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ABSTRACT

A new U.S. Climate Reference Network (USCRN) was officially and nationally commissioned by the Department of Commerce and the National Oceanic and Atmospheric Administration in 2004. During a 1-yr side-by-side field comparison of USCRN temperatures and temperatures measured by a maximum–minimum temperature system (MMTS), analyses of hourly data show that the MMTS temperature performed with biases: 1) a systematic bias–ambient-temperature-dependent bias and 2) an ambient-solar-radiation- and ambient-wind-speed-dependent bias. Magnitudes of these two biases ranged from a few tenths of a degree to over 1°C compared to the USCRN temperatures. The hourly average temperatures for the USCRN were the dependent variables in the development of two statistical models that remove the biases due to ambient temperature, ambient solar radiation, and ambient wind speed in the MMTS. The model performance was examined, and the results show that the adjusted MMTS data were substantially improved with respect to both systematic bias and the bias associated with ambient solar radiation and ambient wind speed. In addition, the results indicate that the historical temperature datasets prior to the MMTS era need to be further investigated to produce long-term homogenous times series of area-average temperature.

1. Introduction

Over the last two decades climate scientists have spent considerable effort assembling climate data and evaluating data homogeneity, especially for the air temperature and precipitation datasets. The motivation, in large part, is the interest in evaluating global climate change purported to be associated with the greenhouse effect at local, regional, and global scales. The U.S. Historical Climatology Network (USHCN) dataset has been widely used for evaluating the temperature time series and climate trends. Adjustments of temperature data in the USHCN dataset have been made to account for systematic biases introduced by changes in the time of observation (Karl et al. 1986), urban heat islands (Karl et al. 1988), changes of station location and station exposure (Karl and Williams 1987), and changes of instruments (Quayle et al. 1991). The magnitudes of these adjustments range from a few tenths of a degree [changes of instruments in Quayle et al. (1991) and urbanization in Karl et al. (1988)] to as high as 2°C [time of observations in Karl and Williams (1987)]. Easterling et al. (1996) summarized the temperature adjustment procedures. The adjustments were mostly made to original temperatures at a USHCN station and/or records of temperature at a neighboring station. Obviously, the quality of these adjustments is very critical for surface air temperature datasets because most of the climate applications are based on the adjusted USHCN dataset.

Among the various adjustment procedures used to derive the USHCN datasets, only the adjustment statistically developed by Quayle et al. (1991) was due to changes in instruments. The transition from the liquid-in-glass (LIG) maximum and minimum thermometer in a cotton-region shelter (CRS) to the thermistor-based maximum–minimum temperature systems (MMTSs) in the 1980s was the main bias. The results based on 424 MMTS stations and 675 CRS stations showed that average minimum temperature changes of +0.3°C and average maximum temperature changes of −0.4°C were introduced (Quayle et al. 1991). At the same time, a side-by-side comparison was conducted that concluded that the MMTS underestimated the maximum temperature by as much as 0.6°C but that found virtually no bias for minimum temperature (Wendland and Armstrong 1993). Neither study stated which temperature

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TABLE 1. MMTS and USCRN air temperature sensor characteristics.

Network	COOP	USCRN	
Sensor model	MMTS	Met-One 062	PRT
Sensing elements	Thermistor	Thermistors	PRT
Sensing element model	A 1140	YSI 44020	PRT Class A
Resistance at 25°C (ohms)	20 000	19 165.67	1000 at 0°C
Temperature range (°C)	−50 to 50	−50 to 50	−50 to 50
Resistance at −40°C	−44 980		
Sensitivity at 0°C	−3340	−129.23	0.385
(Ohms °C^{-1}) at +40°C	−429	(nearly linear)	(nearly linear)
Interchangability (±°C)	0.45 to 0.2	0.1	Not available

system produced higher quality observations, but they suggested that ambient solar radiation and wind speed are two factors that likely affect the air temperature difference between the MMTS and CRS systems because both shields were nonaspirated. Currently, a new aspirated air temperature system is being deployed nationally in the U.S. Climate Reference Network (USCRN) by the Department of Commerce/National Oceanic and Atmospheric Administration (NOAA). The primary goal of the USCRN is to provide future long-term homogeneous observations of surface air temperature and precipitation that can be coupled to past long-term observations for the detection and attribution of present and future climate change. The USCRN temperature system consists of a temperature sensor (Thermometric Co.) and an aspirated radiation shield (Model 076B, Met One Instruments, Inc.). Since the USCRN temperature system is new, we consider it essential to compare the difference between the MMTS and USCRN temperatures. The objective in this study was to investigate the MMTS temperature biases, including the bias associated with solar radiation and ambient wind speed relative to the USCRN temperature system.

