Rain Gauge and Disdrometer Measurements during the Keys Area Microphysics Project (KAMP)

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ABSTRACT

Four impact disdrometers and 27 tipping bucket rain gauges were operated at 11 different sites during August and September 2001, as part of the Keys Area Microphysics Project. The rain gauge and disdrometer network was designed to study the range dependency of radar calibration and rainfall verification in tropical storms. The gauges were collocated at eight sites, while three to five gauge clusters were deployed at three sites. Four disdrometers were also collocated with rain gauges. Overall the experiment was quite successful, although some problems did occur including flooding of gauge loggers, vandalism, and excessive noise at disdrometer sites.

Both a south-to-north and east-to-west rainfall gradient was observed, whereby the gauges on the western and northern sides of the Lower Keys recorded more rainfall. Considering the campaign-long rain accumulations, collocated gauges agreed well, with differences generally less than 2%, except for one gauge cluster where the rain accumulation difference was attributed to individual gauge calibration error. The duration of a rain event was sensitive to the definition of a rain event, while this was not a factor in rain intensity. Only 7% of the rain events had significant storm total differences in excess of 2.5 mm. All of these events occurred at storm conditional mean and maximum rain rates higher than 5 and 50 mm h^{-1}, respectively. Nevertheless, there were many other rain events for which the storm total differences were not significant in heavy rainfall. Combining most of the rain events from all collocated gauge sites, the correlation coefficient and mean percent absolute difference between the gauge storm totals were 0.99 and about 9%, respectively, on average. A rain gauge was typically able to measure rainfall within ± 1.2 mm. As the storm total increased, the standard deviation of the rain total difference and correlation coefficient increased, while mean percent absolute difference decreased. Considering the gauge that recorded higher overall accumulation as the reference, and ignoring the natural variability of rainfall between collocated gauges, the gauge rainfall error was about 9%. Two disdrometers that were placed away from noise sources performed well and recorded higher rainfall accumulation than their collocated rain gauges.

1. Introduction

Rain gauges and disdrometers are an integral component of many meteorological field campaigns. From planning to post data analysis, rain gauge and disdrometer operations encounter many scientific and logistical challenges, particularly at sites where land coverage is limited (e.g., the Florida Keys), where logistical limitations may force one to compromise scientific objectives and operational requirements. A practical solution is usually found for many of these challenges and it is important to document these aspects of the experiment for future field studies.

The Keys Area Microphysics Project (KAMP) was held in the lower and middle Florida Keys from 15 August 2001 through 28 September 2001. KAMP was conducted as part of the Fourth Convection and Moisture Experiment, a National Aeronautics and Space Administration (NASA) sponsored program. The main goal of the experiment was to study the kinematic, dynamic, and microphysical structure of tropical storms. The results could lead to improved microphysical parameterization of cloud-resolving models in tropical storm environment.

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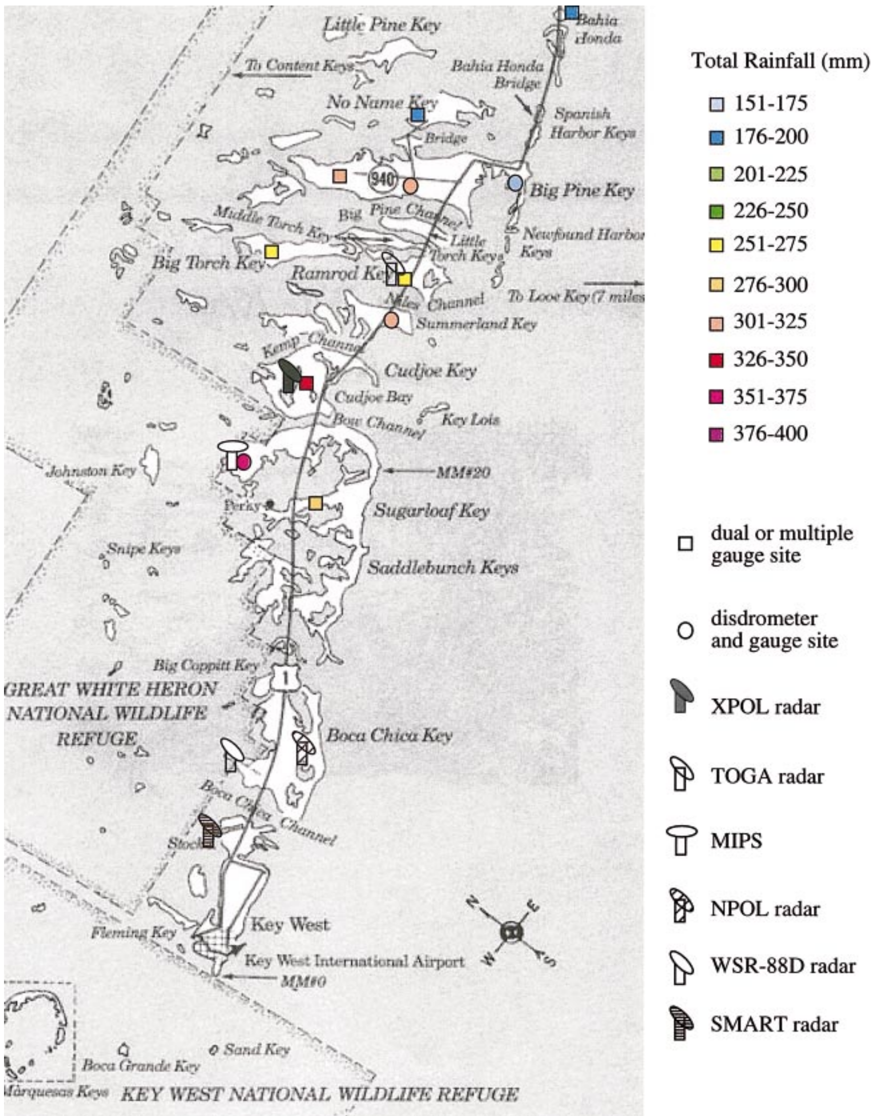

FIG. 1. Keys Area Microphysics Project instrument sites. The rain cluster site on Marathon is marked at the uppermost site of the map near Bahia-Honda Key. The map includes the lower Florida Keys, while Marathon is in the middle Florida Keys. The sites that are north and south of US 1 highway at Big Pine and Sugarloaf Keys are distinguished by adding *upper* and *lower* in front of the Key name, respectively.

Figure 1 shows the instrument locations and gauge rainfall accumulations in the lower Florida Keys. During KAMP, four research Doppler radars were deployed in addition to the operational Key West Weather Surveillance Radar-1988 Doppler (WSR-88D) radar located on the northern end of Boca Chica Key. Two of the four research radars, operated at X-band (XPOL) and S-band (NPOL) wavelengths, respectively, and had polarimetric capability. The experiment also included two C-band Doppler radars, namely, Shared Mobile Atmospheric Research and Training (SMART) and Tropical Ocean Global Atmosphere (TOGA), and a mobile integrated profiling system (MIPS). As part of the in situ surface rain measurements, the NASA Goddard Space Flight Center (GSFC) Tropical Rainfall Measuring Mission (TRMM) Satellite Validation Office (TSVO) operated four Joss–Waldvogel disdrometers (JWD) and 27 tipping bucket (TB) rain gauges at 11 different sites. Three additional TB rain gauges were also available on Key West, Boca Chica, and Marathon Keys as part of the National Weather Servicec Automated Surface Observing System.

This study presents an analysis of rainfall measurements from rain gauges and disdrometers that were operated by the TSVO during KAMP. The rain gauges provide *point* measurements of rainfall and are commonly used for both calibration and verification of radar rainfall estimates. Radar reflectivity and rain intensity are integral products of the drop size distribution that can be measured by a disdrometer. The disdrometer measurements are often employed for calibrating the radar measurements and for deriving the relations between radar measurements and surface rainfall. In this study, we examine the performance of each gauge and disdrometer during the KAMP field campaign. A brief survey of the measurement errors for the TB rain gauges and JWD are presented in section 2. Section 3 summarizes the gauge and disdrometer operation during the field campaign. The rainfall measurements, including gauge and disdrometer cumulative rainfall and mean rain rate, are presented in section 4. The rain duration and intensity of a typical rain event in KAMP are also included in this section. Sections 5 and 6 present the performances of gauges and disdrometers, respectively. These sections discuss the reasons for the malfunctioning of a few of the gauges and disdrometers and also include the rainfall statistics between the collocated gauges, and between the gauges and disdrometers. The statistics provide a perspective on the accuracy of a single gauge and disdrometer operated in a field campaign where the rainfall is mainly driven by intense convection. Section 7 discusses lessons learned and offers recommendations for improving the gauge and disdrometer operation. A brief summary of the findings of this study is presented in section 8.

2. A brief survey of tipping bucket rain gauge and Joss–Waldvogel disdrometer measurement errors

An automated tipping bucket rain gauge was developed by Joss and Tognini (1967) to interpret radar measurements. Joss and Tognini (1967) lay out the requirements for the performance of such gauges including measuring rainfall of all intensities with an accuracy better than 10%, and providing rain rate for a minute and longer time intervals. Since then, various types of TB rain gauges have been developed for use by the meteorological, hydrological, and agricultural communities, and are now widely used as part of automated weather stations by federal, state, and local institutions, as well as by interested private individuals.

Tipping bucket rain gauges exhibit both systematic and random errors. Although TB gauges are generally calibrated and tested by the manufacturer, they require periodic field calibration. The calibration error is just one of the systematic errors of the TB rain gauges. Systematic errors also result in underestimation of rainfall due to wind, wetting, evaporation, and splashing (Habib et al. 2001b). Assuming the gauge is well calibrated, the wind-induced error is the largest component of the systematic error that has been investigated through numerical simulations, laboratory, and field experiments. As cited by Neff (1977), it is well recognized that placing the rain gauge in a pit with the orifice at ground level minimizes wind-induced errors. An experimental study by Duchon and Essenberg (2001) showed that a tipping bucket rain gauge would underestimate 4% of rainfall in a typical rain event relative to the tipping bucket pit gauge. They also reported that the underestimation of the tipping bucket gauge was 15% in a single rain event during the passage of an intense squall line in windy conditions. Considering the deployment of a dense rain gauge network for a short-term field campaign, the pit gauge is not practical. Rather, a windshield could be an alternative to reduce the wind-induced errors. Duchon and Essenberg (2001) compared the rain totals of two TB rain gauges, one of which had a wind shield. The rainfall accumulation difference between the shielded and nonshielded TB gauges was 1.8%. Through numerical simulations, Nespor and Sevruk (1999) demonstrated the sensitivity of wind-induced errors to drop size distribution, rain intensity, and wind speed. They showed an increase in wind-induced errors with increasing wind speed and decreasing rain intensity. They concluded that the drop spectra at low rain rates are typically composed of small drops that are more affected by windy conditions.

