ASOS HEATED TIPPING BUCKET PERFORMANCE ASSESSMENT AND IMPACT ON PRECIPITATION CLIMATE CONTINUITY

Richard D. Butler

Thomas B. McKee

Atmospheric Science Department
Colorado State University
Fort Collins, CO 80523-1371

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ABSTRACT

ASOS HEATED TIPPING BUCKET PERFORMANCE ASSESSMENT AND IMPACT ON PRECIPITATION CLIMATE CONTINUITY

The National Weather Service (NWS) has been installing Automated Surface Observing Systems (ASOS) at all first order weather stations since 1991 as part of the NWS modernization program. This program was a joint effort between the NWS, Federal Aviation Administration (FAA), and the Department of Defense (DOD) to automate the measurement of surface meteorological elements. The introduction of this system has brought with it inherent differences in the measurements of the meteorological parameters induced by instrument changes and spatial variation brought on by the decision to change the locations of official observing sites. The instrument of concern in this study was the gauge measuring accumulated liquid precipitation, the Heated Tipping Bucket Rain Gauge (HTB). ASOS uses a non-linear correction algorithm to produce a corrected accumulated precipitation measurement which is intended to correct one-minute precipitation totals with a more significant correction being made during higher rain rate events. Early comparisons of HTB to the Universal Rain Gauge (UNIV) at sites located in the Midwestern U.S. uncovered a significant pattern of undermeasuring accumulated liquid precipitation by the HTB. ASOS HTB Modification 35 (MOD 35) began in early 1996 to correct problems with the HTB including its tendency to undermeasure liquid

precipitation. Thus, the scope of this investigation was to assess the operational performance of the HTB MOD 35 gauge at 4 sites and to quantify the impact of the ASOS HTB on climate continuity at 13 sites located around the country.

Examination of total accumulated precipitation measurements made by operational HTB gauges, taken from 1 minute recorded observations (1MIN), compared to Collocated Rain Gauges (CRG) showed the HTB to be performing quite well. The ratios of total accumulated precipitation from the HTB 1MIN to the CRG compiled from data at Greenville/Spartanburg, South Carolina (GSP), Jackson, Mississippi (JAN), Lake Charles, Louisiana (LCH), and Springfield, Missouri (SGF), showed values of: 0.97, 0.93, 1.02, and 1.02 respectively. Slope measurements from least-squares fit line analyses of HTB 1MIN versus CRG comparisons at these four sites produced values of: 0.97, 0.92, 1.02, and 1.03 respectively. The high order of stability in the data used to generate these slope measurements, and the demonstrated agreement with the total accumulated precipitation ratios indicate that the confidence in these ratio values is high. Even though the ratios and least squares slope measures from each individual station would suggest that the HTB is performing well, the variation in HTB to CRG relationship among the four stations illustrates that the single precipitation correction algorithm used in all of the 933 ASOS units does not produce a uniform HTB to CRG relationship. Results from this study suggest that an additional site specific linear correction must be made to the existing generic ASOS non-linear precipitation accumulation correction algorithm.

We examined the combined impacts of the ASOS HTB and its new observation site by comparing ASOS HTB measurements to UNIV measurements. The combined impacts of the new gauge and the siting variation are inseparable given that the collocated precipitation measurement relationship between the HTB and UNIV is not understood for each site from the data used in this investigation. The results of the comparisons indicated a significant range of variation, even in locations where the ASOS and UNIV separation distances were as small as 660 ft. This variation was illustrated through a comparison of 1MIN, hourly (HRLY), and Summary of the Day (SOD) products from ASOS to UNIV measurements at 13 sites.

The climate continuity analysis performed at Wilmington, North Carolina (ILM) revealed that the combined effects of instrumentation differences and a separation distance between ASOS and UNIV of a little more than a mile resulted in a 13% undermeasuring of total accumulated precipitation by the HTB. Circumstantial evidence indicated that this result could primarily be attributed to spatial differences due to convective precipitation.

From the results of the HTB 1MIN to UNIV total accumulated precipitation ratios for Jackson, Kentucky (JKL) and Paducah, Kentucky (PAH) of 0.90 and 0.77 and slope measurements of 0.87 and 0.81, respectively, the gauges at these 2 sites were identified as faulty gauges. The spatial distance between the gauges was less than 1300 ft; therefore, it is likely that the difference is due to ASOS instrumentation errors, not spatial variation. The comparison of the above ratios to the SOD to UNIV ratios, 1.00 and 0.98, and to the slope measures of 1.00 and 0.96, leads to the conclusion that NWS Offices responsible for these sites edited the ASOS SOD accumulated precipitation totals to provide more accurate rainfall representation in their respective climate records.

The final assessment put forth by this investigation, is for the 11 remaining sites, after excluding results from JKL and PAH. The effect of the ASOS program and site relocation on precipitation climate continuity at each individual site is conservatively estimated to be in the range of ± 10%. The effect is nearly negligible when the results from the individual sites are averaged as a collective group.

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1.0 INTRODUCTION

This paper presents results from an in-depth analysis of precipitation data collected during the *Climate Data Continuity Project* (CDCP) with the Automated Surface Observing System (ASOS), Figure 1.1, which was introduced in 1991. The project was designed to evaluate the performance of ASOS and the impact it would have on the continuity of the climatological records. To conduct the precipitation portion of the evaluation, measurements were collected and intercompared from Universal Weighing Rain Gauges (UNIV) at 13 National Weather Service (NWS) Field Offices (WFO), 13 remotely located commissioned ASOS arrays, and 4 Rain Gauges (CRG) collocated with ASOS. The ASOS measures precipitation with a custom-engineered Heated Tipping Bucket Rain Gauge (HTB).

Early investigations of ASOS precipitation accuracy began during the first stages of ASOS installations where it was discovered that a small number of ASOS sites in the central U.S. were frequently undermeasuring precipitation when compared to the UNIV that the HTB replaced. The HTB was found to be inadequate for observing frozen precipitation (McKee et al, 1995), and at many sites rainfall was undermeasured, particularly at greater rainfall rates. After the NWS conducted its own performance investigation of the HTB from 1993-1995, modifications were made to the gauge. These modifications, known as MOD 35, include a funnel tube extension, tipping assembly magnet, and reed switch upgrade, and tipping mechanism stops. Prior to fielding this

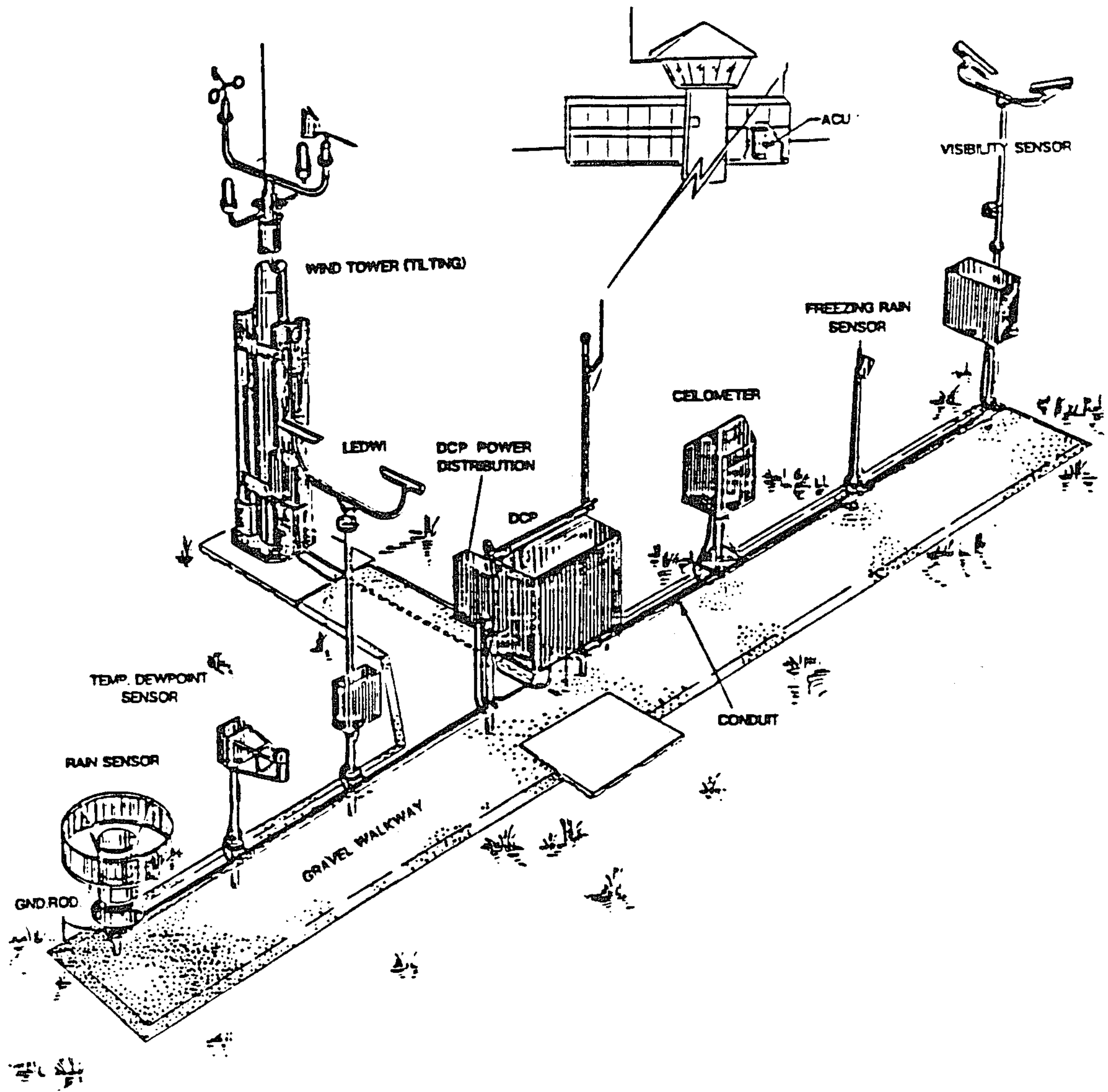


Figure 1.1 Typical ASOS Sensor Array. (ASOS LEVEL II Systems Manager Training Course Student Guide, 1992)

modification, an evaluation of the MOD 35 HTB compared to the Standard 8″ Non Recording Rain Gauge (SRG) was performed at the NWS Sterling Research and Development Center. The evaluation period was limited to a total gauge catch of 2.0 inches or 30 days, whichever criteria was met first. Results presented in an April 11, 1996 internal NWS memorandum showed that the HTB undermeasured by 2.4% which was within the ±4% design criteria (Dinges, 1996). All 13 of the sites in this comparison study received MOD 35 prior to the start of data collection.

Since the CDCP used four CRG's, some of the results of the CDCP will add information taken from the operational setting in contrast to the dedicated tests performed at the NWS Sterling Research and Development Center.

1.1 Modernization

In keeping with an agreement reached in the late 1980's between the National Weather Service, Federal Aviation Administration, and the Department of Defense, the National Weather Service has been installing ASOS throughout the United States since 1991 (Nadolski, 1995). The installation of these automated systems is an ongoing portion of the National Weather Service's Modernization Plan. As of October 1, 1997, there were 933 ASOS arrays installed throughout the country (Nadolski, 1998).

The primary mission of the ASOS program was to field an array of instrumentation to automate weather observations. This automation was intended to reduce costs, expand areal coverage, provide data 24 hours each day, and eliminate the subjectivity inherent in some manual observations such as visibility and estimates of wind (Shrumpf et al, 1996). An introduction to ASOS is included in the *ASOS User's Guide*

(National Weather Service, 1998). ASOS is a microprocessor-based system which uses an array of sensors with advanced algorithms to process not only synoptic weather data, but to disseminate a Surface Aviation Observation (SAO) for the station (Nadolski, 1995). As of July 1996, the ASOS was producing a METAR format observation instead of the SAO.

1.2 The Data Set

All of the ASOS data sets used for this analysis were provided by the National Climate Data Center (NCDC) in Asheville, North Carolina. The ASOS One Minute (1MIN) observation data were downloaded by NCDC every 12 hours from each ASOS unit in the study. These data, along with the hourly ASOS METAR (HRLY) observations and ASOS Summary of the Day (SOD) were disseminated electronically to the Colorado Climate Center (CCC) at Colorado State University, Fort Collins, Colorado, for the CDCP with the ASOS HTB.

Data from the UNIV was manually read by each participating WFO from the recorded strip charts to produce 6 hour precipitation totals manually transferred to monthly precipitation summary data sheets. These monthly data sheets were then mailed to CCC where they were manually digitized for use in the analysis. It should be noted that the UNIV and ASOS array are geographically separated up to one in distance.

In addition to the above data, four WFO locations placed a rain gauge, CRG, within a few feet of the HTB. Two of the four sites collocated an SRG with ASOS while Springfield, MO (SGF) used a Non-Recording 4″ Gauge and Lake Charles, LA (LCH) used a UNIV. These gauges were read periodically throughout a given month, and precipitation totals and observation times were recorded. Again, data was sent to CCC for intercomparison with the 1MIN, HRLY, SOD, and UNIV data

For the purpose of this study, it should be noted that all precipitation events in which the temperature dropped below 3°C were eliminated in order to remove any possible snow or freezing precipitation events. The current HTB in use has inherent inaccuracies that make it unsuitable for measuring winter precipitation accumulations. A test conducted at Marquette, Michigan by the NWS Office of Hydrology showed a catch deficiency by the HTB during solid precipitation events of nearly 30% when compared to an SRG during the winter of 1994-1995 (National Weather Service, 1996).

For performance and spatial comparison of the HTB to the UNIV at all 13 sites and the CRG at 4 sites, approximately 6,665,000 1MIN observations were analyzed. Of the three data sets providing precipitation measurements recorded by ASOS, the 1MIN data provides the only recorded observations to which the CCC had access for this study that could not be edited by the ASOS's controlling WFO assigned operational responsibility. Hence, the 1MIN observations provide the most accurate event data for HTB performance assessment when compared with UNIV and CRG observations, barring any malfunctions. HRLY and SOD reports are subject to quality control procedures, outlined in the *Quality Control of ASOS Observations*, in which an ASOS measurement can be manually edited (Mannarano, 1997). HRLY and SOD reports are, however, important in investigating WFO practices of altering ASOS precipitation reports and possible erroneous measurements discovered in the 1MIN observation data. This study will assess precipitation climate continuity with 1MIN, HRLY and SOD measurements compared to the UNIV.

1.3 The Purpose

The NWS is in the final stages of the ASOS installation; all installations are scheduled to be completed by late 1998 (Nadolski, 1998). The intent of this study is to determine the performance and climate impact of the ASOS HTB by comparing the HTB observations to the CRG and UNIV gauges previously used by the NWS at first order weather stations. Since the NWS Sterling Research and Development Center uses the SRG as ground truth when testing prototype and modified field gauges such as the prototype for the All Weather Precipitation Accumulation Gauge (AWPAG) and HTB MOD 35 respectively, the 1MIN observation accumulations were compared to the CRG at four sites to assess HTB performance. Furthermore, the comparison of 1MIN data with UNIV data is intended to provide insight to the impacts introduced to the climatological record for each WFO due to the instrument and location change of the official precipitation measurement site. Comparative analysis of the 1MIN observations to results produced from the UNIV also provides a subjective evaluation of HTB performance.

2.0 THE DATA

2.1 The Instruments

The three instruments compared in this study are very different in the methodology they use to derive precipitation accumulation to a resolution of 0.01″. The automated HTB, as depicted in Figure 2.1, accumulates precipitation through a tipping mechanism. Every tip constitutes an uncorrected 0.01″ of precipitation. The UNIV gauge in Figure 2.2 uses a precipitation weight equivalent in order to measure precipitation and records the running total on a revolving strip chart. Finally, the SRG shown in Figure 2.3 collects precipitation into a smaller internal cylinder which is read manually with the use of a container specific measuring stick. It should be noted that the latter two gauges must be read and recorded manually to document precipitation accumulated over time. Thus, both the UNIV and SRG introduce a human error factor which ultimately lead to the possibility of undetectable errors in the data being compared to the HTB.

2.1.1 HTB

The HTB is manufactured by the Frise Engineering Company of Baltimore, MD. This gauge is a modified version of the Belfort tipping bucket precipitation accumulation gauge (National Weather Service, 1995). The HTB gauge operates by catching precipitation in a 12″ diameter open funnel. The water is funneled down a tube and

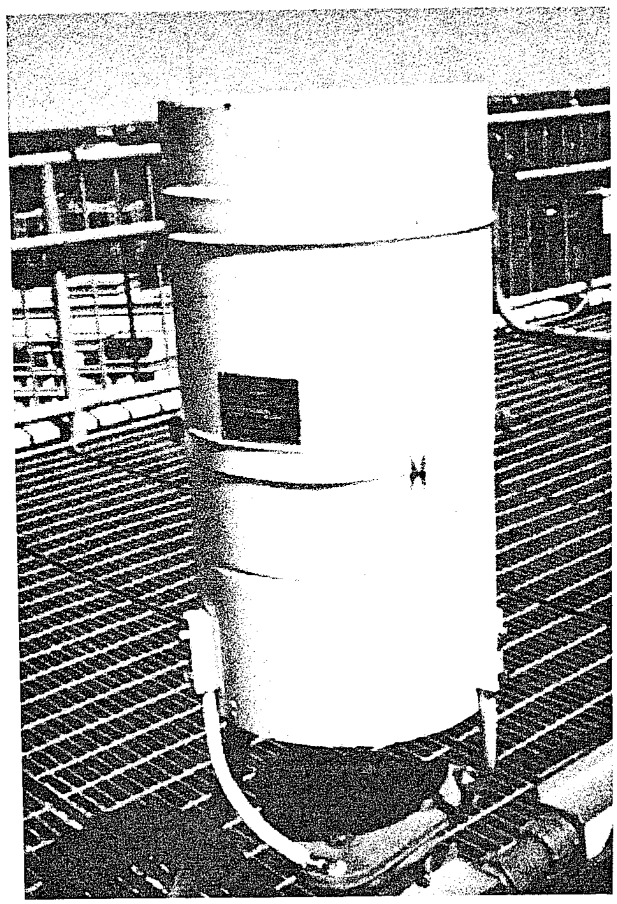


Figure 2.1 ASOS Heated Tipping Bucket (HTB). (National Weather Service, 1997)

Figure 2.2 Universal Weighing Rain Gauge. (Belfort Instruments, 1985)

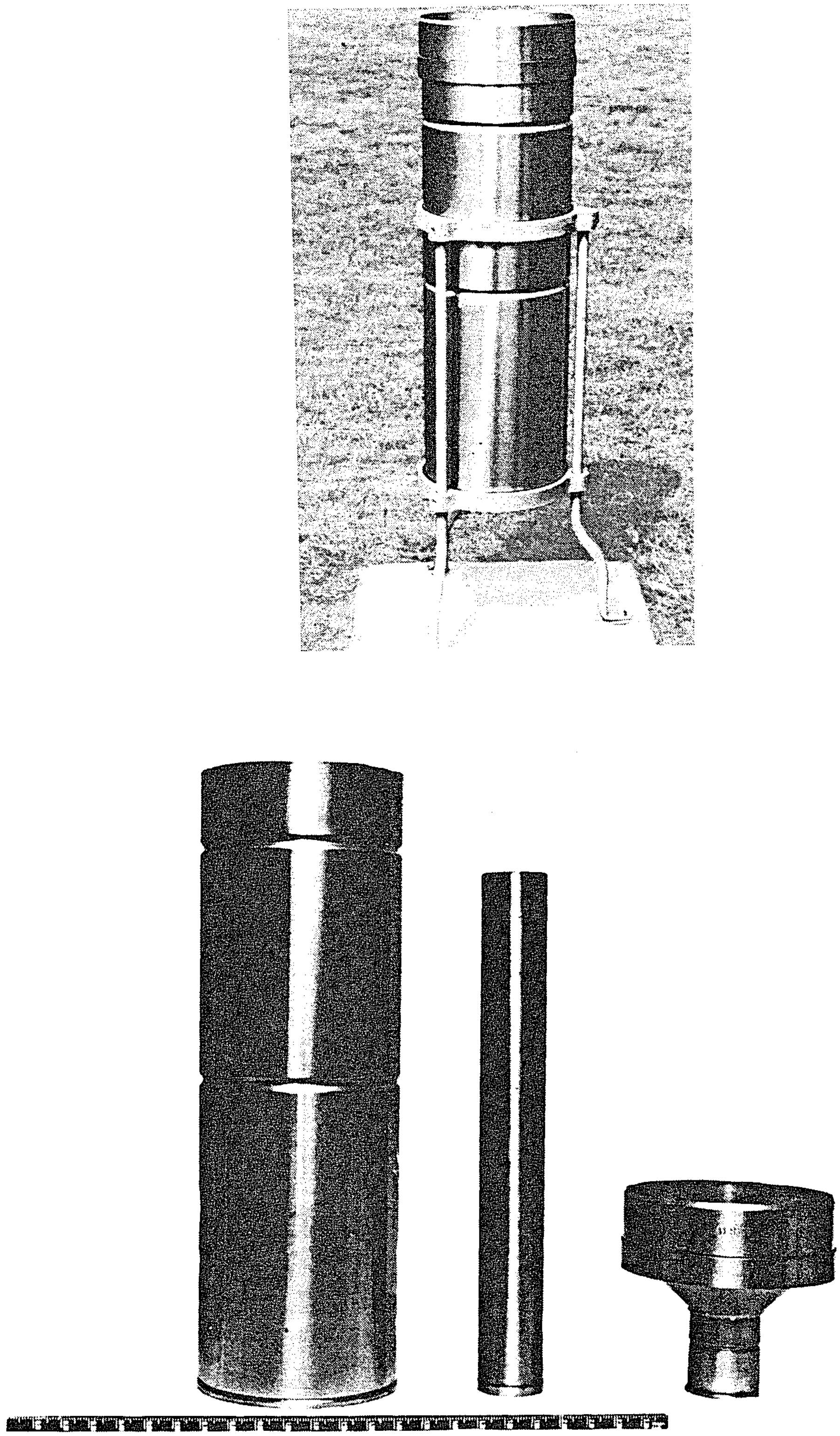


Figure 2.3 Non-Recording Standard Rain Gauge shown in (A) Installed Gauge and (B) Indiviual Gauge Parts. (National Weather Service, 1972)

released directly into a light, metal, two compartment, divided bucket which is balanced in unstable equilibrium about a horizontal axis. In its equilibrium position, the bucket in the HTB rests on one of two non-corroding, polyethylene stops which controls the collecting reservoir's range of motion. After the raised bucket collects the predetermined, uncorrected 0.01″ of precipitation, the bucket becomes unstable about its horizontal directed tip axis and empties the accumulated uncorrected 0.01″. As the bucket tips in the HTB, a magnet moves past a sensor called a reed switch that electronically signals the accumulation of an uncorrected 0.01″ of precipitation. After each tip, the measured water is released through a funnel out of the bottom of the gauge.

The ASOS HTB is manufactured and adjusted by the Frise Engineering Company and is delivered to the NWS where a 100 tip constant rain rate test is accomplished. HTB gauges that pass the NWS 100 tip test within ±4% are then sent to ASOS units for installation. A final 10 tip functional test is performed on the HTB after the installation is completed. Once the HTB is shipped from the manufacturing facility, no calibration adjustments can be made to the unit.

As described in the originally agreed upon specifications for ASOS, the HTB, used solely as the liquid precipitation accumulation sensor, must be capable of measuring the amount of precipitation accumulated within a range of 0 to 10 inches per hour, with a measuring resolution of 0.01″, and measuring with an accuracy of ±0.02″ or ±4% of the hourly total, whichever is greater.

According to *Algorithms for the Automated Surface Observing Systems* (Chu, 1994), the ASOS obtains a cumulative precipitation measurement for the past minute to the nearest 0.01″. There is a built-in algorithm that is used to apply a rainfall rate correction to the measured amount using the following equation:

$$C = A + 0.60A^2 \tag{2.1}$$

where C is the corrected cumulative precipitation for the minute rounded to the nearest 0.01″, and A is the uncorrected cumulative precipitation amount derived from the number of tips recorded by the HTB. If the cumulative precipitation reading from the HTB is not available, then the one minute precipitation total is set to read "missing." When the cumulative precipitation amount is available, and the previous minute's cumulative precipitation is 0.01″ or greater, the above algorithm is applied providing a corrected cumulative precipitation measurement which is recorded in the 1MIN observation. Any remaining digits past the hundredths place from the corrected cumulative precipitation calculation are stored in memory until remainders from successive calculations add up to 0.01″ at which time it is reported in addition to the corrected cumulative precipitation measurement in the 1MIN observation. This process of correcting precipitation makes it impossible to reconstruct the actual number of tips made by the HTB.