The MMTS sensor is shielded from radiation by a multiple-plate, cylindrical, plastic shield about 25 cm high and about 20 cm in diameter. The MMTS sensor uses a Dale/Vishay 1140 thermistor (Vishay Intertechnology, Inc., Malvern, Pennsylvania) with 20 000-ohm nominal resistance at 25°C. Three USCRN temperature sensors are housed in a single aspirated temperature shield that consists of two anodized lightweight aluminum cylinders, a 12-V fan located inside the upper portion of shield body, and a spherical cap or cover over the top. In 2001, a thermilinear network device was tentatively selected as an air temperature sensor and gradually employed in USCRN. This USCRN temperature sensor was a YSI44212 thermilinear network (YSI Inc., Yellow Springs, Ohio), which consists of two subcomponents—a thermistor component (YSI 44020) and a resistor set (YSI 44312). The YSI 44020 thermilinear composite includes three thermistors, and the YSI 44312 resistor composite includes three fixed resistors. Unlike the single thermistor in the MMTS, the resistance sensitivity of the Met-One 062 sensor is nearly constant at −129.23 ohm °C^{-1}. The benefits of the YSI 44212 thermilinear are ease of design, low-cost electrical circuits, and high-resolution measurements. Around 1 yr later, another USCRN platinum resistance thermometer (PRT) sensor replaced the previous USCRN thermistor. The fundamental characteristics of both MMTS and USCRN temperature sensors are listed in Table 1.

2. Instrument siting and model development

Our intercomparison experiments were conducted from April 2001 at the University of Nebraska's Horticulture Experimental Site (40°83′N, 96°67′W; elevation 383 m). The site had flat terrain and the grass was mowed regularly to maintain a uniform ground surface. There were no physical obstructions within 25 m of the sensors installed. During the observations, at the end of October 2001, we switched the USCRN thermistor sensors and the USCRN PRT sensors. The experiments consisted of three USCRN thermistor sensors (after October 2001 they were two USCRN PRT sensors), two MMTS systems, one silicon pyranometer for global solar radiation measurements (Kipp & Zonen, Co., Canada), and one anemometer (model: Met One 034A-L, Met One Instruments). The installation height of all temperature sensors, the pyranometer, and ambient wind speed sensor was 1.5 m. It should be noted that the installation height for the aspirated USCRN temperature sensors refers to the bottom height of the USCRN radiation shield, that is, the height of the air intake. The installation height of the MMTS sensor refers to the height inside the MMTS radiation shield of the temperature sensor.

All temperature sensors, as well as solar radiation and wind speed sensors, were measured by using a CR7 measurement and control system (Campbell Scientific, Inc.). For the MMTS sensors, we used a 24 900-ohm resistor (±0.01% tolerance and 5-ppm temperature coefficient; Micro-Ohm Corp.) in series with the MMTS thermistor and measured the air temperature using a three-wire half-bridge circuitry. This circuitry provided high signal sensitivity, high signal resolution by the CR7 system, and correspondingly higher accuracy in the measurements thus taken than those that would be obtained from the original MMTS readout (Lin et al. 2001; Lin and Hubbard 2003).

In this study, data were collected continuously during the period June 2002–July 2003. The data sampling rate

TABLE 2. Performance of monthly MMTS bias adjustment.

Observations	Days	Hours	USCRN Ta (°C)	95% confidence monthly MMTS bias (°C) Raw bias	Adjusted bias
Jun 2002	30	719	26.3	[−0.47 to 0.39]	[−0.12 to 0.17]
Jul 2002	27	624	27.2	[−0.47 to 0.40]	[−0.17 to 0.16]
Aug 2002	31	744	24.4	[−0.47 to 0.29]	[−0.24 to 0.16]
Sep 2002	28	638	20.8	[−0.55 to 0.38]	[−0.19 to 0.18]
Oct 2002	26	578	7.4	[−0.66 to 0.22]	[−0.38 to 0.27]
Nov 2002	29	659	4.0	[−0.69 to 0.22]	[−0.29 to 0.19]
Dec 2002	28	611	0.7	[−0.73 to 0.20]	[−0.29 to 0.18]
Jan 2003	31	744	−3.4	[−0.70 to 0.16]	[−0.29 to 0.20]
Feb 2003	24	547	−3.7	[−0.84 to 0.35]	[−0.39 to 0.30]
Mar 2003	31	715	5.3	[−0.64 to 0.23]	[−0.26 to 0.19]
May 2003	29	564	15.4	[−0.62 to 0.39]	[−0.25 to 0.17]
Jun 2003	29	694	20.7	[−0.57 to 0.51]	[−0.25 to 0.21]
Jul 2003	29	695	26.5	[−0.51 to 0.43]	[−0.21 to 0.15]