Tipping bucket rain gauges are also subject to sampling errors. The sampling error is a function of resolution volume, sampling time of the gauge, and the frequency of precipitation. The resolution volume typically ranges between 0.1 and 0.5 mm. The sampling time typically ranges from the actual time of the tip, to the number of tips recorded over some sampling frequency (one or more minutes). Rain rates are typically calculated for a minute, an hour, or a day. Habib et al. (2001b) studied the sampling errors of a TB rain gauge by simulating TB gauge records with a collocated optical rain gauge. They concluded that the sampling errors are reduced for smaller resolution volume, shorter sampling time, and longer time interval of rain-rate integration. More specifically, the sampling errors were not significant for sampling times 10 s or less and rain-rate integration 15 min or longer for a 0.01-in. (=0.254 mm) bucket gauge.

Many applications in meteorology, hydrology, and agricultural and soil sciences require rain-rate measurements at a high temporal scale (e.g., mm min^{-1}). Although TB rain gauges are subject to considerable sampling errors for such a high temporal resolution, TB measurements are often interpolated linearly (Habib et al. 2001b) or through a cubic spline (Sadler and Busscher 1989) to determine the 1-min rain rates. The interpolation is confined between the first and last tip of the rain event. Therefore, the start and end time of the rain event is subject to error, especially in light rain events. The bucket resolution plays a key role in the performance of the interpolation algorithm. For example, for a bucket of 0.254-mm resolution at a steady rain rate of 0.1 mm h^{-1}, it takes 152.4 min to fill one tipping bucket. This means that rain could start 152 min before the first tip and last 152 min after the last tip. This is, of course, an extreme example.

Table 1a. Tipping bucket rain gauge operation and rainfall.

Rain gauge site	Start date and time (UTC)	End date and time (UTC)	Rain total (mm)	Mean rain rate (mm h^{-1})	Missing record start and end date and time
BP01 (upper Big Pine)	8 Aug 1436	1 Oct 1651	320.3	0.25	—
BP02 (upper Big Pine)	8 Aug 1425	1 Oct 1655	287.0	0.22	—
BP03 (upper Big Pine)	7 Aug 1404	30 Sep 1956	303.0	0.23	19 Sep 2134–20 Sep 1326
BP04 (upper Big Pine)	7 Aug 1517	30 Sep 2009	299.0	0.23	—
BP05 (upper Big Pine)	7 Aug 1517	30 Sep 2003	210.6	0.26	21 Aug 1555–11 Sep 1718
BP10 (lower Big Pine)	11 Aug 1846	29 Sep 2309	161.3	0.14	—
BP11 (lower Big Pine)	11 Aug 1850	1 Oct 1415	120.9	0.12	11 Sep 2022–19 Sep 2309
BT01 (Big Torch)	8 Aug 2009	30 Sep 1654	270.7	0.21	—
BT02 (Big Torch)	8 Aug 2013	30 Sep 1648	176.8	0.22	19 Aug 1543–21 Aug 1737 4 Sep 1732–21 Sep 1548
CJ01 (Cudjoe)	9 Aug 1503	30 Sep 1621	349.7	0.28	—
CJ02 (Cudjoe)	9 Aug 1510	30 Sep 1610	312.7	0.25	—
MH01 (Marathon)	11 Aug 1358	30 Sep 1858	191.8	0.16	—
MH02 (Marathon)	11 Aug 1403	30 Sep 1859	191.3	0.16	—
MH03 (Marathon)	11 Aug 1408	30 Sep 1859	188.5	0.16	—
NN01 (No Name)	8 Aug 1704	30 Sep 1949	183.6	0.14	—
NN02 (No Name)	8 Aug 1708	30 Sep 1938	180.3	0.14	—
RR01 (Ramrod)	9 Aug 1424	30 Sep 1628	178.8	0.18	26 Sep 1548–30 Sep 1628
RR02 (Ramrod)	9 Aug 1428	30 Sep 1628	266.2	0.25	—
SL11 (upper Sugarloaf)	13 Aug 1452	1 Oct 1407	382.5	0.32	—
SL12 (upper Sugarloaf)	14 Aug 2055	1 Oct 1410	332.5	0.29	—
SL13 (upper Sugarloaf)	14 Aug 1456	1 Oct 1356	312.4	0.27	—
SL14 (upper Sugarloaf)	14 Aug 1508	1 Oct 1353	385.6	0.33	—
SL15 (upper Sugarloaf)	14 Aug 1520	1 Oct 1400	65.5	0.16	16 Aug 1721–20 Aug 1527 4 Sep 1450–1 Oct 1400
SM01 (Summerland)	10 Aug 1523	1 Oct 1720	205.1	0.26	6 Sep 1453–25 Sep 1350
SM02 (Summerland)	14 Aug 1925	1 Oct 1425	308.3	0.27	—
SL03 (lower Sugarloaf)	10 Aug 1611	30 Sep 1556	282.9	0.23	—
SL04 (lower Sugarloaf)	10 Aug 1614	30 Sep 1559	280.2	0.23	—

An automated impact type Joss–Waldvogel disdrometer (JWD) was originally developed by Joss and Waldvogel (1967) to measure radar reflectivity, and it has been widely used in many experiments. A disdrometer is complementary to a rain gauge, and it is important to operate a rain gauge within 1–2 m of a disdrometer.

A shortcoming of the JWD is that it is sensitive to background noise. Laboratory measurements revealed that a noise level of 50 dB or less had little effect on signals corresponding to drop diameters of 0.3 to 0.4 mm, whereas a noise level of 55 dB reduced the detected number of such sized drops significantly. When noise levels reached 70 dB, the detection of drops of 0.3–0.8-mm diameter was almost completely suppressed (D. Högl, Distromet Ltd., 2000, personal communication). In addition to the background noise, small drops are not detectable in heavy rain due to the disdrometer's *dead time* (Tokay and Short 1996).

An impact type disdrometer such as the JWD infers the size of the individual drops from the measured impact velocity of the drops through a nonlinear relation between terminal velocity and drop diameter. Each disdrometer unit has been calibrated under laboratory conditions and the manufacturer provides the calibration table for 127 drop size intervals ranging from 0.3-mm to about 5.0–5.5-mm diameter. In windy conditions, the velocities of falling drops diverge from their terminal fall speed, causing an underestimation or overestimation of drop size. Since the terminal fall speeds of raindrops merely gradually increase at drop diameters above 5 mm, the JWD cannot distinguish the size of these very large drops. Rather, all the very large drops are grouped

Table 1b. Joss–Waldvogel disdrometer operation and rainfall.

Disdrometer site	Start date and time (UTC)	End date and time (UTC)	Rain total (mm)	Mean rain rate (mm h^{-1})	% time of rain	Conditional mean rain rate (mm h^{-1})
JWD_KDR (upper Big Pine)	8 Aug 1621	1 Oct 1452	248.9	0.19	3.9	4.9
JWD_HOUSE (lower Big Pine)	13 Aug 2014	1 Oct 1631	187.2	0.16	4.4	4.3
JWD_MIPS (upper Sugarloaf)	14 Aug 2123	13 Sep 0155	116.4	0.17	2.2	7.5
JWD_MOTE (Summerland)	14 Aug 2154	1 Oct 1521	266.8	0.23	4.2	5.7

TABLE 2a. Disdrometer rain event duration and intensity. The rain event is defined based on a 15-min or less time gap between two consecutive disdrometer records.

Disdrometer site	No. of rain events	Mean rain duration (min)	Median rain duration (min)	Std dev rain duration (min)	Mean rain rate (mm h^{-1})	Median rain rate (mm h^{-1})	Std dev rain rate (mm h^{-1})
KAMP (KDR)	73	42	19	57	4.9	2.0	7.3
KAMP (HOUSE)	77	40	15	64	2.9	1.1	3.9
KAMP (MOTE)	81	36	14	67	4.0	1.3	5.8
TEFLUN-B	95	31	13	49	3.2	0.9	4.9

together and counted in the largest size bin of the JWD. This causes an underestimation of heavy rain intensities where the size range of the spectrum extends over very large drops.

3. Rain gauge and disdrometer operations during KAMP

The rain gauge and disdrometer network for KAMP was designed to study the range dependency of radar calibration and rainfall verification in tropical storms (Fig. 1) and more generally in the tropical environment indigenous to the Florida Keys. All gauge sites were within 45–80-km range of the various radars. The disdrometer sites were within 40-km range of the radars. To have a reliable and continuous rainfall record, each site included at least two gauges, and the sites were visited at least once a week during which data was downloaded and copied to a personal computer for prompt analysis. This allowed for the timely determination of any problems that may have occurred with the gauges and loggers and helped provide a high quality dataset. Three gauge clusters were deployed to study the small-scale variability of rainfall, two with three gauges each; one with five gauges. Two gauges were collocated at all other sites except at a site on upper Big Pine Key. Disdrometers were collocated with one or two rain gauges at all sites. ''Collocated'' refers to gauges less than 2 m apart. Despite these efforts, some gauge measurements were interrupted by unknown data logger failures and/or unexpected high tides that flooded some gauge locations. Fortunately, at least one rain gauge at every site recorded rainfall, which emphasizes the necessity of installing two or more gauges at a site.

The gauge and disdrometer network was installed in early August 2001 and operated for 48–53 days (Tables 1a,b). Vandalism that occurred at a site forced to relocate the one of the gauge clusters to another site. This incident prompted a reassessment of where gauges could be safely and securely deployed for this and future field programs. The disdrometer operation at upper Sugarloaf Key was terminated early, simultaneously with the MIPS operation because the MIPS generator was the power source for the disdrometer's indoor units.