The basic tipping bucket rain gauge design has some unique sources of error that should be noted. Sources of error that involve undermeasuring accumulated precipitation include heavy rain events. During such events, as the bucket tips, precipitation can continue to add to the already filled reservoir prior to the passage of the partition separating the filled container from the empty one. Thus, more water passed through than was indicated by the predetermined value of one tip. Another source of undermeasuring can result when moisture adheres to the bucket and is not completely eliminated during the emptying stage of the tip. The bucket was designed to create a precise counterweight;

therefore when that weight is increased by the moisture, additional precipitation is required beyond the predetermined 0.01″ in order to initiate a tip. Tests on waxed buckets produced a 4% reduction in the volume required to tip the balance over non-waxed buckets (World Meteorological Organization, 1996). Error can also result during the transfer of precipitation from the funnel to the tipping bucket. Depending on the distance and alignment of the funnel with respect to the bucket assembly, precipitation may miss the catchment area of the tipping bucket or force premature tips by funnel induced spiraling motions as accumulated precipitation converges and exits out the bottom of the funnel towards the tipping bucket.

Finally, the tipping bucket, just like the UNIV and CRG, is susceptible to wetting and evaporation errors as well as wind induced catch errors. An analysis of wind effects as related to catch differences was accomplished and is later discussed in Section 3.3.4.

2.1.2 UNIV

In the mid 1930's a number of stations became equipped with one of three designed weighing-type recording rain gauges, with the UNIV being the most generally used. The gauge consists of an 8″ diameter receiver through which precipitation is funneled into a bucket mounted on a weighing mechanism. The weight of the precipitation catch is recorded on a clock driven chart as inches of precipitation. The gauge has a standard capacity of 12″ of precipitation and has to be manually emptied.

The UNIV, being susceptible to wind induced catch errors is also vulnerable to a condition known as wind pumping (World Meteorological Organization, 1996). Wind pumping results from high winds creating turbulent motions around the precipitation catchment orifice which cause oscillations in the weighing mechanism and produce errors in the recorded precipitation chart. In addition, friction within the moving parts of the weighing mechanism, if not properly maintained, can cause undermeasuring errors in the UNIV.

2.1.3 SRG

The SRG has been used from the inaugural years of the Weather Bureau to the modern day NWS as the official precipitation measurement device.

The device consists of three parts: the 8″ receiver or funnel, the 8″ overflow receptacle, and the measuring tube with a diameter of 2.53 inches. The tube is designed so that the true rainfall collected in the receiver is magnified 10 times; hence, the depth can easily be measured to a precision of a hundredth of an inch.

A performance evaluation of the SRG was accomplished at the Valdai Polygon, Russia by Golubev et al., 1992. The SRG was among the many gauges that were installed at this testing location in the mid 1960's and were tested until 1970. Tests at Valdai illustrated that the SRG is susceptible to the negligible wetting and evaporation errors along with a negligible systematic bias in precipitation readings due to capillary and meniscus forces at the interface between dry and wet portions of the dipstick (Golubev et al, 1992).

2.2 Site Locations

NWS sites participating in this study did so on a voluntary basis. Federal Aviation Administration (FAA) sites were not allowed to be used in the CDCP with

ASOS HTB project. The 13 stations with the MOD 35 upgrade, displayed in Figure 2.4, were selected based on a defined set of criteria. Since the ASOS array's installation location differs from the location of the UNIV, it was necessary to develop guidelines to make the stations within the study as uniform and comparable as possible. Thus, three requirements were established for stations entering the study. The first of these requirements was that the ASOS array be within one mile of the UNIV. An exception was made in the case of Wilmington, North Carolina, ILM, in which the ASOS and HTB were between 1 and 1 1/16 of a mile apart. Requirement two stipulated that the UNIV could not be located on a rooftop. One exception was made for Seattle, WA, SEA, because they made a special request to be added to the study. The third and final constraint placed on sites that were allowed to enter the study was that the UNIV could not have been moved as a result of a WFO building relocation.

Table 2.1 gives a complete listing of all the stations that participated in the study including station identifier (SID), station name, station location, study participation dates,

Table 2.1 ASOS Site Summary

Station ID	Station Name	Period of Study	MOD 35 Installed	Shielded ASOS	Shielded UNIV	≅ Distance (ft.) ASOS-UNIV
ALB	Albany, NY	Aug 96-May 97	7/31/96	Y	Y	N/A
AMA	Amarillo, TX	Jul 96-May 97	5/21/96	Y	Y	5419
AST	Astoria, OR	Jul 96-May 97	5/21/96	Y	Y	660
BRO	Brownsville, TX	Oct 96-Aug 97	6/27/96	N	N	N/A
CAE	Columbia, SC	Jul 96-Jun 97	5/7/96	N	N	1320
GSP	Greenville/Spartanburg, SC	Jul 96-May 97	5/14/96	N	N	365
ILM	Wilmington, NC	Jul 96-Apr 97	5/6/96	N	N	5280-5808
JAN	Jackson, MS	Jul 96-Nov 97*	6/27/96	N	N	829
JKL	Jackson, KY	Jul 96-Nov 97*	5/9/96	N	N	1200
LCH	Lake Charles, LA	Jul 96-May 97	5/96	N	N	3300
PAH	Paducah, KY	Jul 96-Nov 97*	5/17/96	N	Y	1320
SEA	Seattle, WA	Jul 96-May 97	6/3/96	N	N	2640-3960
SGF	Springfield, MO	Jul 96-Nov 97*	6/3/96	Y	N	2970

* September 1997 ASOS 1MIN observations unavailable from NCDC

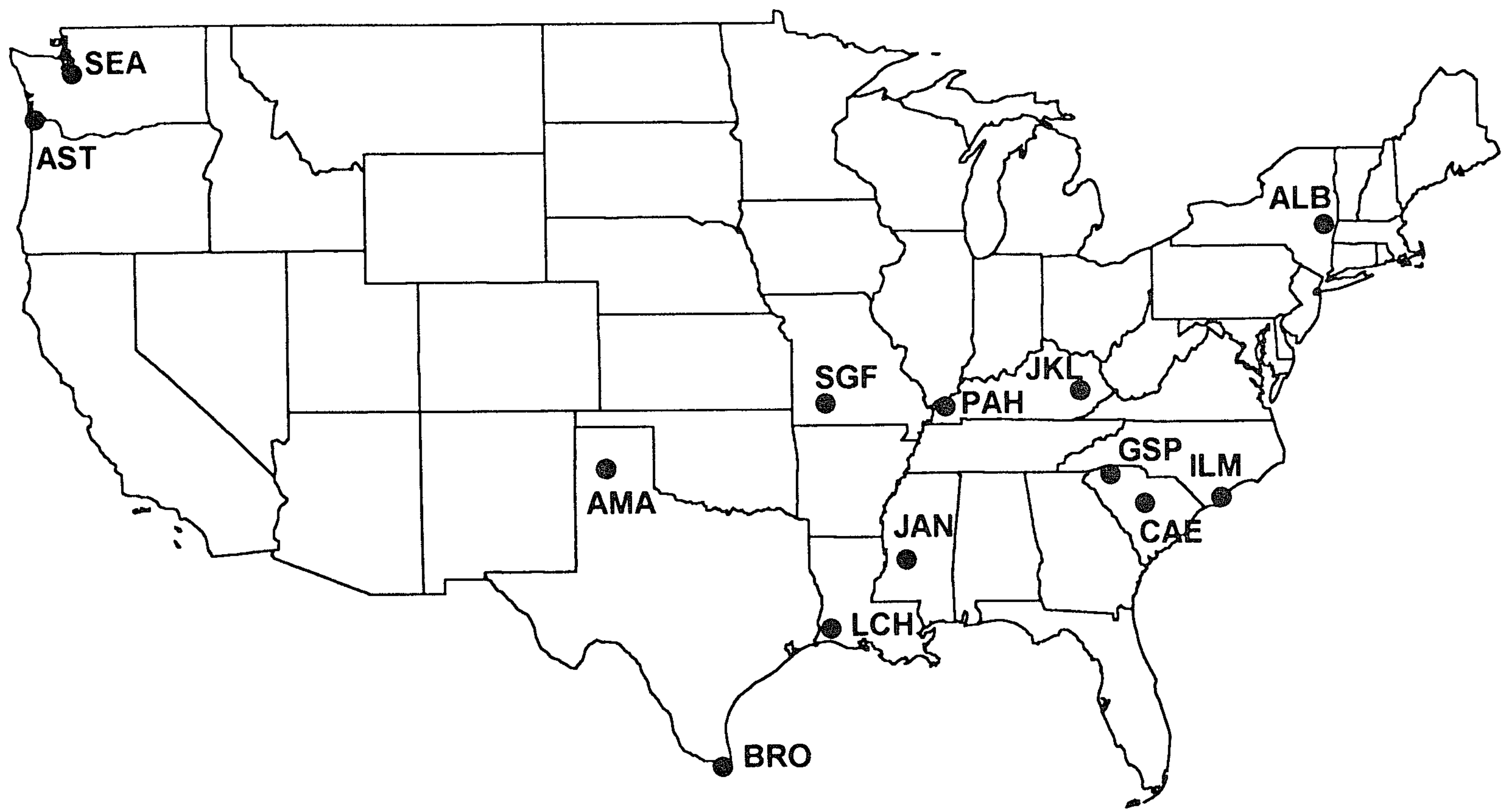


Figure 2.4 ASOS locations used in the CDCP with the Heated Tipping Bucket (HTB).

and HTB modification date if available. The distance between the ASOS HTB and the UNIV are included along with the indication of shielded or non-shielded instruments.

2.3 Observations

The data examined in this study consist of over 6,665,000 1MIN observations from the 13 stations that participated. ASOS HRLY observation and SOD reports also represent HTB measurements in this study. Additionally, the monthly summaries of 6 hour UNIV precipitation totals from all stations and monthly CRG summary data from a smaller subset of four stations are included. July 1, 1996 marks the beginning of the study for some of the stations in the study with 12 of the 13 stations active in the study by October 1996. The end date established for the purpose of this document was November 30, 1997. There were still a few stations actively participating beyond the above mentioned end date.

When intercomparing the available data fields in a study such as this, the various methods employed to create each individual report must be fully understood in order to correctly compare the data sets described in this investigation. The 1MIN observations are a summary of the number of corrected tips resulting after the precipitation algorithm has been applied. The HRLY observations are the sum of the previous 60 minutes of observations and are reported at 56 minutes past the hour. The SOD contains the summary of all precipitation that has occurred from Midnight to Midnight over a consecutive 24 hour period. The UNIV 6 hour totals from the 00, 06, 12, 18 GMT were manually extracted and recorded by WFO personnel onto a monthly summary sheet after being read from the recorded strip chart produced by the UNIV. The time accuracy of the

UNIV is a function of the accuracy of the observer and the internal clock drum in the gauge. Finally, the CRG measurements were read at varying, and often long, time intervals. Thus, for correct intercomparison between the data fields available for analysis, it was necessary to compare events from start to finish. In this analysis, especially when accomplishing comparison between the HTB and CRG data, the non-synchronized gauge reading times made it necessary to accumulate precipitation over multiple events in order to avoid interrupting an event at any given gauge. In some cases this lead to an accumulation period over several weeks long. This solved the possible problem of comparing data sets that might not have been exposed to an equal number of event periods.

Events were eliminated after review if it was determined that missing observations during an event or comparison period lead to undermeasuring of an event within a given data field. It is important to mention that, overall, approximately 10% of the HTB 1MIN data was unavailable for use in this investigation. Notably, approximately 20% of the HTB 1MIN data was unavailable to the study from July through September of 1996. Additionally, lack of 1MIN data in the last week of December 1996 contributed to an unavailability near 16% for that particular month. The degradation of the 1MIN data during the summer of 1996 was a result of communication hardware limitations interfering with NCDC's download of each ASOS's complete 12 hour 1MIN data archive prior to the programmed automatic erasure of the local ASOS 1MIN observation memory. It is important to reiterate that only events with complete 1MIN data records could be compared to CRG and UNIV measurements because the

1MIN data was the only unaltered ASOS HTB data field available to this study; thus it alone revealed exactly how the HTB performed.

3.0 PRECIPITATION ACCUMULATION COMPARISON

3.1 Concepts

The installation of ASOS marks a transition in the method of observation in the NWS from a human process to a fully automated observation one. It also creates two other important factors: a change in instruments and a change in location. All of these factors have compounding effects on the local climate record and, more importantly, on the climate record as an aggregate. Any observed precipitation accumulation differences between the HTB and the UNIV will be a result of a combination of the above mentioned inseparable factors.

For each station, the 1MIN observations were summed into appropriate hourly totals. These HTB 1MIN combined hourly totals were then available for comparison with UNIV and CRG data sets. An assessment of the performance of the HTB to the CRG at the four sites was achieved by using the following equation:

$$\text{Performance Ratio} = \sum \text{ASOS}_{1\text{MIN}} / \sum \text{CRG} \qquad (3.1)$$

In order to ascertain the impact of the ASOS program to the precipitation record at each of the 13 sites, a variation of equation 3.1 was used yielding equation:

$$\text{Impact Ratio} = \sum \text{ASOS}_{1\text{MIN}} / \sum \text{UNIV} \qquad (3.2)$$

By taking the average of the calculated impact ratios across all sites, an assessment of the mean impact of the HTB on the collective group of CDCP stations can be accomplished.

The other data fields contributed to by the HTB, namely the HRLY and SOD reports, are not used to directly assess the HTB performance. Rather they are used to qualitatively assess the quality control practices of each WFO in the study, the inherent impact on each station's climate record, and the impact on the collective climate record of the group of stations in this study.

3.2 Data Problems

There are several problems that need to be addressed within the group of data sets that have been used to construct this analysis. Without fully understanding the errors that are possible, incorrect conclusions may be derived with respect to the quality and reliability of the HTB.

3.2.1 ASOS 1MIN

Let us first discuss errors that were discovered in the 1MIN observations. It must be stated that the errors detailed below cannot be explained in their entirety due to our inability to obtain and decode the system log files for use in this study. These system logs are produced on any ASOS array and detail when a particular instrument system is inoperative or any ASOS product is edited. Even though the 1MIN observations are not edited, detailed instrument outage records would have enabled this study to omit data that may not have otherwise been flagged as an inaccurate accounting of a precipitation event. Having made that point, this analysis of HTB data illustrates that it is possible for unrealistic values to show up in the precipitation accumulation field. For example, over a three minute period on June 10, 1997 at Jackson, MS (JAN), ASOS reported 2.18″

observations regardless of the magnitude of differences if meticulous analysis suggested that data from each instrument was complete. An event was only removed from the study of it was evident that part of the data record was incomplete for one of the instruments.

3.2.2 ASOS HRLY

In this study, the ASOS HRLY observations served mainly to confirm or deny the validity of the 1MIN observations. Therefore, the errors encountered in this particular data set, though worthy of being recognized, are not entirely crucial to the validity of the study. The errors are, however, relevant to any researcher using HRLY observations for the construction of any type of precipitation climatological record.

It was noticed that on occasion the HRLY observations suffered from what has been identified as a "warm start" problem caused by "improper parameter size" errors produced within the ASOS Acquisition Control Unit (ACU) software version 2.40 (National Weather Service, 1998a.). This warm start problem manifests itself when the system memory is inadvertently cleared and thereby removes any accumulated precipitation totals since the last precipitation report had been registered. For example, on July 2, 1996 at SGF, the complete precipitation reports from HTB 1MIN, HRLY and UNIV show 1.12″, 0.55″, and 1.26″, respectively. This indicates a clear example of the "warm start" phenomenon. The "warm start" problem is to be corrected by the release of ASOS ACU software version 2.60 (National Weather Service, 1998a.). Another problem encountered in this data set was the incomplete reporting of precipitation in what will be identified here as a "P" group. It is found in the remarks section of an HRLY observation report in which precipitation accumulation is being reported. There were numerous accumulated precipitation. At 2134 LST, the first minute of the suspect 1MIN reports, the 1MIN data showed 0.15″ accumulated precipitation. The next two minutes chronologically reported 1.66″ and 0.28″ precipitation. This erroneous event was verified and eliminated from the analysis through intercomparisons with the HRLY and the SOD and from the absence of any measured precipitation at the UNIV during the 6 hour period which would have contained such an event.

Further cross-analysis of possible erroneous events against the ASOS's Light Emitting Diode Weather Identifier (LEDWI) which is designed to differentiate between rain and snow for ASOS proved fruitful in eliminating large 1MIN observed precipitation amounts. Reports from the HTB and LEDWI are independent of one another. Examination of both the coinciding LEDWI data for "no precipitation" (NP) observations and HTB observations before and after a false positive precipitation report brings forth a higher level of confidence in interpreting and eliminating false positive accumulation occurrences. Making the same conclusions about false zero precipitation 1MIN observations using LEDWI reports of positive precipitation does not lead to any concrete conclusions. Reports of rain of varying intensity by the LEDWI when no precipitation accumulation was recorded by the HTB is encountered frequently throughout the data. Intuitively, the rate at which the HTB reports tips is a direct function of rainfall rate or intensity; thus, the report of a single or multiple corrected tip is not required in every 1MIN observation.

To reiterate, without access to the necessary system logs, conclusions to the above detailed false measurements can only be speculative. Therefore, it was the policy of this investigation not to discard precipitation measurements of the UNIV, CRG, and 1MIN occasions at all of the sites in this study in which the "P" group was immediately succeeded by only three of the required four digits. In most cases, this meant that the hundredths digit had been truncated, but there were instances in which comparison against the 1MIN accumulated hourly precipitation suggested that the tenths digit was omitted. It can not be determined whether this problem originates in ASOS or in the processing of the data at NCDC prior to electronic dissemination to CCC for use in this study. Occurrences, while numerous in the fourth quarter of 1996, have become nearly nonexistent for 1997 data used in this study. All of the aforementioned problems can be corrected during a quality control audit accomplished at the WFO if detected during the correction period prescribed in the NWS policy on quality control for ASOS observations unless the problems originate at NCDC.

3.2.3 ASOS SOD

Few errors were detected in the ASOS SOD data set. The data set, however, was not provided in the electronically disseminated reports from NCDC until October 1996. Therefore, there are several stations in this study that have less than a year of this data subset for comparison.

As stated earlier, this is a data set that is edited at the discretion of each WFO Office. Hence, this data only provides insight on the climatological record over the period of study and, more importantly, whether precipitation measurements in the SOD are actual ASOS derived precipitation totals or edited reports consistent with the UNIV.

3.2.4 UNIV

Errors within the UNIV data set are generally undetectable by this investigation. These undetectable errors can be broken down into categories of instrument and human error. Instrument errors would results from improper operation of all the mechanical components contained within the UNIV. Human errors can be inadvertently introduced in a variety of ways from incorrect installation of the recording charts to erroneous transfer of data recorded on the strip charts to the monthly summary sheets. The errors outlined above are by no means an all-inclusive list of errors that could contaminate the data used in this study. Since there are no means available to quantify the significance of the above mentioned errors in our data set, an artificiality will be introduced by assuming that these errors are negligible in magnitude.

Occasional detectable errors discovered during the digitization of this data set include entries on the monthly summary sheet for which precipitation totals were wrongfully entered into time/date fields, usually ±24 hours or one row too high or low on the summary sheet. In other instances, data was recorded from the UNIV and annotated that timing of precipitation was unknown, most likely due to some type of malfunction by the clock and/or strip recorder. Overall, participating WFO stations were thorough in reporting the 6 hourly UNIV precipitation totals; but nonetheless, there were discontinuities in these records that precipitated event omissions from this study.

3.2.5 SRG

Since the SRG does not have moving parts and is a non-recording gauge, errors introduced to this investigation are mainly due to human error. Such errors materialize when the observer reads and/or records the data incorrectly. Blatant errors in the SRG data are evident when the 1MIN observations and UNIV show reasonable agreement and the SRG grossly under or overmeasures with respect to the other gauges. A quantitative assessment of an evaporation induced error is unavailable, but it should be recognized as a possible source of error due to the random, and in some cases, lengthy (i.e. approximately 7-10 days) period of time between SRG readings.

3.3 Analysis Method

3.3.1 Eliminated Data

In order to assess HTB performance and its impact on the climate record, it was necessary to gather and compare the most error-free data possible. The events eliminated are listed in Table 3.1. Events eliminated due to ASOS malfunction were done so by analyzing the 1MIN data for events greater than 0.01″ with LEDWI reports of NP. In each case, significant accumulations were measured in a one minute period with no precipitation being reported by the LEDWI or HTB for the five minutes leading to or after the event in question. Events eliminated due to "ASOS PNO" in the remarks section of Table 3.1 were done so by seeing that the HTB 1MIN showed long time periods (e.g. 6 hours or longer) of consecutive zero accumulated precipitation while UNIV measured considerable accumulated precipitation totals. Investigation of coinciding HRLY observations for the questioned 1MIN data uncovered "PNO" alerts in the remarks section indicating that the HTB was non-operational (National Weather Service, 1998a.). The removal of events from comparison due to "Unsure of UNIV value" were done so because of the sizable accumulations reported within the 1MIN and HRLY data with zero

Table 3.1 Eliminated data from comparisons

Station	Date	UNIV	CRG	1MIN	HRLY	Remarks
ALB	9/24/96	0.00	N/A	0.15	0.15	Unsure of UNIV value
ALB	11/19/96	0.00	N/A	0.41	0.41	Unsure of UNIV value
BRO	8/5/97	0.30	N/A	0.00	0.00	ASOS PNO
BRO	8/26/97	1.32	N/A	0.09	1.02	ASOS PNO
ICT	10/27/96	0.70	N/A	0.02	Trace	ASOS PNO
ICT	11/16/96	2.27	N/A	0.00	Trace	ASOS PNO
ICT	11/18/96	0.00	N/A	0.00	0.75	ASOS PNO
JAN	6/9/97	6.80	6.72	6.32	4.13	ASOS PNO
JAN	7/13/97	0.21	0.19	0.00	0.00	ASOS PNO
JAN	7/17/97	0.23	0.21	0.00	0.00	ASOS PNO
JKL	5/15/97	0.09	N/A	0.28	0.05	Can't isolate problem
JKL	11/8/97	0.00	N/A	0.19	0.19	Unsure of UNIV value
LCH	5/18/97	0.00	0.49	0.47	0.47	Unsure of UNIV value
PAH	7/3/96	0.00	N/A	0.25	0.25	Unsure of UNIV value
PAH	9/4/96	0.27	N/A	0.27	0.00	ASOS PNO
SEA	12/2/96	0.00	N/A	0.15	0.15	Unsure of UNIV value

precipitation measured by the UNIV. In these events, it was questioned whether or not the UNIV was functioning properly. Finally, events deleted due to "Can't isolate problem" were done so because measurements were uncharacteristic for a given station within the rest of the data analyzed by this investigation.

Table 3.1 illustrates that ASOS is capable of reporting precipitation when precipitation is not occurring, usually isolated within one or a few one minute observations. This table also shows that ASOS can report no precipitation when precipitation has actually happened.

3.3.2 HTB Performance Assessment

The performance assessment of the ASOS HTB in this study is accomplished through the direct comparison of the HTB with the CRG at four sites within the study. Due to the random readings of the CRG as mentioned earlier, only cumulative totals from the HTB and CRG could be used; hence, in several cases numerous events were combined together.

The two methods deemed appropriate for comparing precipitation cumulative totals recorded by the HTB and the manually recorded CRG included a least-squares analysis between comparable cumulative periods and a comparison of summations of all comparable events over the entire data record between the two gauges at each site.

