J5.5 ANALYSES AND APPLICATONS OF THE PACRAIN TIPPING BUCKET GAUGE DATASET

Michael D. Klatt*, Mark L. Morrissey, and J. Scott Greene
Environmental Verification and Analysis Center
University of Oklahoma, Norman, Oklahoma

1. INTRODUCTION

The Pacific Rainfall Program (PACRAIN) is located at the Environmental Verification and Analysis Center at the University of Oklahoma. PACRAIN is the home of the Comprehensive Pacific Rainfall Database (Greene et al., 2008) and the Schools of the Pacific Rainfall and Climate Experiment (Postawko et al., 1994). PACRAIN is also involved in various initiatives in support of the local meteorological services throughout the tropical Pacific basin.

PACRAIN is part of the Pacific Islands Global Climate Observing System (PI-GCOS) initiative to establish a regional network of tipping bucket rain gauges (TBG). Fifty gauges have been distributed to seven nations and the United States territory of Guam (see Figure 1). PACRAIN provides technical support for the gauges, and the data collected from them are used locally by the meteorological services and sent to PACRAIN for inclusion the in the rainfall database. Table 1 shows the data collected from the network so far.

There is a clear operational need for automated gauges in this region. Access to many of the remote islands and atolls is difficult, and there is often limited manpower available to make regular observations. In addition to satisfying the requirement for automation, the tipping bucket gauges also provide high-resolution data that is useful for researchers. The Pacific is sparsely instrumented, especially in relation to its importance to global climate and weather, so increasing the amount and quality of available data is an important undertaking. While previous work has focused on assimilating the TBG data into the PACRAIN database (Klatt et. al, 2008), the focus now is on taking advantage of this new data set by assessing its accuracy and using it for research.

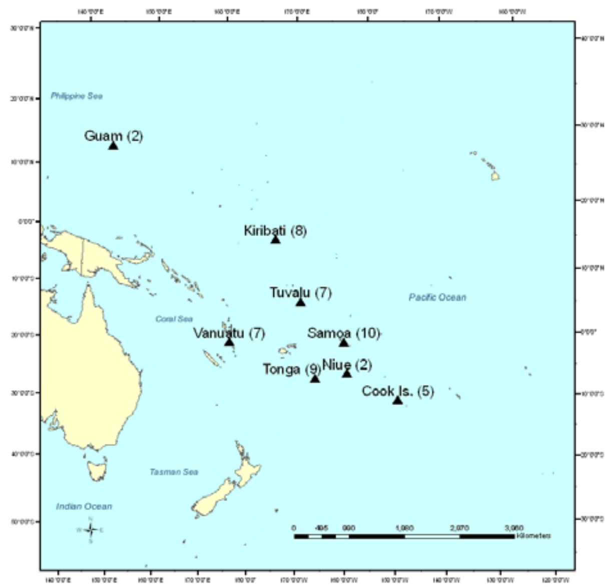

FIGURE 1. The distribution of PI-GCOS tipping bucket gauges. The number in parentheses is the number of gauges sent to that location; not all gauges are currently operational.

Site	Begins	Ends	# Tips
Nikao, CK	2007-03-13	2008-06-20	8545
Hanan, NU	2006-07-06	2006-08-07	814
Makefu, NU	2005-08-20	2005-11-22	5216
Afiamalu, WS	2006-01-20	2006-02-10	8150
Fua'amotu, TO	2005-05-03	2007-08-08	16262
Funafuti, TV	2007-03-28	2007-12-09	3779
Port Vila, VU	2005-02-15	2005-12-30	6425

TABLE 1. TBG data received to date.

2. SATELLITE COMPARISON

The PACRAIN rainfall database was previously compared with satellite data in order to highlight any systematic discrepancies in the observation times reported therein (Klatt et al., 2006). The TBG data were not part of the database at that time, so a similar comparison of TBG data and satellite data was done to verify the accuracy of the times being reported by the TBG data loggers. The Tropical Rainfall Measuring Mission (TRMM) 3B-42 satellite rainfall product was used again as the comparison data

*Corresponding author address: Michael Klatt, EVAC, University of Oklahoma, 100 E. Boyd, SEC 410, Norman, OK, USA 73019; e-mail: mdklatt@ou.edu

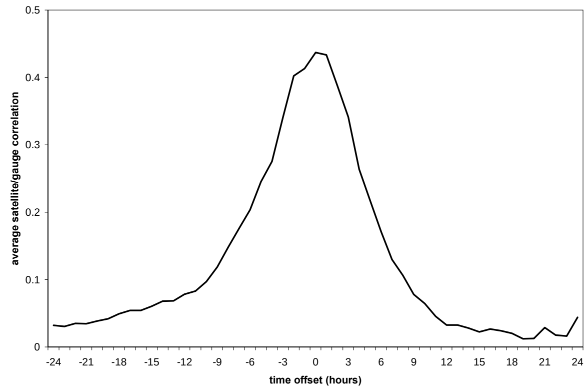

FIGURE 2. Time offset v. satellite/TBG correlation, averaged for all sites.

