98
10000 m N	709	1613
Wind Speed (kt)		
1000 m ME	-1.67	-0.79
1000 m MAE	2.53	3.01
1000 m RMSE	4.02	4.46
1000 m RMSVE	2.53	3.17
1000 m N	719	1776
5000 m ME	0.08	0.03
5000 m MAE	1.58	2.38
5000 m RMSE	2.13	3.57
5000 m RMSVE	1.48	3.02
5000 m N	718	1801

List of Statistical Results	Colorado Domain	STORM-FEST Domain
10000 m ME	-0.10	-0.11
10000 m MAE	2.44	3.07
10000 m RMSE	3.35	5.06
10000 m RMSVE	2.58	3.86
10000 m N	741	1646
SURFACE		
Altimeter (in. Hg)		
ME	.004	-.003
MAE	.025	.011
RMSE	.039	.016
N	5731	3248
Temperature (F)		
ME	.310	-.0027
MAE	1.539	1.361
RMS	2.334	2.140
N	14927	6411
Dewpoint (F)		
ME	.723	-0.77
MAE	1.860	1.927

List of Statistical Results		
	Colorado Domain	STORM-FEST Domain
RMS	3.033	3.174
N	14389	6230
Relative Humidity (%)		
ME	.441	-.162
MAE	4.570	5.709
RMS	7.154	9.079
N	14329	6227
Wind Speed (kt)		
ME	-3.228	-.332
MAE	4.360	1.843
RMS	6.881	2.684
N	15107	6267
Wind Direction (deg) for speeds >= 10 kt		
ME	-6.087	-.332
MAE	14.261	1.843
RMS	23.820	2.684
N	6481	6267
Cloud Top Height (100s ft)		

List of Statistical Results		
	Colorado Domain	STORM-FEST Domain
ME	14.801	-4.340
MAE	77.077	77.869
RMS	95.340	107.390
N	777	713
Ceiling Height (100s ft)		
ME	.211	-.525
MAE	6.468	5.682
RMS	12.887	13.990
LOG	.097	-.001
N	1222	1262
Visibility (miles)		
ME	1.549	0.02
MAE	2.602	0.74
RMS	5.190	1.37
LOG	0.066	0.009
N	1930	2610
Precipitation Amount (in./1-h)		
ME	-0.010	-0.004
MAE	0.012	0.006
RMS	0.034	0.027

List of Statistical Results		
	Colorado Domain	STORM-FEST Domain
N	3736	1678
ICING		
PODyes	0.718	0.564
PODno	0.500	0.760
BIAS of Yes	0.808	0.580
BIAS of No	2.070	6.670
FAR	0.111	0.028
CSI	0.659	0.555
HSS	0.151	0.094
TSS	0.218	0.342
Pct Correct (%)	68.48	57.85
TURBULENCE		
PODyes	0.783	0.841
PODno	0.310	0.367
BIAS of Yes	1.240	1.190
BIAS of No	0.634	0.654
FAR	0.371	0.292
CSI	0.536	0.624
HSS	0.097	0.222
TSS	0.091	0.204
Pct Correct (%)	59.29	67.24

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