The least-squares fit allows one to investigate the mathematical relation between two measures, in this case, the HTB and the CRG. This study assumes that the relationship between the HTB and CRG is linear, therefore our least-squares equation takes the form:

$$y = A + Bx \tag{3.3}$$

where A and B are constants. The constant A is the y-intercept, and constant B is the slope of the least-squares line for variables x (CRG) and y (HTB). For the purpose of this study, constant A is forced to zero because it was assumed that both gauges would report values of zero in the absence of precipitation. The slope of the least-squares line is determined by the following equation:

$$B = [N(\Sigma x_i y_i)-(\Sigma x_i)(\Sigma y_i)] \;/\; [N(\Sigma x_i^2)-(\Sigma x_i)^2)] \tag{3.4}$$

where events x_i and y_i represent CRG and HTB measurements respectively, which were then summed linearly over N events. If all of the measurements produced by the HTB were equal to the measurements made by the CRG, the graph of the HTB against the CRG would produce a least-squares line with a slope of one. A slope of one would depict a one-to-one ratio between HTB and CRG indicating that the HTB measured 100% of what the CRG recorded. Since the HTB and CRG did not have a one-to-one ratio, a least-square fit line was computed. The slope of this least-squares fit line is one measure of the fraction or ratio of precipitation measured by the HTB compared to the CRG. The distance of an actual data point from this least-squares fit line is considered to be a measure of the uncertainty of the fit of the least-squares line. To simplify our analysis, it was assumed that the measurements from the HTB had some degree of uncertainty while the uncertainty in our measurements from the CRG were negligible. This made sense since the CRG was being used as the ground truth for the assessment of the HTB performance. The uncertainty in the measurements of the HTB were estimated by calculating the sum of squares using the following equation:

$$\sigma_y^2 = 1/N \sum(y_i - Bx_i)^2 \tag{3.5}$$

The uncertainty in the slope of the least-squares fit line, represented by σ_B, can then be determined from the following equation:

$$\sigma_B^2 = N\sigma_y^2 / [N(\sum x_i^2)-(\sum x_i)^2)] \tag{3.6}$$

The results provide insight on the magnitude of the error in the least-squares fit line representing the assumed linear relationship between the HTB and CRG. Table 3.2

Table 3.2 Slope of least-squares fit line, calculated σ_B of slope for comparison between measurements recorded by ASOS and CRG, and CRG total precipitation.

STATION	1MIN to CRG			HRLY to CRG			SOD to CRG		
	Slope	σ_B (in)	CRG (in)	Slope	σ_B (in)	CRG (in)	Slope	σ_B (in)	CRG (in)
GSP	0.97	0.008	32.81	0.96**	0.008	30.20	0.96	0.009	18.06
JAN	0.92	0.009	44.50	0.92	0.009	44.50	0.92	0.009	39.16
LCH	1.02	0.005	12.43	1.01	0.005	12.43	1.01	0.004	12.43
SGF*	1.03	0.013	25.86	1.01**	0.013	18.92	1.02	0.009	17.24
Mean	.99			0.98**			0.98		

* 4″ gauge used in place of CRG
** Eliminated erroneous or missing HRLY data

details the extent of this error for each station. Uncertainty in the slopes of the least-squares fit lines were very small for the four stations with the largest uncertainty being listed just over 0.01″. Plots of the data used to derive Table 3.2 are depicted in Figures 3.1-3.4. Accumulated precipitation per comparison period recorded by the various HTB data fields are displayed on the y-axis with corresponding accumulation measured by the CRG along x-axis. The solid line on each plot represents the ideal one-to-one relationship between the HTB measurements and those collected by the CRG. The dashed line illustrates the least-squares fit line to the data displayed.

The observations from GSP 1MIN data in Figure 3.1(A), indicate significant stability in the HTB versus CRG relationship leading to the conclusion that the HTB regularly undermeasured precipitation when compared to the CRG at this site. Of the 45 compared cumulative precipitation periods, all but 9 events were placed at or below the ideal-one to-one ratio line. It should be noted that cumulative overage by those nine events was 0.19″. Excluding comparative measurements recorded in the 1MIN and CRG that differed by less than ±0.02″ or ±4%, as outlined by the *ASOS USER's Guide* (National Weather Service, 1998b.) for HTB performance specifications, 10 events undermeasured by 4.2%-11.0% with a mean of 7.9%. On the other hand, only two cumulative event periods overmeasured, and they ranged from overages of 4.2%-4.6% with a mean of 4.8%. Figures 3.1(B) and 3.1(C) represent data provided by the HRLY and SOD, and they respectively show good agreement with 1MIN data suggesting that it was not a common practice at GSP to edit precipitation measurements made by the HTB. Two event periods used by 1MIN and SOD were eliminated from the HRLY comparison to CRG because HRLY data was missing.

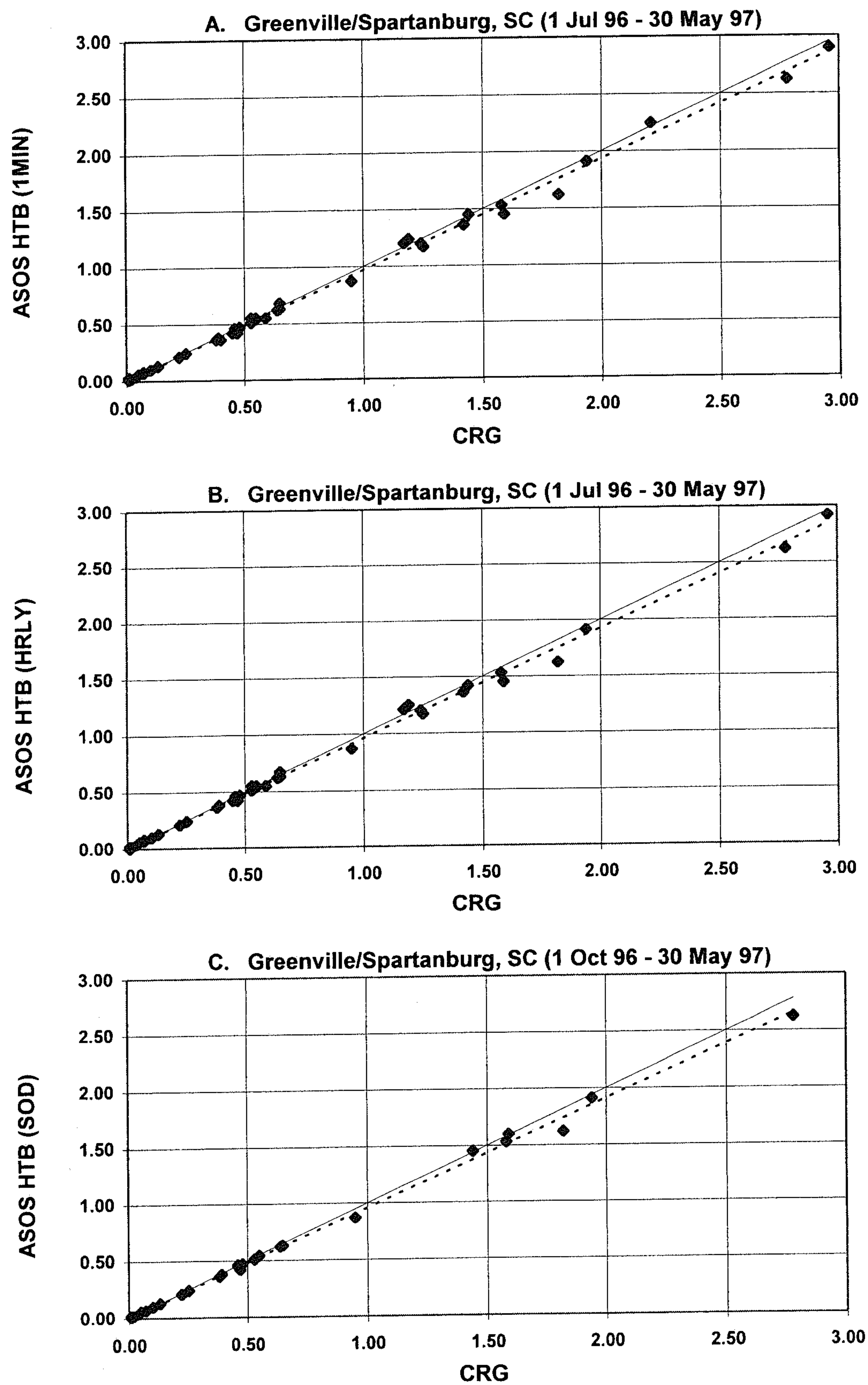


Figure 3.1 ASOS HTB versus CRG (SRG) at GSP for (A) 1MIN, (B) HRLY, and (C) SOD.

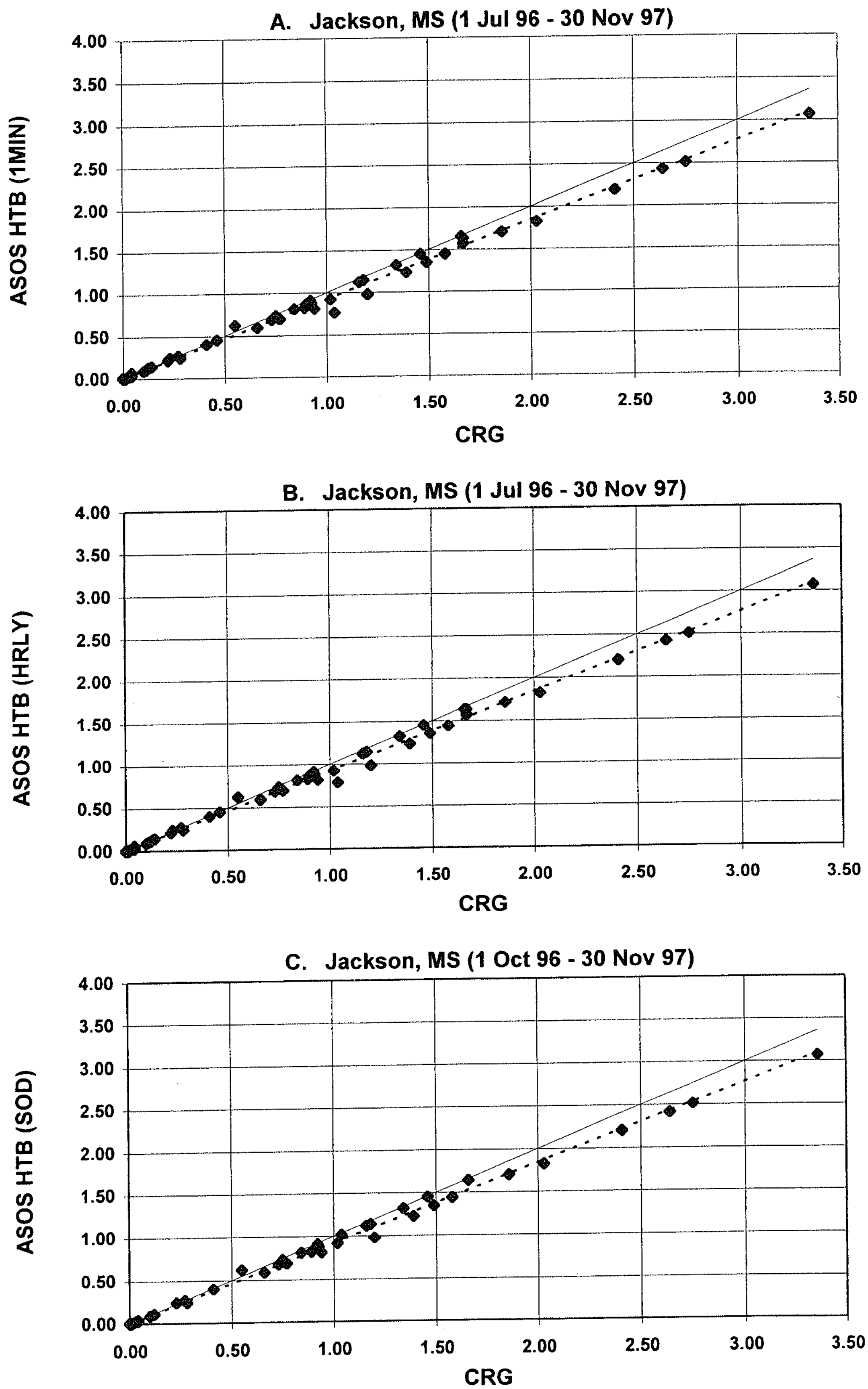


Figure 3.2 ASOS HTB versus CRG (SRG) at JAN for (A) 1MIN, (B) HRLY, and (C) SOD.

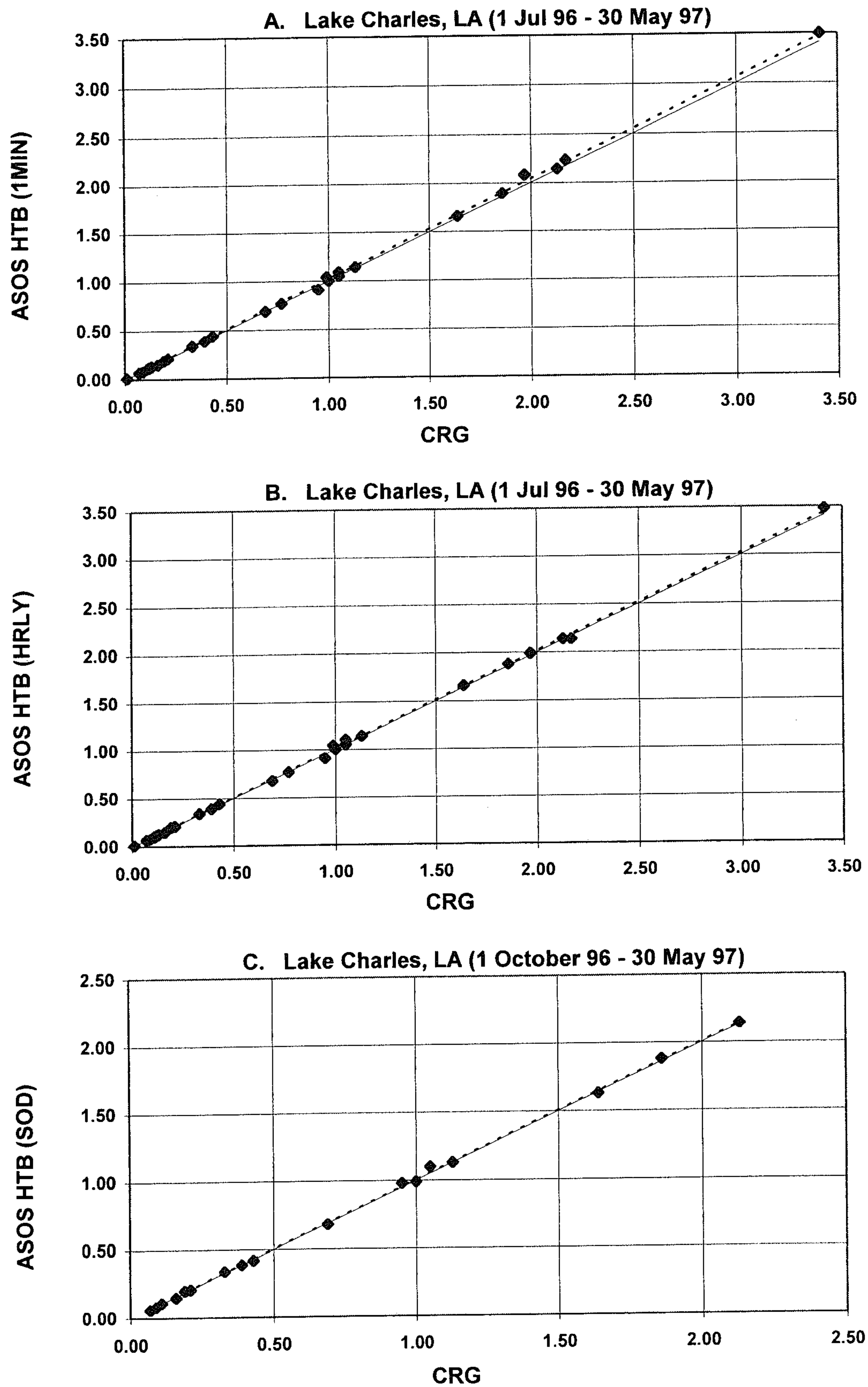


Figure 3.3 ASOS HTB versus CRG (UNIV) at LCH for (A) 1MIN, (B) HRLY, and (C) SOD.

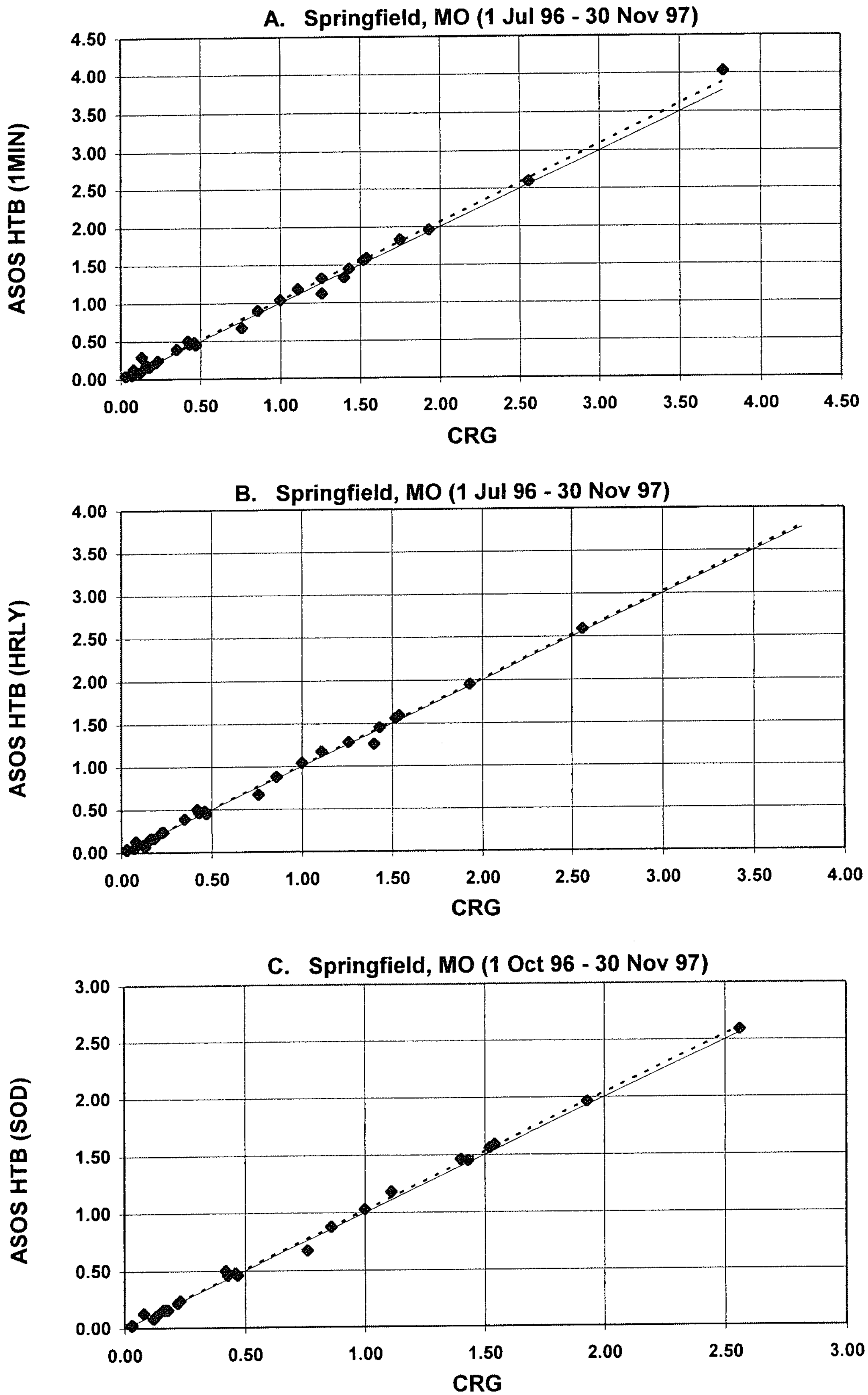


Figure 3.4 ASOS HTB versus CRG (4″ Gauge) at SGF for (A) 1MIN, (B) HRLY, and (C) SOD.

From Figure 3.2(A) for JAN 1MIN data, it is clear that an overwhelming number of the total events compared fell either on or below the ideal one-to-one ratio line. JAN shows considerable constancy in the HTB tendency to undermeasure when compared to the CRG. When the amount of accumulated precipitation in an event is large, the data points fall below the one-to-one ratio line but very near to the least-squares fitted line. This behavior indicates a deficiency in the amount of precipitation recorded by the HTB in the 1MIN data. After applying the previously stipulated guidelines for assessing gauge performance, 26 out of 52 accumulation periods for JAN, show HTB undermeasuring with respect to the CRG. Twenty of those periods showing an undermeasurement range of 6.0%-26.9% with a mean of 10.5%. The least-squares fit slope indicates a 8% undermeasuring from all events used to assess the JAN HTB performance. Overmeasuring only occurred in two events with an overage range of 12.3%-75% with a cumulative overmeasurement of 0.10″. Analysis using HRLY and SOD reports compared to the CRG at JAN shown in Figures 3.2(B) and 3.2(C) respectively, produced results similar to the 1MIN to CRG comparison.

Figure 3.3(A) for LCH 1MIN data shows a stable, but opposite pattern when compared to GSP and JAN HTB versus CRG results. All but 3 of the 27 compared cumulative precipitation periods, showed the HTB reporting values equal to or higher than the CRG. The cumulative undermeasuring of the three isolated events was 0.06″. The slope of the least-squares fit line suggest that 1MIN HTB from LCH was higher than the CRG on the order of 2%. Using the guidelines based on the ASOS HTB performance standards described above for excluding cumulative event periods, only two events were left that overmeasured precipitation when compared to the CRG. Their overmeasuring was in the range of 5.1-5.6% with a mean of 5.3%. Furthermore, in one event from the data used for this analysis at LCH, the HTB undermeasured 0.04″ of precipitation causing a 4.2% undermeasure. Figures 3.3(B) and 3.3(C) that represent data provided by HRLY and SOD respectively are consistent with the 1MIN data. However, the slopes of the derived least-squares fit line improve such that the slopes are closer to the ideal one-to-one ratio between the HTB and CRG, thereby suggesting that HRLY and SOD reports are edited to some degree.

At SGF, Figure 3.4(A), the 1MIN data comparison to the 4″ gauge demonstrated a high order of stability along with a pattern showing measurements made by the HTB to be higher than the 4″ gauge. After isolating out 17 of 31 events that met the HTB prescribed specifications, the result is still an inclination by the HTB to overmeasure precipitation by 5%-123% manifested in a cumulative overage of 0.87″ from 10 of the 31 cumulative precipitation periods. It was noteworthy that in 3 of the 10 cumulative event periods, the HTB overmeasured by more than 19% per event, with the three event total of the HTB being 0.92″ compared to measurements totaling 0.65″ from the 4″ gauge. On the other hand, 4 of the 31 cumulative events were undermeasured by the HTB in comparison to the 4″ gauge by 5%-25% massing a precipitation deficit of 0.33″. As for the HRLY and SOD shown in Figures 3.4(B) and 3.4(C) respectively, occasional editing of a small number of accumulation periods lowered the 3.2% overmeasuring indicated by the least-squares fit slope in the 1MIN to 1% in the HRLY. SOD editing appeared to be minimal and only improved to an least-squares fit slope measure to 2% overmeasuring by the HTB.

The other valuable tool used to assess the performance of the HTB compared to the CRG was the comparison of the total precipitation accumulated by each gauge throughout the entire period of study. Results from this form of analysis are presented in Table 3.3.

Table 3.3 Cumulative precipitation recorded by the HTB and CRG.

