

Evaluation of Rainfall Measurements from the WXT510 Sensor for Use in the Oklahoma City Micronet

Jeffrey B. Basara^{*}, Bradley G. Illston, Thomas E. Winning Jr. and Christopher A. Fiebrich

Oklahoma Climatological Survey, University of Oklahoma, USA

Abstract: A network of 40 real-time, automated atmospheric monitoring stations was deployed in Oklahoma City and officially commissioned on 8 November 2008: the Oklahoma City Micronet (OKCNET). The Oklahoma City Micronet includes 36 stations mounted on traffic signals which utilize the Vaisala WXT510 sensor. As part of the design of the WXT510, an impact sensor is utilized for the collection of rainfall observations. Prior to deployment in Oklahoma City, an array of 33 WXT510 sensors were deployed at the OKCNET intercomparison facility and compared with traditional instruments used to measure rainfall including tipping bucket rain gauges and a Geonor weighing gauge. The results of the comparison revealed that a consistent, linear bias was present between the WXT510 sensors and the traditional gauges whereby, on average, the traditional gauges measured approximately 26% less precipitation than the WXT510 sensors. In addition, the variation in recorded rainfall between WXT510 sensors was consistent with that recorded by the tipping bucket gauges. As such, a correction was developed using the WXT510 and tipping bucket data. This correction was applied to the WXT510 rainfall observations and cross-verified using the Geonor gauge data. The overall result of the study yielded a bulk correction that can be applied to rainfall observations recorded by the WXT510 to greatly improve the accumulated rainfall values. This correction is designed to improve the overall accuracy of the observations without specifically calibrating each individual WXT510 sensor and is valid regardless of rainfall intensity, length of the precipitation event, seasonal characteristics of the rainfall, or rainfall type (i.e., stratiform, convective, etc.).

1. INTRODUCTION

A recent study by the United Nations found that by 2025, 80% of the world's population will live in cities [1]. Further, by 2015, 26 megacities will exist worldwide with populations in excess of 10 million inhabitants [2]. At the same time, recent studies have continued to document the critical role of urban areas on local weather, climate and hydrology. As urbanization continues to increase globally, the collection of representative measurements of atmospheric conditions within urban areas continues to pose a major challenge [3].

Perhaps the most studied impact is the urban heat island (UHI) whereby temperature values within the urban core are warmer than surrounding rural areas [4]. Such conditions are enhanced during the nocturnal period with clear skies and calm wind conditions [5-8]. Additional areas of urban-atmosphere research have focused on surface humidity [9,10], varying roughness and turbulence [11-14], the energy and radiation budgets [15-17], the development of the urban boundary layer [18-21], and air quality, dispersion, and pollution [22-27].

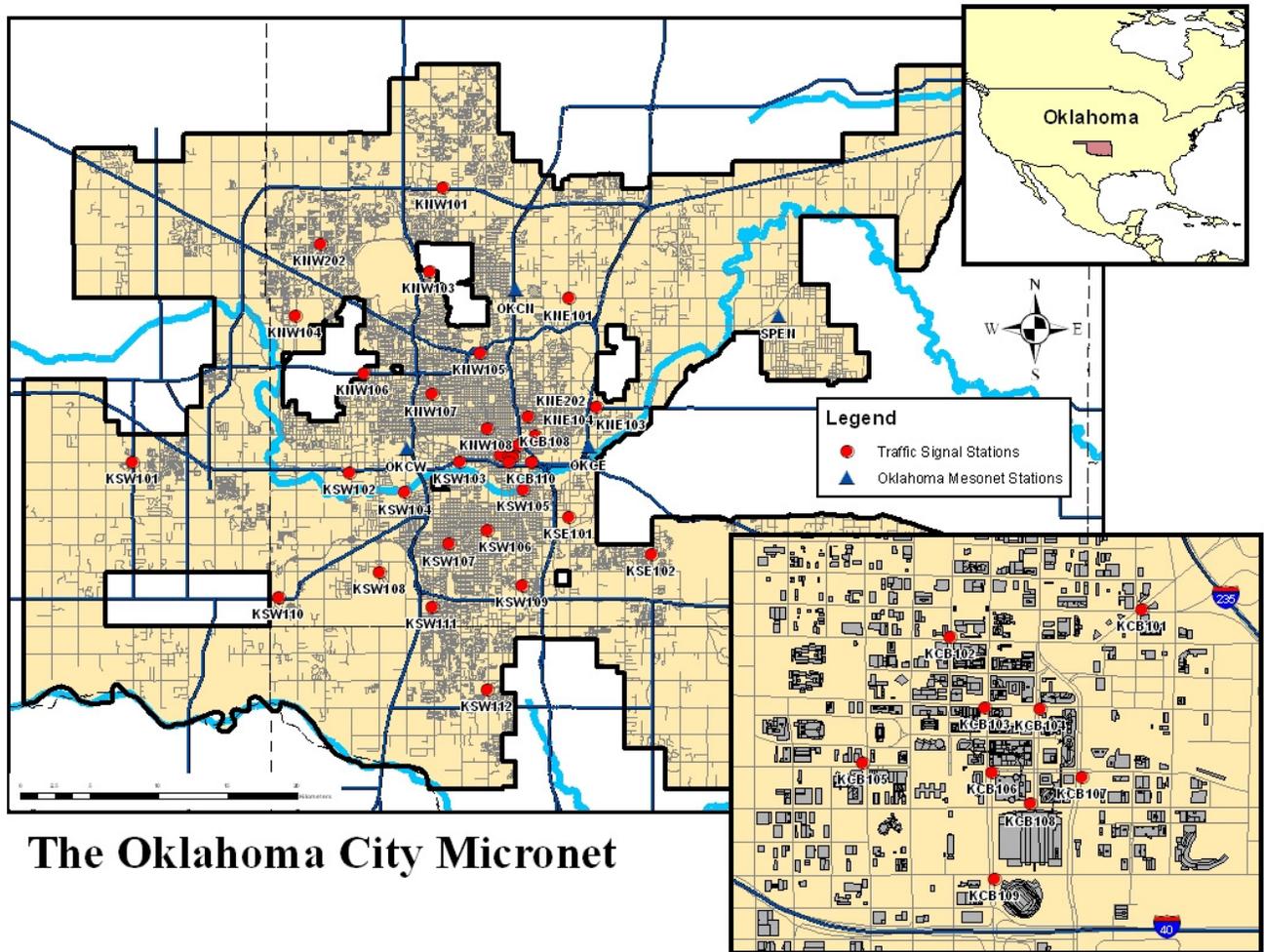
The role of precipitation and hydrological processes is also an area of emphasis for urban-atmosphere research [28-30]. Because of increased impermeability within urban zones, excessive precipitation can lead to increased runoff and urban flooding. At the same time, numerous additional