Tipping bucket rain gauges manufactured by Qualimetrics (Model 6011-A) were mounted on 20-cm-tall wooden boxes of 61 cm × 61 cm, following manufacturer instructions. Data logger units, equipped with an 8-pack D-battery and a termination strip, were attached to elevated wooden boards on the side of the boxes (Fig. 2). Two conductor cables connected the gauge to the data logger. Neither a pit gauge nor a wind shield for reducing wind effects was ecologically feasible due to the protected coral beneath the top soil. As noted in the owner's manual, the gauges were calibrated in the factory and were tested but not calibrated during the experiment. The volume resolution of the tipping bucket rain gauges was 0.254 mm, and the gauges were set to record the number of tips every 15 s. The gauges also reported a time stamp every 15 min in rain-free conditions so that some certainty that a given gauge was operating at a given time was possible.

The sensor of the JWD was placed on a foam-padded cinder block and linked to its indoor processing units via a 100-m cable (Fig. 2). The requirement for indoor shelter and power for the processing units posed limitations in finding appropriate sites for the disdrometers. The candidate sites needed to be far from any background noise source. In KAMP, out of four candidate sites, only one, lower Big Pine, was identified as ideal. The other sites were subject to undesired ambient noise, minimizing their ability to detect small drops effectively. Actual noise measurements of 50, 52, and 60 dB for Upper Big Pine, Upper Sugarloaf, and Summerland

TABLE 2b. Disdrometer rain event duration and intensity. The rain event is defined based on a 30-min or less time gap between two consecutive disdrometer records.

Disdrometer site	No. of rain events	Mean rain duration (min)	Median rain duration (min)	Std dev rain duration (min)	Mean rain rate (mm h^{-1})	Median rain rate (mm h^{-1})	Std dev rain rate (mm h^{-1})
KAMP (KDR)	61	47	21	71	5.3	2.7	7.7
KAMP (HOUSE)	66	50	18	71	2.9	1.3	3.5
KAMP (MOTE)	68	42	19	67	4.1	1.6	5.7
TEFLUN-B	78	38	18	49	3.3	0.9	4.6

TABLE 2c. Disdrometer rain event duration and intensity. The rain event is defined based on a 1-h or less time gap between two consecutive disdrometer records.

Disdrometer site	No. of rain events	Mean rain duration (min)	Median rain duration (min)	Std dev rain duration (min)	Mean rain rate (mm h^{-1})	Median rain rate (mm h^{-1})	Std dev rain rate (mm h^{-1})
KAMP (KDR)	52	59	30	76	5.2	2.8	7.0
KAMP (HOUSE)	50	62	18	104	3.1	1.5	3.5
KAMP (MOTE)	58	50	16	75	4.2	1.8	5.8
TEFLUN-B	66	45	21	57	3.7	1.3	4.9

Keys, respectively, were made via acoustic sensors. The JWD was set to record 1-min drop size distributions. It is noted that the disdrometers were calibrated by the manufacturer and tested at the field at NASA Wallops Flight Facility.

4. Rainfall measurements

a. Overall analysis

In addition to the operational period and missing records dates and times, Table 1a presents gauge cumulative rainfall and *unconditional* mean rain rate. The unconditional mean rain rate is the ratio of the cumulative rain to the duration of gauge operation. The rainfall accumulations presented in Fig. 1 represent the average rainfall between double or multiple gauges at a site. The gauges that did not operate properly throughout the experiment were not included in gauge rainfall accumulations. Considering then the gauges that had no missing records, there were both south–north and east–west gradients of rainfall. At upper Sugarloaf Key, the gauges measured 0.04 to 0.1 mm h^{-1} higher rain rates than those at lower Sugarloaf Key. Similarly, the two sites at upper Big Pine Key measured 0.08–0.11 mm h^{-1} higher readings than the gauges at lower Big Pine Key. Lower Big Pine, No Name, and Marathon Keys, all on the east side of the gauge network, were relatively drier with unconditional rain rates of 0.14–0.16 mm h^{-1}. The remaining sites had rain rates higher than 0.2 mm h^{-1}. Regarding the south–north gradient, rain was more intense and lasted longer on the north side than on the south side of the same Key. Similarly, rain was more intense and lasted longer on the western Lower Keys than on the eastern Lower Keys and Marathon Key. Here, the comparison of duration and intensity of rain between the gauges was performed at three different timescales: number of rainy records (i.e., 15 s), rainy minutes, and rainy hours. The rain intensity, or *conditional* rain rate, is the ratio of the cumulative rainfall to the duration of the rainy period. As noted in section 2, gauge-based rain duration and intensity are subject to sampling errors.

The rain duration and intensity derived from disdrometer measurements are less sensitive to temporal sampling errors. Table 1b presents disdrometer-estimated cumulative rainfall, unconditional and conditional mean

FIG. 2. A rain gauge–disdrometer site on lower Big Pine Key. The gauges were mounted on 20-cm-high wooden boxes of 61 cm × 61 cm, while the disdrometer (between the gauges on the back) was placed on a foam-padded cinder block.

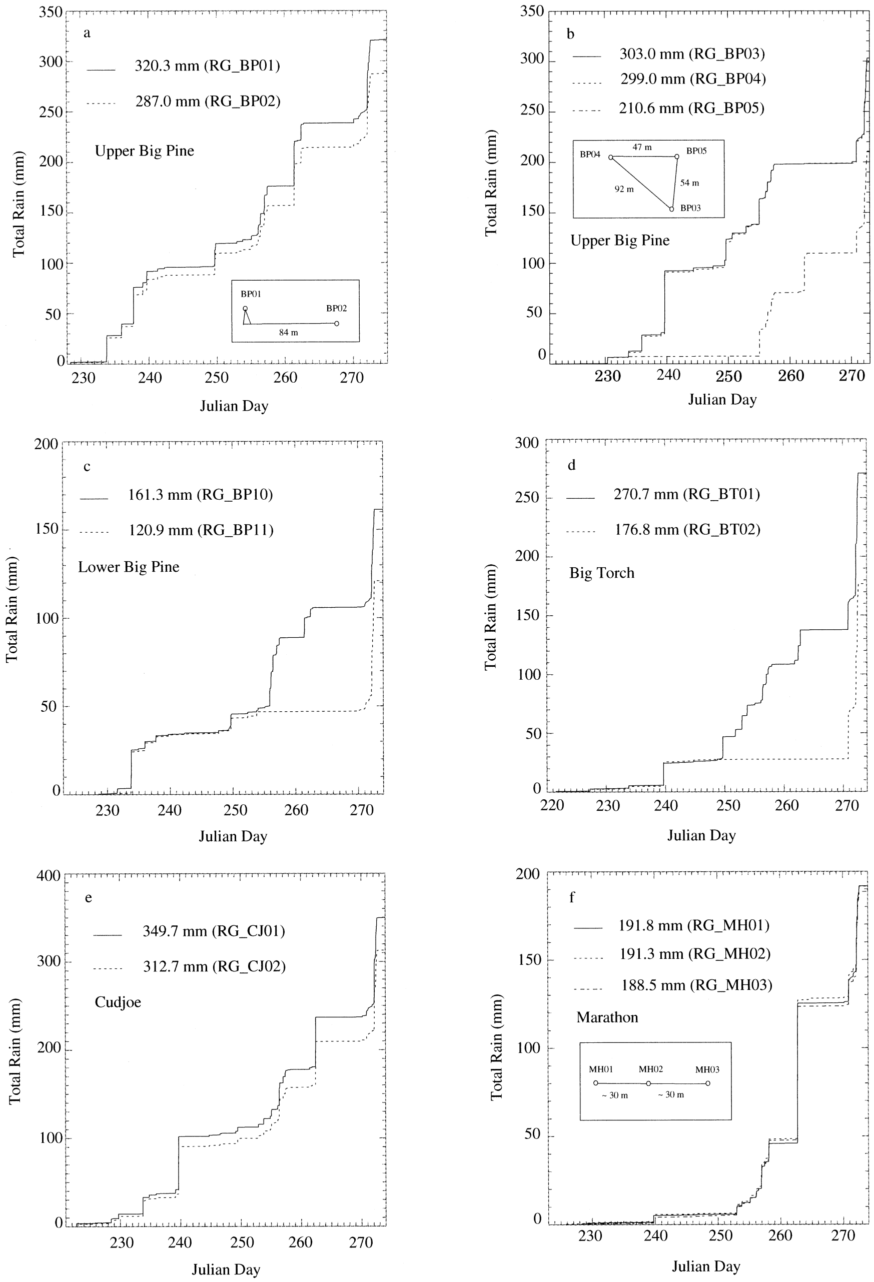

FIG. 3. Gauge rainfall accumulation diagrams at (a) upper Big Pine KDR headquarters, (b) upper Big Pine meteorological station, (c) lower Big Pine, (d) Big Torch, (e) Cudjoe, (f) Marathon, (g) No Name, (h) Ramrod, (i) upper Sugarloaf, (j) Summerland, and (k) lower Sugarloaf Keys. The configuration of the gauge clusters was also shown at four sites. The gauges at the other sites were collocated.

rain rate, and percent of time raining. Due to the measurement errors of the disdrometers at upper Big Pine and Summerland Keys and the early termination of operation at upper Sugarloaf Key, the disdrometer unconditional mean rain rates were substantially lower than the collocated gauge unconditional mean rain rates. The measurement errors of the disdrometers resulted in underestimation of rainfall, as will be discussed under the performance of the disdrometers. Regarding the duration of precipitation, the events lasted slightly longer on lower Big Pine Key than on upper Big Pine Key. Despite the disdrometer measurement errors at upper Big Pine Key, the conditional rain rate was higher at upper Big Pine Key than at lower Big Pine Key, confirming a south–north rainfall gradient (Table 1b). On lower Big Pine Key, 82% of the time the rain intensity was less