	Total Accumulation				Ratio of Accumulated Precipitation		
STATION	CRG (in)	1MIN (in)	HRLY (in)	SOD (in)	1MIN/CRG	HRLY/CRG	SOD/CRG
GSP	32.81 30.20* 18.06**	31.83	29.20 29.20*	17.39**	0.97	0.89 0.97*	0.96**
JAN	44.50 39.16**	41.39	41.36	36.42**	0.93	0.93	0.93**
LCH	23.16 12.43**	23.54	23.33	12.49**	1.02	1.01	1.00**
SGF	25.86 18.92* 17.24**	26.63	19.63 19.08*	17.58**	1.02	0.76 1.01*	1.02**
				Average	0.99	0.90 (0.98*)	0.98**

* Eliminated events due to missing or erroneous HRLY
** Analysis of SOD start 1 October 96

There is good agreement between the calculated slopes produced from the least-squares fit line for the HTB 1MIN versus CRG plots of the four stations and the cumulative precipitation ratio results provided in Table 3.3. The slope of the least-square fit line represents the calculated ratio of precipitation measured by the HTB compared to the CRG. Since the slope of the least-squares fit line is constant, the slope can be interpreted as the ratio of the total accumulated precipitation which can be compared to the ratio of the HTB and CRG total accumulated precipitation derived from the summation of the actual precipitation observations for each station. In this investigation, the slope derived ratios compared very well, within 0.01 or less, to the ratios of the total accumulated precipitation. Hence, this result produces a high level of confidence in our least-squares fit line for the data analyzed in this portion of the study.

Summarizing the above assessment of the ASOS HTB, it is apparent from the high order of stability in the HTB versus CRG data presented and the results from the total accumulated precipitation ratio and least-squares slope analysis methods that the HTB is performing quite well when measuring liquid precipitation. Using the worst case values of HTB 1MIN to CRG comparisons from the two analysis methods yields precipitation accumulation performance in the range of -8% to 3%. For the data available to this study, the HTB to CRG relationship stability and the above given performance range suggests that the algorithm used for ASOS HTB precipitation accumulation correction is good, but should be custom tailored for each gauge to achieve the desired one-to-one HTB versus CRG relationship. Therefore, it is proposed from the results of this study that the correction algorithm, Equation 2.1, needs an additional linear correction to the non-linear correction currently used in every ASOS. The proposed new correction algorithm takes the form:

$$C = B\,(A + 0.60A^2) \qquad (3.7)$$

where B is the linear correction proposed by this study. Given the variation in the relationship results of HTB to CRG comparisons from the four sites used in this investigation, the linear correction must be site-specific. The linear correction can be determined by comparing a large sample, from the annual average total accumulated liquid precipitation, of ASOS HTB event measurements to those measured by an ASOS collocated SRG. The linear relationship of ASOS HTB versus SRG for compared event measurements will illustrate the magnitude of the linear correction need for a given

ASOS HTB to achieve the desired one-to-one relationship with the SRG. For the four sites used in the HTB performance assessment, using the data and results from this study, the proposed linear correction based on slope measure calculations are: 1.03 for GSP, 1.08 for JAN, 0.98 for LCH, and 0.97 for SGF.

3.3.3 Spatial and Climate Continuity Impact of the HTB at Sites with CRG and UNIV

Results presented in section 3.3.2, along with the UNIV to CRG results illustrated in Table 3.4, can be used to compare the HTB to the UNIV. The purpose of this analysis is to gain an understanding of the magnitude of the spatial variation between the ASOS site and the UNIV site and to examine the net impact the implementation of the ASOS program is having on the ASOS program to the precipitation climate records. The foundation of this comparison involves the assumption that the CRG and UNIV would produce identical results if they were collocated. Figures 3.5(A-D) depict the UNIV versus CRG at the four sites. The fourth column of Table 3.4 shows the total

Table 3.4 Cumulative precipitation recorded by the UNIV and CRG

STATION	Total Accumulation			Least-Squares Fit Line	
	CRG (in)	UNIV (in)	Ratio UNIV/CRG	Slope	σ_B (in)
GSP	32.81	32.91	1.00	1.00	0.006
JAN	44.50	43.43	0.98	0.96	0.011
LCH	23.16	22.80	0.98	1.00	0.029
SGF	25.86	27.86	1.08	1.11	0.021
Total	126.33	127.00	1.01		
Mean of all station CRG/UNIV			1.01	1.02	

accumulation ratio which illustrates the impact of the spatial variation resulting from the NWS decision to change the official meteorological observation site. The spatial

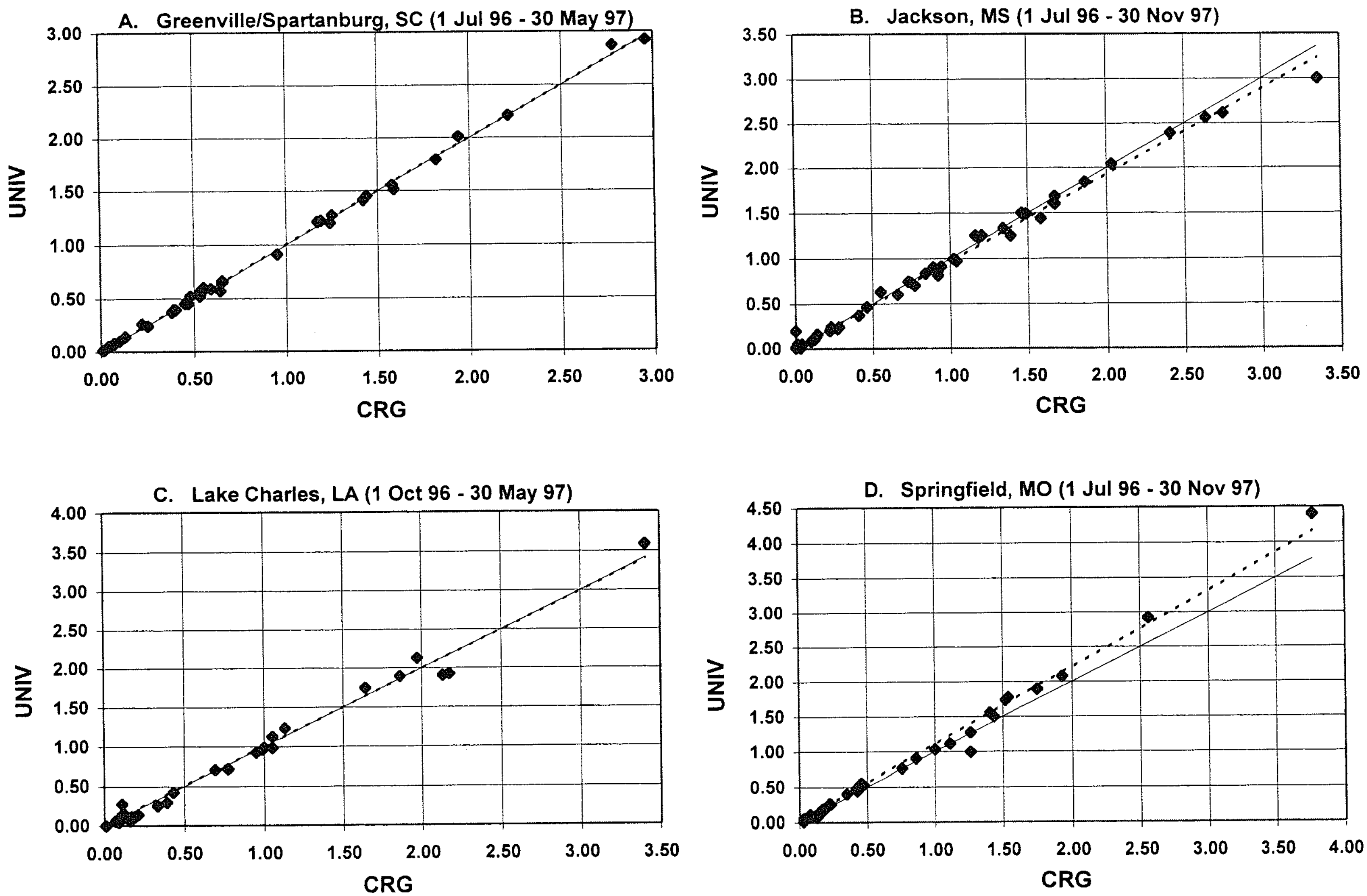


Figure 3.5 UNIV versus CRG at (A) GSP, (B) JAN, (C) LCH, and (D) SGF.

variation results using the total accumulated precipitation UNIV to CRG ratios, with positive values indicating an increase in measured precipitation, for the four sites are approximately: 0% for GSP, 2% for JAN, 2% for LCH, and -8% for SGF. In comparison, the slope measures of the UNIV versus CRG relationship produced values of: 0% for GSP, 4% for JAN, 0% for LCH, and -11% for SGF. The magnitudes of these spatial variations relate strongly to location differences, Table 2.1, with the largest spatial impact being observed at the station with the largest distance between ASOS and the UNIV. Now to determine the impact of ASOS on precipitation climate continuity, the spatial variation results are added to gauge performance results from ASOS 1MIN and CRG comparisons listed in the fifth column of Table 3.3. For example, the total accumulation ratio from the 1MIN and CRG comparison at JAN shows a -7% in the precipitation measured. This value added to the spatial variation of 2% at JAN yields a net impact on the precipitation climate continuity of -5%. In other words, during the course of this study 5% less precipitation was measured at the new site with the ASOS HTB. Applying this analysis to the results from other stations shows a climate continuity impact of: -3% for GSP, +4% for LCH, and -6% for SGF. Accomplishing the same analysis, using least-squares slope measurements from 1MIN versus CRG results shown in Table 3.2 and UNIV versus CRG results in Table 3.4, yields a climate continuity impact of: -3% for GSP, -4% for JAN, 2% for LCH, and -8% for SGF. Further comparison of Table 3.3 and Table 3.4 total precipitation accumulation ratios shows a mean ratio of 0.99 from the 1MIN to CRG comparison and 1.01 from the UNIV to CRG comparison for all four stations. These results suggest that the collective group impact of ASOS HTB on climate continuity to be -2%. Accomplishing the same collective group analysis, but using Tables 3.2 and 3.4 and the collective mean least-squares slope measurements yields an impact of ASOS on precipitation climate continuity of -3%.

To summarize the impact of the ASOS HTB at the individual sites on the precipitation climate continuity, this investigation has demonstrated that there is an individual site climate continuity impact range of -8% to 4% using the worst values produced from total precipitation accumulation ratios and least-squares slope methods. The collective group mean results produce a climate continuity impact range of -4% to -2%, suggestive of the ASOS HTB's overall tendency to undermeasure precipitation when compared to the UNIV.

3.3.4 Climatological Impact of ASOS HTB

This portion of the CDCP is an attempt to illustrate the impact that the ASOS HTB will have on the precipitation climate record. For this portion of the study, the HTB and UNIV data from all of the stations that participated in this investigation were analyzed. It is important to state that in this portion of the analysis there was no attempt made to separate the precipitation differences due to spatial variation from those due to the actual gauge performance. Instead, this study examined the combined impact that the change in site and the change in instrumentation had on the precipitation record that would have been used if ASOS did not exist.

As a note, an attempt was made to analyze the possible impact of wind on the differences in precipitation measurements made by the HTB and UNIV. This was accomplished by using wind speeds extracted from the ASOS 1MIN observations for each 1MIN report containing measured precipitation. The sum of the wind speeds for a given precipitation event was divided by the event's total precipitation recorded by the HTB to derive a mass weighted average wind speed. There was no discernible relationship between the average wind speed and the difference in measurements taken by the HTB and UNIV.

Figures 3.6-3.18 show the relationship between the HTB 1MIN and the UNIV for each site. Figures 3.19(A-M) show the HTB SOD versus the UNIV for each location. From theses two sets of figures, a subjective assessment can be made on the apparent impact of ASOS within our period of study. In addition, this investigation intends to show whether or not WFO's edit SOD reports to reflect what they consider to be truth for precipitation reports. Table 3.5 provides a summary of the above figures, to include total precipitation accumulated over the course of this study, calculated ratios, and slopes from least-squares fit calculations.

From Table 3.5, it is apparent that there is considerable variation in the results of

Table 3.5 Summary of 1MIN and SOD to UNIV

Station	1MIN (in)	UNIV (in)	1MIN / UNIV	Slope		SOD (in)	UNIV (in)	SOD / UNIV	Slope
ALB	11.74	11.83	0.99	0.96		5.47	5.27	1.04	1.00
AMA	8.21	7.60	1.08	1.08		5.21	4.88	1.07	1.05
AST	48.90	46.24	1.06	1.03		42.91	41.04	1.05	1.03
BRO	13.10	12.71	1.03	0.99		32.51	32.80	0.99	0.99
CAE	23.06	25.30	0.91	0.90		23.58	25.32	0.93	0.92
GSP	26.55	27.43	0.97	0.96		21.26	22.00	0.97	0.97
ILM	26.42	30.21	0.87	0.78		20.15	22.95	0.88	0.87
JAN	52.50	55.27	0.95	0.94		61.19	63.12	0.97	0.96
JKL	43.82	48.89	0.90	0.87		51.89	52.14	1.00	1.00
LCH	52.61	50.49	1.04	0.99		47.59	45.43	1.05	1.00
PAH	39.95	51.86	0.77	0.81		60.91	62.07	0.98	0.96
SEA	21.07	20.11	1.05	1.04		27.90	26.64	1.05	1.05
SGF	33.30	35.19	0.95	0.92		45.32	48.33	0.94	0.92
		Mean	0.97	0.94			Mean	0.99	0.98

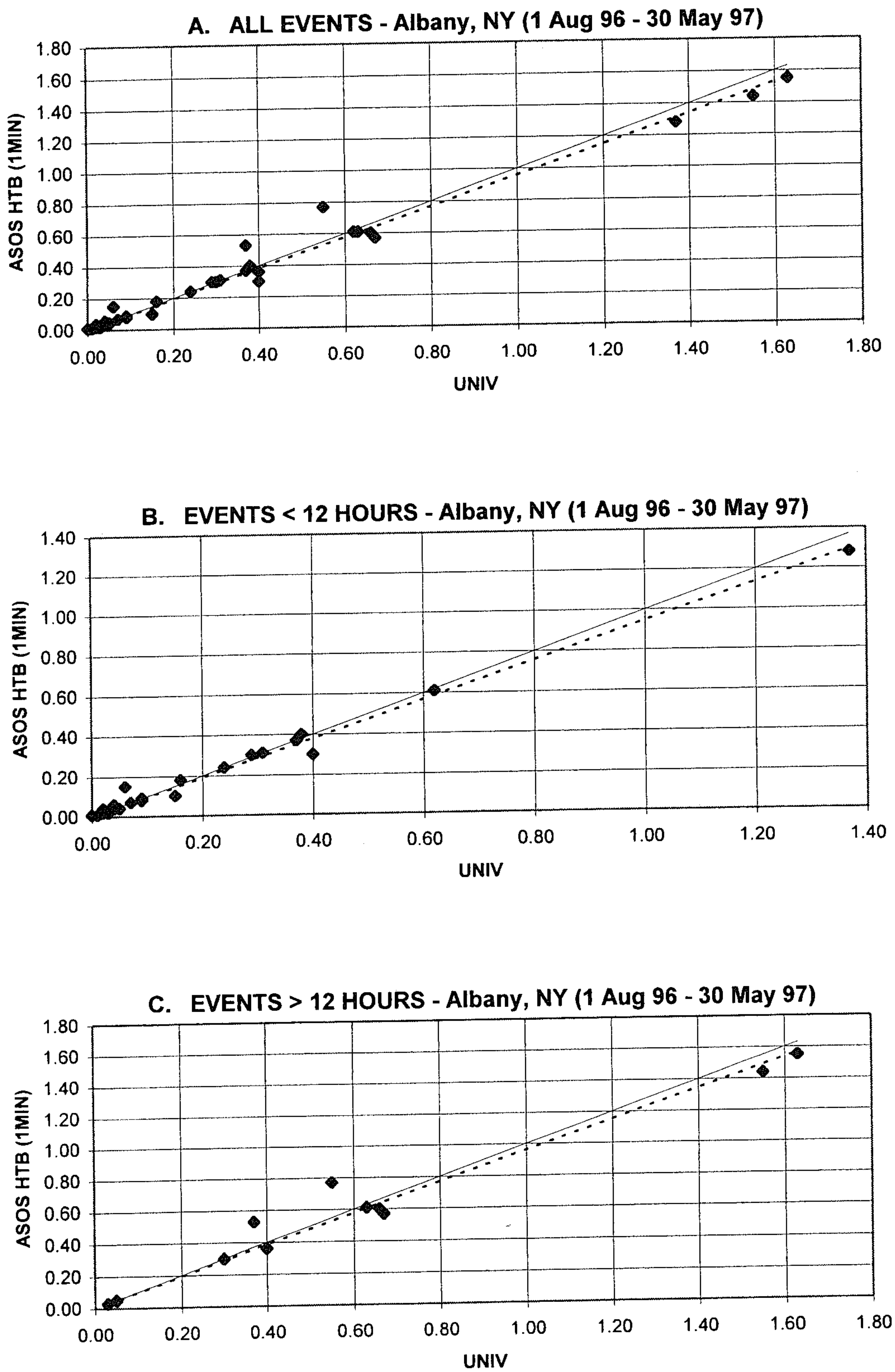


Figure 3.6 ASOS HTB 1MIN versus UNIV at ALB for (A) All Events, (B) Events < 12 Hours, and (C) Events > 12 Hours.

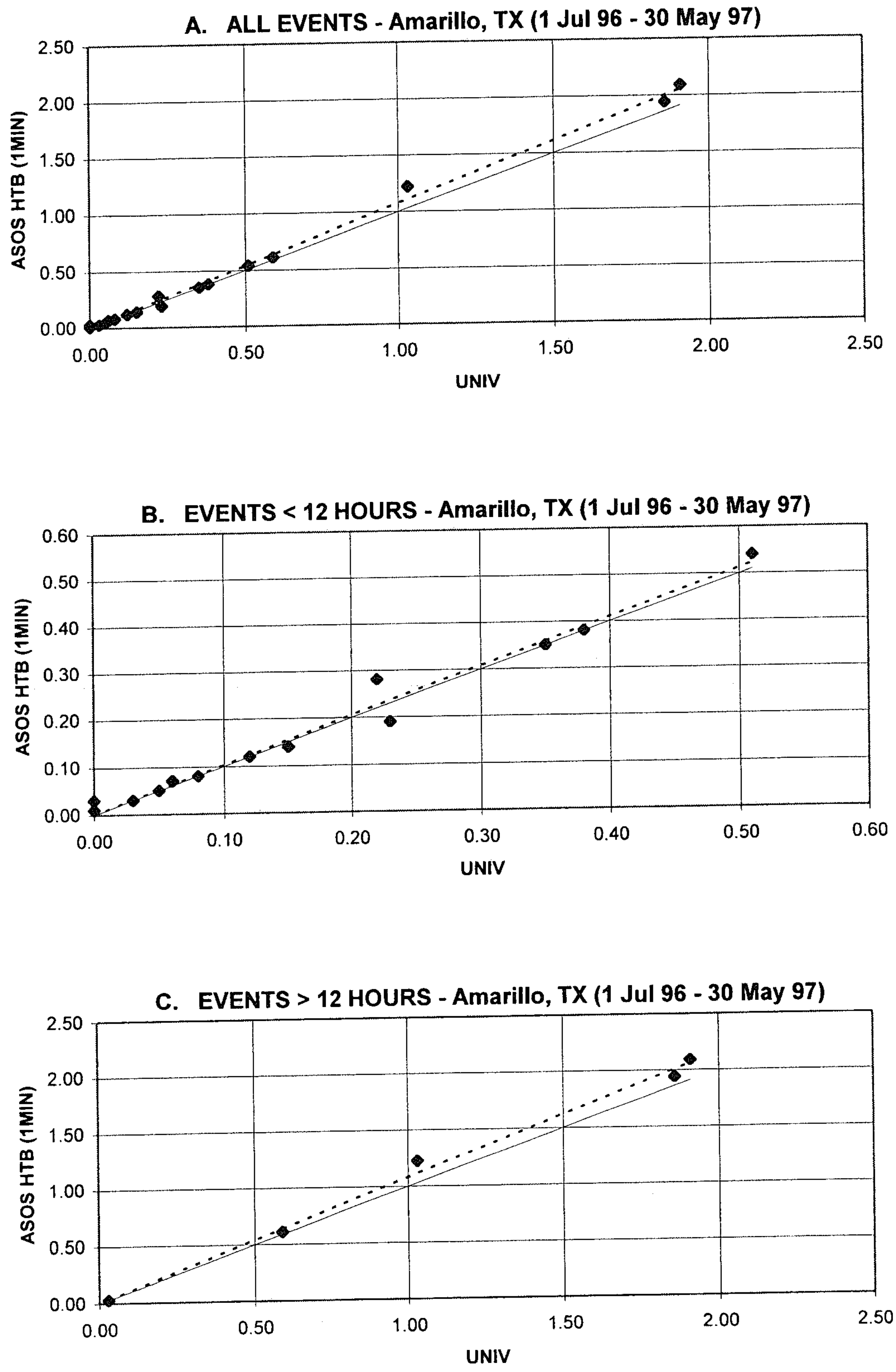


Figure 3.7 ASOS HTB 1MIN versus UNIV at AMA for (A) All Events, (B) Events < 12 Hours, and (C) Events > 12 Hours.

