Estimating Rain Rates from Tipping-Bucket Rain Gauge Measurements

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ABSTRACT

This paper describes the cubic spline–based operational system for the generation of the Tropical Rainfall Measuring Mission (TRMM) 1-min rain-rate product 2A-56 from tipping-bucket (TB) gauge measurements. A simulated TB gauge from a Joss–Waldvogel disdrometer is employed to evaluate the errors of the TB rain-rate estimation. These errors are very sensitive to the time scale of rain rates. One-minute rain rates suffer substantial errors, especially at low rain rates. When 1-min rain rates are averaged over 4–7-min intervals or longer, the errors dramatically reduce. Estimated lower rain rates are sensitive to the event definition whereas the higher rates are not. The median relative absolute errors are about 22% and 32% for 1-min rain rates higher and lower than 3 mm h^{-1}, respectively. These errors decrease to 5% and 14% when rain rates are used at the 7-min scale. The radar reflectivity–rain-rate distributions drawn from the large amount of 7-min rain rates and radar reflectivity data are mostly insensitive to the event definition. The time shift due to inaccurate clocks can also cause rain-rate estimation errors, which increase with the shifted time length. Finally, some recommendations are proposed for possible improvements of rainfall measurements and rain-rate estimations.

1. Introduction

The Tropical Rainfall Measuring Mission (TRMM) is a satellite program designed to systematically measure tropical rainfall between 35°N and 35°S (Simpson et al. 1996; Kummerow et al. 1998). Measuring rainfall from space poses a difficult challenge due to the extreme spatial and temporal variability of tropical rainfall and imperfect measuring technologies. There are also limitations in our understanding of precipitation processes that affect how accurately surface rainfall can be measured remotely from space. The TRMM Ground Validation (GV) program, situated in the TRMM Satellite Validation Office (TSVO) at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center, was established to validate the satellite-inferred rainfall estimates. Many rain products and their quality evaluations have been produced by TSVO. Rain gauges have played a crucial role in this validation effort (Wolff et al. 2005).

TSVO has deployed tipping-bucket (TB) rain gauge networks over several tropical sites. TSVO's operational system interpolates 1-min rain rates with a cubic spline (CS) algorithm, using data collected from the TB gauge networks. The CS effectively transforms a time series of discrete TB measurements into a quasi-continuous time series of 1-min rain rates. The rain product generated with this algorithm is known as the TRMM Standard Product 2A-56. The 7-min averages of 2A-56 rain rates are used in the Window Probability Matching Method (WPMM) to derive radar reflectivity–rain-rate (Z_e–R) relations (Rosenfeld et al. 1994; Amitai 2000), which are then used to estimate rain intensities. Product 2A-56 is also widely used for the calibration of the ground-based radar estimates and the validation of monthly satellite rainfall estimates, as well as being disseminated as data files to the scientific community in general (Habib and Krajewski 2002; Datta et al. 2003; Tokay et al. 2003a; Fisher 2004; Wolff et al. 2005).

The uncertainty of rain-rate estimates from TB gauges can vary widely when considered over the full spectrum of rain rates. Rain observations are least accurate at the low rain rates where consecutive rain records are separated by longer intervals of time much greater than 1 min. By averaging the 1-min rain rates over longer time intervals, sampling related errors are effectively reduced. The CS algorithm also requires a

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somewhat arbitrary rain event definition based on the time gap between consecutive tips in the time series. TSVO defines the end of an event when this time gap exceeds 15 min, but other definitions are possible. The rain rates generated from the CS are affected with this definition.

There are a few prior studies about the TB gauge rain-rate estimation. Williams and Erdman (1988) estimated rain rates by simply dividing the TB bucket volume by the time between tips. Sadler and Busscher (1989) employed a CS to fit the cumulative rainfall time series, and then differentiated the spline to generate the rain rates. Habib et al. (2001) used an optical rain gauge to simulate the TB gauge and linearly estimated rain rates from the simulated TB data, and then discussed the sampling errors of TB gauge measurements. They found that estimated 1-min rain rates suffer from significant errors, but the errors decrease substantially as the time scales of the estimated rain rates increase. More recently, Ciach (2003) applied an intertip interpolation scheme and a tip-counting scheme to compute average rain rates. If the tip times were recorded accurately, the intertip interpolation scheme was used to compute average rain rates between each pair of two consecutive tips. If only the numbers of tips in predetermined intervals were recorded, the tip-counting scheme was used to compute interval-average rain rates. The local random error was defined as the discrepancy between single-gauge rates and all closely collocated gauge averages. The error was considerable and highly dependent on the local rain intensity and time scale. Nonparametric regression was applied to estimate these dependencies.

This study is to describe the CS-based operational system used by TSVO for the generation of the TRMM 1-min rain-rate product 2A-56 from TB gauge measurements, and then examine the sampling-related errors of TB rain-rate estimation. A description about rainfall measurements from the gauge and disdrometer along with their comparisons is given in section 2. Section 3 provides the methodologies of the rain-rate estimations. Section 4 discusses certain relevant details on employing the CS in the rain-rate estimation. Section 5 describes the simulation of TB gauge measurements using a disdrometer. In section 6, errors of the TB rain-rate estimation are evaluated for different time scales, rain event definitions, and time shifts. A brief summary and discussion are offered in section 7.

2. Rainfall measurements

This study uses two sets of rainfall measurements listed as follows:

1) gauge tip times recorded by a TB gauge located on the islet of Roi Namur at Kwajalein (KWAJ) Atoll, Republic of the Marshall Islands (RMI), and
2) raindrop spectra recorded by a Joss–Waldvogel (JW) disdrometer collocated with the TB gauge.

Actually, two TB gauges were closely installed with the JW disdrometer on Roi Namur on 8 April 2005. The distances among the three devices are about 0.3 m. Comparisons among the three devices show that one gauge constantly failed to record rain events, whereas the other gauge agreed with the disdrometer. Therefore, only the good gauge and the disdrometer are used in this study.

a. TB gauge measurements

The TB rain gauge is a simple mechanical device that directly measures rainfall in increments of 0.254 mm, or one tip, at a discrete point location on the earth's surface. The rain gauge on Roi Namur used in this study is equipped with an event-driven MadgeTech datalogger that records the time of each tip to the nearest second. Nonrainy periods are inferred from the absence of tip records. The TB gauge suffers sampling problems as well as systematic errors and mechanical and electrical failures.

b. JW disdrometer measurements

An impact-type JW disdrometer measures the raindrop size distribution at the ground. It records raindrop numbers within each of 127 dropsize categories from 0.3- to 5.5-mm diameter during a time interval of 1 min (Joss and Waldvogel 1967). When a raindrop hits the 50 cm^2 conical styrofoam surface of the JW disdrometer, the mechanical impulse of the impacting drop is converted to an electrical impulse that is proportional to the diameter of the raindrop. Environmental and man-made noise can decrease the JW disdrometer's detection efficiency for small drops. In processing data, raindrop spectra with fewer than 20 drops per minute were removed because they were likely the result of nonmeteorological factors such as debris and insects. Raindrop spectra with rain rates less than 0.2 mm h^{-1} were also removed because they were prone to large sampling errors (Hagen and Yuter 2003).

c. Comparisons between gauge and disdrometer measurements

Figure 1 shows the cumulative daily rainfall computed from the TB gauge and JW disdrometer for the period from 9 April to 22 November 2005, excluding the periods from 3 June to 1 July and from 25 to 30