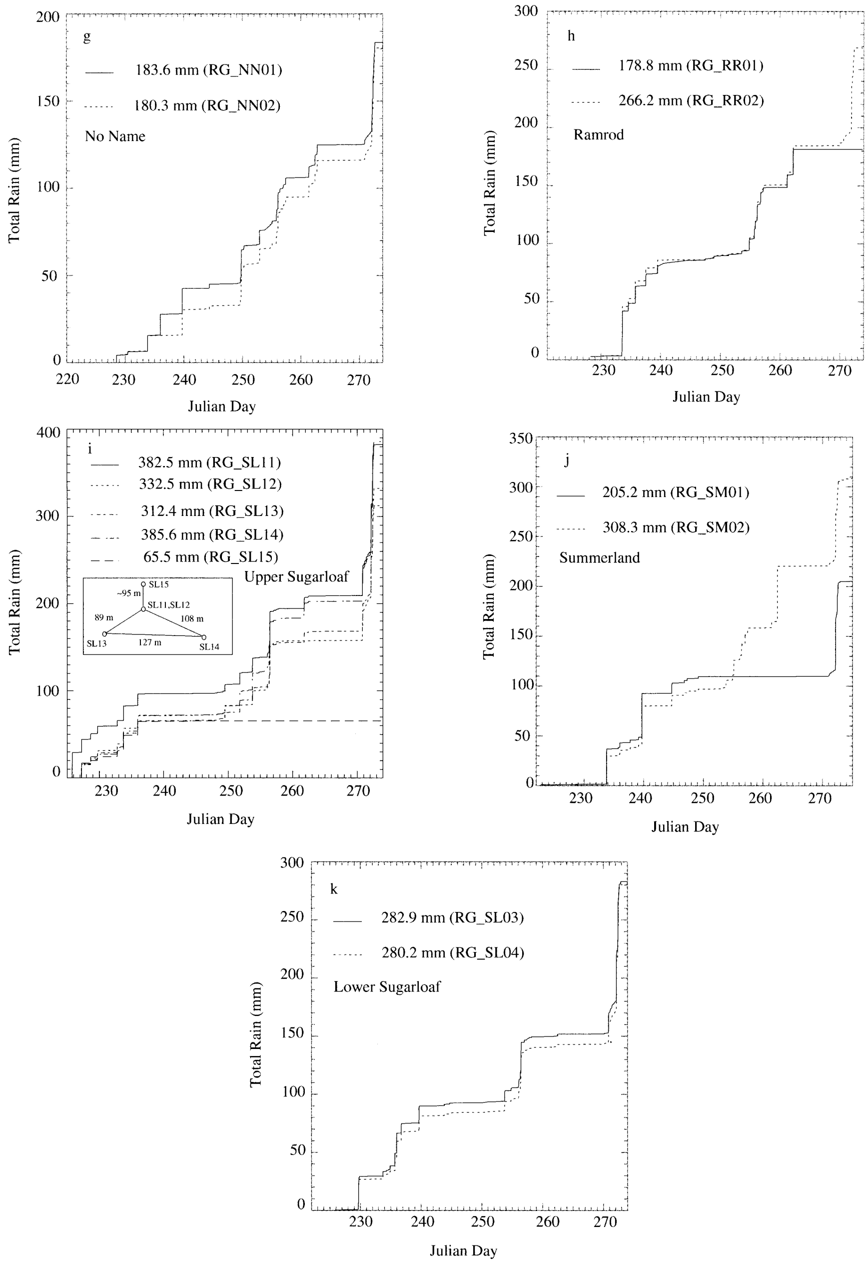

FIG. 3. (*Continued*)

than 5 mm h^{-1}, while 77% of the total rain fell at a rate above 5 mm h^{-1}. On upper Big Pine and Summerland Keys, where rain fell at higher intensities, 79% of the time the rain intensity was less than 5 mm h^{-1}, while rain rates above 5 mm h^{-1} counted for 83% of the total rainfall. The percent time raining and intensity of the rainfall at upper Big Pine and Summerland Keys were within a few percent of similar statistics at central Florida (Tokay et al. 2001). The disdrometer measurements in central Florida were collected during the Texas Florida Underflights Experiment (TEFLUN-B) between August and September 1998.

b. Rain event analysis

There is no standard criterion to define a rain event from gauge and disdrometer rainfall time series. Conceptually, there are two main observations in defining a rain event: the maximum time gap between two consecutive gauge tips or disdrometer records, and the minimum threshold of rain intensity or rain total in an event. In this study, a rain event was defined based on at least one gauge tip occurrence in a 30-min period, similar to Cosgrove and Garstang (1995), and Habib and Krajewski (2002). In all these studies, the tipping bucket data was collected at a time interval of 1 min or less. To be consistent, the same criterion (i.e., a 30-min time gap) was applied to the 1-min disdrometer measurements. However, we also used 15-min and 1-h time gaps to determine the sensitivity of the results to the definition of a rain event. The disdrometer records that had less than 10 drops in 1 min or a rain rate less than 0.1 mm h^{-1} were disregarded. Rain events that had less than three tips in gauge or less than three 1-min spectra in disdrometer were also disregarded.

A comparison of rain event totals were used to study the performance of collocated gauges and disdrometers. Duration and intensity of rain events were also examined through disdrometer measurements. Tables 2a–c present the mean and median event duration and intensity, as well as the standard deviation, for the three KAMP disdrometer sites and TEFLUN-B. Tables were grouped based on three different definitions of a rain event. Since the frequency distributions of rain event duration and intensity were skewed toward rare long (>1 h) and heavy (>10 mm h^{-1}) rain events, the median rather than mean event duration and intensity were considered more representative of a typical rain event. Among the KAMP sites, the rain events at upper Big Pine Key tended to be longer and more intense. The duration of typical rain events at Summerland and Lower Big Pine Keys was about the same, while rain events were relatively lighter at lower Big Pine Key. In comparison to the TEFLUN-B field campaign, rain events were more intense and usually longer during the KAMP experiment. However, when a rain event was defined by a 1-h maximum time gap between two consecutive records, TEFLUN-B rain events were longer than two of the KAMP sites in Table 2c. As rain event was defined for a longer time gap between consecutive records, the duration of a typical rain event increased as expected, while there was no significant change in rain intensity. The increase in rain duration reflects the rain intermittence in time, a major obstacle in fitting routines to the TB rain gauge data to obtain high temporal scale rain rate.

5. Performance of tipping bucket rain gauges

The cumulative rainfall curve in Fig. 3 exhibits the continuity of the gauge record at each site during KAMP. During the experiment, the rain gauge record was interrupted in 7 of the 27 gauges. In one instance, gauge BP03 was moved from one site to another to replace a failed data logger, BP11 (on lower Big Pine Key); however, a new gauge was mounted at the original BP03 site within 24 h. Unusually tidal flooding ruined the data loggers for BT02 and SL15. Data logger failure interrupted the operation of BP05. SM01 and RR01 data could not be retrieved during the latter part of the experiment. SL15 operated only 17 days (35%), while BP05, BT02, and BP11 failed to operate 21 (39%), 19 (37%), and 8 (16%) days, respectively. Data transfer failure in SM01 and RR01 caused the loss of 19 (37%) and 4 (7%) days of data, respectively (Table 1a).

In addition to the operational problems mentioned above, several rain events were not recorded by one or two gauges at few sites. For instance, there were rain events on 18–19 September that were recorded by BP05, but not by the two gauges nearby (BP03 and BP04). Since the rain event on 19 September was heavy, it is questioned why BP03 and BP04 did not record any rain. Unfortunately, no radar data were available for the heavy rain period, but the TOGA and WSR-88D radars, and BP05 recorded a light rain event later on 19 September. It is suggestive that BP03 and BP04 may have had temporary instrument problems in which the loggers occasionally would fail to operate during periods of excessive humidity or water infiltration into their cases from recent heavy rain events. Similarly, SL12 did not record three rain events on 8, 18 and 19, September yet the collocated SL11 accumulated 27.1 mm of rainfall during these rain events.

At extreme rain intensities, a single rain gauge record showed four tips within one reporting interval, which corresponds to 243.8 mm h^{-1}. In a rain event on 27 September, BT01 registered one five-tip record and one six-tip record; however, the collocated BT02 recorded no more than a three-tip record in this rain event. Interestingly, BT02 accumulated 15.7 mm more rainfall than BT01. The rain totals of these two collocated gauges differed the most during this event; unfortunately, there was no radar data available to confirm the rain accumulation, suggesting that this dataset might be unreliable since this was the first rain event for which BT02 was operational subsequent to changing its logger and termination strip after the gauge was found submerged in saltwater. Nevertheless, both gauges agreed well in subsequent rain events. Regarding other unusually high tip counts, BT01 registered a nine-tip record in a rain event on 19 September, where no more than two-tip records were observed during the remainder of the event. BT02 did not operate during this rain event. The nine tips were changed to two tips. SL14 recorded 16 tips in a single record on 28 September, where nearby observations indicated no more than a single tip in a record. Therefore, 16 tips were changed to a single tip.

a. Collocated rain gauges

Throughout the experiment, four out of the eight sites where two of the gauges were collocated provided a continuous rainfall record for both gauges. At No Name and Lower Sugarloaf Keys, the gauge accumulations differed from each other by 1.8% and 1.0%, respectively (Figs. 3g, 3k), while a 10.5% difference was observed between the two gauges at Cudjoe Key (Fig. 3e). At upper Sugarloaf Key, the difference was 5.9%, but this was mainly due to the fact that SL12 did not record rainfall during three rain events. If we consider only the rain events where both gauges reported rainfall, SL12 recorded 6.8 mm more rainfall and the difference was only 2.0%. For the remaining four sites, both gauges operated at least 1 month. For the period where both gauges were operating, the accumulation differences were 0.1%, 1.5%, 9.4%, and 13.6% at Ramrod, Summerland, Big Torch, and lower Big Pine Keys, respectively. Since BP11 was replaced during the experiment, the statistics between the two gauges should be interpreted with caution. A single rain event, where the gauges widely disagreed, was solely responsible for the relatively high accumulation differences at Big Torch Key. Excluding these rainfall statistics at lower Big Pine and Big Torch Keys and the anomaly at Cudjoe Key, the rain accumulation differences were less than 2%. There is no evidence to determine why the gauge accumulations differed substantially at Cudjoe Key. However, since one gauge had higher readings than the other in almost all rain events, a gauge calibration error might account for the differences among these gauges.