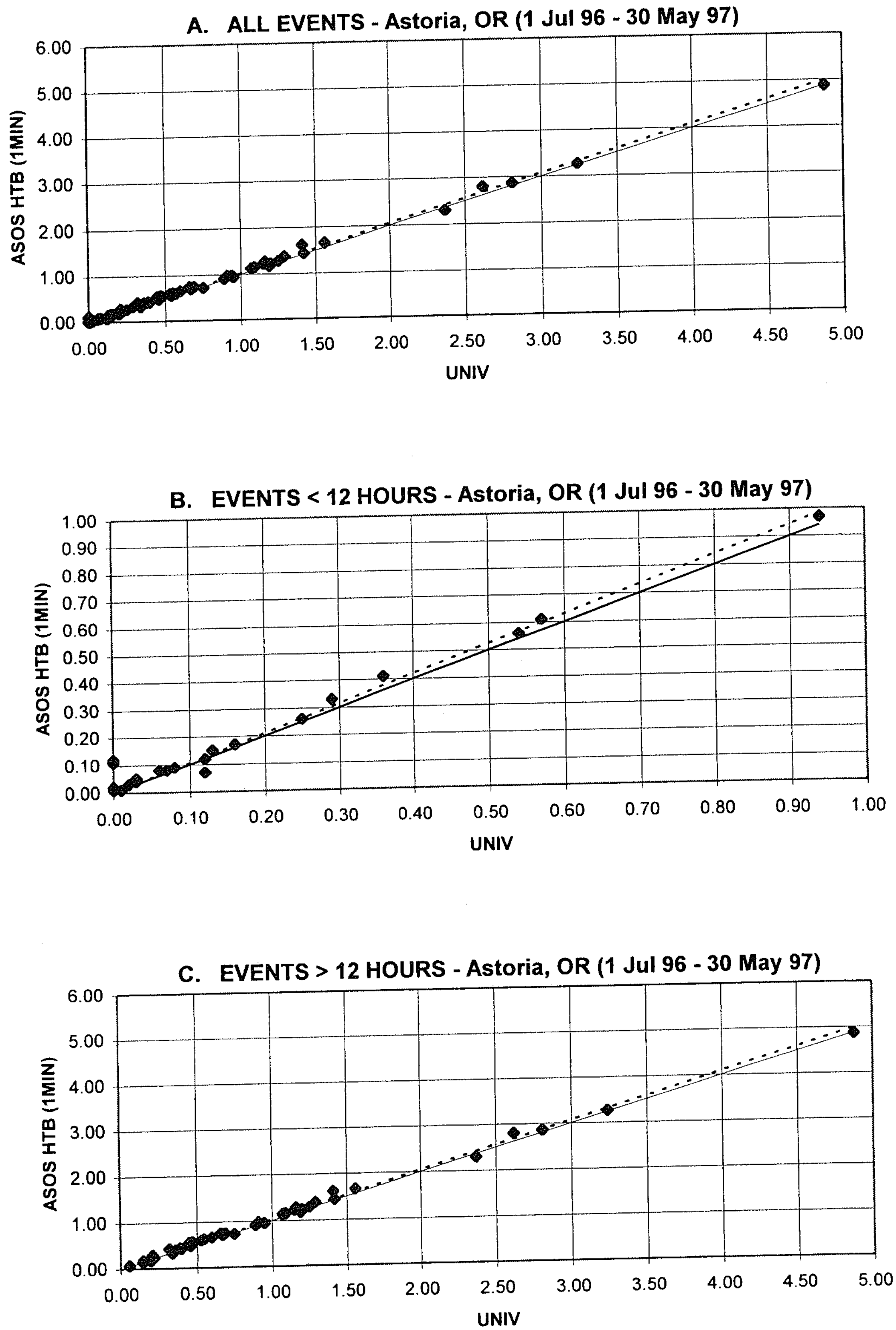
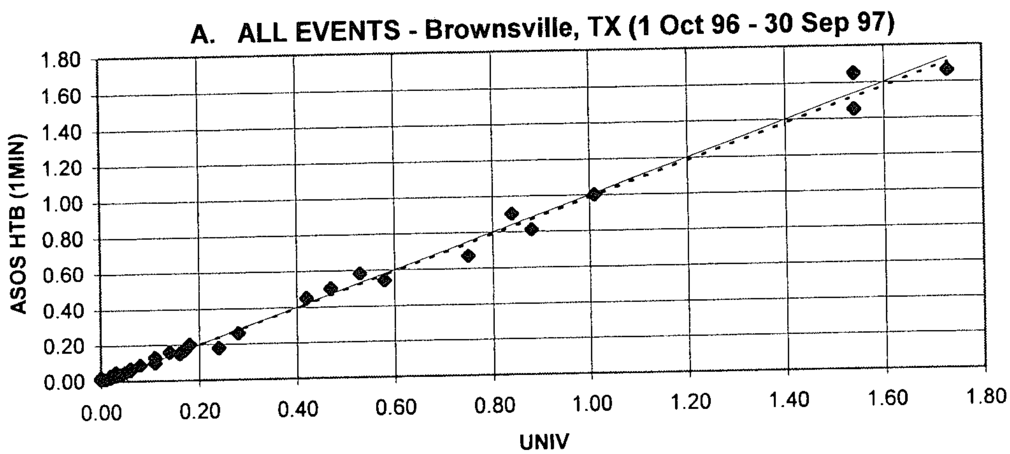
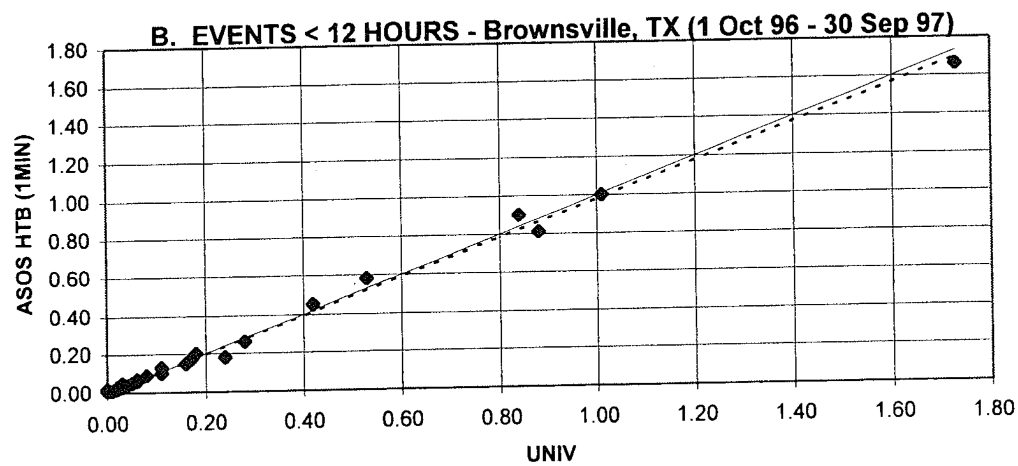


Figure 3.8 ASOS HTB 1MIN versus UNIV at AST for (A) All Events, (B) Events < 12 Hours, and (C) Events > 12 Hours.





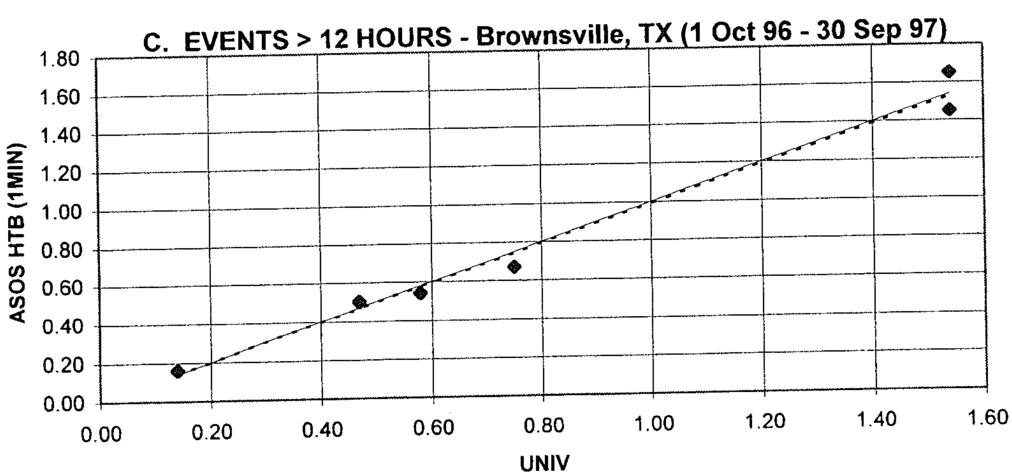


Figure 3.9 ASOS HTB 1MIN versus UNIV at BRO for (A) All Events, (B) Events < 12 Hours, and (C) Events > 12 Hours.

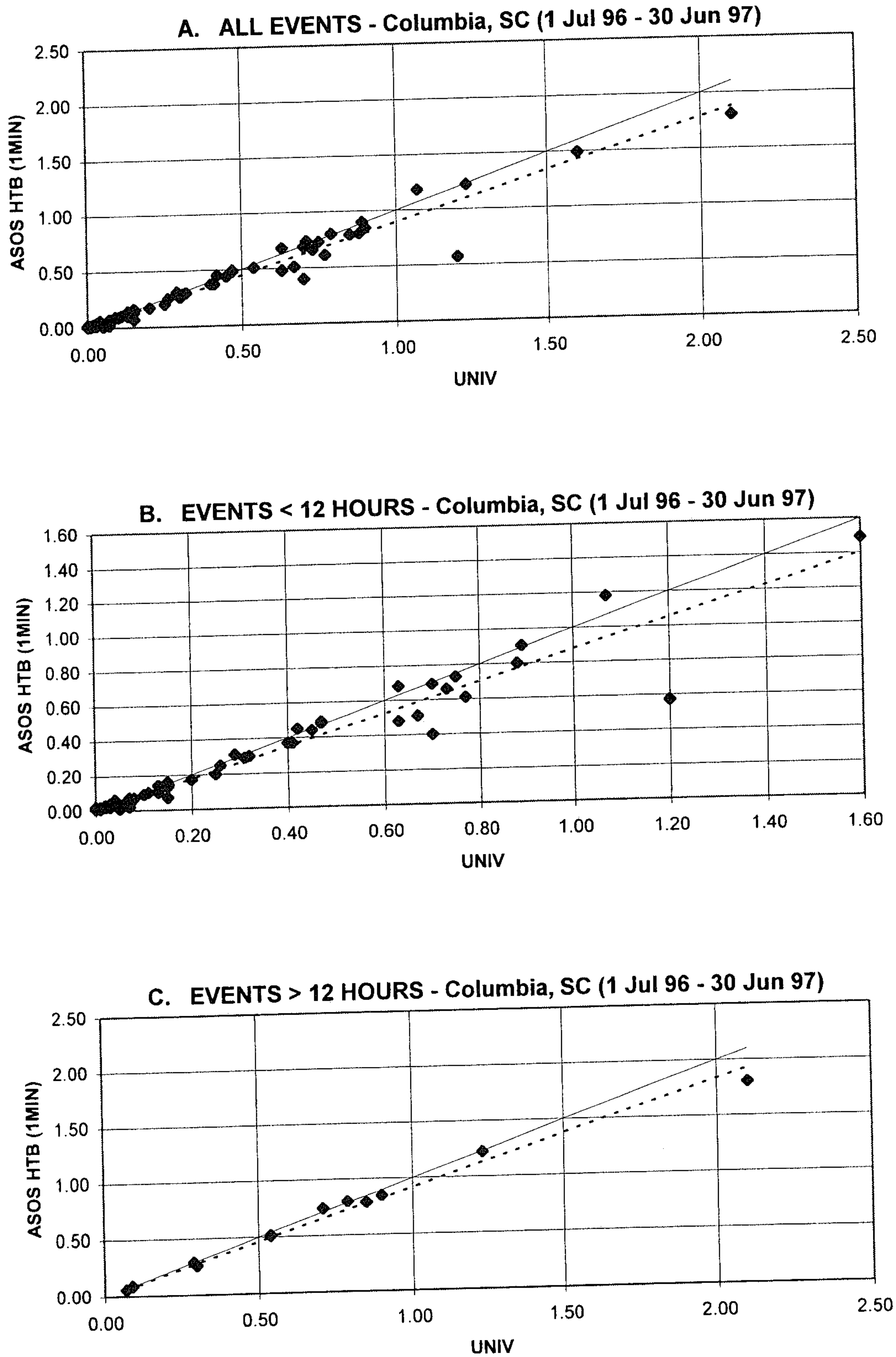


Figure 3.10 ASOS HTB 1MIN versus UNIV at CAE for (A) All Events, (B) Events < 12 Hours, and (C) Events > 12 Hours.

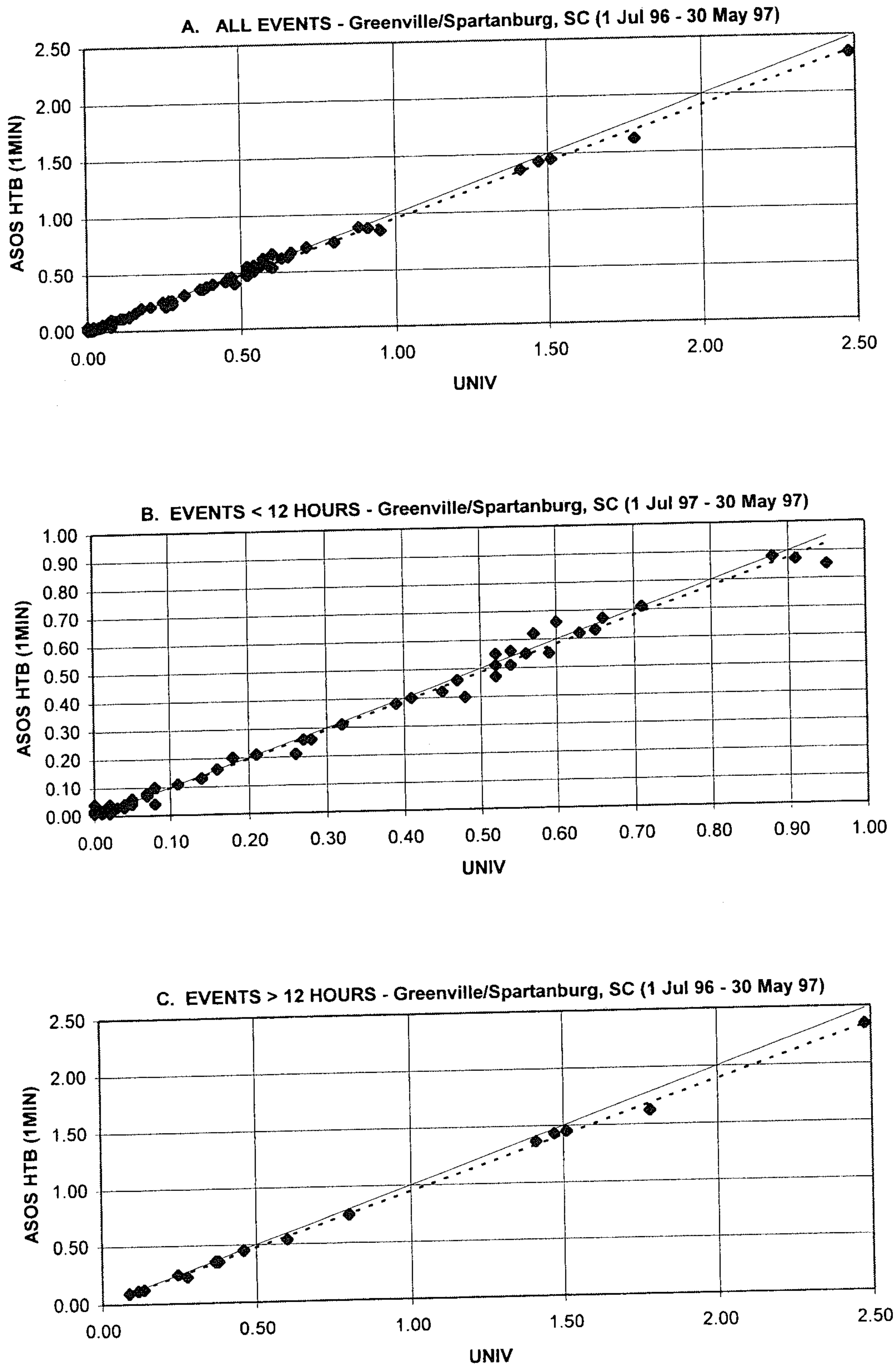


Figure 3.11 ASOS HTB 1MIN versus UNIV at GSP for (A) All Events, (B) Events < 12 Hours, and (C) Events > 12 Hours.

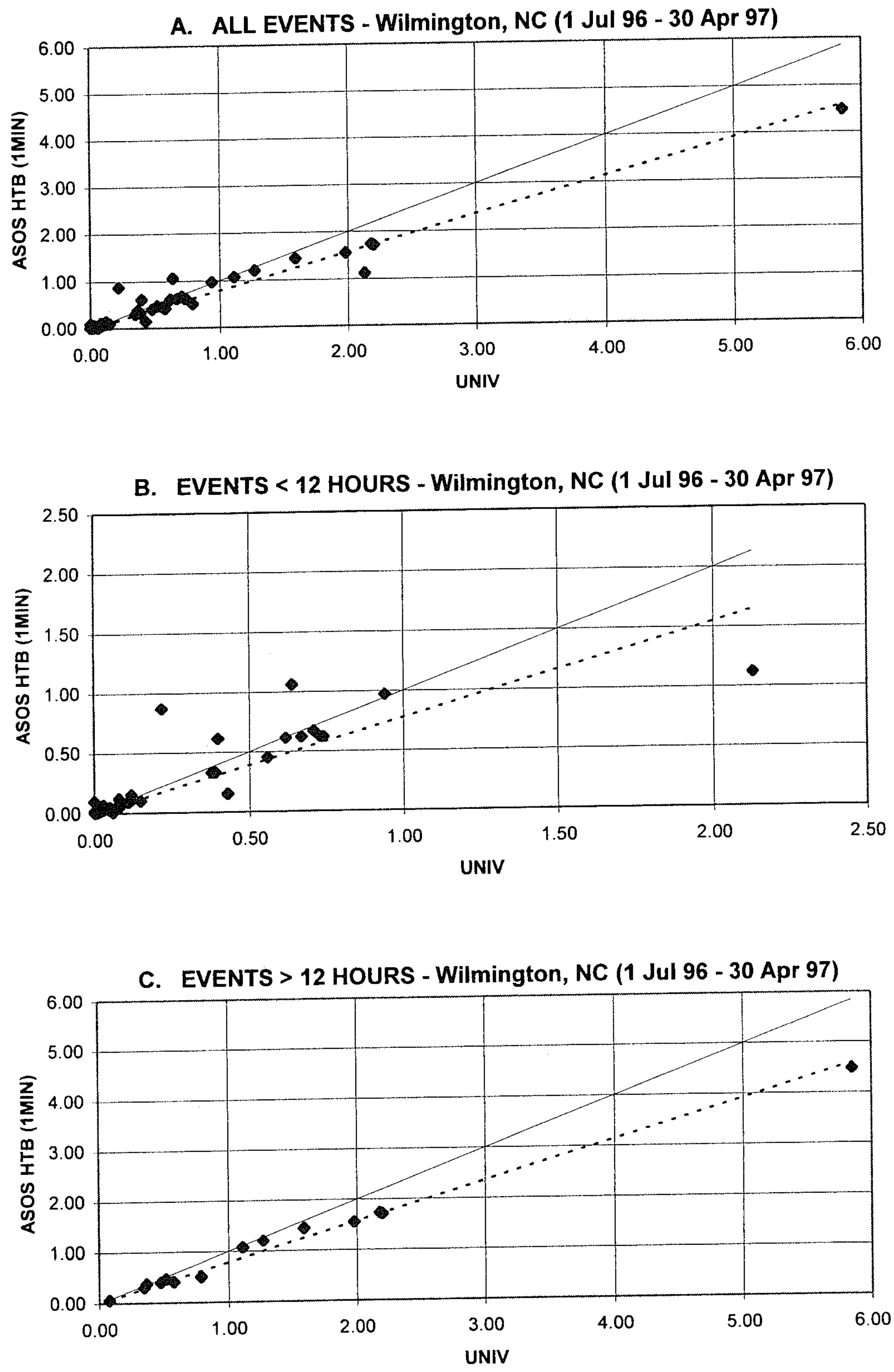


Figure 3.12 ASOS HTB 1MIN versus UNIV at ILM for (A) All Events, (B) Events < 12 Hours, and (C) Events > 12 Hours.

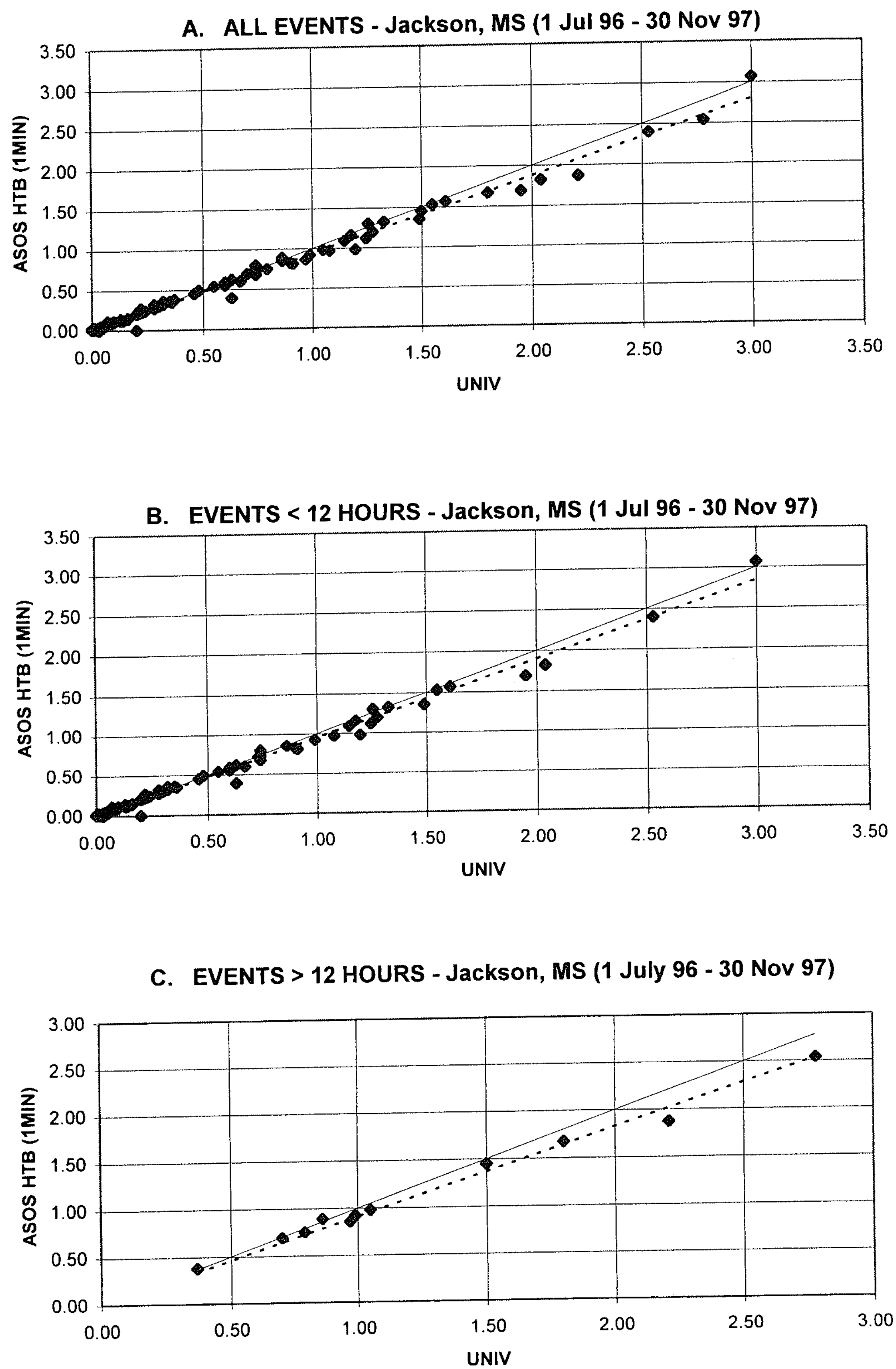


Figure 3.13 ASOS HTB 1MIN versus UNIV at JAN for (A) All Events, (B) Events < 12 Hours, and (C) Events > 12 Hours.

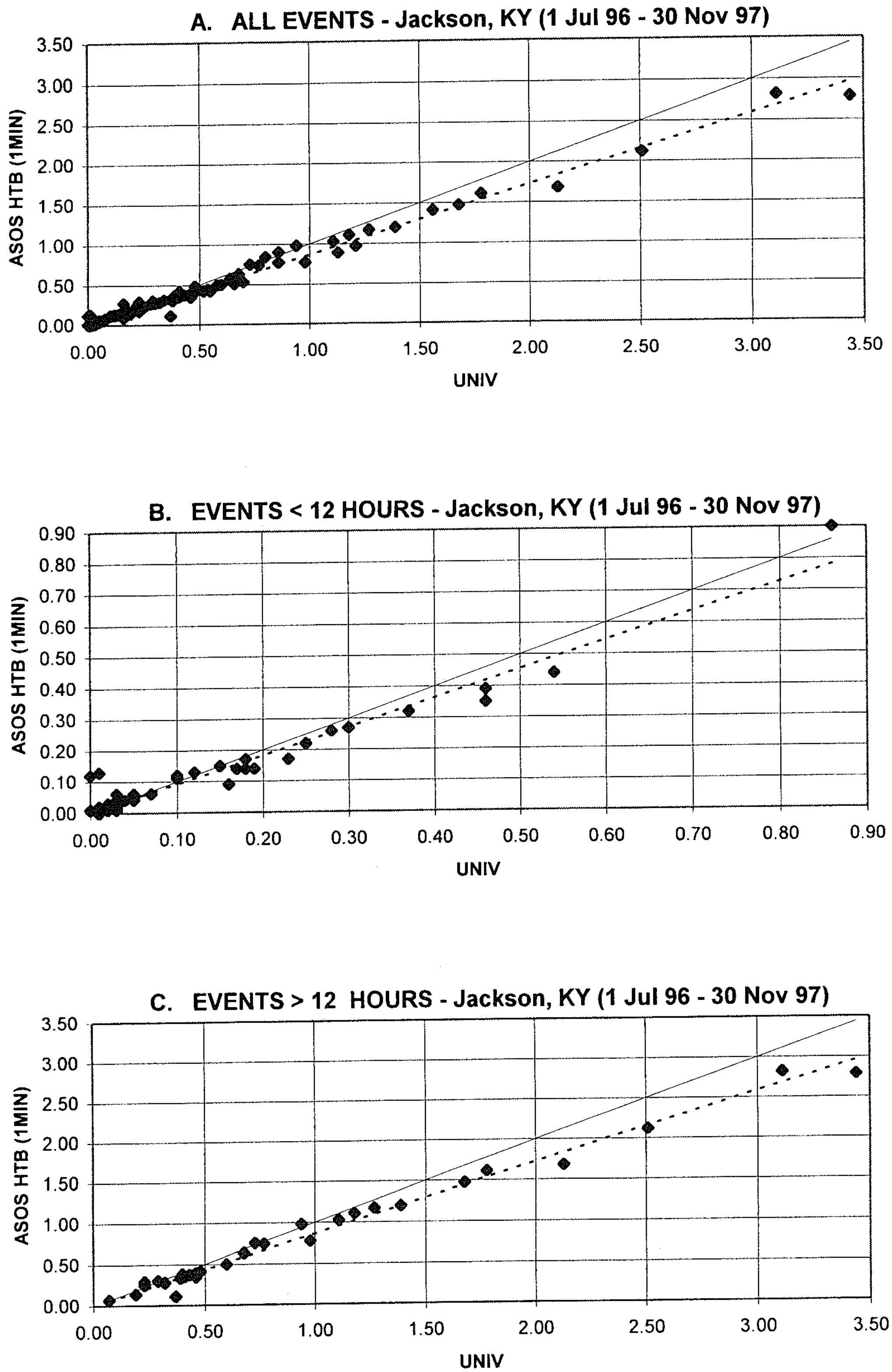


Figure 3.14 ASOS HTB 1MIN versus UNIV at JKL for (A) All Events, (B) Events < 12 Hours, and (C) Events > 12 Hours.