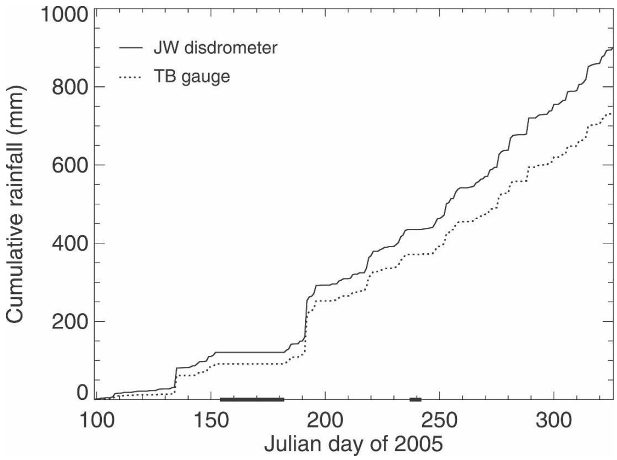

FIG. 1. Comparison of TB gauge and JW disdrometer rainfall measurements from 9 Apr to 22 Nov 2005. Two heavy lines on the abscissa denote two excluded periods. The solid and dotted lines are for cumulative daily rainfall from the JW disdrometer and TB gauge, respectively.

August 2005. The excluded periods are denoted as heavy lines on the abscissa in Fig. 1. According to RMI field operational staff, the JW disdrometer stopped recording between 3 June and 1 July 2005 due to a computer software problem. It also failed between 25 and 30 August 2005 for unknown reasons. The TB gauge failed to record rain events from 23 November to 3 December 2005; after that, it did not seem to work properly for the rest of 2005 based on comparisons with the disdrometer. The data used in this study consisted of time periods when the JW disdrometer and TB gauge were both working.

During the entire available reliable data period (Fig. 1), the disdrometer recorded 901.19 mm and the gauge recorded 735.58 mm of rainfall, which is 81.62% of the disdrometer. The correlation coefficient (Corr) of the two measurements was 0.996. The overall agreement between the gauge and disdrometer was good, although the gauge was usually lower than the disdrometer.

Several researchers have shown that the rain differences between a gauge and disdrometer were mostly on the order of 10%–20% (McFarquhar and List 1993; Sheppard and Joe 1994; Tokay et al. 2003b; Hagen and Yuter 2003). These differences might result from the spatial rainfall variability, relative instrument accuracy, or environmental effect. According to the JW disdrometer manufacturer, the difference of event rain totals measured by the rain gauge and collocated JW disdrometer should be within 15% for a rain event with a total rainfall of 5–10 mm or more (Tokay et al. 2005). As a data quality check, the event rain totals from the TB gauge and collocated JW disdrometer need to be compared.

A rain event is usually defined based on the time gap between two consecutive records from a TB gauge or JW disdrometer. Any two records in the time series separated by 15 min or more are interpreted as the end of one event and the beginning of the next one. Now if the above event definition were used for the original JW disdrometer records, the number of determined JW disdrometer rain events and their event durations would be very different from those of the TB gauge. The difference is due to the mechanical sampling of rainfall by each device. Whereas the JW disdrometer is an impact device that responds to rain drops impinging on its measuring surface in 1 min, the TB gauge is an accumulating device that observes rainfall in 0.254-mm increments, which means TB gauge often takes more than 1 min to record 1-tip rainfall during light rain periods. The rain event defined using the disdrometer should be more accurate. However, the purpose of this study is to estimate rain rates from discrete TB gauge measurements using the CS algorithm. Moreover, disdrometers are usually not available for most gauge networks. To approximately match the timing of the rain event for both devices, one can simulate the JW disdrometer as a TB gauge. The simulation will be discussed in section 5. Thirty rain events with event totals of at least 5 mm were determined. Whereas the JW disdrometer recorded 412.74-mm rainfall from all these 30 events, the TB gauge recorded 382.78 mm, which was 7.26% lower than the JW disdrometer. For most events, the difference was less than 15%. When the rain events with gauge rain totals of at least 10 mm were compared, only one event on 8 October had the difference greater than 15%. The agreement was better for heavier rain events. A total of 382.78 mm from all 30 rain events (of at least 5 mm) was 52.04% of the rain total from the entire data period observed by the TB gauge, whereas 412.74 mm was 45.80% of the rain total observed by the JW disdrometer. This may imply that the gauge has a tendency to undercatch light rainfall, which could be caused by the evaporation of a partial rain tip in the bucket, blockage of gauge apertures, wind, turbulence, etc., due to its design (Groisman and Legates 1994; Nespor and Sevruk 1999).

Figure 2 is the scatterplot along with the regression line for the 30 rain events. Corr between the TB gauge and JW disdrometer event rain totals was 0.999 and the mean absolute error (MAE) was 1.07 mm. The standard deviation (STD) of the event rain total differences was 0.91 mm. It is immediately apparent that the TB gauge and JW disdrometer agreed reasonably well.

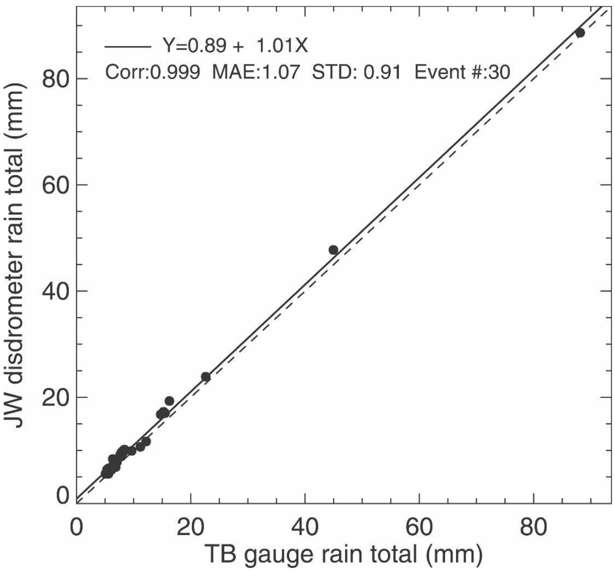

FIG. 2. Scatterplot for event rain totals from the TB gauge and JW disdrometer. The solid line is a regression line. The diagonal dashed line indicates 1:1 correspondence. Also shown are the regression equations between the gauge and disdrometer event rain totals, their Corr and MAE as well as the STD of the event rain total differences and the number of events.

3. Methodologies for rain-rate estimation

The numbers of raw TB tips in a rain event are summed into cumulative tip numbers at each "tip minute." A tip minute is defined as the minute when a tip occurs. These cumulative tip numbers are then converted into the cumulative rainfall in millimeters by multiplying the TB size of 0.254 mm. The cumulative rainfall, a monotonically increasing function of the tip minute, should be more suited to rain-rate interpolations than the raw TB tips. Several methods can be considered for the interpolations, such as linear, quadratic, and cubic algorithms.

The linear algorithm simply connects two data points with a straight line. It is the simplest way to estimate the rain rate, which can be described as

$$R(x_{i+1} - x_i) = \Delta \upsilon/(x_{i+1} - x_i), \tag{1}$$

where $R(x_{i+1} - x_i)$ is rain rate during two consecutive TB tip minutes x_i and x_{i+1} for $i = 1, 2, \ldots, n - 1$ (n is the total number of tip minutes), and $\Delta \upsilon$ is the gauge bucket size, which is 0.254 mm here. The linear interpolation always results in constant rain rates between any two consecutive tip minutes. This may not be desired for coarse sampling intervals with high rain gradients. A typical problem associated with the linear interpolation is that interpolated rain rates are never zero even during a no-rain period, which becomes an issue when the time interval between consecutive tips is very large. For example, for 1-tip rainfall in a 20-min interval with rain peaks and stoppages, the linear estimates of rain rates are 0.762 mm h^{-1} for the entire interval.