was 0.2 Hz (5 s), and temperature signals were averaged over 1-min outputs. An hourly average of all measurement quantities, including temperatures, solar radiation, and ambient wind speed were formed for this study. The available data for each month were taken after deleting all records wherein data from any one variable was missing (Table 2). Note that there were no observations taken in April 2002 because of site maintenance and sensor cleaning. The MMTS air temperature bias was defined as the difference between measured air temperature from the MMTS and the USCRN on an hourly basis. When calculating the MMTS bias we used the average value of three or two (after November 2002) USCRN sensors and the average value of two MMTS readings.

Development of the MMTS air temperature bias models is based on the effect of solar radiation and ambient wind speed on the accuracy of air temperature measurements in the field. We first classified all available hourly observations into daytime data (when solar radiation was greater than 0 W m^{-2}) and nighttime data. We assume that the systematic bias of the MMTS air temperature during nighttime was also present in the daytime bias. Therefore, the first step was to detect any systematic biases inherent in the MMTS sensing element by using nighttime observations. These temperature-dependent biases are hereafter referred to as MMTS bias I. MMTS bias I was expressed as a single temperature-dependent polynomial,

$$\text{MMTS Bias I} = a + bT + cT^2 + dT^3 + eT^4, \quad (1)$$

where T is the raw MMTS temperature (°C) and a, b, c, d, and e are the fifth-order polynomial coefficients. All nighttime hourly observations (total 3774 data points) were used in deriving Eq. (1). The second step was to develop a model for removing the bias of the MMTS air temperature additively introduced by the effects of solar radiation and ambient wind speed. After removing the MMTS bias I in the daytime MMTS observations, a nonlinear regression model similar to Hubbard and Lin (2002) was formed by using the Table Curve 3D software (SPSS, Inc.):

$$\text{MMTS Bias II} = \alpha \times \exp\left(-0.5 \times \left\{\left[\frac{\ln(\text{SR}/\beta)}{\gamma}\right]^2 + \left(\frac{\text{WS} - \mu}{\upsilon}\right)^2\right\}\right), \quad (2)$$

where the MMTS bias II was defined as the MMTS bias introduced by the solar radiation and ambient wind speed. Coefficients α, β, γ, μ, and υ are determined by the nonlinear regression. Here SR and WS are the solar radiation (W m^{-2}) and the ambient wind speed (m s^{-1}), respectively, at the experimental site. A total of 4759 hourly observations were used for deriving coefficients for Eq. (2) when the site solar radiation was larger than zero.

3. Results and discussion

Figure 1 shows the ambient wind speed effects on the original MMTS bias for all observations. Overall for nighttime observations, the MMTS data had a −0.4°C average bias (Fig. 1a). However, we may ask whether or not this average bias reflects the real characteristics of the MMTS bias during nighttime observations. This is because daily, monthly, seasonally, and yearly average might mask some discriminating biases. In fact, there was a systematic temperature-dependent bias in Fig. 1 that is discussed in the following section based on Eq. (1). For all observations when solar radiation was larger than zero, there were strong variations of the MMTS bias with changes of ambient wind speeds (Fig. 1b).

a. MMTS bias I as a function of the MMTS temperature

Figure 2 shows all the nighttime observations and presents a relationship between the MMTS bias and the ambient temperature. Unlike Fig. 1a, the nighttime MMTS bias is a function of the MMTS temperature simulated using Eq. (1) with the following polynomial

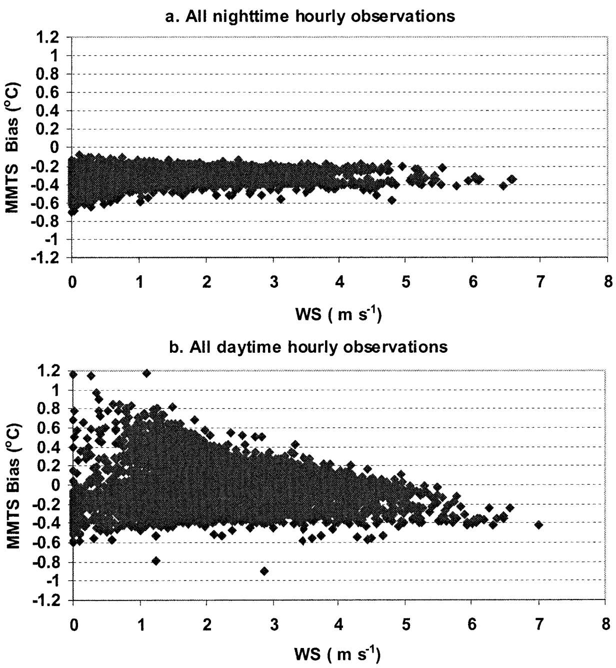

FIG. 1. Variations of raw MMTS bias with changes of ambient wind speed during (a) nighttime and (b) daytime observations.