studies have identified a link between large urban areas and regions of enhanced precipitation in and around the urban zone. Thus, a need exists for real-time, research quality observations of precipitation in and around urban areas.

In the United States, the majority of real-time, continuous, research-quality atmospheric observations are not collected within the core regions of cities. In addition, much of the current understanding of the impacts of urban areas on atmospheric processes has resulted from field programs with limited intensive sampling periods [31-36]. Even so, precipitation specific networks have been deployed in urban areas such as Atlanta [37] and Denver [38] to quantify the variability of rainfall for a variety of research and public service applications.

Fully deployed in the summer of 2008 and commissioned on 1 November 2008, the Oklahoma City Micronet (OKCNET) was designed to collect real-time observations of atmospheric conditions across the metropolitan area of Oklahoma City, USA. The network of 40 stations (Fig. 1) includes 36 sites mounted on traffic signals which utilize the WXT510 sensor manufactured by Vaisala Inc. (<http://www.vaisala.com>) to collect observations of air temperature, humidity, wind speed, wind direction, pressure, and precipitation at an interval of one minute. The precipitation measurements represent a critical component to the goals of OKCNET, however, the WXT510 sensor utilizes technology to measure precipitation that is uncommon to most meteorological stations: an impact sensor. Thus, prior to deployment in Oklahoma City, the WXT510 sensors were deployed in a test array for a period of 15 months to evaluate the precipitation measurements versus other calibrated sensors. As such,

^{*}Address correspondence to this author at the Oklahoma Climatological Survey, University of Oklahoma, 120 David L. Boren Blvd., Suite 2900, Norman, OK 73072, USA; Tel: 405-325-2541; Fax: 405-325-2550; E-mail: jbasara@ou.edu



The Oklahoma City Micronet

Fig. (1). The location of Oklahoma City Miconet stations. The insert in the lower right displays stations within the central business district of Oklahoma City while the insert in the upper right displays the State of Oklahoma (shaded in red) which lies in the central portion of the United States; Oklahoma City is the capitol city of Oklahoma and is located in the geographic center of the state.

this study focused on quantifying the accuracy of the WXT510 precipitation measurements and overall variability between sensors.

2. EXPERIMENT OVERVIEW

The Vaisala WXT510 Weather Transmitter (Fig. 2) is a compact instrument that collects observations of air temperature, relative humidity, pressure, wind speed, wind direction, and precipitation. The WXT510 requires little maintenance once deployed on account of minimal power use during data collection and the absence of moving parts. Such qualities make the WXT510 a significant candidate instrument package for use in urban areas and was chosen as the core instrument for the traffic signal stations deployed in the Oklahoma City Micronet.

The portion of the WXT510 instrument that collects precipitation measurements is referred to as the RAINCAP sensor which utilizes acoustic rain/hail impact measurement technology. Precipitation accumulation is measured as a function of the voltage signal of the hydrometeors as they impact the sensor. Each voltage signal is proportional to the volume of a specific hydrometeor which is subsequently converted to accumulated precipitation.



Fig. (2). A vaisala WXT510 weather transmitter.