The quadratic interpolation produces a sawtooth rate curve, which is very different from a real rain-rate curve (Sadler and Busscher 1989). Only cubic and higher-order interpolations produce a smooth and continuous rate curve. Because of its easy implementation as discussed below and its prior satisfactory experience, the CS is often chosen to interpolate rain rates (Sadler and Busscher 1989; Tokay et al. 2003a).

The basic idea behind the CS is from an engineer's drafting tool, a flexible rod often called spline, which is used to help draw smooth curves connecting widely spaced points. The mathematical CS accomplishes the same result for numerical data points (Press et al. 1992; Bartels et al. 1987). A series of unique cubic polynomials are constructed to fit the curves between each of the data points. The fitting curves must be continuous and appear smooth.

A CS essentially is a piecewise function in the form of $f(x) = f_i(x)$ ($x_i \leq x < x_{i+1}$, $i = 1, 2, \ldots, n - 1$), where x_i is the same as in Eq. (1) and $f_i(x)$ is a cubic polynomial defined as

$$f_i(x) = a_i(x - x_i)^3 + b_i(x - x_i)^2 + c_i(x - x_i) + d_i. \tag{2}$$

Since $f(x)$ interpolates all of data points, one can have $y_i = f_i(x_i)$ ($i = 1, 2, \ldots, n$), where y_i is the cumulative rainfall at the tip minute x_i. The coefficients a_i, b_i, c_i, and d_i of Eq. (2) can be uniquely determined through a symmetric linear tridiagonal system once two boundary conditions are imposed (Press et al. 1992). Most commonly, the second derivative of each polynomial is set to zero at both endpoints x_1 and x_n. This produces a so-called natural CS.

The CS is popular because of its easy implementation and seamless fitting curve. However, notice that it is only piecewise continuous, which means it may not be the best choice for data sensitive to the smoothness of the third or higher derivatives. It is a reasonable assumption that the time series of cumulative rainfall during a rain event is piecewise continuous; therefore, the CS can be used for the rain-rate estimation on the rain event basis.

4. Estimation of rain rates using CS

The cubic polynomial defined in Eq. (2) is analytically constructed for the cumulative rainfall at each tip interval in a rain event. In applying (2), we consider the longest event observed from the TB gauge at Roi Namur. The event began at 1838 UTC 11 July and ended at 0052 UTC 12 July 2005. A total of 347 tips were recorded by the TB gauge over a period lasting 374 min. Some minutes in the event included multiple tips whereas no tip was recorded at other minutes. There were 176-min recorded rain tips at unequally tipped minutes of 1838, 1842, . . . , 2356, 0000, 0003, . . . , 0045, 0052 UTC, resulting in 175 tip minute intervals and 175 cubic polynomials. In Eq. (2), we first define $x_1 = 0$ as the first tip minute at 1838 UTC. The other tip minutes are then defined relative to the first tip minute at $x_1 = 0$, with $x_i = 4, 8, \ldots, 367$ for $i = 2, 3, \ldots, 175$ at the second, third, . . . , 175th tip minutes. Coefficients a_i, b_i, c_i, and d_i for each of 175 cubic polynomials can then be determined for this event.

Equation (2) gives the cumulative rainfall as a function of time, which can be evaluated at each integer minute during a tip interval. The rainfall during each minute can be obtained by subtracting the cumulative rainfall at the previous minute from that at the current minute. This 1-min rainfall can then be easily converted into 1-min rain rate in millimeters per hour by multiplying by 60.

For the first tip interval in the above event, the parameters of Eq. (2) for the first cubic polynomial were ($i = 1$; $x_1 = 0$; $a_1 = 0.000\,143$; $b_1 = 0$; $c_1 = 0.065\,79$; $d_1 = 0.254$).

Equation (2) for the first tip interval could be written as

$$f_1(x) = -0.000\,143x^3 + 0.065\,79x + 0.254,$$

where $x = 0, 1, 2, 3$ at 1838, 1839, 1840, and 1841 UTC, respectively.

Similarly, for the second tip interval,

$$f_2(x) = 0.000\,716(x - 4)^3 - 0.001\,718(x - 4)^2 + 0.058\,919(x - 4) + 0.508,$$

where $x = 4, 5, 6, 7$ at 1842, 1843, 1844, and 1845 UTC, respectively. Notice that $f_1(4) = f_2(4) = 0.508$ when $x = 4$ at 1842 UTC because $f(x)$ was continuous across the entire x interval from 0 to 374 (i.e., from 1838 UTC 11 July to 0052 UTC 12 July 2005). The 1-min rain rate at 1839 UTC could be estimated as $[f_1(1) - f_1(0)] \times 60 = 3.94$ (mm h^{-1}). One-minute rain rates at any other integer minutes could be similarly estimated.

The CS algorithm is employed within a rain event. A typical problem associated with any rain-rate interpolation from TB gauge measurements is the lack of information about the start and end times of a rain event. The first (last) tip time in a rain event recorded by a TB gauge does not indicate the real start (end) time of the event. A rain event always starts before the first tip time and often ends after the last tip time. The TB bucket is often partially filled when an event ends. This partial tip of rainfall amount will subsequently be recorded within the first tip of the next event. The exact amount of the partial tip cannot be precisely determined. Here one-half tip is fairly assumed. The maximum possible error of an event rain total caused by this assumption is one tip, which is trivial for most rain events. One can extrapolate the first cubic polynomial backward to the time when the cumulative rainfall reaches one-half tip. This time can be estimated as the start time. Similarly, the end time of a rain event can be estimated by extrapolating the last cubic polynomial forward to one-half tip beyond the last tip. This arbitrary estimation is not expected to result in good extrapolations for all rain events, but it preserves the event rain totals. For the event of 11–12 July 2005, the estimated start time was at 1837 UTC 11 July, which was 1 min ahead of the first tip. The estimated end time was at 0055 UTC 12 July, which was 3 min after the last tip.

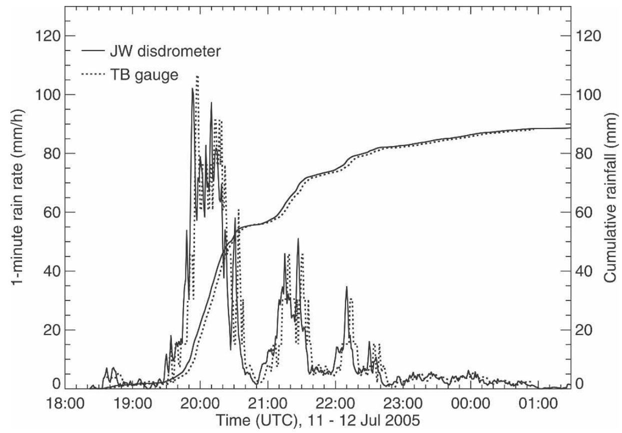

FIG. 3. Time series of 1-min rain rates measured from the JW disdrometer (solid line), and estimated from the TB gauge (dotted line) using the CS algorithm for the event of 11–12 Jul 2005. Also shown is cumulative rainfall from measured JW rates and that from estimated TB rates. The left ordinate is for rain rates and the right ordinate is for cumulative rainfall.