coefficients: $a = -0.3925$, $b = 7.081 \times 10^{-3}$, $c = 2.552 \times 10^{-4}$, $d = -8.296 \times 10^{-6}$, and $e = -1.216 \times 10^{-7}$. This led to a coefficient of determination of 0.66 for the 3774 hourly observations. The top and bottom lines in Fig. 2 represent 95% confidence bounds. The blue data points are within one standard deviation, the red data points two standard deviations, the green data points three standard deviations, and the pink data points represent the data points beyond three standard deviations. The MMTS bias I (Fig. 2) reflects a systematic temperature-dependent bias inherent in the MMTS Dale/Vishay 1140 thermistor. Therefore, the MMTS sensor was found to have a cooling bias that varied with the ambient MMTS temperatures. There was more than a 0.2°C temperature variation when the ambient MMTS temperature was changed from about −10° to 15°C. After removing or adjusting for MMTS bias I for the nighttime observations, the possibility of nighttime ambient wind speed cooling effects on the MMTS observations was examined, but, in our study, no evidence for this bias was found. The MMTS bias after removal of the MMTS bias I during nighttime was centered around 0°C with ±0.1 bounds at the 95% confidence level. Only when the ambient wind speed was less than 0.5 m s^{-1} did we find a cooling of the MMTS of around 0.05°C on the statistical average. Therefore, our results indicated that after removal of the MMTS bias I, the ambient wind speed effect for nighttime MMTS observations could safely be ignored. It should be emphasized that the MMTS bias I is also present during daytime observations because it is a systematic bias.

b. MMTS bias II as a function of the solar radiation and ambient wind speed

For the daytime observations, when solar radiation was more than 300 and 500 W m^{-2}, an obvious tendency of the MMTS bias II was found in Fig. 3; that is, the MMTS bias II increased with decreases in ambient wind speed. The larger the solar radiation at the site, the more obvious these variations were (Figs. 3a,b). For the relationships between the MMTS bias II and the solar

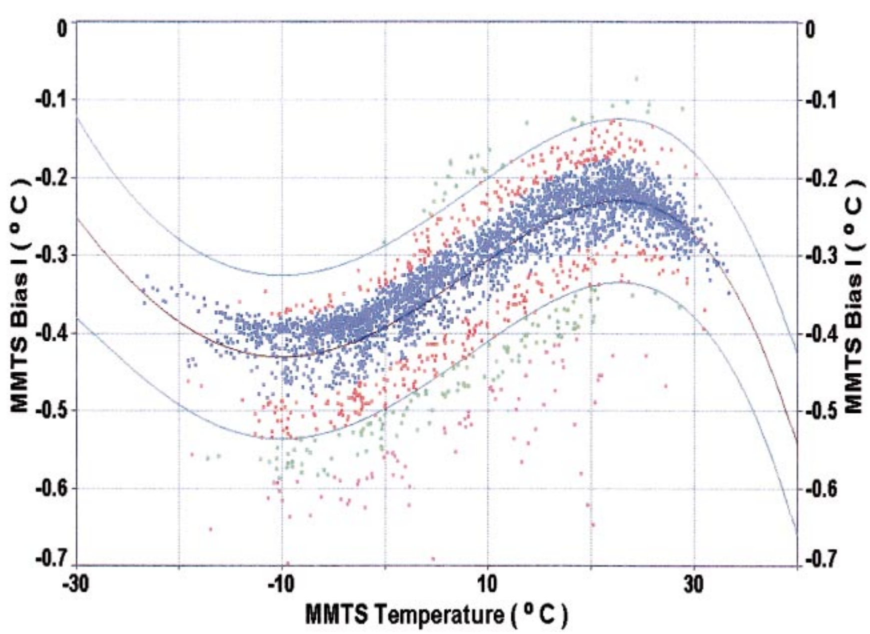

FIG. 2. MMTS bias I as a function of ambient temperatures.