In June 2006, the OKCNET intercomparison facility was erected in an open area in Norman, Oklahoma, USA (35° 15'



Fig. (3). A picture of the intercomparison facility for the WXT510 sensors.

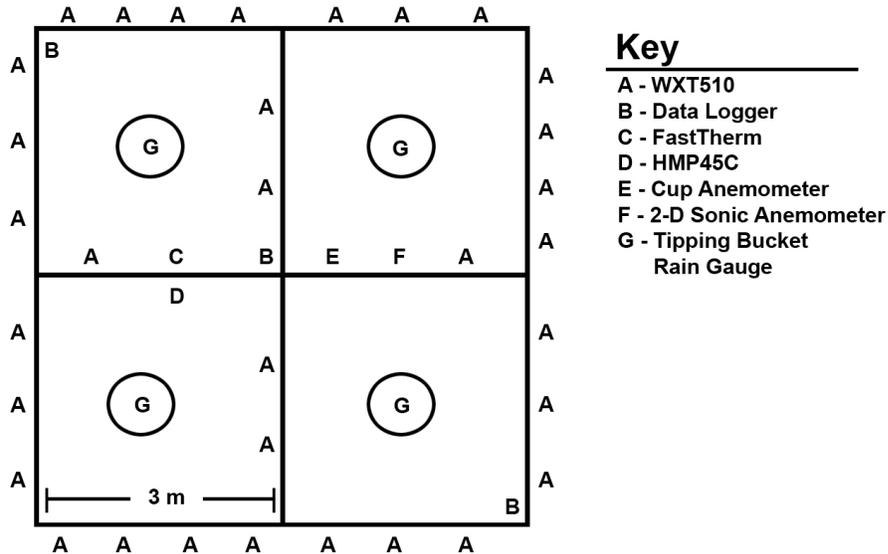


Fig. (4). A schematic diagram of the intercomparison facility for the WXT510 sensors.

N 97° 29' W) that is used to test and calibrate atmospheric instruments. The intercomparison facility was comprised of 33 WXT510 sensors and four WaterLog H-340 (<http://www.waterlog.com>) tipping bucket rain gauges (Figs. 3, 4). This study also utilized a number of additional rain gauges located nearby (Fig. 5). A pit-level Geonor T-200B3 (<http://www.geonor.com>) weighing gauge was located approximately 65 m from the center of the intercomparison facility. Pit-level gauges are generally used as “ground truth” for liquid precipitation measurements because wind-induced under-catch is nearly eliminated. Additionally, data from up to eight tipping bucket gauges installed nearby were used in the comparisons. These gauges consisted of: (a) five Hydrological Services TB3 (<http://www.hydroserve.com.au>) rain gauges and two MetOne 380 (<http://www.metone.com>) tipping bucket rain gauges installed in an array approximately 70 m from the center of the intercomparison facility and (b) a MetOne tipping bucket rain gauge installed at the Norman

Oklahoma Mesonet station [38] located approximately 140 m from the center of the intercomparison facility. Manufacturer supplied sensor specifications are listed in Table 1.

From 1 July 2006 through 30 September 2007 observations of precipitation from 105 events were collected. The timeframe of each “event” was defined to encompass the time of which the first gauge recorded precipitation (regardless of sensor) until the last measured value of precipitation was recorded (regardless of sensor). On a few occasions, more than one precipitation event occurred during a day with a separation of at least 90 minutes between the last measurement of the first event and the first measurement of the second event. Of the 105 events, nine were not included in the analysis due to presence of frozen precipitation (seven events), rogue measurements during clear skies (one event), and measurement totals outside the range (100 millimeters) of the study (one event).