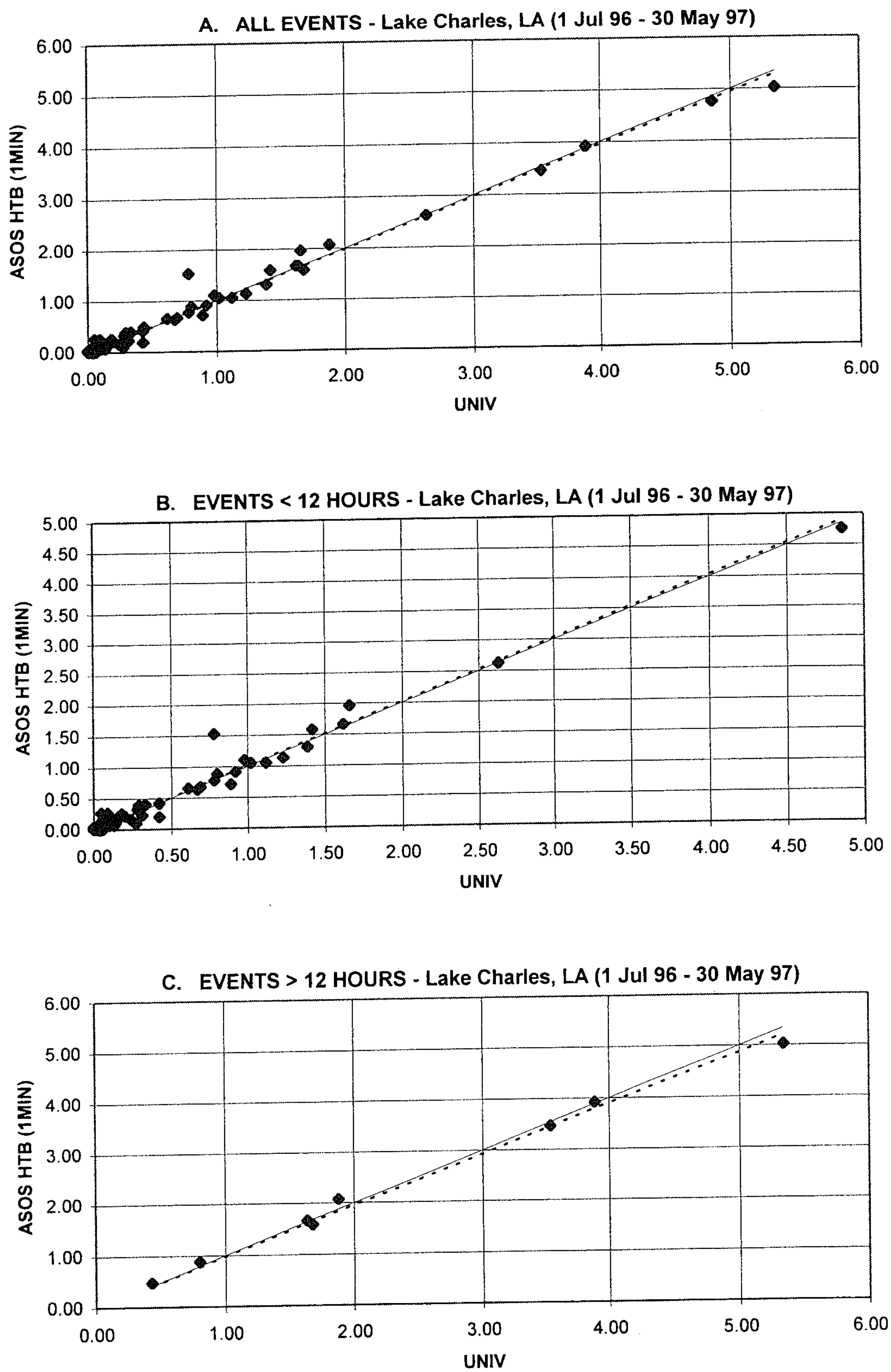
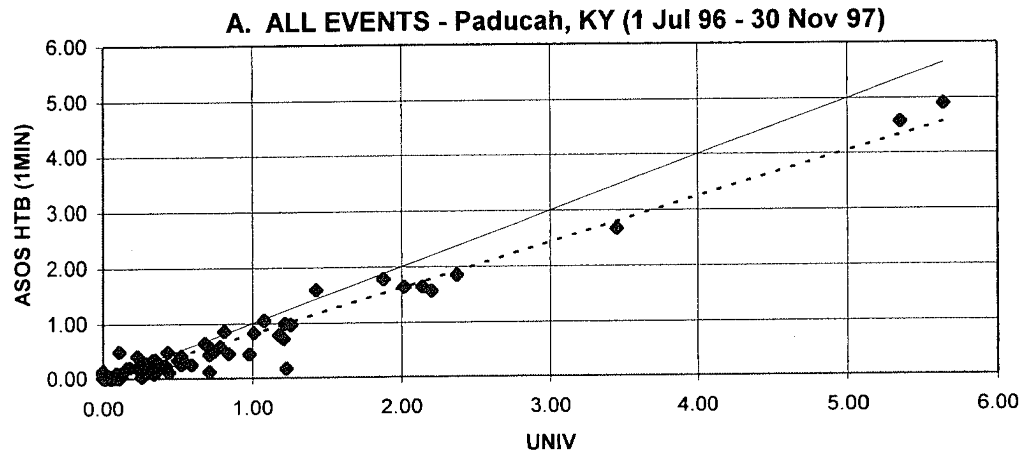
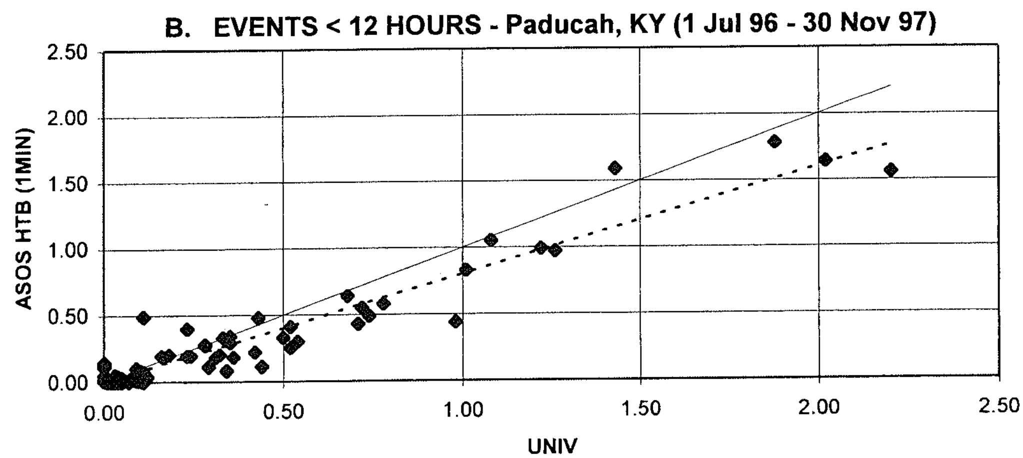


Figure 3.15 ASOS HTB 1MIN versus UNIV at LCH for (A) All Events, (B) Events < 12 Hours, and (C) Events > 12 Hours.





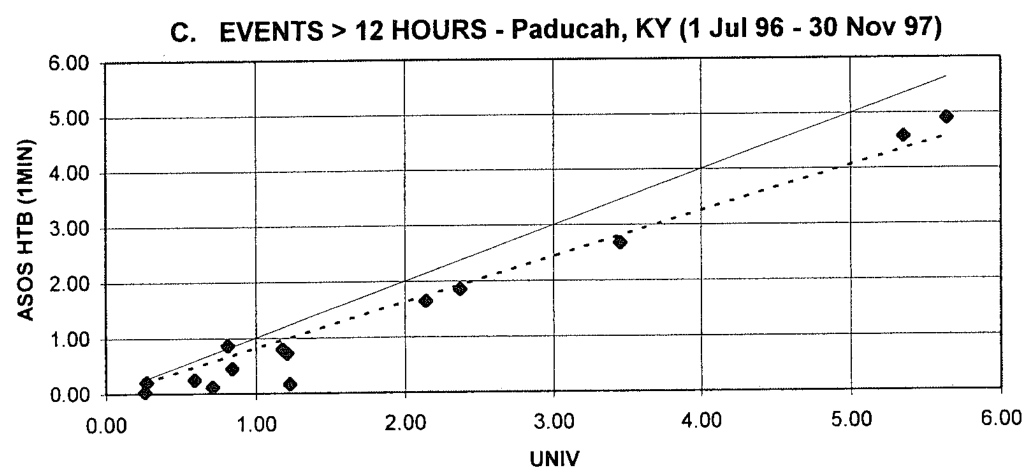
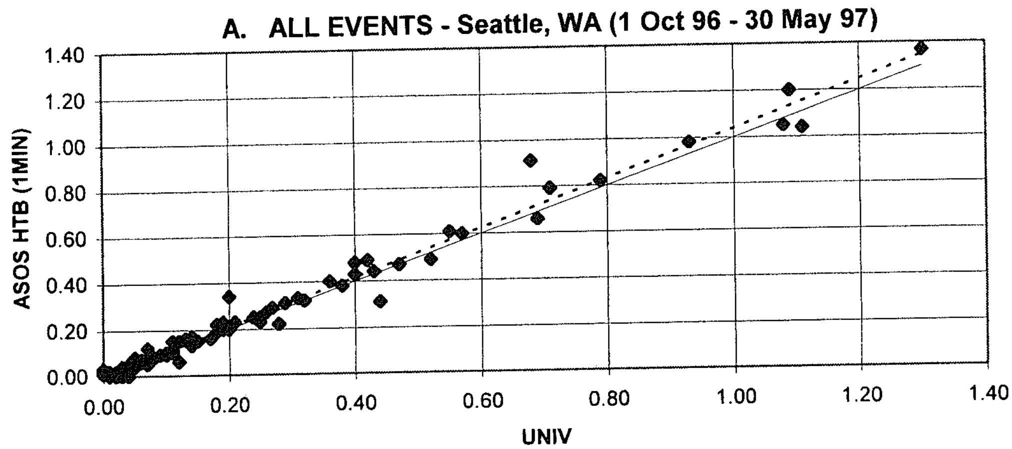
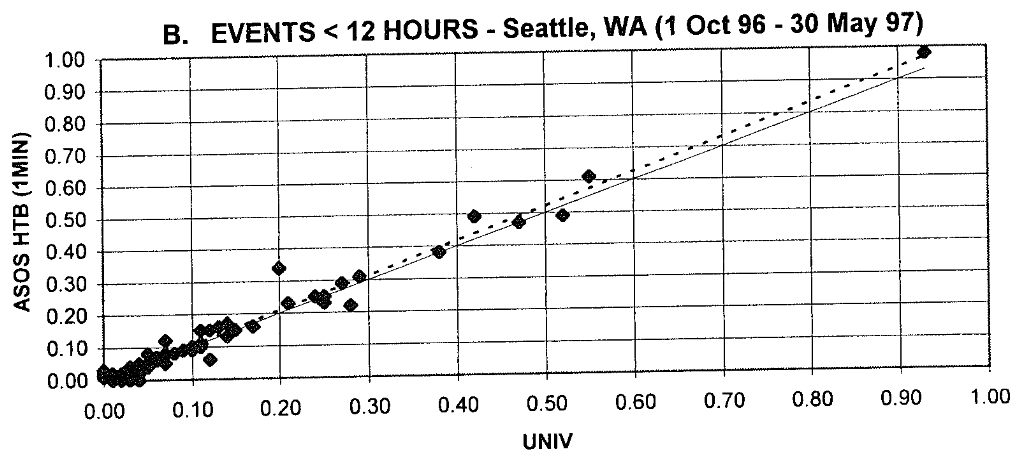


Figure 3.16 ASOS HTB 1MIN versus UNIV at PAH for (A) All Events, (B) Events < 12 Hours, and (C) Events > 12 Hours.





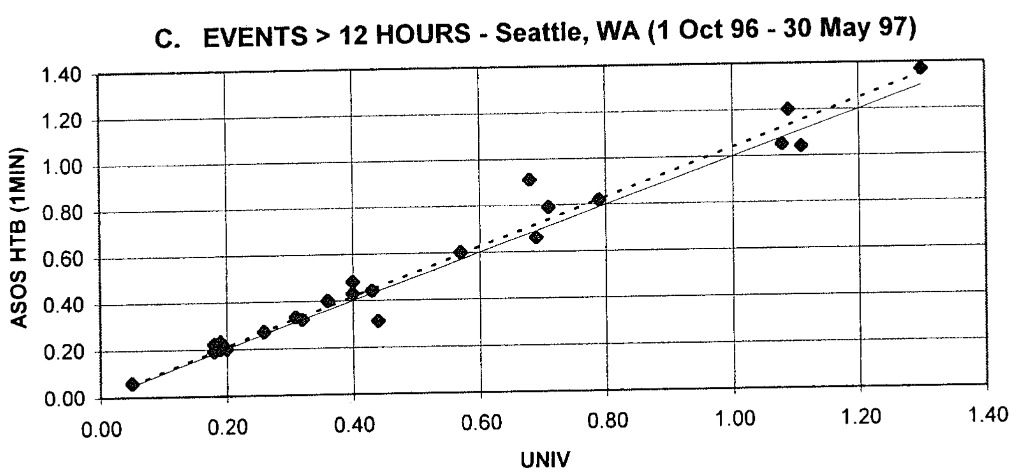


Figure 3.17 ASOS HTB 1MIN versus UNIV at SEA for (A) All Events, (B) Events < 12 Hours, and (C) Events > 12 Hours.

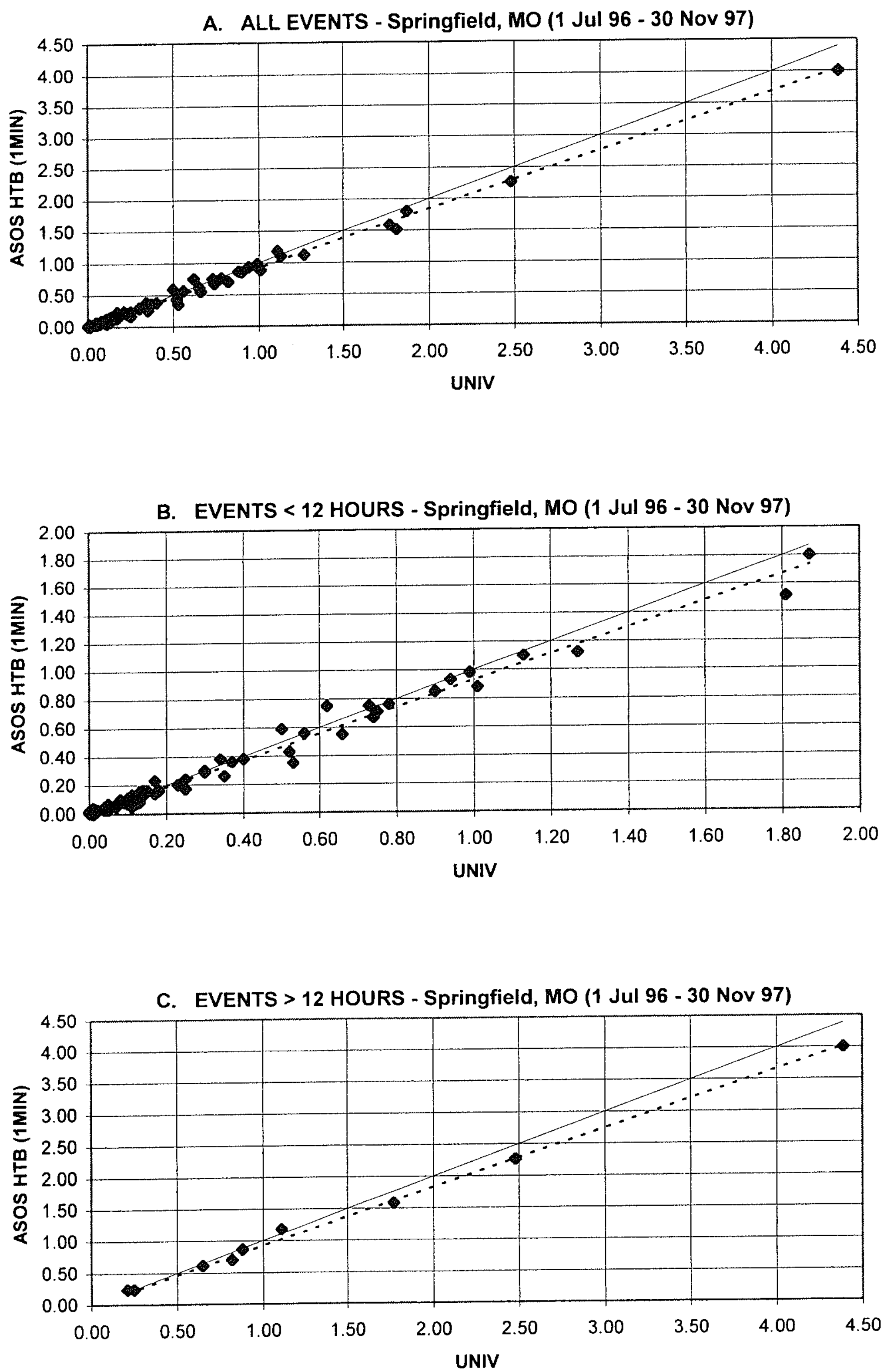


Figure 3.18 ASOS HTB 1MIN versus UNIV at SGF for (A) All Events, (B) Events < 12 Hours, and (C) Events > 12 Hours.

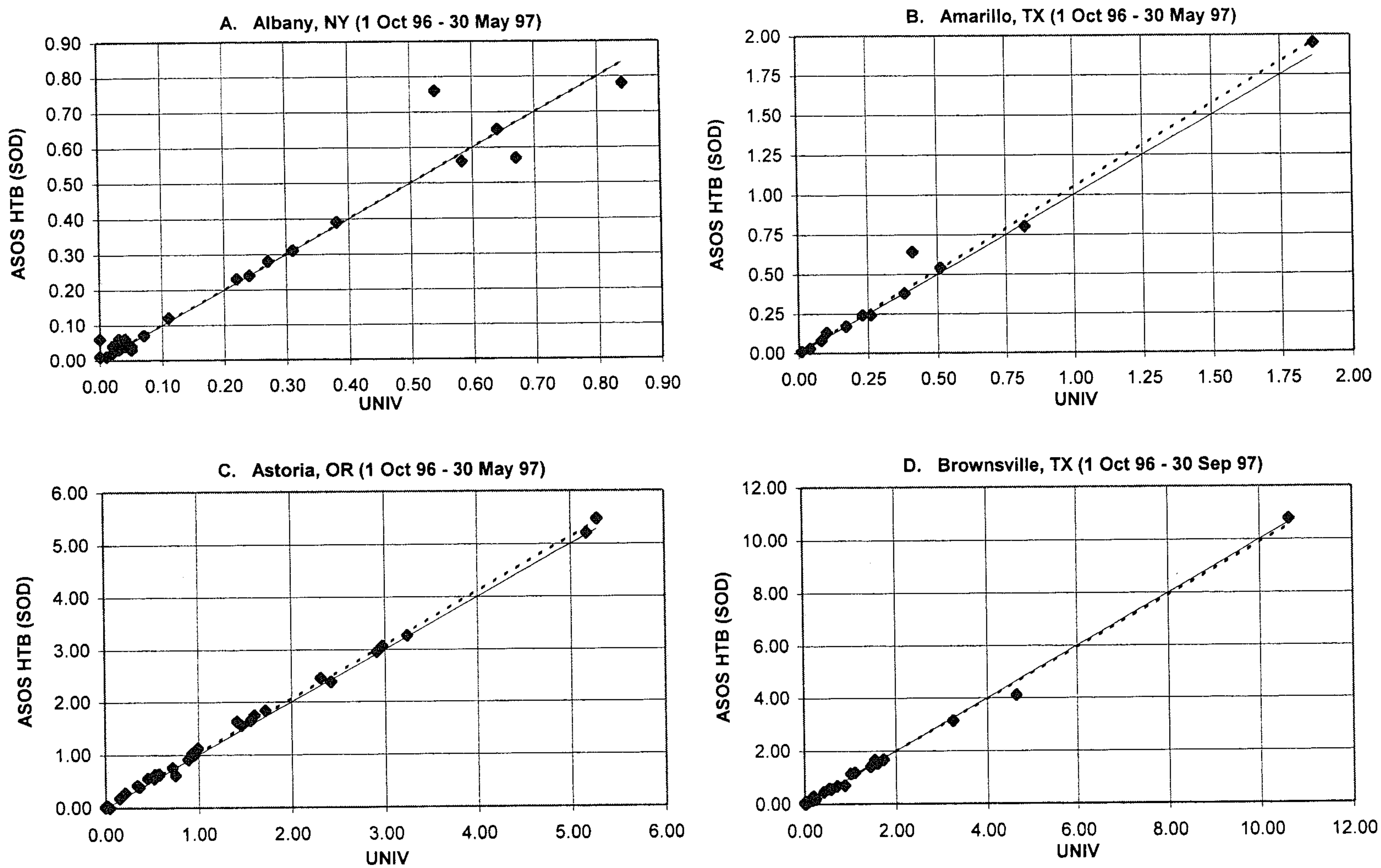


Figure 3.19 ASOS HTB SOD versus UNIV for sites at (A) ALB, (B) AMA, (C) AST, and (D) BRO.