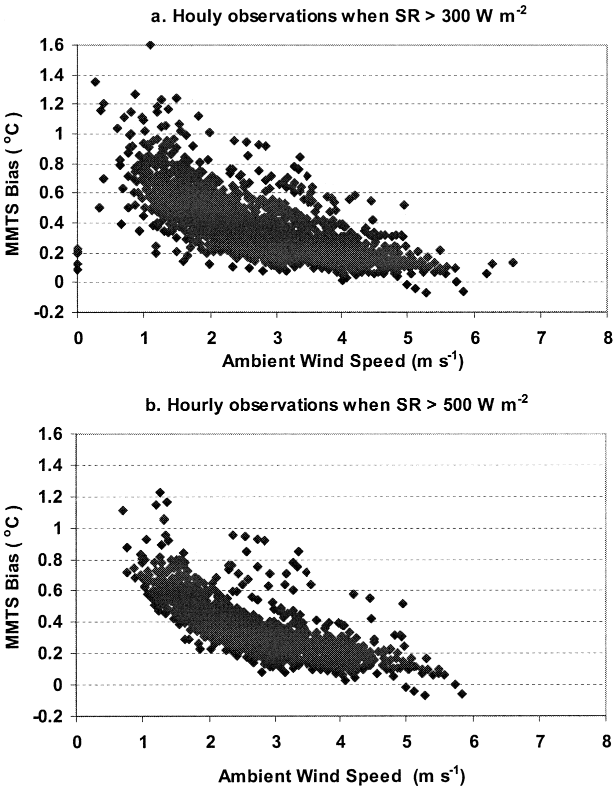

FIG. 3. Variations of MMTS bias I with changes of ambient WS when the SR was more than (a) 300 and (b) 500 W m^{-2}.

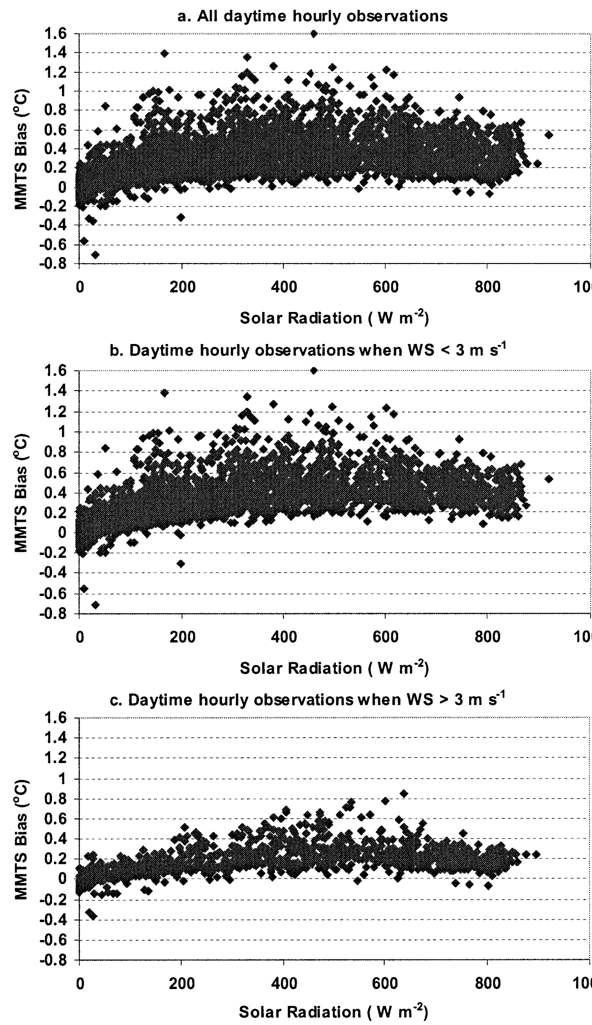

FIG. 4. Variation of MMTS bias I with changes of SR: (a) all daytime hourly observation, (b) daytime observations when WS < 3 m s^{-1}, and (c) daytime observations when WS $\geq$ 3 m s^{-1}.

radiation loading, few MMTS observations had a cooling bias (negative bias) when solar radiation was larger than 200 W m^{-2} (Figs. 4a–c). However, there were warming biases (positive bias) in daytime observations, and these were even larger than 0.8°–1.0°C when the ambient wind speed was small (<3 m s^{-1}). Obviously, most daytime MMTS observations had a warming bias, while there was a cooling bias for most of the nighttime MMTS observations (Figs. 1–4). These characteristics of the MMTS bias led us to derive the MMTS bias models to improve or adjust the MMTS air temperature observations.