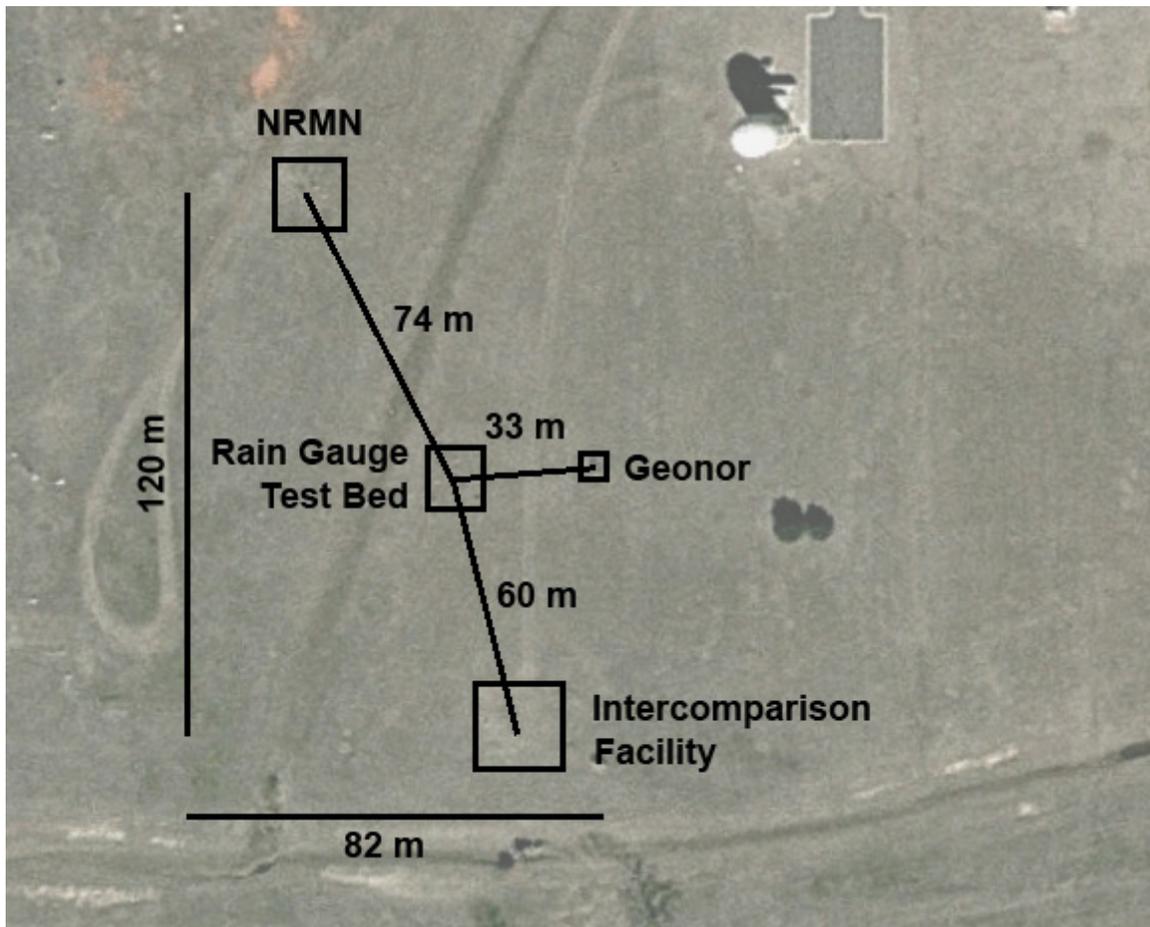


Fig. (5). An aerial map of the overall study site including the WXT510 intercomparison facility, the location of the Geonor pit gauge, the rain gauge test bed, and the Norman Mesonet site (NRMN).

Table 1. Specifications of the Various Rain Gauges Used in the Analysis

Gauge	Mounting Height	Orifice Diameter	Specified Accuracy
WXT510 Impact Sensor	1.5 m	9 cm*	5%
Waterlog H-340 Tipping Bucket Gauge	0.6 m	20.32 cm	Not listed
Geonor T-200B3 Weighing Gauge	0.0 m	15.96 cm	0.1%
Hydrological Services TB3 Tipping Bucket Gauge	0.6 m	20.32 cm	+/- 2% at 2.5 to 50 cm h ⁻¹
MetOne 380 Tipping Bucket Gauge	0.6 m	30.48 cm	+/- 0.5% at 1.27 cm h ⁻¹ ; +/- 1.0% at 2.54 to 7.62 cm h ⁻¹

* Diameter of impact sensor.

During the 96 events used in the study, varying precipitation intensities and durations occurred: four events were the result of drizzle, eight events were light rain (< 1 mm), 37 events were rain (steady precipitation with no thunder), and 47 events were convective precipitation (thunder present and/or large rainfall rates over a short period of time). Short duration (less than 1 hour) events comprised 11 of the 96 events, medium duration (1 to 4 hours) included 22 events, and 63 events spanned a duration greater than 4 hours.

Data from each sensor was quality assured *via* visual inspection and all tipping bucket measurements underwent standard Oklahoma Mesonet quality assurance procedures

[39]. For the 33 WXT510 sensors, any data measured by a sensor that was more than three standard deviations from the mean of all the sensors was removed from the event's statistics. The Geonor data was manually inspected to remove any suspect or incorrect data as a result of sensor malfunction or maintenance.

3. RESULTS

3.1. Analysis of Precipitation Totals

The primary objective of the study was to quantify any systematic error associated with the rainfall measurements collected by the WXT510 sensor. As such, WXT510 precipi-

tation observations from the OKCNET intercomparison facility were compared with the tipping bucket rain gauges at the study site.

Unfortunately, precipitation measurements are subject to errors due to various physical processes and have been well documented for numerous technologies including tipping bucket rain gauges. Most notably are errors due to under catch during both very light and heavy precipitation events as well as underestimation due to wind [40-43]. The result of such errors is that, even when identical, calibrated gauges are deployed in close proximity to one another, variability in the observations can occur.

At the same time, the spatial and temporal distribution of precipitation is not uniform, even at relatively small scales. Past studies have demonstrated that rainfall can vary by as much as 5% among above ground, unshielded tipping bucket rain gauges [44]. Further [40], found that precipitation variability in the Southern Plains averages approximately 4 – 5 mm per month during the summer and 3 – 6 mm per month during the winter.