There have been a few field campaigns where dual or multiple TB gauges were collocated. During TEFLUN-B, pairs of the TB rain gauges were operated within a dense rain gauge network (Habib et al. 2001a; Habib and Krajewski 2002). The pair of gauges was separated by 1 m. The accumulation differences were 2.8% and 4.6% for about 50 days of operational period. A similar study in central Oklahoma resulted in an accumulation difference of 0.8% between the two TB rain gauges that were separated by 7 m (Duchon and Essenberg 2001). In the latter study, the gauges were well calibrated and maintained during the 13-month-long field campaign. The percent differences presented here are the ratio of the gauge rain total difference to the rain total of the gauge that accumulated the most rainfall. If the gauge that accumulates higher rainfall is considered to be reference gauge, the percent difference is referred to as *overall* percent error. Here, the natural variability of the rainfall between the collocated gauges is considered to be of secondary importance.

Figure 4 presents the storm totals of the collocated gauges with respect to one another at a given site. The rainfall statistics that were derived between the collocated gauges are presented in Table 3a. The statistics were based on the rain events where both gauges had at least a 1-mm rain accumulation. High correlation coefficients were evident in all sites. The correlation coefficients in lower Big Pine and Big Torch Keys were relatively low, as expected. The *mean* percent error (MPE), which shows the mean bias of the gauge rain total, ranged from 1.3% to 16.0%. The MPE was calculated as

$$\mathrm{MPE} = \frac{1}{N}\sum_{i=1}^{N}\frac{\mathrm{G1}_i - \mathrm{G2}_i}{\mathrm{G1}_i} \times 100, \qquad (1)$$

where G1 and G2 represent the gauge rain totals and N is the number of rain events. The gauge that accumulates less rainfall (G2) is again considered to be erroneous. The mean percent error weights light and heavy rain events equally. Since most of the rain events have lower accumulations, this statistic is dominated by the percent errors in light rain. Therefore, mean and overall percent errors of a gauge differed from one another.

The high correlation coefficients and low mean percent errors indicate a good agreement between the collocated gauges, but this could be misleading in terms of gauge performance on an event-by-event basis. It is possible that one gauge measured higher accumulations in some of the rain events, while the other gauge measured higher accumulations in other rain events. This would result in high correlations, but the standard deviation of rain total difference would also be high. The standard deviation of rain total difference (SDRTD) is given as

$$\mathrm{SDRTD}(\mathrm{G1} - \mathrm{G2}) = [\sigma(\mathrm{G1}) + \sigma(\mathrm{G2}) - 2\,\mathrm{cov}(\mathrm{G1}, \mathrm{G2})]^{1/2}, \qquad (2)$$

where the first two terms on the right side are the variance of G1 and G2, and the third term is two times the covariance between G1 and G2. The standard deviation indicates the accuracy of a gauge in measuring rain total. For instance, at Cudjoe Key, the gauges were able to measure rainfall within ± 1.6 mm (Table 3a). The gauges at Summerland Key had a higher SDRTD. This is probably due to the fact that the gauges were mounted on a roof where the conditions were probably more turbulent and windy. The standard deviations of rain total differences at Big Torch and lower Big Pine Keys were also high due to an anomalous rain event, and replacement of the gauges, respectively.

As a comparative study, the rainfall statistics from previously mentioned studies in central Oklahoma and central Florida were also included in Table 3a. Like overall percent difference, mean percent difference was also very low in central Oklahoma, while mean differences in central Florida were within the range of the KAMP sites. The correlation coefficients were high and SDRTD were low in both central Oklahoma and central Florida.

The storm totals from collocated gauges at different sites were merged to determine the performance of the gauges in general. The rain events on Summerland Key were not included since the gauges were on a roof. The rain events on lower Big Pine Key were limited to the period before the replacement of the gauge, and the rather suspicious rain event on Big Torch Key was also excluded. The resultant comparison then used 143 rain events. The correlation coefficient and SDRTD were 0.9964 and ± 1.2 mm, respectively, while mean percent absolute error (MPAE) was 8.7% (Table 3b). The MPAE is calculated similarly to Eq. (1) except that the absolute value of gauge rain total difference was considered.

Table 3b also shows the rainfall statistics for different storm total intervals. As the storm total rainfall increases, the standard deviation of the rain total difference

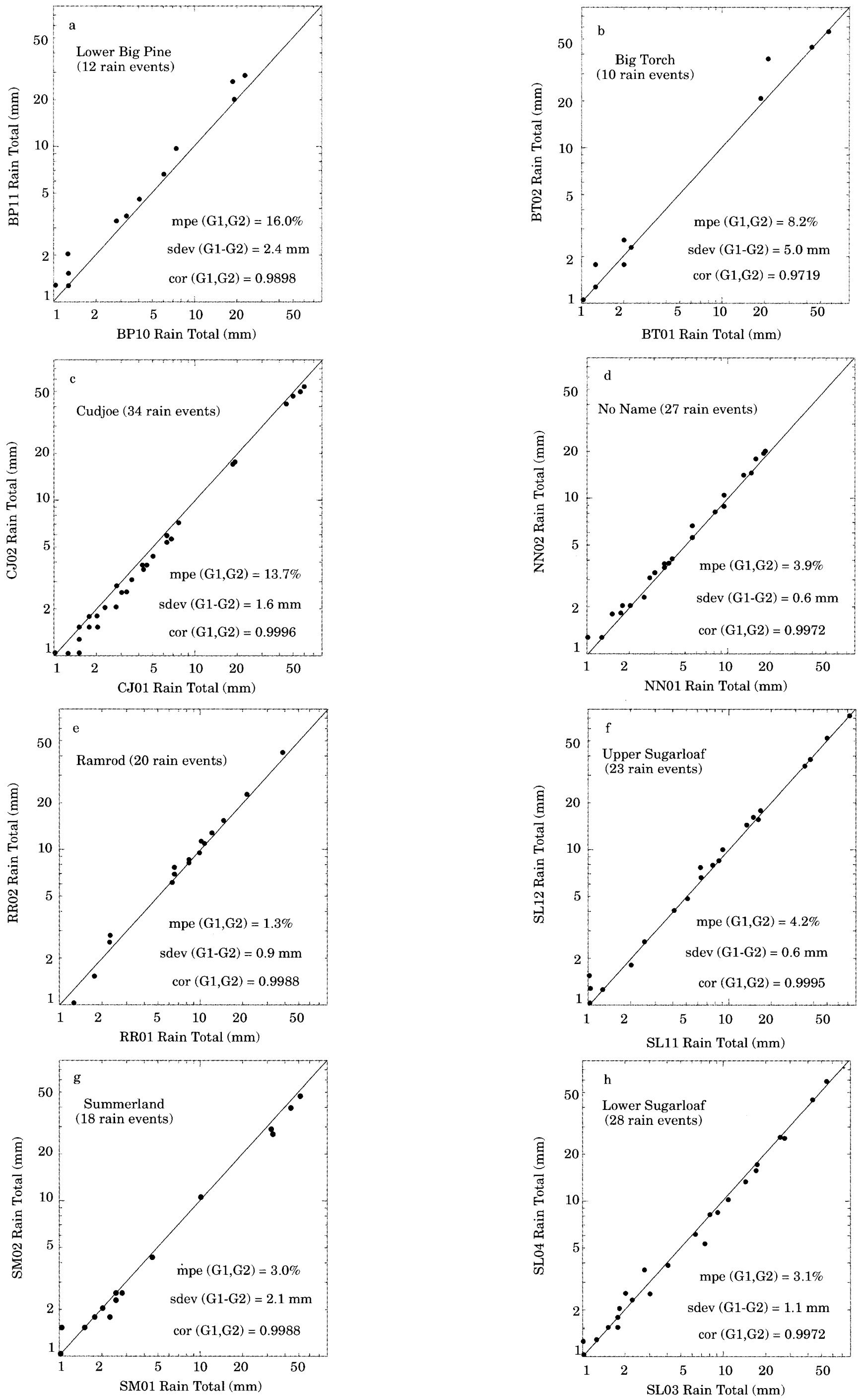

FIG. 4. The 1:1 storm total of the collocated gauges at (a) lower Big Pine, (b) Big Torch, (c) Cudjoe, (d) No Name, (e) Ramrod, (f) upper Sugarloaf, (g) Summerland, and (h) lower Sugarloaf Keys. The rainfall statistics between the two collocated gauges are also given. The statistics were based on rain events that had at least 1-mm accumulation.

and correlation coefficient increases, while mean percentage absolute error decreases. Convective showers dominate the rainfall in the Florida Keys. The maximum rain rate in a rain event, where storm totals are less than 5 mm, typically exceeds 10 mm h^{-1}. A few-tip difference between the collocated gauges results in high MPAE and low correlations in these short but heavy rain events. In longer rain events, the collocated gauges occasionally exhibit greater differences in rain accumulation. This is indicated by higher standard deviations

TABLE 3a. Collocated rain gauge statistics by site. Similar statistics from central Oklahoma (OK1–OK2), and central Florida (TB2A–TB2B, TB3A–TB3B) are also given.

Collocated gauges	No. of events	⟨G1⟩ (mm)	⟨G2⟩ (mm)	Var (G1) (mm²)	Var (G2) (mm²)	Corr (G1, G2)	MPE (G1, G2)	SDRTD (G1−G2)
BP10–BP11	12	7.4	9.1	64.4	101.5	0.9898	16.0	2.4
BT01–BT11	10	15.2	16.9	423.2	454.3	0.9719	8.2	5.0
CJ01–CJ02	34	10.0	8.9	273.2	223.3	0.9996	13.7	1.6
NN01–NN02	27	5.9	6.2	30.3	34.9	0.9972	3.9	0.6
RR01–RR02	20	8.4	8.7	79.7	93.9	0.9988	1.3	0.9
SL11–SL12	23	13.7	14.0	333.2	335.6	0.9995	4.2	0.6
SM01–SM02	18	11.0	9.9	277.4	216.6	0.9988	3.0	2.1
SL03–SL04	28	9.7	9.5	180.6	193.9	0.9972	3.1	1.1
OK1–OK2	51	18.3	18.2	251.0	246.3	0.9989	0.8	0.7
TB2A–TB2B	27	9.8	10.3	193.1	207.9	0.9995	6.3	0.7
TB3A–TB3B	24	10.8	10.4	234.6	227.3	0.9997	2.6	0.4

of rain total differences; however, the MPAE is lower and correlation coefficients are higher in these relatively longer rain events.