Hubbard and Lin (2002) developed a nonlinear regression model, based on the solar radiation and ambient wind speed, to filter or transform the original temperature data for four nonaspirated air temperature systems, including the MMTS system. Unlike Hubbard and Lin (2002), in this study the MMTS bias I was first removed, and both solar radiation and ambient wind speed effects on the MMTS air temperature measurements, MMTS bias II, are illustrated in Fig. 5. The result shown in Fig. 5 is based on Eq. (2), with the following coefficients: $\alpha = 6.416$, $\beta = 699.441$, $\gamma = 1.373$, $\mu = -13.907$, and $\upsilon = 7.153$. This led to a coefficient of determination of 0.71 for the 4759 daytime hourly observations. Color associated with data points has the same meaning as in Fig. 2. For this three-dimensional response surface, the MMTS bias II increased from lower solar radiation to higher radiation when the ambient wind speed was lower. The result suggests that the ambient wind speed effects on the MMTS observations were the most prevalent when the solar radiation was high. In other words, for the MMTS observations, without solar radiation loading on the MMTS, the ambient wind speed is not important and will not significantly improve the data quality of MMTS observations. With increases of the solar radiation, the MMTS bias II could reach as high as 1°C (Fig. 5). When the ambient wind speed was higher (e.g., >5 m s^{-1}), the solar radiation effects on the MMTS bias II became less significant and could be ignored.

c. MMTS bias modeling performances

Figures 6 and 7 show the time series of the MMTS bias during daytime and nighttime over more than 1 yr

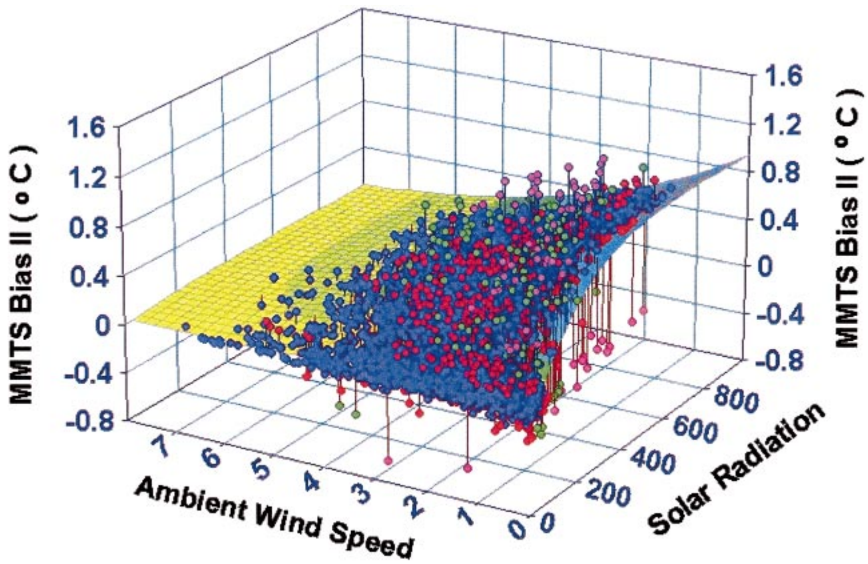

FIG. 5. MMTS bias II as a function of solar radiation (W m^{-2}) and ambient wind speed (m s^{-1}).

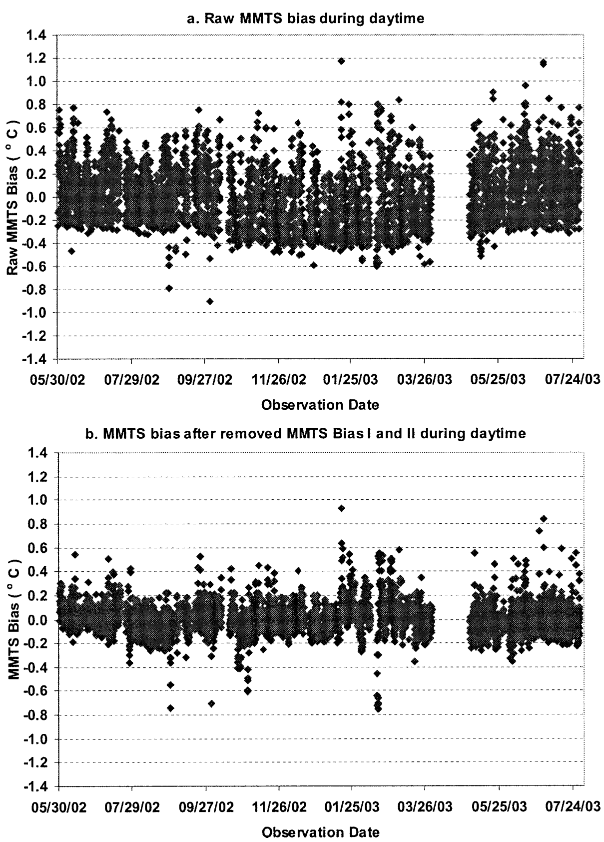

FIG. 6. Time series of (a) raw MMTS bias and (b) adjusted MMTS bias during daytime observations.