To account for the inherent variability of rainfall observations, mean values of precipitation were analyzed instead of specific observations from specific sensors. Thus, the mean rainfall totals from the array of WXT510 sensors (WXT_{MEAN}) for a specific event were compared with the mean rainfall totals from the local tipping bucket rain gauges (Tip_{MEAN}).

The results of the analysis demonstrated that while the WXT_{MEAN} and the Tip_{MEAN} of rainfall were highly correlated (R^2 value of 0.9552) a significant bias was also evident whereby the WXT_{MEAN} values were greater in magnitude than the Tip_{MEAN} values (Fig. 6). At the same time, the over-

all bias, which included all precipitation conditions (i.e., drizzle, stratiform rain, convective rain, etc.), between the observations was linear. Thus, a simple correction was applied to the WXT_{MEAN} observations to improve the precipitation estimates:

$$WXT_{CORR} = 0.74 * WXT_{RAW} \tag{1}$$

where, WXT_{CORR} is the corrected WXT values and WXT_{RAW} is the raw, measured WXT values.

Once adjusted, the corrected WXT_{MEAN} values were compared with the Tip_{MEAN} values which displayed a reduced bias in the observations (Fig. 7). To further test the validity of the WXT_{CORR} estimates of accumulated precipitation, the WXT_{CORR} observations were compared with the independent precipitation totals from the Geonor rain gauge (Fig. 8). This analysis revealed that the WXT_{CORR} values were very similar to the Geonor totals with an R^2 value of 0.9522, no bias, and overall reduced error; the Geonor totals were, on average, approximately 3.5% greater than the WXT_{CORR} values.

3.2. Analysis of Variability

The analysis performed in Section 3.1 provides a bulk correction that can be applied to the raw precipitation values measured by the WXT510 sensors. To determine the overall sensor-to-sensor variability of the WXT510 observations, values of standard deviation and mean absolute deviation were computed for the WXT_{CORR} values for each precipitation event during the study period at the OKCNET intercomparison facility. In addition, similar statistics were computed to measure the variability between the tipping bucket rain gauges during the period.

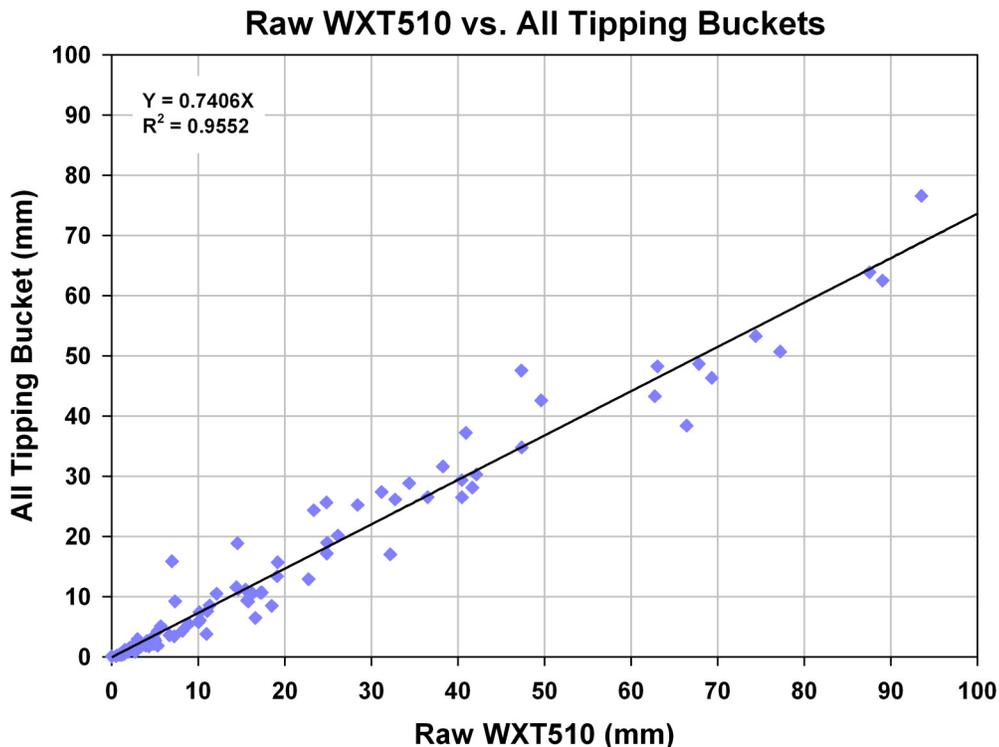


Fig. (6). Raw WXT510 precipitation measurements (in millimeters) plotted versus all tipping bucket precipitation measurements.