Figure 3 shows the time series of the rain rates measured from the JW disdrometer (solid line) and estimated from the TB gauge using CS (dotted line) for the event of 11–12 July 2005. The TB gauge recorded a rain total of 88.1 mm during the event that lasted 374 min. The JW disdrometer recorded slightly more rainfall. The cumulative rainfall from the TB gauge and JW disdrometer were very close. In general, rain rates estimated from the CS agreed well with the rain rates measured from the JW disdrometer.

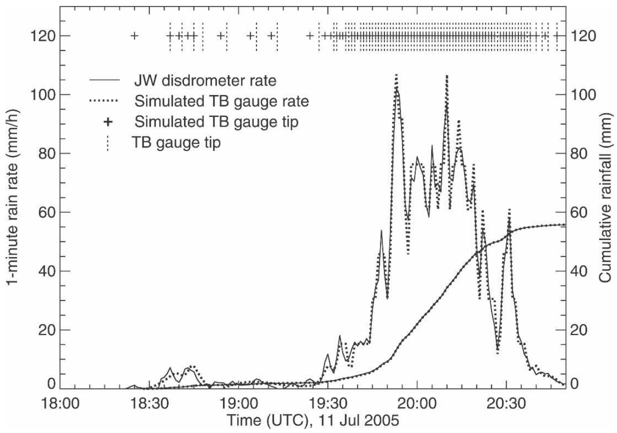

FIG. 4. Performance of the simulated TB gauge. The solid and dotted lines are for 1-min rain rates measured from the JW disdrometer and estimated from the simulated TB gauge using the CS algorithm, respectively. In the upper part of the figure, the plus sign and vertical dotted bar indicate the tip times of the simulated TB gauge and real TB gauge, respectively. Also shown are cumulative rainfall from measured JW rates and that from simulated TB rates. The left ordinate is for rain rates and the right ordinate is for cumulative rainfall.

However, the TB gauge lagged the JW disdrometer by a couple of minutes in Fig. 3. The small-scale rain variability should be random in nature and should not be the major factor for the lag since the two devices were closely installed. A preview of the JW disdrometer and simulated TB gauge in Fig. 4 of the next section reveals that the lag caused by the different sampling mechanisms was very small. More likely, the lag in Fig. 3 should be caused by the synchronization problem between the two devices because they reported to two different computers equipped with their own clocks.

There are situations where the CS cannot be applied such as in the case where a rain event only consists of 1 tip minute. In this case, neither a first or second derivative in the CS algorithm can be determined from the TB rain information. The 1-min event rainfall is usually one tip recorded at the minute by the TB gauge. Actually this amount of rainfall could be accumulated during a heavy rain period of several seconds or a light rain period of several hours if observed from a disdrometer or radar. Through discussions with members of the TRMM science team, rain rates are estimated by evenly distributing the 1-min event rainfall over a 5-min interval, which begins 3 min prior to the tip minute. For example, for a 1-min event with only a single tip, this treatment results in a constant rain rate of 3.048 mm h^{-1} at each of the 5 min. The estimation for a 1-min event is necessitated more by the need for accurate rainfall totals than the need for the rain-rate information.

Another special case occurs for a 2-min rain event. In this case, the natural CS becomes a linear line because second derivatives are set to zero at both minutes. A linear extrapolation is actually applied to estimate rain rates as well as the start and end times of the event.

A problem in the rain-rate estimation using the CS is that the interpolated rain rates could occasionally be negative. This happens when large rain gradients exist at low rain rates. An example is around 1926–1930 UTC 11 July 2005. When this problem happens, the interpolated negative rates are set to zero. This results in a bias of the estimated event rain total relative to the observed event rain total. Therefore, it is necessary to adjust all estimated rain rates in the event so that the bias after the adjustment is zero. The bias before the adjustment is usually less than 5%. When the bias is greater than 50%, the linear algorithm, instead of the CS, is employed for the event. There were 3 events with biases larger than 50% among all 374 events defined by the 15-min gap for the TB gauge from 9 April to 22 November 2005. They were all short events with large rain gradients adjacent to nonrainy minutes.

5. Simulation of TB gauge measurements using a JW disdrometer

Since the JW disdrometer has its own inherent detection problems as discussed in section 2, the records with less than 20 drops per minute and rain rate less than 0.2 mm h^{-1} are treated as noise. Then, these quality-controlled JW rain rates are considered a reference for the evaluation of the TB gauge accuracy. For this evaluation, the 1-min rainfall measured from the JW disdrometer is accumulated to integer multiples of the TB bucket size of 0.254 mm, or the number of tips. Once the accumulation reaches 0.254 mm, a discrete tip record is generated with a corresponding time stamp. The fractional remainder of the tip at the tip time is carried forward and used to accumulate into next integer tip. By doing so, the rain total is preserved during this simulation. The simulation is conducted for the entire data period from 9 April to 22 November 2005. The CS algorithm is then applied to all rain events defined from the simulated TB gauge to get the 1-min simulated TB rain rates.

The linear interpolation is also applied to estimate the 1-min rain rates for all of the simulated TB data. Rain-rate curves estimated from both the CS and linear algorithms agreed generally well with that observed from the disdrometer. However, the CS revealed finer features than the linear interpolation, especially when the time interval between the tips was large. The linear interpolation only evenly distributed a tip of rainfall to each minute of the large interval. A statistical comparison between two algorithms is conducted for all rain rates when the JW disdrometer observed rain. For the CS algorithm, the correlation coefficient between the estimated TB and measured JW rain rates was 0.956 and the standard deviation of the difference between two rates was 2.92 mm h^{-1}. For the linear algorithm, the correlation coefficient decreased to 0.934 and the standard deviation increased to 3.55 mm h^{-1}. Quantitatively, the CS algorithm is better than the linear interpolation.

Figure 4 shows the time series of rain rates measured from the JW disdrometer (solid line) and estimated by the CS from the simulated TB gauge (dotted line) for the first fragment of the rain event of 11–12 July 2005. The upper part of Fig. 4 shows the tip times of the simulated TB gauge (plus sign) and real TB gauge (dotted bar). A perfect match between the tip times of the real TB gauge and simulated TB gauge should not be expected because the real TB gauge and JW disdrometer suffer a lot of environmental and operational factors that affect their measurements. The cumulative rainfall of the JW disdrometer ideally matches that of the simulated TB gauge (right ordinate). The time series of rain rates from the simulated TB gauge slightly lagged that from the JW disdrometer because of the TB gauge sampling mechanism. This can be seen in Fig. 4 during the event start period between 1826 and 1940 UTC. The simulated TB gauge has the same sampling problem as the real TB gauge. They record the tip time only when rain accumulates to the full bucket size, which means it cannot be able to respond promptly to the changes in rain rates. The simulated TB gauge, as well as the TB gauge, cannot tell the start and end times of the rain event. The comparison between the JW rain rates (solid line) and the simulated TB tips (plus sign) shows that the rain event started before the first simulated tip at 1825 UTC 11 July. This event did not stop immediately after the last simulated tip at 0055 UTC 12 July (not shown in Fig. 4). The simulated gauge cannot reproduce all detailed features observed by the JW disdrometer, especially when rain rates are low or rate gradients are high; however, the example in Fig. 4 does show that the simulated gauge is able to reproduce the general feature of a rain event and suffer the same sampling problem as a real TB gauge. Therefore, the sampling-related errors of the TB rain-rate estimation can be investigated by comparing the simulated TB gauge with the JW disdrometer. By using the simulated TB gauge rather than the real TB gauge, systematic errors and mechanical and electrical failures are excluded in the comparison.