of observations. Obviously, there was a trend for the MMTS bias in the daytime and nighttime MMTS observations (Figs. 6a and 7a), which indicated the existence of the MMTS bias I (i.e., temperature-dependent bias). During the wintertime observations, the MMTS bias had lower values than during the summertime. After applying the MMTS bias I for nighttime and adjusting both MMTS bias I and II for daytime by using Eqs. (1) and (2), the data quality of MMTS air temperature measurements was significantly improved (Figs. 6b and 7b). This can be clearly seen by using the same data to produce the normalized frequency distributions of the MMTS bias for daytime and nighttime observations (Fig. 8). In Fig. 8 the normalized frequency of the original (raw) bias is shown along with the normalized frequencies after the raw biases are adjusted to remove biases. The MMTS biases after removal of the MMTS bias I in daytime observations ranged mostly from 0° to 1°C, which suggests that the MMTS bias during daytime had a warming bias even after removing the systematical temperature-dependent bias of the MMTS sensor itself (MMTS bias I).

To investigate the monthly MMTS bias, Table 2 summarizes the original MMTS bias, the adjusted MMTS bias, monthly average air temperature, and hourly observation numbers for each month. For the 95% confidence level, the adjusted MMTS biases were greatly improved. For either hourly data or for monthly data, our study clearly shows the need to transform the MMTS data before they are made part of the USHCN dataset. The current MMTS data adjustments (Quayle et al. 1991) leading to 0.4°C cooler daily maximum air temperature in the MMTS records (Quayle et al. 1991) suggest that observations from the pre-MMTS era, that

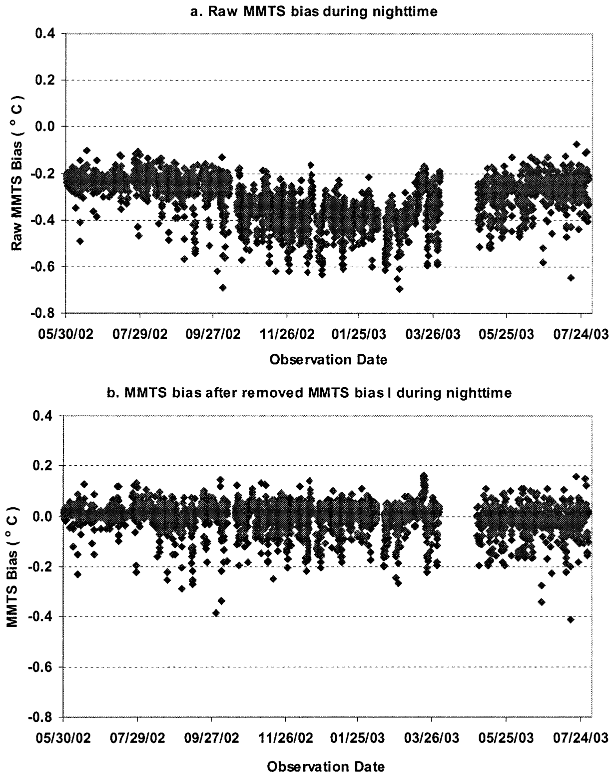

FIG. 7. Time series of (a) raw MMTS bias and (b) adjusted MMTS bias during nighttime observations.