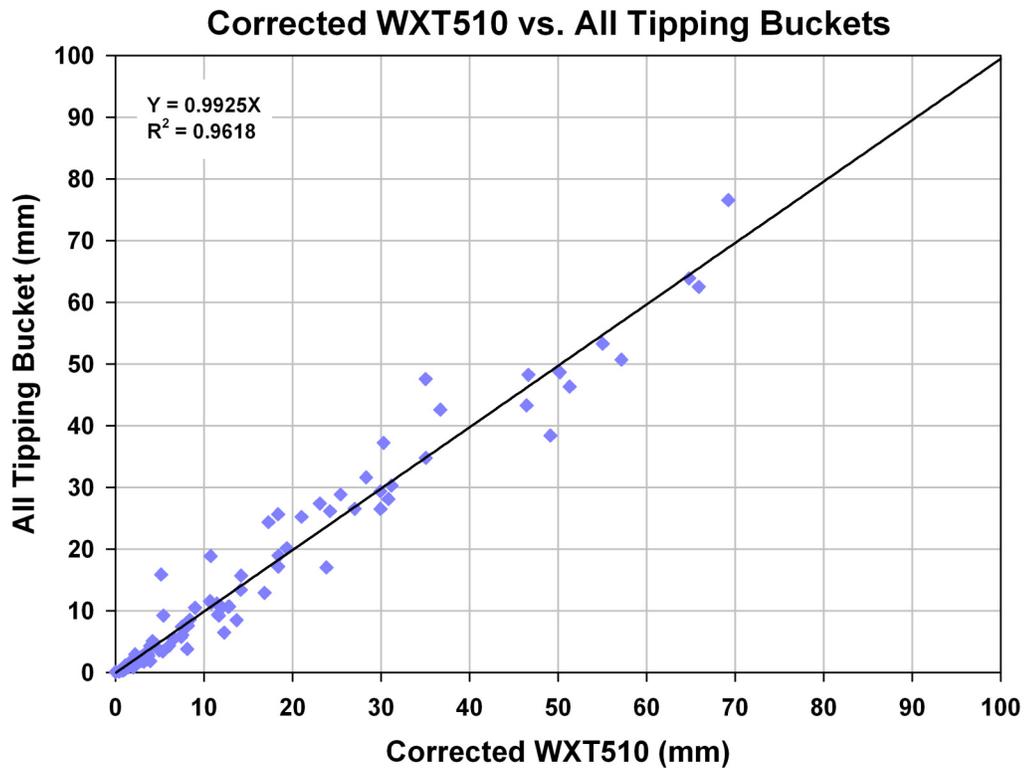


Fig. (7). Corrected WXT510 precipitation measurements (in millimeters) plotted versus all tipping bucket precipitation measurements.

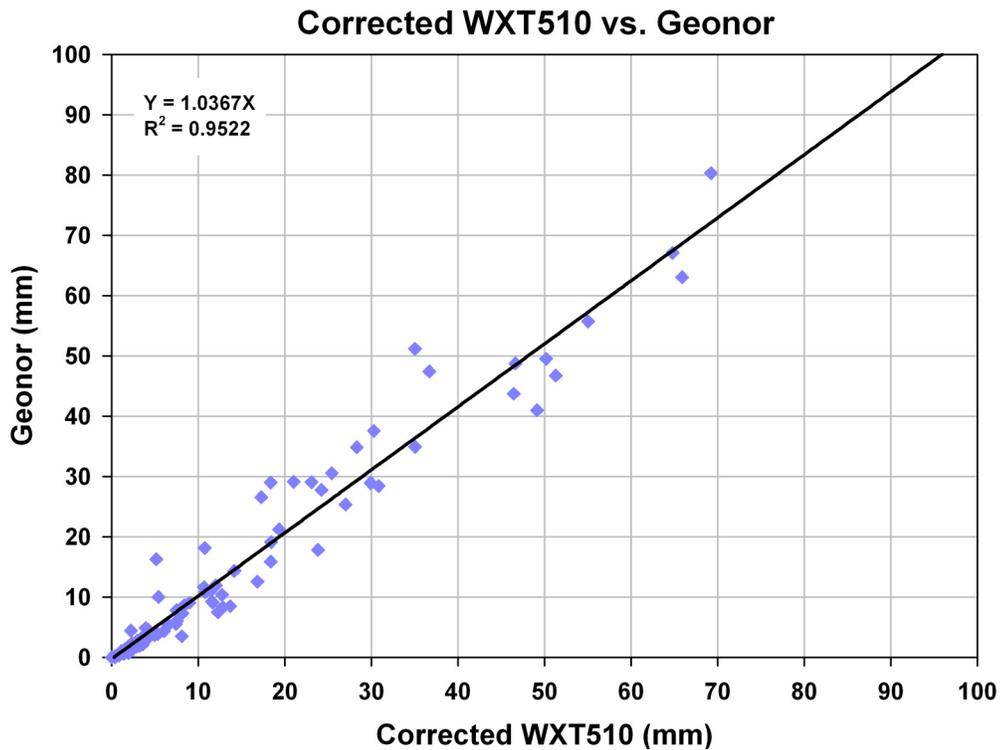


Fig. (8). Corrected WXT510 precipitation measurements (in millimeters) plotted versus the Geonor precipitation measurements.