Figures 5a and 5b show the absolute storm total difference as a function of gauge conditional mean and maximum rain rates. The gauge rain rate was calculated using a cubic spline interpolation algorithm similar to Sadler and Busscher (1989). The sites on Big Torch, No Name, and Upper Sugarloaf Keys had no rain event with significant storm total differences (>2.5 mm). Here, the anomalous rain event on Big Torch Key was excluded. For the remaining sites, there were only 12 rain events for which the storm total differences were significant. Interestingly, most of these rain events occurred during a few storms that passed several sites along the Keys. For instance, an early morning rain event on 29 September resulted in significant storm differences at four sites. Overall, the significant differences in storm totals occurred in rain events where the conditional mean and maximum rain rates were above 5 and 50 mm h^{-1}, respectively. Nevertheless, most of the storm total differences were less than 2.5 mm regardless of gauge conditional mean or maximum rain rate.

Rain gauges are often deployed to verify radar rainfall estimates. Traditionally, each site has a single rain gauge. The presence of collocated gauges in KAMP provided an opportunity to study gauge rainfall errors. Considering the gauge with higher rainfall is the reference and there was no natural variability of rainfall between the collocated gauges, percent rainfall error was 9.2%. The percent rainfall error was calculated as

$$\%\ \text{Rainfall error} = \frac{\sum_{i=1}^{N} G_{Li}}{\sum_{i=1}^{N} G_{Hi}}, \tag{3}$$

where G_L and G_H represent gauge rainfall accumulations at a given site i with the condition, $G_L < G_H$, and N represents number of sites where the gauges were collocated. Here, N was 7 since we did not include the Summerland Key where the gauges were on the roof.

TABLE 3b. Collocated rain gauge statistics by rain accumulation range.

Rain total (mm)	No. of events	Cor (G1, G2)	MAE (G1, G2)	SDRTD (G1 − G2)
1–2	20	0.3869	16.2	0.3
2–5	43	0.9113	11.5	0.4
5–10	26	0.9475	7.7	0.7
10–30	34	0.9897	4.5	1.0
>30	20	0.9940	3.3	2.7
All	143	0.9964	8.7	1.2

b. Gauge clusters

The small-scale variability of rainfall was studied by examining rainfall statistics of gauge clusters. Here, the gauges were spaced from about 30–60 m on Marathon Key to about 90–130 m on upper Sugarloaf Key. Therefore, the rainfall statistics reflect, at least partially, the microscale variability of rainfall. The gauge sampling and measurement errors were also embedded in these statistics. Utilizing a dense rain gauge network during TEFLUN-B, Habib and Krajewski (2002) demonstrated the small-scale variability of rainfall at various temporal and spatial scales. They recognized the random sampling and measurement errors of the TB rain gauges on the rain total differences, where the gauges were separated from 1 m to 2880 m at timescales of 5–60 min.

On Marathon Key, three gauges were positioned in a line as shown in Fig. 3f. All gauges performed throughout the experiment and agreed well with each other. The rainfall statistics presented in Table 4 show high correlation coefficients, low mean percent errors, and low standard deviations of rain total differences, similar to the statistics presented for the collocated gauges in Table 3a. Specifically, MH01 and MH02 had excellent agreement in each rain event, and MH03 had a lower reading in only one rain event. This resulted in 1.7% lower overall accumulation in MH03 than in the other two gauges.

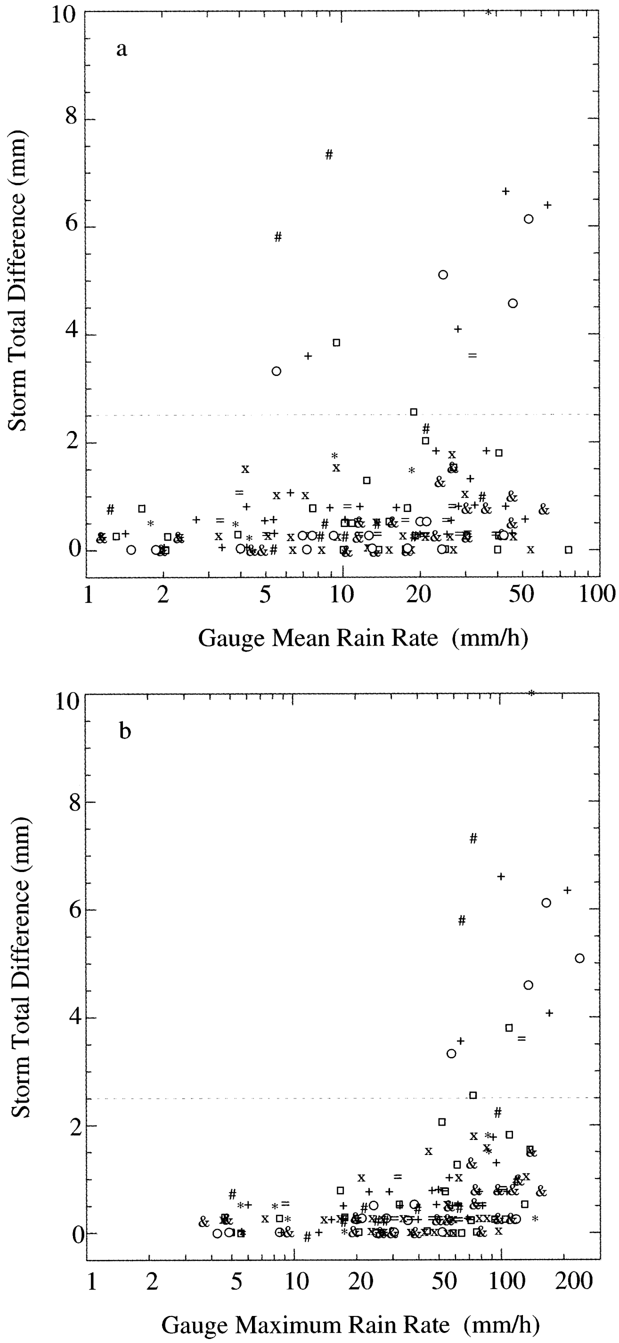

FIG. 5. Composite gauge storm total differences as a function of (a) conditional mean, and (b) maximum rain rate. The symbols denote lower Big Pine (#), Big Torch (*), Cudjoe (+), No Name (×) Ramrod (=), upper Sugarloaf (&), Summerland (○), and lower Sugarloaf ( ) Keys. The conditional mean and maximum rain rates of a rain event were calculated utilizing cubic spline interpolation algorithm. The rain events that had at least 1-mm accumulation were only considered in the analysis.

At the meteorological station on upper Big Pine Key, three gauges were positioned in a triangular configuration (Fig. 3b). No rainfall was observed for the period that BP03 was out of the field on 19–20 September. The data logger failure of BP05 reduced the period where all three gauges were operational to 32 days. BP03 and BP04 agreed well during this period such that BP03 measured only 1.2% lower accumulation for the period that all the gauges were operating. As noted earlier, both BP03 and BP04 failed to record a series of rain events on 18–19 September. This resulted in 22.8% and 17.6% less accumulation in BP03 and BP04, respectively, than in BP05. Considering the rain events where all three gauges were reporting rainfall, BP05 had slightly higher accumulations in a few more rain events, but there was no trend that one gauge had the lowest or highest accumulation on an event-by-event basis. The rainfall statistics showed relatively higher mean percent errors and low correlations at upper Big Pine Key than at Marathon Key.

Upper Sugarloaf Key was designed where the gauges were spaced farther apart. The cluster included five gauges; however, one gauge (SL15) operated for only a limited time and, therefore, was not included in the analysis. One of the other gauges (SL12) was collocated with SL11 and failed to record a series of rain events. Therefore, SL12 was also not included in the analysis. The remaining three gauges were positioned in a triangular configuration (Fig. 3i). All three gauges operated throughout the experiment and showed substantial differences in rain accumulations. SL14 was the rainiest site, having 9.1% and 23.4% higher accumulations than SL11 and SL13, respectively. SL11, on the other hand, had 13.1% more rainfall than SL13. The rainfall statistics presented in Table 4 show high mean percent errors and SDRTD of accumulation differences. This indicates the natural variability of rainfall at this site. SL14 had highest accumulations in 69% of the events, while SL13 had the lowest accumulations in 56% of the rain events. This shows that possible gauge calibration errors had little contribution to the differences in rain totals. In order to distinguish between gauge errors and natural variability of rainfall, it may be beneficial in the future for each site within a cluster to have multiple gauges.

At KDR headquarters on upper Big Pine Key, BP01 was mounted on a 2.4-m-high roof of a shelter, while BP02 was 84 m away on the ground (Fig. 3a). BP01 recorded 11.6% higher accumulation than BP02. Interestingly, BP01 had higher accumulation in all rain events. Similarly, a TB rain gauge that was located on the roof a trailer recorded 6.2% and 8.9% more rainfall than a nearby pair of TB rain gauges at ground level during TEFLUN-B. The gauge on the roof had higher reading in all rain events as well. During TEFLUN-B, another pair of collocated rain gauges that were separated about 2 m in the vertical resulted in 5.0% difference in rain totals, but there was no indication that one gauge recorded higher rainfall in most of rain event.

TABLE 4. Rain gauge cluster statistics.

Gauge clusters	ΔD (m)	No. of events	$\langle G1 \rangle$ (mm)	$\langle G2 \rangle$ (mm)	Var (G1) (mm²)	Var (G2) (mm²)	Corr (G1, G2)	MPE (G1, G2)	SDRTD (G1 − G2)
BP01–BP02	84	31	10.0	9.0	138.8	115.1	0.9971	9.9	1.3
BP03–BP04	92	25	11.7	11.5	213.2	209.1	0.9990	0.1	0.7
BP03–BP05	54	12	13.2	13.1	167.0	155.5	0.9981	0.5	0.9
BP04–BP05	47	16	10.0	10.2	144.0	140.3	0.9986	6.1	0.6
MH01–MH02	~30	19	9.7	9.6	309.2	299.6	0.9995	0.2	0.6
MH01–MH03	~60	19	9.7	9.5	309.2	283.2	0.9993	1.7	1.0
MH02–MH03	~30	19	9.6	9.5	299.5	283.2	0.9991	1.0	0.8
SL11–SL13	89	23	14.7	13.1	318.1	217.1	0.9963	4.7	3.4
SL11–SL14	108	24	14.2	15.5	311.0	341.6	0.9961	5.8	1.8
SL13–SL14	127	24	12.6	15.5	213.7	341.0	0.9955	13.8	4.2

Therefore, for the first two sites, a calibration difference has contributed to the accumulation differences between the gauges.