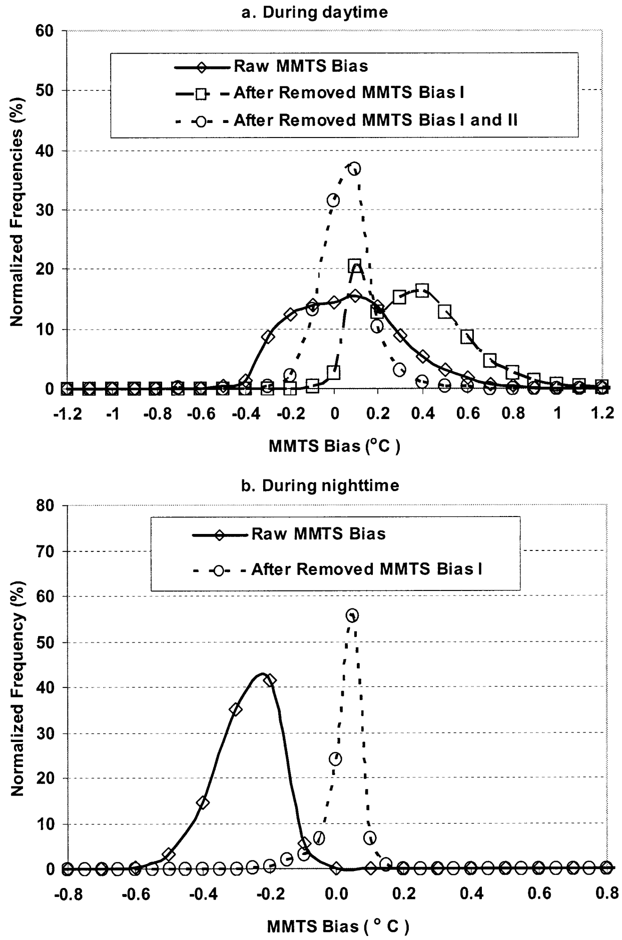

FIG. 8. Normalized frequency distribution before and after removal of the MMTS bias I and MMTS bias II during (a) daytime and (b) nighttime.

is, the CRS temperature records, have even larger warming biases during daytime observations. Similarly, the 0.3°C warmer daily minimum air temperature of the MMTS records (Quayle et al. 1991) suggests that the CRS temperature records might have a larger bias for the daily minimum air temperature observations. This is because the USCRN air temperature record is a more accurate system, and the daily maximum temperature of MMTS records had warmer bias dominated by the MMTS bias II and the daily minimum temperature had a cooler bias dominated by the MMTS bias I in this study. As concluded in the side-by-side comparison made by Wendland and Armstrong (1993), we concur with the statement that a transformation from the LIG records to the MMTS records cannot be implemented without satisfactory wind and solar observations. However, with the introduction and future use of the USCRN records, we suggest that temperature records from both the LIG in the CRS and the MMTS must be readjusted. Balling and Idso (2002) and Pielke et al. (2002) both noted that the air temperature adjustments in the USHCN dataset were ‘‘spurious’’ and ‘‘skeptical’’ and requested more detailed evidence for doing area-average temperature on local and regional scales rather than using a single adjustment factor for the MMTS data adjustments.

4. Conclusions

Although the MMTS temperature records have been officially adjusted for cooler maxima and warmer minima in the USHCN dataset, the MMTS dataset in the United States will require further adjustment. In general, our study infers that the MMTS dataset has warmer maxima and cooler minima compared to the current USCRN air temperature system. Likewise, our conclusion suggests that the LIG temperature records prior to the MMTS also need further investigation because most climate researchers considered the MMTS more accurate than the LIG records in the cotton-region shelter due to possible better ventilation and better solar radiation shielding afforded by the MMTS (Quayle et al. 1991; Wendland and Armstrong 1993).

A simple temperature-dependent polynomial model was developed from our statistical analysis by using 1 yr of side-by-side MMTS and USCRN temperature observations. The MMTS bias I model from Eq. (1) can be used to adjust the MMTS temperature records and remove the MMTS systematic bias. We found this bias to be a function of temperature, and its magnitude varied from about −0.4° to −0.2°C in our study. The nighttime MMTS temperature records were affected by the MMTS temperature-dependent bias but not by the ambient wind speed. The daytime MMTS temperature records were first adjusted by using the temperature-dependent bias (i.e., the MMTS bias I model), then using a nonlinear regression model (i.e., the MMTS bias II model) associated with the solar radiation and ambient wind speed effects at the observation site. Without the information of site solar radiation and ambient wind speed, the MMTS temperature data cannot be accurately transformed into the current USCRN temperature data. However, MMTS observations could be adjusted using measured solar radiation and ambient wind speed at the historical National Weather Service (NWS) First Order stations or modeled estimates from reanalysis data or some combination of these.

This study examined the performances of both MMTS bias I and MMTS bias II in the MMTS temperature records over more than 1 yr of observations. Although our analysis in this study was based on hourly temperatures, the daily maximum and minimum temperatures are certainly subject to the same mechanisms that produce the MMTS biases. After adjusting or removing the MMTS bias I and MMTS bias II from the MMTS temperature records in our study, the adjusted MMTS temperature data improved substantially relative to the USCRN air temperature measurements.

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