The results of the statistical analysis are displayed in Figs. (9, 10). Overall the variability between the WXT510 sensors was limited and demonstrated a consistent, linear pattern as overall precipitation totals increased. In fact, both statistical analyses revealed that the variability between the WXT510 sensors was less than 2.1 mm for total precipitation

events less than 30 mm and less than 4.0 mm for precipitation events between 30 and 70 mm. In broader context, the variability between the WXT510 sensors was also very consistent with the variability displayed by the tipping bucket rain gauges.

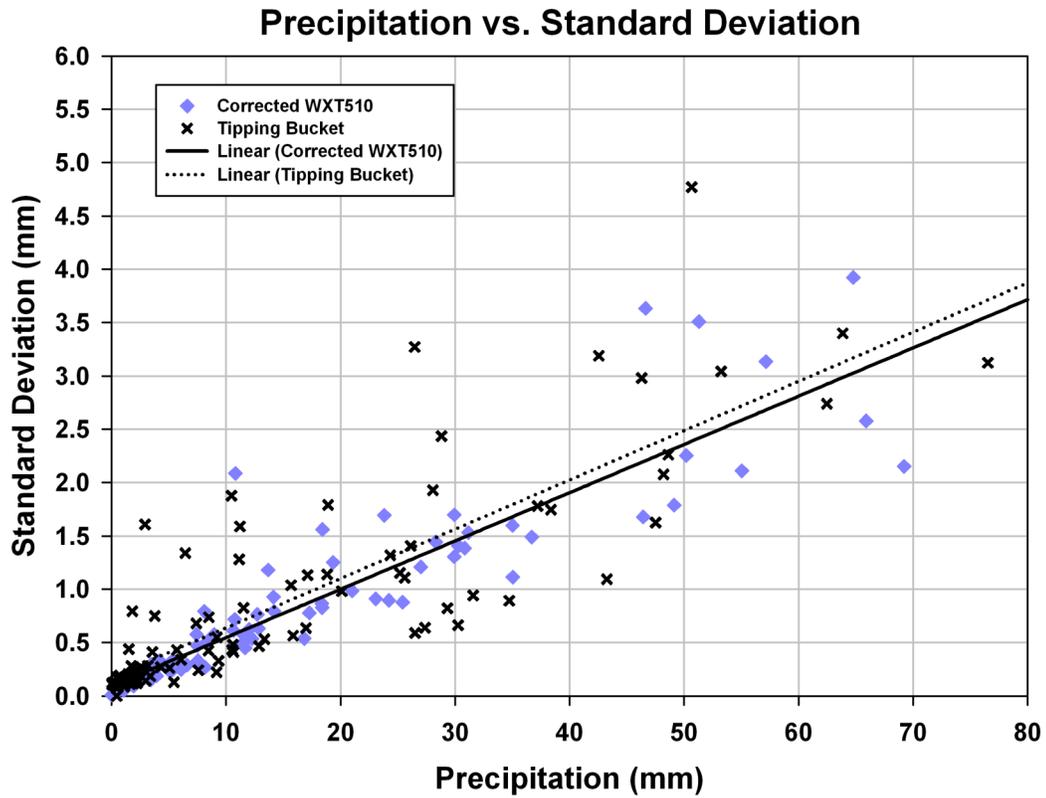


Fig. (9). The variability (using standard deviation) of corrected WXT values and tipping bucket values as a function of precipitation amount (in millimeters).