6. Errors of TB rain-rate estimation

TSVO produces TRMM Standard Product 2A-56, a time series of 1-min rain rates, using the CS algorithm discussed in sections 3 and 4. Product 2A-56 plays a key role in the generation of radar rain products and their validations. It is therefore important to understand errors of the TB gauge measurements and rain-rate estimations.

Many factors could affect the TB gauge measurements and rain-rate estimations (Humphrey et al. 1997; Nespor and Sevruk 1999; Habib et al. 2001; Wolff et al. 2005). As a precision instrument, the TB gauge suffers the systematic problem due to inadequate calibration before and after its deployment. The calibration should be performed in a sheltered site or a laboratory where wind effects are negligible, though this is often impossible at remote gauge sites. The gauge can also incur mechanical and electrical problems mainly due to the harsh environment where the gauge is usually deployed. The most common mechanical problem is due to debris falling into the orifice and blocking the apertures that direct water through the gauge. Lightning strikes and water impinging on the gauge's electrical contacts can cause anomalous tips to be recorded. The datalogger on board the gauge may fail to record rain tips due to battery failure or logger glitches. Most of these systematic, mechanical, and electrical problems can be detected and accounted for through regular gauge maintenance and the careful quality control of the collocated gauge data. Deployment of collocated gauges was recommended by Krajewski et al. (1998), Ciach and Krajewski (1999), and Steiner et al. (1999). This concept has been gradually used in rain measurements and related researches (Krajewski et al. 2003; Tokay et al. 2003b; Anagnostou et al. 2004; Wolff et al. 2005; Ciach and Krajewski 2006).

Besides the systematic, mechanical, and electrical problems, the TB gauge sampling mechanism is also a significant source of rain-rate estimation errors. The TB gauge cannot provide actual start and end times of a rain event. The extrapolation method provided in section 4 can be used to estimate the start and end times, but its result cannot be expected to be good for all rain events with different structures and types. As an accumulating instrument, the TB gauge always delays to respond to rapid rain-rate changes, especially during light rain periods due to the time required for the bucket to fill up and dispense. Problems may also occur in extreme events when the rainwater impinging on the gauge exceeds the flow rate through the aperture leading into the bucket. In this case, the rainfall is underestimated because the bucket cannot tip fast enough to keep up with the water entering the gauge. Consequently, the TB gauge is often unable to provide accurate information about the rain-rate temporal distributions due to sparse tip intervals and high gradients of rain intensities.

The CS algorithm is developed to estimate 1-min rain rates from the rain tips recorded by the TB gauge. The estimated rain rates suffer the TB gauge sampling–related errors. These errors need to be investigated because these estimates are instrumental in the calibration of the GV radar and the validation of the satellite rainfall estimates (Rosenfeld et al. 1994; Fisher 2004, 2007; Wolff et al. 2005).

a. *Effect of time scales on errors of rain-rate estimation*

To estimate the effect of time scales on errors of rain rates, similar to Habib et al. (2001), we use the rain rate measured from the JW disdrometer as a reference and define the TB gauge error as follows:

$$E_{\mathrm{TB}} = R_{\mathrm{TB}} - R_{\mathrm{JW}}(R_{\mathrm{TB}} > 0 \text{ or } R_{\mathrm{JW}} > 0). \qquad (3)$$

Here R_{TB} is the estimated rain rate from the simulated TB gauge at a given time scale; R_{JW} is the measured rain rate from the JW disdrometer at the same time scale; and E_{TB} is the error of the R_{TB} estimate at the applied time scale. All 1-min rain rates from all rain events, including 1-min events, are used here. Both 1-min rain rates from the JW disdrometer and simulated TB gauge are averaged to 2-, 4-, 7-, 10-, 15-, 30-, and 60-min scales. The TB gauge error is evaluated individually for each time scale. Equation (3) is performed only when either the JW disdrometer rain rate or simulated TB rate is greater than zero. By setting this condition, nonrainy periods are excluded from the comparison.

The error scatterplots are shown in Fig. 5, where E_{TB} is the ordinate and the rain rate is the abscissa. The sample size of E_{TB}, STD of E_{TB}, and MAE between R_{TB} and R_{JW} decreased, but Corr between R_{TB} and R_{JW} increased with the time scales as shown in Figs. 5a–h. A comparison of Fig. 5a with Habib et al.'s (2001) Fig. 7b exhibits good consistency between the two studies for the same 1-min sampling resolution. The scatter of the error E_{TB} decreased as the time scale increased from 1 to 60 min. At the 4- and 7-min time scales, the errors (Figs. 5c,d) dramatically reduced in comparison with 1- and 2-min scales (Figs. 5a,b). At the 10- and 15-min time scales, the errors are further reduced (Figs. 5e,f). When the time scale was increased to 30 min or longer, the errors were very close to zero (Figs. 5g,h) and therefore could be treated as negligible. It is interesting to notice that errors in Fig. 5 were bounded to a linear line $E_{\mathrm{TB}} = R_{\mathrm{TB}}$ when R_{JW} was zero so that E_{TB} was at its maximum value R_{TB}.

Figure 5 shows larger TB gauge errors located at low rain rates. This is caused by the poor performance of the TB gauge during light rain periods. During a light rain period in a rain event, a JW disdrometer might record a lot of small rain rates while a TB gauge might record only one tip at the time when the bucket gets full. For this type of light rain, the CS algorithm might interpolate this one tip as several relatively higher rates around the tip time and many zero rates at other times in the entire light rain period. This might cause the light rain rates to be overestimated around the tip time and underestimated at the other times.

From Fig. 5a, we can clearly see the binning of about 15.24 mm h^{-1} for the simulated rain rates. This is due to the 1-min sampling resolution of the simulated TB gauge with the bucket size of 0.254 mm. The simulated TB gauge, as well as the real TB gauge, always records the number of tips or rain amount as multiples of the bucket size at a tip minute. The binning effect disappears as the time scale increases. It is expected that the error defined in Eq. (3) increases with the bucket size. Habib et al. (2001) showed that a bucket size larger than 0.254 mm would lead to increased uncertainties of the TB gauge measurements.

From the above analysis, we can conclude that substantial errors associated with the TB gauge sampling mechanism do exist in low rain rates at the 1- or 2-min scale. These errors could be alleviated when the time scale of the rain rates increases. The estimated TB rain rates would be more reliable if used at the time scales of 4–7 min or longer. This is one of the reasons that TSVO uses the 7-min average of rain rates in WPMM Z_e–R development.

b. *Effect of event definitions on errors of rain-rate estimation*

The TSVO operational application of the CS algorithm is applied to the estimation of rain rates on a rain event basis. The definition of a rain event is based on the time gap between two consecutive TB gauge rain tips. A new event is defined when the gap is longer than a certain specified criterion. A shorter gap could result in more defined rain events by separating a long light event, such as a drizzle, to several shorter events. On the other hand, a longer gap could result in fewer defined rain events by combining several shorter events into a longer event, and introduce more rain stoppages into the event. Consequently, the definition of the rain event applied for the purposes of processing the data