6. Performance of Joss–Waldvogel disdrometers

The individual drop size distributions were combined for five reflectivity ranges to study the characteristics of the raindrop spectra at four JWD sites (Fig. 6). The composite size spectra also provided information on the performance of the JWD at each site. At upper Big Pine and Summerland Keys, the peak drop concentration occurred at 0.6-, 1.1-, and 1.9-mm diameter for the first two, third, and fourth, and highest reflectivity regimes, respectively. The lack of small drops was consistent with the effect of noise of the rain on the metal roof at these two sites. The noise level amplified with the rain intensity that shifted the peak concentration to larger sizes

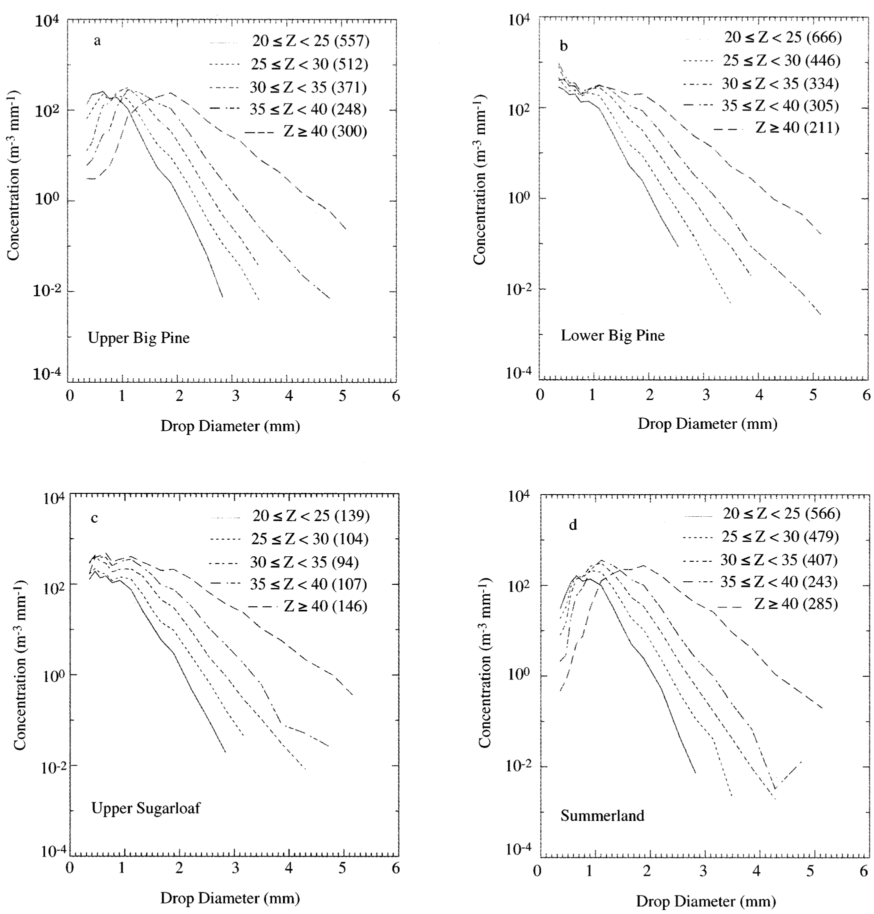

FIG. 6. Composite drop size distributions for five different reflectivity intervals (in dBZ) at (a) upper Big Pine, (b) lower Big Pine, (c) upper Sugarloaf, and (d) Summerland Keys. The number of distributions in each composite is given in parenthesis.

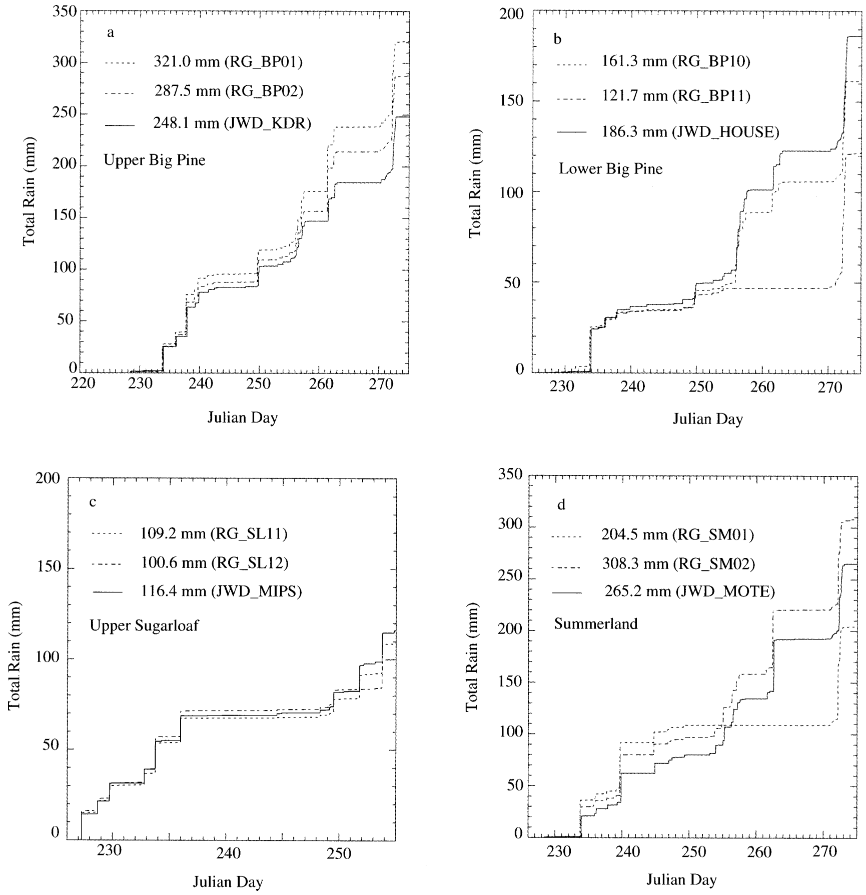

FIG. 7. Disdrometer and collocated gauge rainfall accumulation diagrams at (a) upper Big Pine, (b) lower Big Pine, (c) upper Sugarloaf, and (d) Summerland Keys. The time interval was based on disdrometer operation.

at higher reflectivity regimes. Sauvageot and Lacaux (1995, SL95 hereafter), who studied the shape of the averaged drop size distributions, showed the lack of small drops in continental Africa. The peak drop concentration was near 2.0-mm diameter in heavy rain in their study. SL95 stated that the JWD sensor set up in noise-free environment, therefore, they interpreted the depletion of small drops on a physical basis. Here, we strongly believe that the depletion of small drops was due to the noise generated by the drops hitting the hard surface of the roof.

The composite drop size distributions at lower Big Pine and upper Sugarloaf Keys showed an increase in drop concentration toward smaller sizes, with a small dip near 0.8-mm diameter. At Sugarloaf Key, where the power was supplied through a diesel generator, the peak drop concentration occurred at 0.4–0.6-mm diameter. The noise from the generator perhaps suppressed very small drops. As noted in section 3, it is a difficult task to find ideal multiple sites for the disdrometers in short-term field campaigns. For future experiments, if no alternative sites are available, perhaps such roofs could be covered by sponge foam material to reduce the noise level. Near real-time drop size distribution data analysis is essential to evaluate the performance of the disdrometer.

The rain accumulation of JWD and collocated rain gauges at four sites is shown in Fig. 7. The disdrometer on upper Big Pine Key accumulated less rainfall than the gauges, while reverse was true at lower Big Pine and upper Sugarloaf Keys. The disdrometer rain total was between the two gauges at Summerland Key. During previous field campaigns in central Florida and the Southwest Amazon region of Brazil, a JWD accumulated less rainfall than the collocated gauges (Tokay et al. 2001, 2002). In those field campaigns, the underestimation of rainfall by JWD was observed in almost all rain events and the drop size distribution showed a lack of drops at sizes less than 0.6-mm diameter. No noise measurements were available in those field campaigns. Here, the collocated gauges on upper Sugarloaf and lower Big Pine Keys, where noise was not significant, underestimated the rainfall, compared to the disdrometer, by 6.6% and 13.4%, respectively.

Figure 8 shows the gauge versus disdrometer rain totals on an event-by-event basis at four JWD sites. On upper Big Pine Key, rain gauges recorded higher ac-

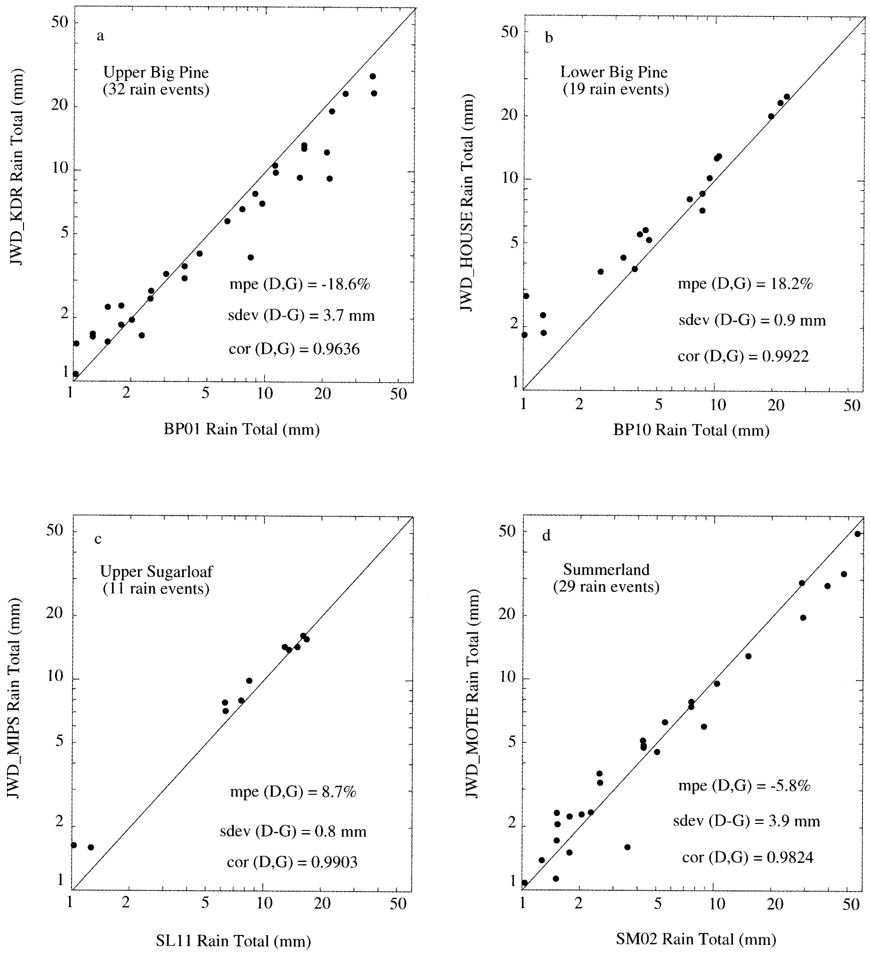

FIG. 8. The 1:1 storm total of the disdrometer and a collocated gauge at (a) upper Big Pine, (b) lower Big Pine, (c) upper Sugarloaf, and (d) Summerland Keys. The rainfall statistics between the two instruments are also given. The statistics were based on rain events that had at least 1-mm accumulation.