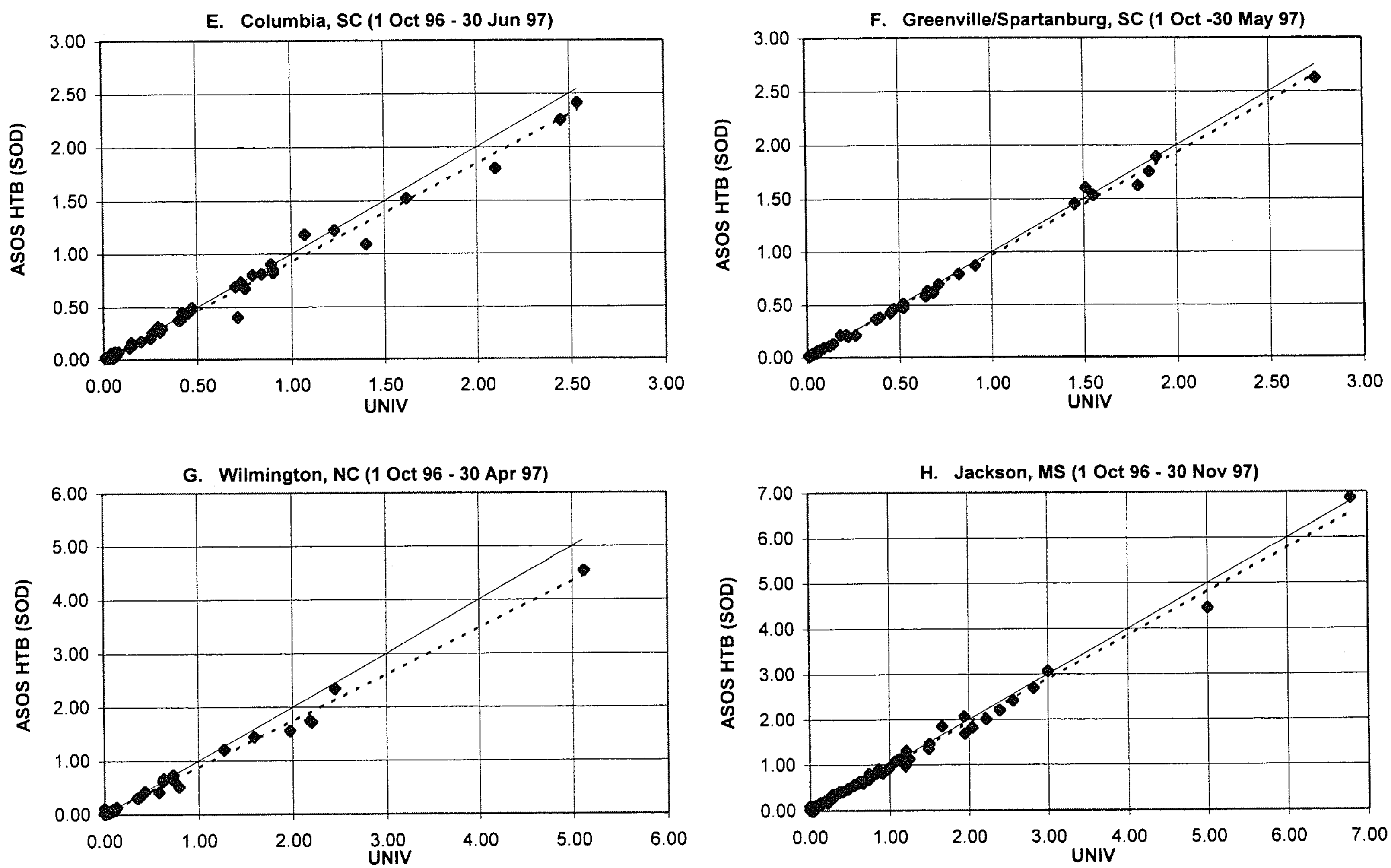


Figure 3.19 ASOS HTB SOD versus UNIV for sites at (E) CAE, (F) GSP, (G) ILM, and (H) JAN.

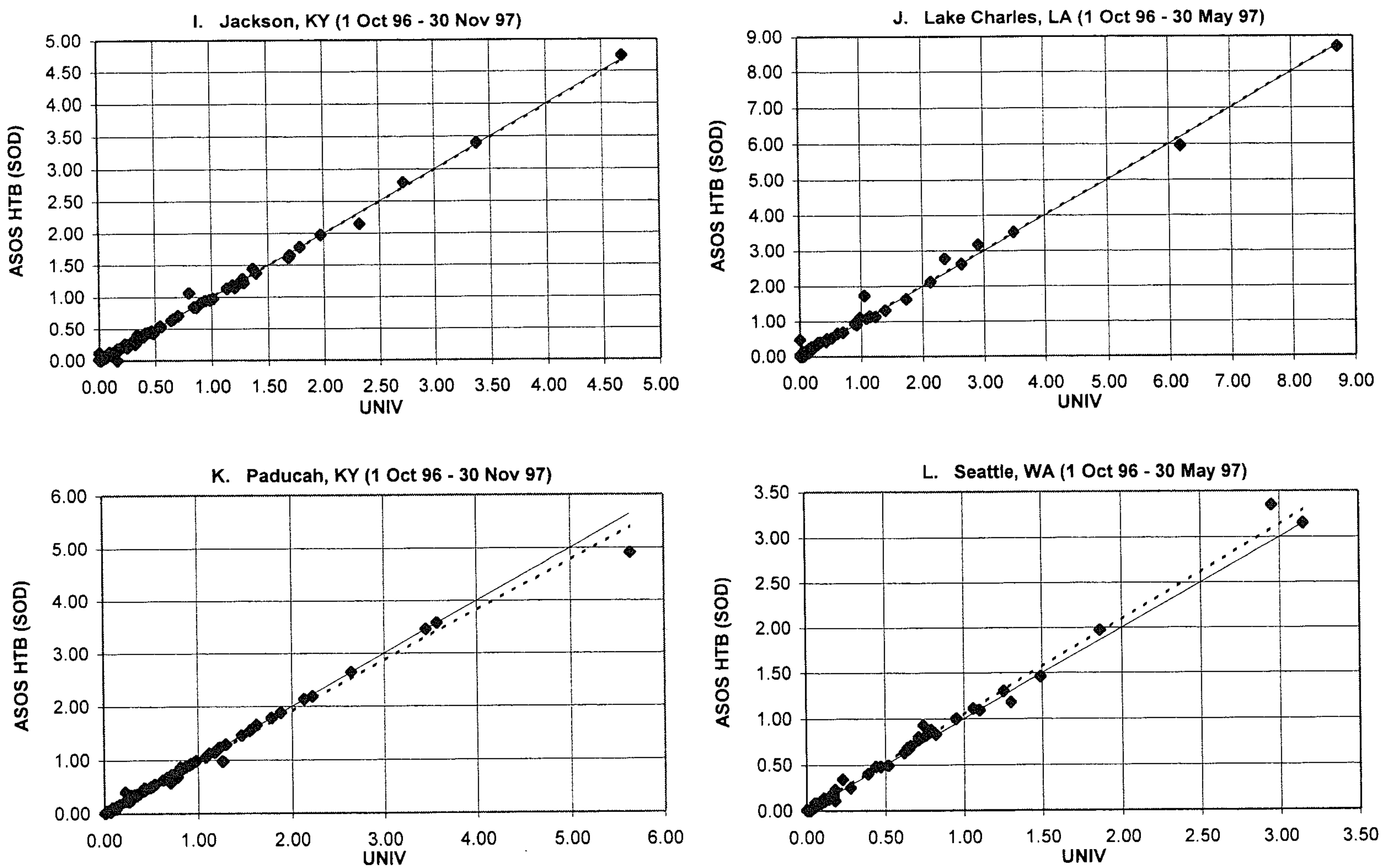


Figure 3.19 ASOS HTB SOD versus UNIV for sites at (I) JKL, (J) LCH, (K) PAH, and (L) SEA.

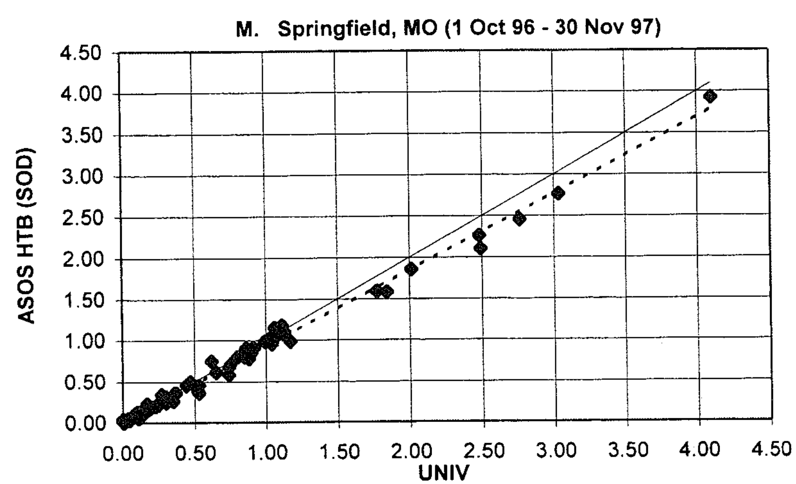


Figure 3.19 ASOS HTB SOD versus UNIV for sites at (M) SGF.

the individual stations. Only three stations, ILM, JKL, and PAH, have slopes or 1MIN versus UNIV ratios less than or equal to 0.90. The stability of the results of the HTB 1MIN to UNIV relationship in Figures 3.14(A) and 3.16(A) for JKL and PAH, respectively, suggest that these two ASOS HTB units are consistently failing operationally. This failure is evident in their demonstrated tendency to significantly undermeasure with respect to the UNIV. The approximate distance between the HTB and UNIV at these two sites is less than 1300 ft, or 0.25 miles, reducing the likelihood that the differences between the gauges were spatially induced. As for ILM, the inconsistency of the measurement comparison between HTB and the UNIV, illustrated in Figure 3.12(A), along with the given gauge separation distance, in excess of a mile, indicates that convective variability was possibly the most significant factor in the observed gauge differences. Therefore, by eliminating the two apparently faulty HTB gauges at JKL and PAH along with ILM, it is evident from this study that, typically, deviations between the HTB 1MIN and UNIV remain within the range of ±10%. Using the mean HTB 1MIN to UNIV ratio of all the stations to project the impact to the precipitation climate record by the group as a whole yields a ratio of 0.97, a climate record change of -3%. Whereas, if JKL and PAH are removed, the remaining group mean ratio indicated a near one-to-one relationship between HTB 1MIN and the UNIV, therefore it could be concluded that there was no impact made on the climate record as a collective set.

From Table 3.5 it is concluded that the slope of the least-squares fit line generally depicts the ratio of 1MIN to UNIV to be the same or lower than the cumulative 1MIN to UNIV ratio does with the exception of PAH. In the case of AST and BRO, the lower ratio of the slope measure depicts the HTB 1MIN as less of a precipitation overmeasuring device than is reflected by the cumulative precipitation ratio. At PAH, the higher ratio of the slope measurement shows a more optimistic agreement between HTB 1MIN and UNIV, however slight it may be, than is represented by the cumulative ratio.

The precipitation record of the SOD was generally much closer to the UNIV than the 1MIN had been as depicted in both the slope of the least-squares fit line and the cumulative ratios. It must be noted that these improvements are in part due to the fact that less precipitation was compared. The HTB SOD data, as stated earlier, did not become available to the study until October 1996, whereas, gauge comparison for HTB 1MIN and UNIV observations started in July 1996 for most sites. For example, this is likely the reason for the instability in the HTB and UNIV relationship at ALB where the results shift dramatically between values derived from HTB 1MIN versus UNIV and HTB SOD versus UNIV. The instability in the HTB and UNIV relationship most likely results because the precipitation recorded at these two sites was very small relative to the other 12 sites.

Even more notable are the remarkable improvements in the reported precipitation of the HTB SOD versus UNIV relative to the HTB 1MIN versus UNIV at JKL and PAH. Figures 3.19(I) and 3.19(J) respectively, show a near perfect relationship in HTB SOD to UNIV measurements with only three points at each station showing any major deviation from the one-to-one ratio line and the least-squares fit line of the data. The improvement at these two sites can only be explained by the fact that JKL and PAH edited daily precipitation reports in the SOD. Of all the SOD reports made during the course of this study, 70% and 80% of them for JKL and PAH respectively, differed from the UNIV by

0.01″ or less -- strong evidence that the UNIV was used to adjust the totals reported in the SOD.

In summary of 1MIN to UNIV comparisons and resulting ratios from total accumulated precipitation and slope measure from least-squares fit lines, it can be concluded that the impact of the ASOS HTB can be quite substantial to the individual site climate record, noted especially at PAH and to a lesser degree JKL and ILM. Removing these sites form the collective group results in individual site climate records being impacted within a range of ±9-10%. The entire group mean ratio of 0.97 and the mean slope of 0.94, shown in Table 3.5, illustrates that the ASOS HTB still favors undermeasuring precipitation in the total climate record of the 13 stations used in this study. Only after extensive editing of SOD reports at PAH and JKL does the collective group mean ratio of total accumulated precipitation reach a near one-to-one ratio.

In an attempt to determine how the HTB 1MIN compared to the UNIV for short versus long duration events, events were divided up into two groups. The two groups created were events that occurred over periods less than 12 hours and those greater than 12 hours. The goal of this portion of the analysis was to isolate convective events within the less than 12 hour event bin. The time resolution of the bins was directed by the 6 hour resolution of the UNIV data. The use of 6 hour event bins was considered, but it was concluded that there would be significant contamination of the longer duration bins by short duration events that perhaps started right before a 6 hour UNIV report and ended shortly thereafter but were not reported until the reading was recorded 6 hours later. Such a scenario would allow a brief event to be classified as a 12 hour event. Limitations to this portion of the analysis reside in the fact that multiple convective events might have occurred during three or more consecutive 6 hour periods and, though they were convective, ended up being classified in the events greater than 12 hour category. Another problem is that at several sites (e.g. BRO), there were few events that last that lasted more than 12 hours due to their climate regime. Figures 3.6-3.18 illustrate the relationship of the HTB 1MIN and UNIV for events less than 12 hours in duration and events greater than 12 hours. Table 3.6 summarizes those figures. In Table 3.6, values

Table 3.6 Summary of 1MIN to UNIV for All Events, Events < 12 Hours, and Events > 12 Hours.

	All Events		Events <12 Hours				Events >12 Hours			
Station	1MIN / UNIV	Slope	1MIN (in)	UNIV (in)	1MIN / UNIV	Slope	1MIN (in)	UNIV (in)	1MIN / UNIV	Slope
ALB	0.99	0.96	4.93	4.99	0.99	0.95	6.81	6.84	1.00	0.96
AMA	1.08	1.08	2.32	2.18	1.06	1.03	5.89	5.42	1.09	1.08
AST	1.06	1.03	4.56	3.93	1.16	1.05	44.34	42.31	1.05	1.02
BRO	1.03	0.99	8.13	7.69	1.06	0.98	4.97	5.02	0.99	0.99
CAE	0.91	0.90	15.43	17.43	0.90	0.89	7.41	7.87	0.94	0.92
GSP	0.97	0.96	15.08	15.29	0.99	0.97	11.47	12.14	0.94	0.95
ILM	0.87	0.78	10.72	10.86	0.99	0.78	15.70	19.35	0.81	0.79
JAN	0.95	0.94	39.50	41.25	0.96	0.95	13.00	14.02	0.93	0.91
JKL	0.90	0.87	16.62	17.88	0.93	0.91	27.20	31.01	0.88	0.86
LCH	1.04	0.99	33.53	31.29	1.07	1.01	19.08	19.20	0.99	0.98
PAH	0.77	0.81	20.72	25.81	0.80	0.81	19.23	26.05	0.74	0.81
SEA	1.05	1.04	8.55	8.18	1.05	1.04	12.52	11.93	1.05	1.04
SGF	0.95	0.92	21.63	22.63	0.96	0.93	11.67	12.56	0.93	0.92
Mean	0.97	0.94		Mean	0.99	0.95		Mean	0.95	0.95

hold relatively constant across the different bins in comparison to the all events bin except in bins that only include a small amount of precipitation. In those bins, deviations can significantly alter the computed ratios. Notice that Figure 3.10(B) of CAE, Figure 3.12(B) of ILM, and Figure 3.16(B) of PAH have the largest number of points for events less than 12 hours that have significant deviations both above and below the least-squares fit line. Further investigation of these significant deviations at CAE, ILM and PAH reveal that these events occurred in spring and summer. This implies that at these three stations, ASOS is located far enough from the UNIV to allow spatial variations to affect measurements taken by the two gauges as well as localized topographical effects. In other words, it was common for more rain to occur at one location than the other which would create a significant scatter of points, and place them randomly above and below the least -squares fit line. The data indicates in the case of ILM that it was actually the random nature of the scatter due to convective influences that over time struck a statistical balance between the ASOS and UNIV sites resulting in the illusion of a one-to-one ratio in the cumulative ratio of the HTB and UNIV. The slope, however, seems to reveal the true nature of the relationship between the HTB and the UNIV with a value of 0.78. That value is consistent with both the cumulative ratio and the slope found from the events greater than 12 hours. This convective effect becomes even more apparent after the analysis of events greater than 12 hours depicted in Figure 3.10(C) of CAE, Figure 3.12(C) of ILM, and Figure 3.16(C) of PAH. Though the number of observed events meeting the greater than 12 hour criteria was considerably smaller, the HTB 1MIN versus UNIV comparisons match up more closely with the least-square fit line producing little scatter. This study suggests that this is because the convective events, with the most significant spatial variations, did not fall in the long duration category, and therefore it was concluded that the greater than 12 hour event category better isolates the gauge variation from the spatially induced variations. In the ILM case, both the cumulative ratio and the slope of the greater than 12 hour events are in agreement, and, strongly suggest that this particular ASOS HTB severely undermeasured precipitation throughout the entire period of this study.

Summarizing the 12 hour event bin analysis, results compare similar to was seen in the all events analysis shown previously in Table 3.5. The noteworthy conclusion of the 12 bin analysis was the ability to see the spatial, convective signature in at CAE, ILM and PAH. Not knowing the extent of the random scattering of convective activity at ILM might lead to a conclusion that ILM's ASOS HTB impact on the precipitation climate record when compared to the UNIV is negligible upon comparing the total precipitation accumulation, listed in Table 3.6, for events less than 12 hours by the two gauges.

To further illustrate the tendencies observed at each site, the 98% confidence intervals of the deviations of HTB 1MIN from the UNIV (1MIN-UNIV) were computed. The 98% was derived from the initial program specification that the HTB produce correct precipitation accumulation observations 98% of the time (NWS, 1992). In calculating the 98% confidence intervals, it was assumed that the data had normal population distributions of precipitation accumulation differences with sample sizes in excess of 30, and that the Central Limit Theorem was applied in calculating the confidence intervals such that:

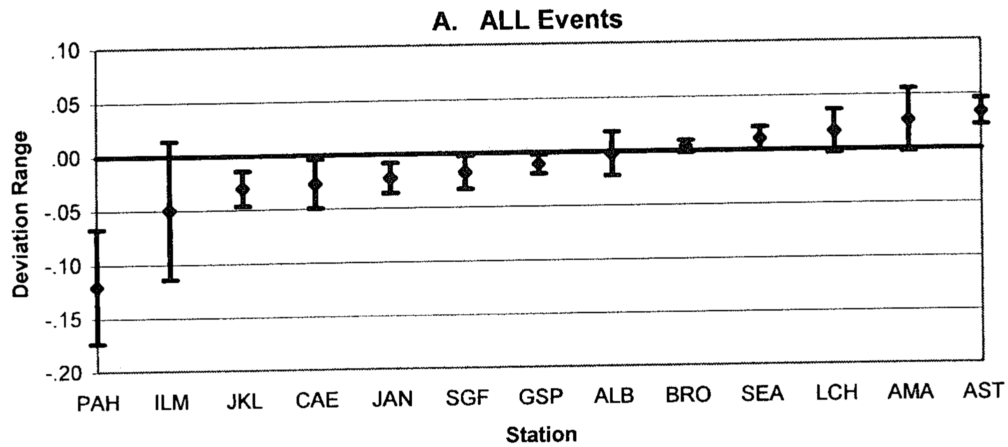
$$\left(\bar{x}-(2.33)\frac{\sigma_{\bar{x}}}{\sqrt{n}}<\mu<\bar{x}+(2.33)\frac{\sigma_{\bar{x}}}{\sqrt{n}}\right) \tag{3.8}$$

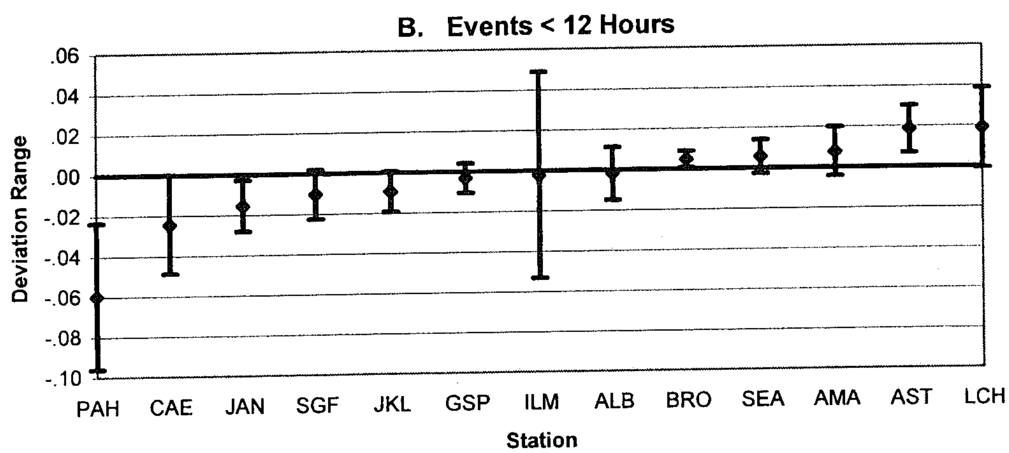
where $\bar{x}$ is the sample mean, n is the sample size, σ_x is the standard deviation of the sample, and μ is the population mean. For stations with sample sizes n<30, a t-distribution with n-1 degrees of freedom was used to calculate the 98% confidence interval by:

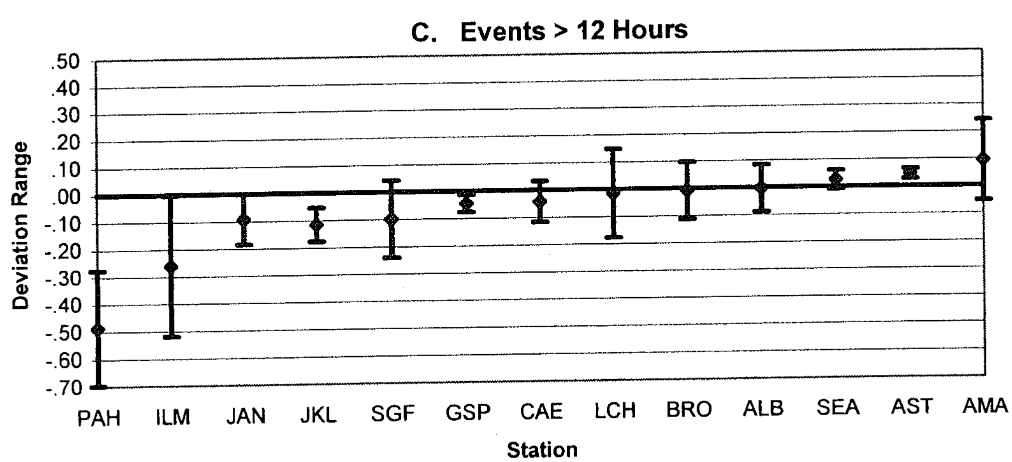
$$\left(\bar{x}-\left(t_{.01,n-1}\right)\frac{\sigma_{\bar{x}}}{\sqrt{n}}<\mu<\bar{x}+\left(t_{.01,n-1}\right)\frac{\sigma_{\bar{x}}}{\sqrt{n}}\right) \tag{3.9}$$

where $t_{0.01}$ is the t-value with 1.0% of the distribution above and below it (Devore, 1995). Figure 3.20(A), shows the range of HTB deviations from the UNIV for all events for each station. Center points on the error bars represent the mean deviation, and 98% of all the HTB deviations from the UNIV for that station fall within the range depicted by the error bars. The most extreme deviations lie outside of that range. If the error bars are below the zero line of the y-axis, that indicates that the HTB undermeasured compared to the UNIV. Summarizing Figure 3.20(A), PAH and ILM appear as gauges with considerably larger deviation ranges than the rest of the sites in the analysis, with both stations showing a strong tendency to undermeasure precipitation events. JKL, CAE, JAN, and SGF also demonstrated undermeasuring tendencies, and are very comparable in the magnitude of this undermeasuring. On the other side of the spectrum, the deviation range for AST showed a tendency to overmeasure precipitation accumulation events with a mean deviation of 0.04″. Caution should be exercised before making conclusions to the climate impact of the ASOS HTB at AMA due to the limited number of events that were analyzed in this study. Both stations had considerably less accumulated precipitation over the course of the study compared to the rest of the sites.

Figures 3.20(B) and 3.20(C) divide the events by length as before, those less than 12 hours and those greater than 12 hours, and depict the confidence intervals for each group at each station. For events less than 12 hours, PAH continued to indicate undermeasured precipitation, while ILM had the largest range of possible deviations reflecting both over and undermeasuring. This large range of both positive and negative deviations at ILM is suggestive of the well randomized spatial, convective signature discussed earlier for ILM, and here it produced an average deviation of 0.00″. The rest of







3.20 Deviation range calculated from 98% confidence interval at each site for (A) All Events, (B) Events < 12 Hours, and (C) Events > 12 Hours.

the stations within this bin of events less than 12 hours exhibited the same pattern they had shown when all the events were included together in Figure 3.20(A).