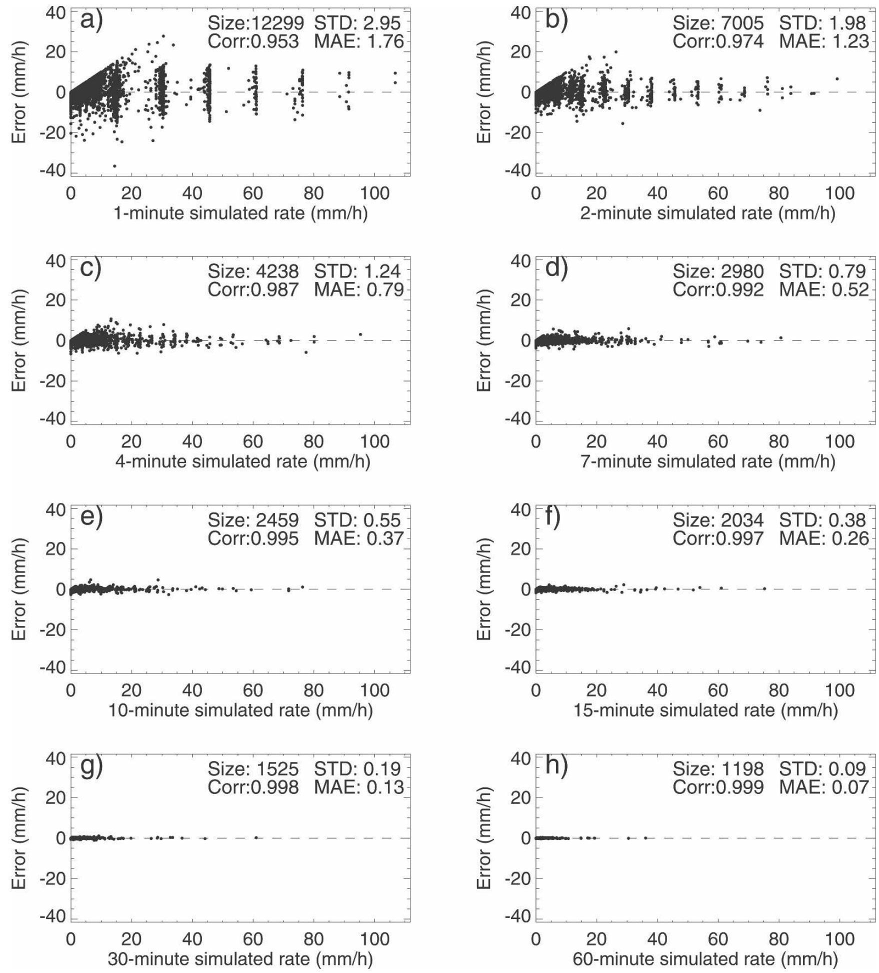

FIG. 5. Error scatterplots for 1-, 2-, 4-, 7-, 10-, 15-, 30-, and 60-min simulated rain rates. The abscissa is for the simulated rain rate at a given time scale. The ordinate is for the TB gauge error (E_{TB}). The sample size and STD of E_{TB} as well as the Corr and MAE between the rain rates simulated from the TB gauge and measured from the JW disdrometer are shown in the inserted texts.

does not necessarily correspond to the duration of the actual rain event.

Other studies have also dealt with this issue and the convention applied varies from one study to another. Sadler and Busscher (1989) set a 10-min gap whereas Cosgrove and Garstang (1995), Habib and Krajewski (2002), and Tokay et al. (2003a,b) set a 30-min gap as the criteria. Tokay et al. (2003b) also set 15- and 60-min gaps to study the sensitivity of the rain event statistics to the definition using observed disdrometer rain rates, and found that no significant change in rain intensity was evident while the rain duration was sensitive to the definition.

Here we identify the rain events when no TB tip is recorded in a 10-, 15-, 20-, 30-, or 60-min interval. The CS algorithm is used to estimate rain rates for all these differently defined events for the simulated TB gauge. One rain event from 0406 to 0835 UTC 16 October 2005 could be defined from the JW disdrometer using the 60-min definition. It could be 7, 6, 4, or 2 events from the simulated TB gauge using the 10-, 15-, 20-, or 30-min definition, respectively. There was a single tip event at 0651 UTC using the 10- or 15-min definition. This single tip event was combined into a longer event if the 20-, 30-, or 60-min definition was used. The number of rain stoppages during a rain event would increase when the event was determined from 10- to 60-min definition. The determination of a rain event was very sensitive to the event definition, but the estimated rain rate was relatively not so sensitive. Figure 6 shows rain rates measured from the JW disdrometer and estimated from the simulated TB gauge using the CS algorithm

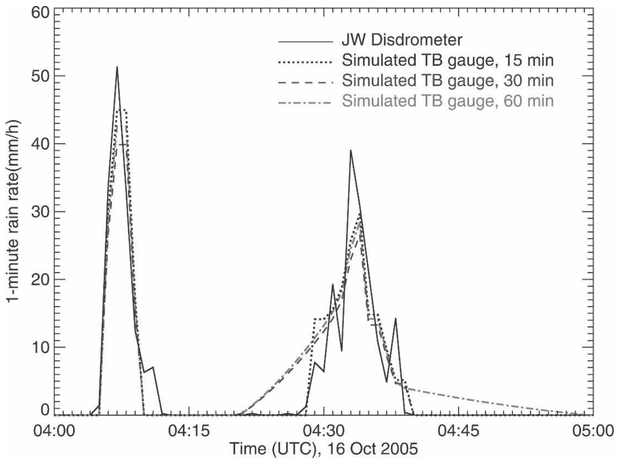

FIG. 6. Time series of 1-min rain rates measured from the JW disdrometer and estimated from the simulated TB gauge using the CS algorithm with 15-, 30-, and 60-min event definitions for the period from 0400 to 0500 UTC 16 Oct 2005. The solid, dotted, dashed, and dashed–dotted lines denote the disdrometer rain rates and gauge rain rates with 15-, 30-, and 60-min event definitions, respectively.

with different rain event definitions for the period from 0400 to 0500 UTC 16 October 2005. A close look at the details of Fig. 6 shows that the CS with longer gap definitions interpolated more low rain rates while they were in fact zero during no-rain periods.

Figure 6 is just a case study for comparisons of estimated rain rates among different event definitions. The boxplots in Fig. 7 show distributions of event durations, event rain totals, and estimated rain rates for all differently defined rain events. The events with event totals less than 1 mm were excluded in Fig. 7. Tokay et al. (2003b) and Cosgrove and Garstang (1995) similarly disregarded small events in their rain event analyses. Many of these small events were identified due to the discrete records of the TB gauge. A small event identified from TB tips could actually be a segment of a bigger event if JW disdrometer or radar records were used. Our test shows that these small events contributed little to the rain-rate distribution but changed the event duration and event rain total distributions. Event durations, event rain totals, and rain rates are highly positively skewed. The median and interquartile range (IQR), as statistical indicators, are robust and resistant to outliers and therefore considered as the better center and dispersion characteristics, respectively. The IQR is simply the difference between the upper (75th) and lower (25th) quartiles and plotted as the black box in Fig. 7. The white bar inside the box is the median. The upper whisker is truncated and the maximum is listed at the upper border of each boxplot. The numbers of events were 156, 154, 151, 143, and 129 in the boxplots for the 10-, 15-, 20-, 30-, and 60-min definitions, respectively. A rain event could be as long as 572 min with an event rain total of 96 mm (Figs. 7a,b) or as short as several seconds with an event rain total of 0.254 mm. Because only the events with a rain total greater than 1 mm were plotted, the shortest event duration and minimum event rain total shown in Figs. 7a,b were 1.4 min and 1 mm, respectively. As expected, the event duration increased as a rain event was defined with a longer time gap, but the event rain total was rather insensitive to the event definition because the event defined with the longer gap might contain more no-rain periods. While a rain event was defined from the 10- to 60-min definition, the number of estimated 1-min rain rates increased from 3448 to 6931 and the IQR decreased rapidly whereas the median rain rate decreased slightly and the maximum rain rate was constant (Fig. 7c). The similar situation happened for 7-min rain rates (Fig. 7d) but less rapidly. Since lower rain rates suffered larger errors as shown in Fig. 5, we separated 1-min rain rates into two groups, higher and lower than 3 mm h^{-1}. Their boxplots are shown in Figs. 7e,f. The higher rates (Fig. 7e) were not sensitive to the event definition, but it was not the case for the lower rates (Fig. 7f). A greater number of lower rates were estimated when a rain event was defined with a longer time gap. The sensitivity of rain rates to the rain event definition was different from Tokay et al.'s (2003b) research. In their case, rain rates were observed directly from JW disdrometers whereas for the case of the above analysis, rain rates were estimated by the CS algorithm from the simulated TB gauge tips.