cumulations for all rain events that accumulated 3 mm or above. On Summerland Key, the disdrometer had higher accumulations for a number of rain events where the rain totals were up to 8 mm. The standard deviation of rain total difference was high, and the correlations were relatively low at both upper Big Pine and Summerland Keys (Table 5). The mean percent errors were also negative in these two sites. The mean percent error was calculated similar to Eq. (1), where G1 and G2 represent the disdrometer (D) and gauge (G) event rain totals, respectively. On upper Sugarloaf and lower Big Pine Keys, the gauges underestimated rainfall by 8.7% and 18.2% on average, respectively (Table 5). At both sites, the disdrometer recorded more rainfall in almost all the rain events. Nevertheless, the storm total difference between the gauge and disdrometer was not significant regardless of rain intensity at upper Sugarloaf and lower Big Pine Keys (Fig. 9). This brings a new perspective to the use of disdrometers as a calibration tool for the tipping bucket rain gauges. The gauges may be more prone to be affected by winds and turbulence due to their design.

TABLE 5. Collocated disdrometer rain gauge statistics.

Collocated disdrometer–gauges	No. of events	$\langle D \rangle$ (mm)	$\langle G \rangle$ (mm)	Var(D) (mm^2)	Var(G) (mm^2)	Corr (D, G)	MPE (D, G)	SDRTD ($D - G$)
JWD_KDR–BP01	32	7.4	9.7	52.9	103.5	0.9636	−18.6	3.7
JWD_HOU–BP10	19	8.7	7.7	50.7	48.9	0.9922	18.2	0.9
JWD_MIPS–SL11	11	9.9	9.6	27.7	32.0	0.9903	8.7	0.8
JWD_MOTE–SM02	29	8.9	10.4	136.3	217.7	0.9824	−5.8	3.9

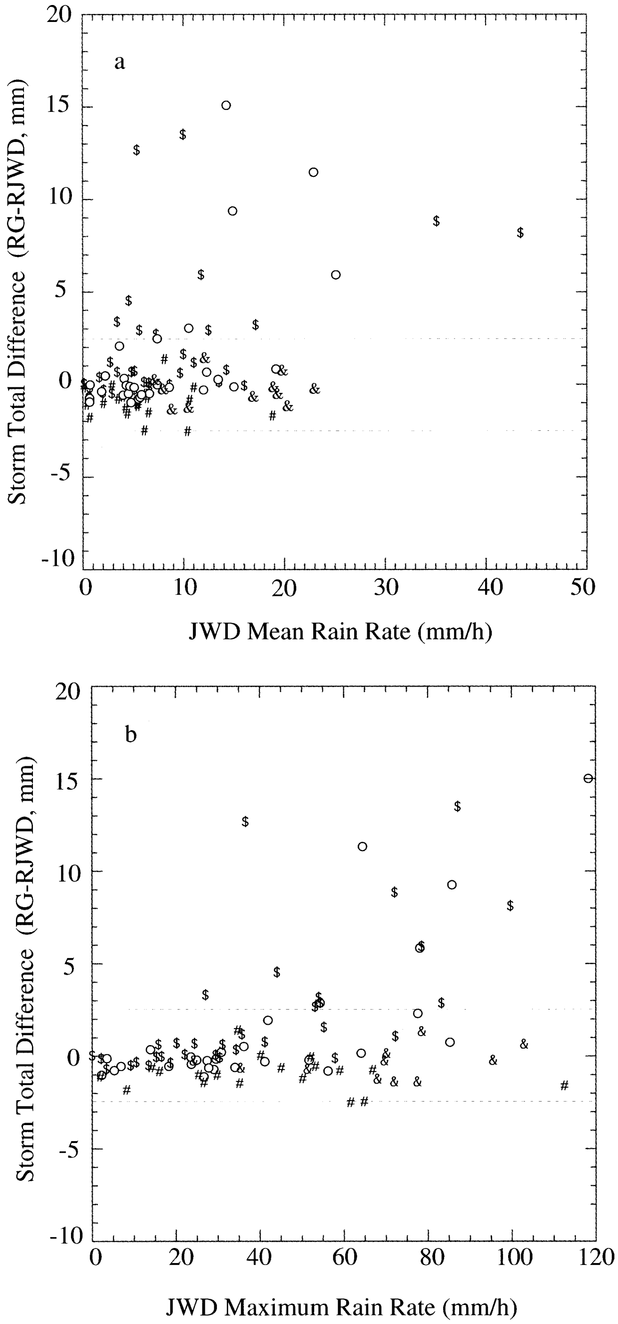

FIG. 9. Composite gauge–disdrometer storm total differences as a function of (a) conditional mean and (b) maximum rain rate. The symbols denote upper Big Pine ($), lower Big Pine (#), upper Sugarloaf (&), and Summerland (○) Keys. The conditional mean and maximum rain rates of a rain event were calculated from disdrometer record.

7. Lessons learned

The deployment of a rain gauge–disdrometer network is a routine exercise in TRMM field campaigns, including KAMP. Here, the following recommendations are suggested to avoid any foreseen failure and to obtain a reliable dataset regarding gauge/disdrometer operation.

1) Collocation of multiple (at least two) gauges, with a maximum separation distance of 1–2 m, is required. All deployed disdrometers should be collocated with multiple gauges as well.
2) Rural, fenced, gated areas are ideal for gauge sites. Urban areas including small developments should be avoided for security reasons. Disdrometers should be located near public buildings in order to provide power and shelter for the processing units and computer system.
3) Gauges and disdrometers should be mounted on platforms and in areas that are not subject to flooding. Posts or stacked blocks are recommended for sites that are subject to flooding. Roofs of buildings should be avoided.
4) Gauges should be calibrated prior to and at the end of each field campaign. The gauge recording interval should be set to 15-s or shorter time periods. It is mandatory to confirm that each gauge is in data collection mode after performing the logger initialization.
5) Gauges and disdrometers should be visited weekly for 2–4-month field campaigns, while biweekly to monthly visits may be sufficient for annual or longer operations.
6) Ambient noise measurements should be taken during rain-free as well as rainy conditions at the sites where impact-type disdrometers (JWD) are deployed.
7) The analysis of gauge and disdrometer data in near–real time is essential to evaluating instrument performance. The analysis should include a thorough review of the measured drop size distributions and rain accumulations. If possible, real-time analysis of coincident radar data would help provide further quality checks on the gauge and disdrometer operations.

8. Conclusions

The following conclusions were drawn through the analysis of the gauge and disdrometer measurements.

1) There were both south–north and east–west rainfall gradients observed over the Florida Keys during KAMP. The gauges on the west side of the Lower Keys recorded more rainfall. Similarly, the gauges on the Gulf side measured more rainfall than those on the ocean side of the same Keys. Disdrometer analysis revealed that both the duration and intensity of rainfall played a role in the rainfall gradients. The south–north rainfall gradient was especially evident through rain event analysis at Big Pine Key. Rain events were longer and more intense at upper Big Pine Key than on lower Big Pine Key.
2) Rain event duration was sensitive to the definition

of a rain event. When a larger time gap was allowed between the two consecutive records, the rain duration increased, however, no significant change in rain intensity was evident.

3) Collocated gauges agreed well with one another at four sites where the difference was less than 2%. The difference was high (10.5%) at one site. The agreement between the two collocated gauges was also poor at three other sites where the gauges were either replaced during the experiment, or recorded anomalous rain events.
4) There were only 12 (7%) rain events where the storm total differences were significant (>2.5 mm). These rain events occurred at when the conditional mean and maximum storm rain rates were higher than 5 and 50 mm h^{-1}, respectively. Nevertheless, there were many other rain events for which the storm total differences were not significant in heavy rain.
5) There were 143 rain events where both collocated gauges recorded at least 1-mm rainfall. The correlation coefficient and mean percent absolute error between the gauge rain totals were 0.99% and 8.7%, respectively, on average. A rain gauge was typically able to measure rainfall within ± 1.2 mm. As the storm total increased, the SDRTD and correlation coefficient increased, while mean percent absolute error decreased.
6) Considering the gauge that recorded higher overall rainfall as a reference, in the absence of natural variability of rain between the collocated gauges, the difference in gauge event rain total was 9.2%.
7) The gauge clusters were not adequate to properly study the natural variability of rainfall. In the future, each site within the gauge cluster should include at least two gauges. Although the site where the gauges were farther apart resulted in lower correlations, higher standard deviations, and mean percent errors than the site where the gauges were closely spaced, it was difficult to differentiate the gauge errors from the natural variability of rainfall.
8) Unlike previous field campaigns, disdrometers consistently recorded higher rainfall accumulation than the collocated gauges. This suggests that impact disdrometers may be used in determining gauge errors.

A web site is available for review of the KAMP experiment. It provides access to the gauge, disdrometer, and radar data: http://trmmfc.gsfc.nasa.gov/Field_Campaigns/KAMP/index.html.

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