Figure 3.20(C) illustrates events greater than 12 hours. The range of deviations in this figure is larger than the events less than 12 hours. This is likely due to the fact that the small events with the smaller deviations have been excluded, so the more extreme deviations that were outside the 98% when all events were considered are now being displayed. It only makes sense that in general the longer the event, the more precipitation accumulates, and the larger the deviations per event become. PAH and ILM show an alarming tendency for the HTB to undermeasure precipitation when compared to the UNIV. JAN, JKL, SGF and CAE also tended to undermeasure on average. AST continued to show overmeasured precipitation by the HTB and while AMA had only five events in the greater than 12 hour category, all of them were overmeasures. The remaining stations showed a smaller and more balanced deviation range including instances of both over and undermeasuring precipitation events.

3.3.5 False Tips

The false tip is a problematic output of the HTB that is currently being reviewed by the NWS for a solution. Simply stated, a false tip is the recording of 0.01″ of precipitation when there is no precipitation actually occurring. This false tip tends to occur when the temperature and dewpoint are within 1°F or less of each other in a stable atmosphere with light to calm winds; in other words, the key ingredients for the onset of dew. The formation of dew typically occurs overnight near the time of sunrise when the surface radiatively cools to a point where the temperature and dewpoint are nearly equal causing the condensation of water vapor on a variety of surfaces. In this case, the water vapor deposits on the precipitation collection area of the HTB.

The purpose of this portion of the study was to isolate such events and quantify their effect on the precipitation records at the stations in this study. Possible false tips were identified in the data by looking for 0.01″ in the HTB 1MIN data when no precipitation had been recorded by the HTB or LEDWI during the five minutes prior to the suspected false tip. The actual minute that the suspect 0.01″ HTB observation was made must be accompanied by a report of no precipitation by the LEDWI. The suspect observations were then analyzed for temperature and dewpoints that were within a degree of one another. The resulting data was then checked against UNIV data to determine if the UNIV had recorded any precipitation. If no precipitation was recorded by the UNIV for an event, then it was concluded that the HTB had recorded a false tip. The HTB false tips our method uncovered are displayed in Figures 3.21(A-L) in a frequency distribution for each station based on the hour the false tip would have been reported in the hourly METAR observation. A figure is not provided for SEA because no false tips were extracted from the 1MIN data set. For stations that produced a relatively large number of false tips, the maximum frequency of occurrence tended to in the hours closest to sunrise. The distribution for stations with a small cumulative frequency of false tips was isolated between midnight and reasonable sunrise times.

Finally, the number of false tips for each station was deducted from the total precipitation recorded by each site's HTB over the course of this study. Results are displayed in Table 3.7 Review of the results from this analysis in Table 3.7 show that impacts are only substantial at BRO due to the number of false tips in comparison to the

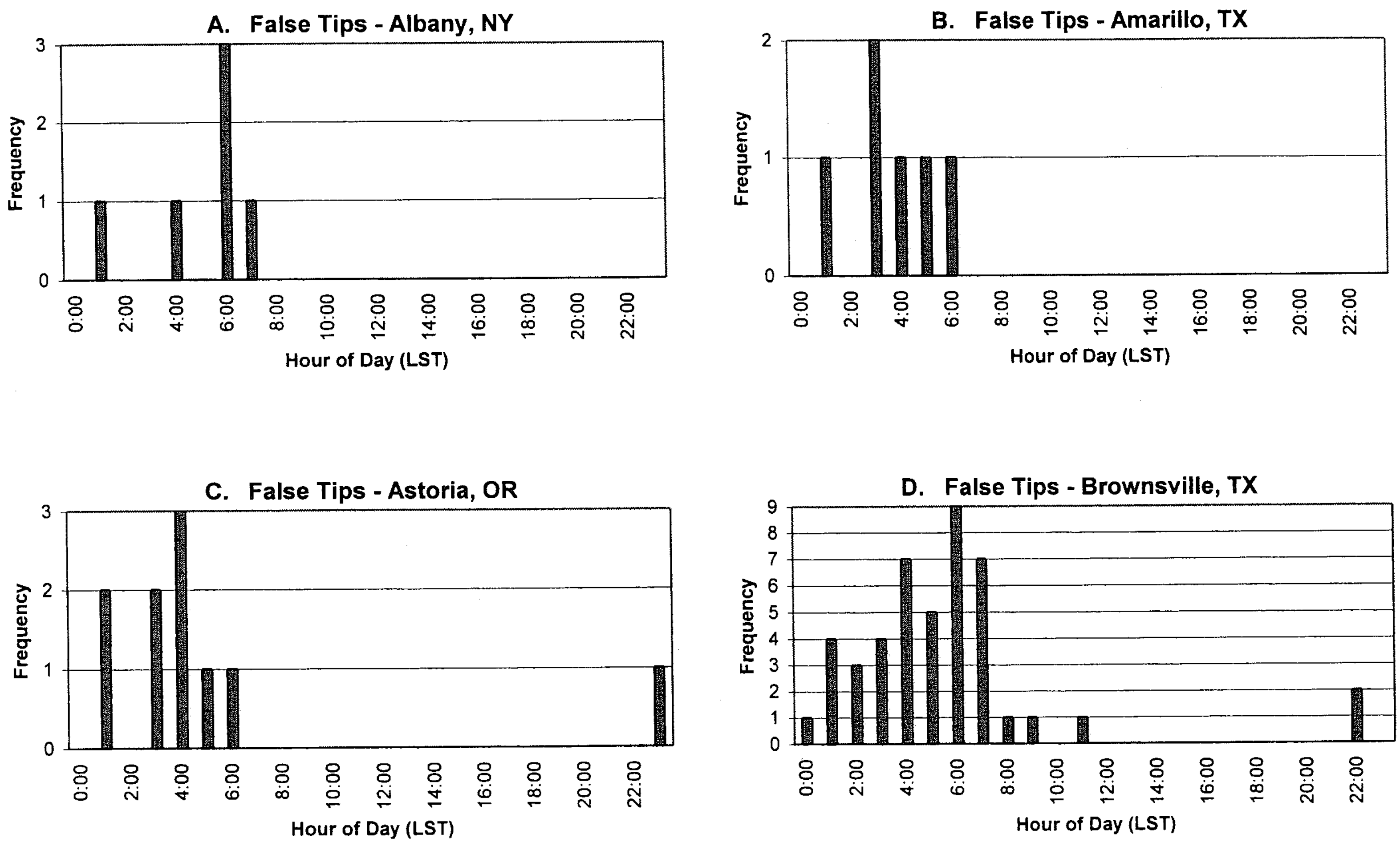


Figure 3.21 Frequency distribution of False Tips at (A) ALB, (B) AMA, (C) AST, and (D) BRO.

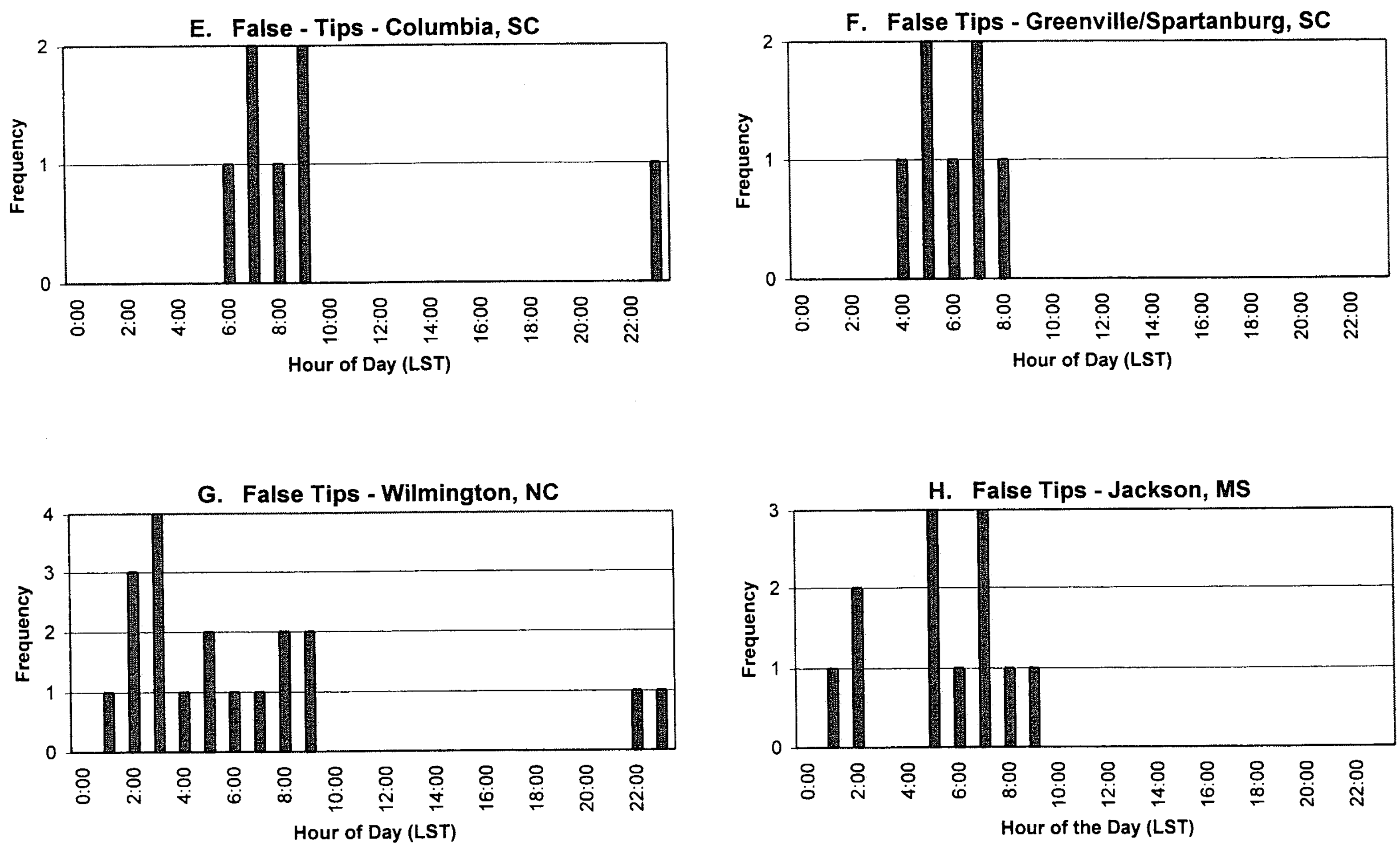


Figure 3.21 Frequency distribution of False Tips at (E) CAE, (F) GSP, (G) ILM, and (H) JAN.

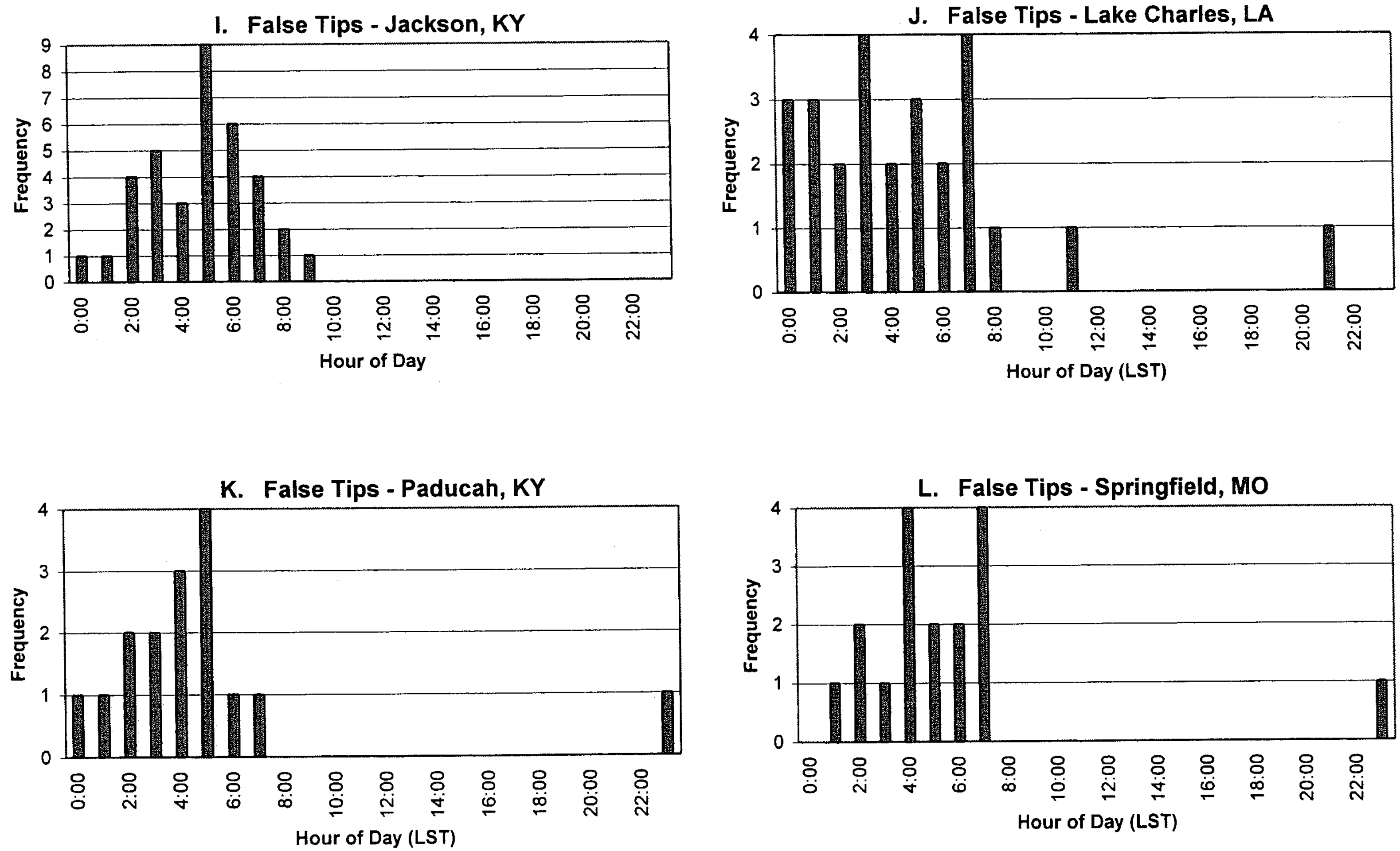


Figure 3.21 Frequency distribution of False Tips at (I) JKL, (J) LCH, (K) PAH, and (L) SGF.

relative amount of total precipitation. JKL and LCH both show a substantial number of false tips, but they represent such a small fraction of the total precipitation that the false tips only amount to problems in the forecast verification arena. A WFO forecast for a period would be rendered in error if no precipitation was forecasted, but 0.01″ of precipitation was measured.

Table 3.7 Results of False Tip Elimination from accumulated precipitation totals for study

Station	ALL EVENTS UNIV (in)	ALL EVENTS 1MIN (in)	ALL EVENTS 1MIN / UNIV		EVENTS MINUS FALSE TIPS #False Tips	EVENTS MINUS FALSE TIPS 1MIN (in)	EVENTS MINUS FALSE TIPS 1MIN / UNIV
ALB	11.83	11.74	0.99		6	11.68	0.99
AMA	7.60	8.21	1.08		6	8.15	1.07
AST	46.24	48.90	1.06		10	48.80	1.06
BRO	12.71	13.10	1.03		45	12.65	1.00
CAE	25.30	23.06	0.91		7	22.99	0.91
GSP	27.43	26.55	0.97		7	26.48	0.97
ILM	30.21	26.42	0.87		19	26.23	0.87
JAN	61.87	58.82	0.95		12	58.70	0.95
JKL	48.89	43.82	0.90		36	43.46	0.89
LCH	50.49	52.61	1.04		26	52.35	1.04
PAH	51.86	39.95	0.77		16	39.79	0.77
SEA	20.11	21.07	1.05		0	21.07	1.05
SGF	35.19	33.30	0.95		17	33.13	0.94
		Mean	0.97	Total	207	Mean	0.96

4.0 CONCLUSIONS

The purpose of this investigation, and the *Climate Data Continuity Project* (CDCP) with the Automated Surface Observing System (ASOS) Heated Tipping Bucket Rain Gauge (HTB), was to assess HTB performance and examine the impact on precipitation climate continuity due to the NWS decision to switch from the Universal Rain Gauge (UNIV) to the automated HTB. In addition to the instrumentation change, the official precipitation accumulation observation site was moved from where the UNIV had resided to a new location for the ASOS array. To determine the performance of the HTB in an operational environment, the HTB One Minute (1MIN) observation accumulated precipitation measurements were compared to a Collocated Rain Gauge (CRG) at four sites. In order to assess the impact on precipitation climate continuity, the HTB 1MIN and UNIV were compared at 13 sites on a total event measurement basis.

The results of the performance analysis of the ASOS HTB to the CRG accomplished in this investigation show that in an operational setting, at four sites, the total accumulation precipitation ratio of the HTB to CRG can be as low as 0.93 as seen in the data from Jackson, Mississippi (JAN). The other sites at Greenville/Spartanburg, South Carolina (GSP), Lake Charles, Louisiana (LCH), and Springfield, Missouri (SGF), show results of 0.97, 1.02, and 1.02 respectively. The results from the latter sites fall within the ASOS specifications of ±4%, outlined in section 3.4.1 of the *ASOS User's Guide* (National Weather Service, 1998b.). These results are also consistent with the results achieved in the dedicated test conducted at the NWS Sterling Development and Research Center which concluded that the ASOS HTB undermeasured by 2.4% compared to a collocated Standard 8″ Non Recording Rain Gauge (SRG). The least-squares fit line analyses of HTB versus CRG at GSP, JAN, LCH, and SGF were similar to the total accumulation ratios with results of 0.97, 0.92, 1.02, and 1.03 respectively. This analysis reveals a tendency in the data from the ASOS HTB at GSP and JAN to push and exceed the 4% undermeasuring threshold specification for ASOS HTB precipitation accumulation measurements. Despite the fact that, in a general sense, the HTB performed adequately, variation observed in the HTB to CRG relationship at different sites illustrates that the standard algorithm incorporated in all ASOS units, Equation 2.1, used for correcting accumulated precipitation, does not compensate for differences in each individual gauge. Therefore, it is proposed from the results of this study that the correction algorithm needs an additional linear correction to the non-linear correction currently used in every ASOS. The proposed new correction algorithm, Equation 3.7, includes the coefficient B, the linear correction proposed by this study. Given the variation in the relationship results of HTB to CRG comparisons from the four sites used in this investigation, the linear correction must be site-specific. The linear correction can be determined by comparing a large sample, from the annual average total accumulated liquid precipitation, of ASOS HTB event measurements to those measured by an ASOS collocated SRG. The linear relationship of ASOS HTB versus SRG for compared event measurements will illustrate the magnitude of the linear correction need for a given ASOS HTB to achieve the desired one-to-one relationship with the SRG. For the four sites used in the HTB performance assessment, using the data and results from this study, the proposed linear correction based on slope measure calculations are: 1.03 for GSP, 1.08 for JAN, 0.98 for LCH, and 0.97 for SGF.

The impact on climate continuity by the ASOS HTB and its new location relative to the UNIV, illustrated by the results provided from the 13 stations in this study, seems to vary considerably with respect to each individual site. Total accumulated precipitation differences between the HTB 1MIN and UNIV from combined effects due to instrumentation performance and spatial variations were shown by this study to be in excess of ±5% for 6 of 13 sites. The HTB 1MIN to UNIV total accumulated precipitation ratio result at Astoria, Oregon (AST) showed an overmeasuring by the HTB on the order of 6%. The least-square slope measurement of the same data yielded a more conservative value of 3%. Considering the small distance between the ASOS and the UNIV at AST, approximately 660 ft, the conclusion was reached that it was not a spatial impact causing such results, but more likely a case in which the accumulated precipitation correction algorithm used in the ASOS software is not exactly correct for this site and particular gauge.

Further comparison of ASOS and UNIV site separation distances to significant differences in measurements taken by the HTB and UNIV at Jackson, Kentucky (JKL) and Paducah, Kentucky (PAH) indicated that these sites have possible faulty HTB units. Analysis of total accumulated precipitation ratios derived from HTB 1MIN to UNIV comparison showed 0.90 for JKL and 0.77 for PAH . Similar results from least-squares slope analysis of HTB 1MIN versus UNIV were achieved at JKL and PAH with end results of 0.87 and 0.81 respectively. The faulty gauge theory is further solidified by the results of total accumulated precipitation ratios constructed from HTB Summary of the

Day (SOD) to UNIV comparisons which produced values of 1.00 and 0.98 for JKL and PAH respectively. This astonishing improvement was determined to be the result of WFO personnel editing SOD precipitation totals to better reflect UNIV measurements at these two sites. Furthermore, the small distance between the UNIV and ASOS array, approximately 0.25 miles, reduces the likelihood that the gauge differences were spatially induced.

Further analysis of the impact of the HTB on climate continuity uncovered problems at Wilmington, North Carolina (ILM). Contrasting results from the analysis of all events and events grouped into bins based on duration criteria, indicated a spatial convective signature. The convective events led to a statistical balance of 0.99 in the total accumulated precipitation ratio derived from the HTB 1MIN and UNIV comparison for events less than 12 hours. On the other hand, total accumulated precipitation ratios and least-squares slope measurements constructed for all events and events greater than 12 hours demonstrated a ratio range of 0.78-0.87 for ILM. These ratios seem to better represent the situation at ILM, and they indicate that the amount of precipitation recorded in the local climate record has significantly decreased since ASOS and the HTB Modification 35 was fielded. The distance between the ASOS array and UNIV was estimated to be in excess of one mile, further supporting the conclusion that convective events induced significant spatial variations between the HTB and UNIV at ILM.

Of the 13 locations used for this investigation of the climate continuity impact of the HTB, 9 sites show individual climate impact results from total accumulation analysis of 1MIN data to UNIV comparisons in excess of ±4%. Individual slope measurements provide similar insight to the impact on site climate continuity with seven stations studied showing numbers in excess of ±4% from HTB 1MIN versus UNIV relationship analysis. Applying the same analysis described above with the substitution of HTB SOD data for HTB 1MIN produced slightly better results with six stations producing total accumulation ratios in excess of ±4%. This improvement in the number of stations observed to be within ±4% is due to a reflection of the editing practices of ASOS SOD reports at PAH and JKL.

Further analysis of the mean HTB 1MIN to UNIV total accumulation ratio of all 13 stations was 0.97 suggesting an undermeasuring impact on the climate record of the collective group. The mean slope from the HTB 1MIN to UNIV comparison produced a value of 0.94 suggesting a more significant undermeasuring impact of the HTB for the collective group. Removal of the isolated faulty gauges at JKL and PAH from the collective group improves the mean total accumulation ratio to 0.99 and the mean slope to 0.96. When using the SOD reports to assess the mean climate continuity impact of the ASOS HTB on the collective group of 13 stations, the results presented by this investigation show a collective mean total accumulated precipitation ratio of 0.99 and a mean slope of 0.98 when compared to the UNIV. This near one-to-one total accumulated precipitation ratio suggests that the ASOS HTB has not significantly impacted the climate continuity for the 13 stations used in CDCP investigation of the HTB when considered as a group. Mean slope measurements showed a tendency to undermeasure by 2% for the collective group of HTB gauges.

In conclusion, after eliminating the results from the faulty gauges at JKL and PAH, the impact of the ASOS program at each of the remaining 11 sites on the precipitation climate continuity is conservatively estimated to fall within a range of ±10%. The results at ILM illustrates the possible impact that spatial variation can introduce to climate continuity. As this report demonstrates, the magnitude of the ASOS HTB impact on climate continuity for individual stations is highly variable, and in some cases very significant. The discovery that 2 of 13 gauges were failing operationally was a very important result of this investigation which leads to a very important question. Out of the 933 ASOS arrays that have been installed nationwide, how many other ASOS HTB units are also failing? From evidence presented in this study, I assert that the only scientific way to assess the operational performance of the ASOS HTB at each NWS site is to collocate an SRG with the ASOS for performance assessment over an extended period of time. SRG measurements should be taken regularly and preferably at a time that offers significant separation between events. These results will establish HTB performance and will also provide a baseline for ASOS to UNIV comparisons. Such studies would provide insight on the impact ASOS is making on the local precipitation climate records.

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