To quantitatively evaluate the error level of estimated TB rain rates, we define the relative absolute error (RAE_{TB}) as

$$RAE_{TB} = |R_{TB} - R_{JW}|/R_{JW}(R_{JW} > 0). \qquad (4)$$

Here R_{TB} and R_{JW} are the same as in Eq. (3). All rain rates from all rain events with event rain totals of at least 1 mm are used in (4). Equation (4) is individually performed for two TB rain-rate groups (higher and lower than 3 mm h^{-1}) and two time scales (1 and 7 min) with different event definitions (10, 15, 20, 30, and 60 min). Table 1 shows the median RAE_{TB} in percentage for 1- and 7-min (in parentheses) TB rain rates. The median RAE_{TB} for higher rates was about 10% less than that for the lower rates. The light rain rate might be either overestimated or underestimated as discussed in section 6a. The underestimation was 100% from Eq. (4) if the estimated TB rain rate was zero for any recorded nonzero JW rain rate.

From Table 1, the median RAE_{TB} was about 22% and 32% for 1-min TB rain rates higher and lower than

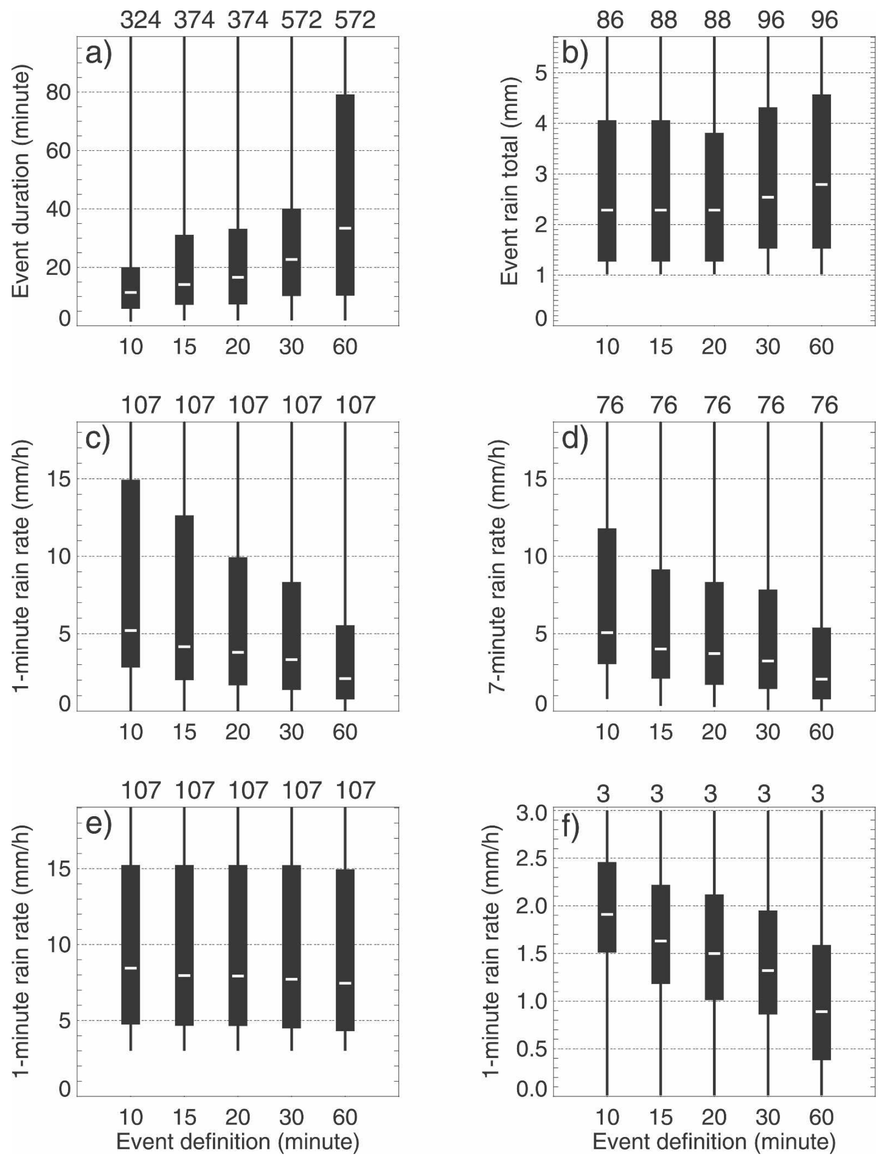

FIG. 7. (a) Boxplots for event durations for rain events with event totals of at least 1 mm. These events are determined by 10-, 15-, 20-, 30-, and 60-min definitions. The black box is the interquartile range. The white bar inside the black box is the median. The upper whisker is truncated and the maximum is listed at the upper border of each boxplot. (b) Same as in (a), but for event rain totals. (c) Same as in (a), but for all estimated 1-min rain rates. (d) Same as in (c), but for 7-min rain rates. (e) Same as in (c), but for rain rates greater than 3 mm h^{-1}. (f) Same as in (c), but for rain rates at almost 3 mm h^{-1}.

3 mm h^{-1}, respectively, for the 15-min event definition. When the TB rain rates were averaged to 7-min scale, the median RAE_{TB} decreased to about 5% and 14% for higher and lower rates, respectively. When a rain event was defined with a longer time gap, the median RAE_{TB} increased, especially for lower rain rates. A rain event defined with a longer tip gap often contains more rain stoppages. The CS algorithm may interpolate rain stoppages in a rain event as light rain. The rain stoppage in an event is a major difficulty in estimating high temporal scale rain rates from TB gauge measurements using the CS or any other algorithms. In this regard, we prefer to choose a shorter definition, for example, 15 min, in order to avoid more rain stoppages in an event.

TSVO also investigated the sensitivity of the WPMM Z_e–R distributions to rain event definitions (see online at http://trmm-fc.gsfc.nasa.gov/trmm_gv/gv_products/

TABLE 1. Median relative absolute errors (RAE_{TB}) in percentage for 1-min TB rain rates and 7-min TB rain rates (in parentheses). RAE_{TB} is individually calculated for two TB rate groups (higher and lower than 3 mm h^{-1}) for differently defined events (10-, 15-, 20-, 30-, and 60-min definitions).