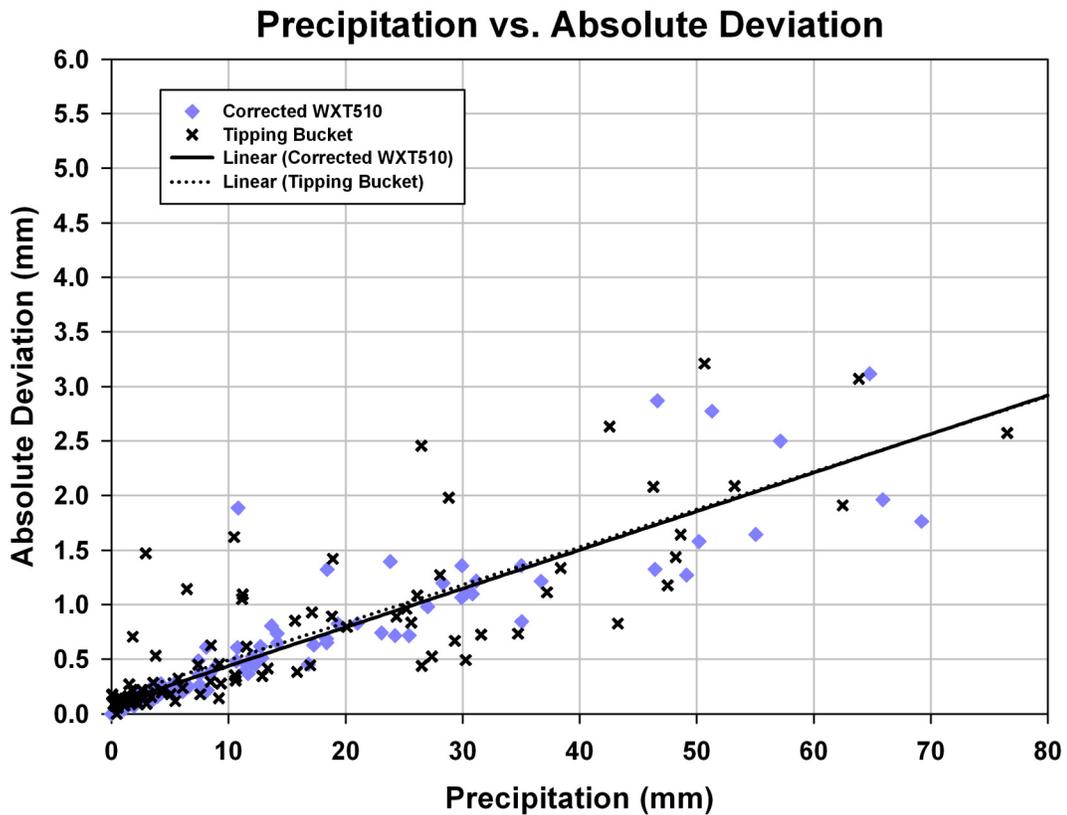


Fig. (10). The variability (using absolute deviation) of corrected WXT values and tipping bucket values as a function of precipitation amount (in millimeters).

4. DISCUSSION AND CONCLUSIONS

Because the WXT510 sensor utilizes a technology to measure rainfall that is fundamentally different than traditional rainfall measurement devices, traditional methods for calibrating and evaluating sensors cannot be easily applied. As such, procedures in a controlled laboratory setting whereby a specific volume of water is passed through a rain gauge during calibration is not applicable based on the physics employed with an impact sensor. To accommodate for such circumstances, the instruments require calibration in controlled, real-world conditions versus instruments that have received thorough laboratory calibration. Unfortunately, precipitation is typically infrequent in occurrence and accurate calibration requires numerous samples. Thus, long-term records are needed to perform a thorough field analysis.

To perform an adequate assessment of the rainfall measurements collected by the WXT510 sensors for use in the Oklahoma City Micronet, this study utilized 33 units deployed at the OKCNET intercomparison facility to quantify the accuracy, systematic error, and variability of the observations. During a 15-month period spanning June 2006 through October 2007, observations were collected by the WXT510 instruments along with measurements from additional tipping bucket gauges and a Geonor gauge. The primary results of the study identified that a significant bias existed between the measurements of rainfall from the WXT510 sensors and the traditional rain gauge values (i.e., tipping buckets and Geonor). However, because the rainfall relation between the instruments was linear, a simple correction was applied using the observations collected by the tipping bucket instruments. When corrected, the rainfall values were subsequently compared with independent observations from the Geonor gauge and the results confirmed the removal of the systematic bias as well as a strong correlation across the magnitudes of the rainfall values. As such, a key finding of this study is that, regardless of rainfall intensity, length of the precipitation event, seasonal characteristics of the rainfall, or rainfall type (i.e., stratiform, convective, etc.), the correction developed as part of this research greatly improves the rainfall values produced by the RAINCAP sensor on the Vaisala WXT510 instrument.

A second critical aspect of the analysis of this study focused on quantifying the inherent variability of rainfall observations between the WXT510 sensors. The results of the analysis demonstrated that (a) the variability was a linear relationship as a function of the overall magnitude of the rainfall event and, (b) the sensor to sensor variability displayed by the WXT510 sensors was very similar to the variability between the tipping bucket rain gauges.

Because of the design of the Vaisala WXT510 sensor which yields a compact size and suite of measured variables, the instrument is a viable option for measuring atmospheric conditions in urban areas. Currently, such sensors are deployed as part of operational urban networks including the Helsinki Testbed (Helsinki, Finland) [45] and the Oklahoma City Micronet. As such, the overall results of this study are important in that they demonstrate that the rainfall measurements from the WXT510 sensor provide accurate observations with limited error once an appropriate correction is applied to the data. This correction represents a bulk relationship designed to improve the overall accuracy of the ob-

servations without specifically calibrating each individual sensor prior to deployment. Unfortunately, individual calibration activities of rainfall with the WXT510 sensor are time intensive due to the need for long-term field measurements in a quasi-controlled environment without developing new laboratory procedures specifically for the WXT510 sensor. However, due to the limited variability between sensors as a function of the magnitude of the precipitation event, it is reasonable to apply the correction in a general manner to individual sensors given that the sensors perform similarly during precipitation events and that the overall rainfall bias is systematic between sensors. Even so, additional, future research should focus on the development of a simpler yet more robust method for individually calibrating each WXT510 sensor with regards to rainfall.

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