	10 min	15 min	20 min	30 min	60 min
>3 mm h^{-1}	22.00 (5.20)	22.12 (5.07)	22.62 (5.33)	22.89 (6.28)	24.68 (8.53)
≤3 mm h^{-1}	32.10 (12.87)	31.87 (13.87)	32.11 (15.62)	33.33 (17.67)	37.69 (27.03)
All	23.90 (6.31)	24.58 (7.33)	25.29 (8.10)	26.67 (9.43)	30.24 (14.27)

level_2/event_definition/rain_event_compare.html). The 7-min rain rates based on 15- and 60-min definitions were used in monthly WPMM Z_e–R development for Kwajalein, RMI; and Melbourne, Florida. By combining large amounts of rain rates from all TB gauges for each site, the effect of the rain event definition was diminished. The resulting Z_e–R distributions were nearly identical for both definitions.

c. *Effect of time shifts on errors of rain-rate estimation*

TB gauge tips are often recorded by a datalogger equipped with an internal clock. The logger clock, which is generally initialized using a computer clock, will drift over time if it is not periodically updated. The MadgeTech logger used at Kwajalein has a time drift of 1 min $month^{-1}$ at 20°C. The Hobo, another commonly used logger, has a time drift of 1 min $week^{-1}$ at the same temperature. The recorded TB tip time can be shifted by several seconds to several minutes or longer due to the time drift of the logger clock and inaccuracy of the computer clock. The time shift can also result in rain-rate estimation errors. To test the effect of time shift on errors of rain-rate estimation, we shift the entire time series of 1-min simulated TB rain rates by 1 to 40 min. Notice that the simulated TB gauge based on the JW disdrometer, instead of real TB gauge, is used in this test. Both the 1-min rain rates from the JW disdrometer and shifted 1-min rain rates from the simulated TB gauge are averaged to a 7-min scale. The MAEs, as well as the Pearson correlation coefficients, between the JW rates and shifted TB rates were individually calculated at 1- and 7-min scales. Figure 8 shows the effect of time shift on errors of rain-rate estimation. A 10-min shift caused the MAE to rapidly increase from 1.76 to 5.25 mm h^{-1} for 1-min rates, and from 0.52 to 2.81 mm h^{-1} for 7-min rates, whereas the same shift caused the corresponding correlation to rapidly decrease from 0.95 to 0.26, and from 0.99 to 0.45, respectively. As the time shift further increased to beyond 10 min, the MAE increased and the correlation decreased slowly. When the shift time reached a threshold of 15 min, the correlation between JW and shifted TB 1-min rates became statistically insignificant under the 5% test level; similarly, the shift time threshold was 25 min for 7-min rain rates.

The gauge network at Kwajalein is maintained on a monthly basis. The MadgeTech logger equipped with each gauge is initialized once every month when the TB data are collected using a computer. Assuming the computer clock is accurate, the time shift caused by the logger itself is about 1 min for 1-month data. According to Fig. 8a, this 1-min shift can result in MAE increases of 0.88 and 0.28 mm h^{-1} for the 1- and 7-min rain rates, respectively. However, if the logger and computer clocks were not accurately adjusted, the effect of time shifts on errors of rain-rate estimation could be huge.

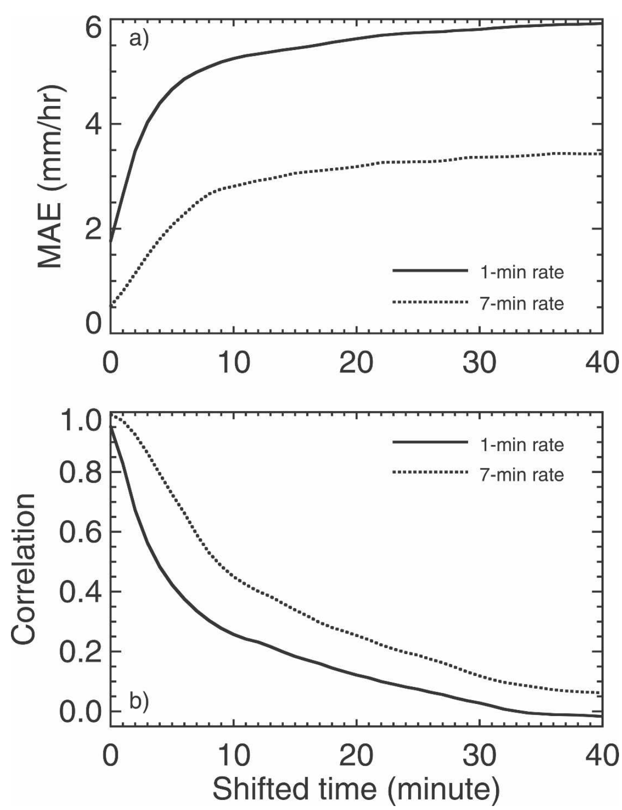

FIG. 8. The effect of time shifts on errors of rain-rate estimation. (a) MAE between the JW disdrometer rates and the shifted simulated TB rates. The solid and dotted lines are for 1- and 7-min rates, respectively. (b) Same as in (a), but for the Corr.

7. Summary and discussion

In this study, we probed the CS-based operational system for the generation of the TRMM 1-min rain-rate product 2A-56 from TB gauge measurements and examined the methodological issues associated with applying the CS to the TB gauge rain-rate estimation. We also investigated the errors of TB rain-rate estimation using a simulated TB gauge based on a JW disdrometer. These errors are very sensitive to the time scale of rain rates, especially at low rain rates. The errors are also affected by the rain event definition and the accuracy of the recorded TB tip times.

This study relied on rainfall measurements from a TB gauge and its collocated JW disdrometer on Roi Namur, RMI. The methodology developed in this study can be applied to any TB gauge rain-rate estimations. The results are helpful for better understanding the challenges and difficulties in accurate TB gauge measurements and rain-rate estimations as well as their related quality issues.

Another issue with regard to the rain-rate estimation is related to the gauge bucket size and time resolution. The gauge used in this study has the bucket size of 0.254 mm and time resolution of 1 s. This gauge is located in the TRMM GV site at Kwajalein. TSVO also provides 1-min rain rates for other TRMM GV sites, such as central Florida (MELB) and southeastern Texas (HSTN). Some MELB gauges have time resolutions of 5 min, whereas all HSTN gauges have bucket sizes of 1 mm. The coarse time resolution and large bucket size would effectively increase the time interval between two consecutive TB tips and easily miss peak rain rates and the finescale temporal variability in each rain event, which would introduce larger sampling errors. Caution should be taken when using the results from this study to evaluate the rain-rate estimates from gauges with coarser time resolutions and larger buckets sizes.

Based on this study, the following recommendations are suggested for rainfall measurements and rain-rate estimations:

1) The gauge bucket size should be no larger than 0.254 mm and the time resolution should be set to 1 s.
2) The gauge should be adequately maintained to ensure reliable rain measurements. The logger and computer clocks should be accurately adjusted.
3) A disdrometer or a high-temporal-resolution optical rain gauge should be collocated with multiple TB gauges if possible. Comparisons among independent and collocated measurements could help to detect or account for systematic, mechanical, and electrical problems, and provide further information on the rain-rate estimation errors.
4) While the CS gave reasonable estimation of rain rates in this study and the linear method also demonstrated acceptable interpolation in other studies, other interpolations, such as trigonometric and related Fourier methods, might also be worth a trial.

A Web site is available for accessing TRMM 1-min rain-rate product 2A-56 (http://trmm-fc.gsfc.nasa.gov/trmm_gv/data/data.html).

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