Site	Δ (h)	r	n
Nikao, CK	1	0.402	3803
Hanan, NU	0	0.695	235
Makefu, NU	1	0.578	755
Afiamalu, WS	-2	0.566	167
Fua'amotu, TO	1	0.399	6595
Funafuti, TV	1	0.214	2046
Port Vila, VU	-1	0.368	2550

TABLE 2. Results of the TBG/satellite comparison showing the site offset (Δ), correlation for that offset, and number of data pairs used to calculate the correlation.

(GESDAAC, 2008). The 3B-42 product has a spatial resolution of 0.25° and a temporal resolution of 3 hours (GESDISC, 2008).

In the original comparison, a series of 24-hour totals were produced from the 3B-42 data for each possible start time (00Z, 03Z,…21Z). These values were then compared to the daily PACRAIN data to determine which start time resulted in the best correlation between the satellite and gauge data. Ideally, the start time closest to the reported time for each PACRAIN record would give the best fit. A significant offset was indicative of a systematic bias in the reported observation times.

A similar procedure was used for the TBG comparison, although this time the 3B-42 data were considered to be fixed in time while the higher-resolution TBG data where aggregated into a series of 3-hour totals with varying start times using a 1-hour time step (00Z to 03Z, 01Z to 04Z, …23Z to 02Z). The 3-hour TBG values where computed by counting the number of tips in a given interval and multiplying by 0.254 mm (the tip volume). Due to the quantized nature of TBG data, this algorithm has an uncertainty of ±0.254 mm per interval.

For each 3B-42 time series (T_{SAT}), the TBG time series for a given offset (Δ) was defined as:

$$T_{TBG} = \{x(t_{TBG}) \mid t_{TBG} = t_{SAT} + \Delta\}$$

For a given site, the product-moment correlation (r) was calculated between T_{SAT} and each possible T_{TBG}:

$$R = \{r(T_{TBG}, T_{SAT}) \mid T_{TBG}, -24 \leq \Delta \leq 24\}$$

The site offset was defined as the value of Δ that maximized the value of R.

If the TBG times are accurate, the maximum correlation should occur at Δ=0, and Figure 2 shows that this is generally the case. Correlation falls off rapidly and symmetrically as the

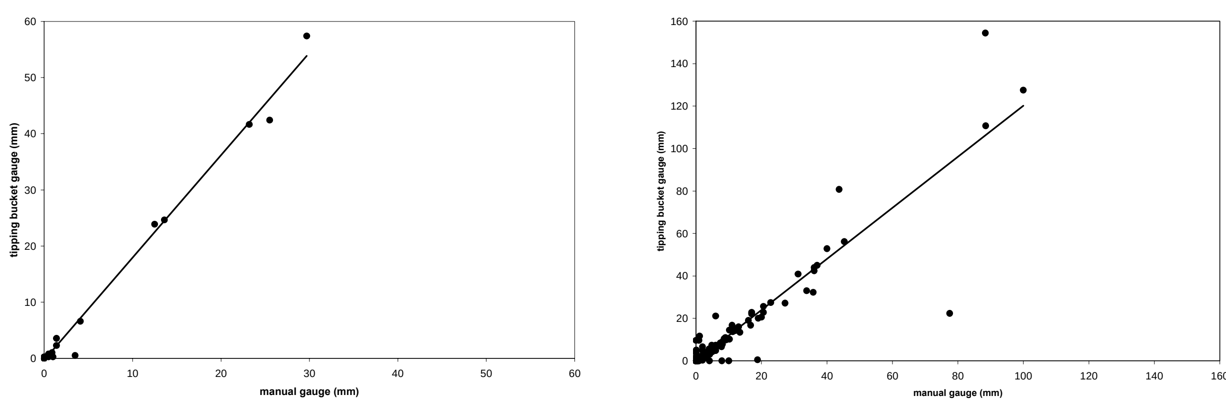

FIGURE 3. Manual observations v. TBG daily totals for Hanan (left panel) and Port Vila (right panel) for all days with overlapping data. Solid lines are linear trend lines. For Hanan, n=30, the correlation is 0.995, and the slope is 1.808. For Port Vila, n=319, the correlation is 0.933, and the slope is 1.200.

magnitude of the time offset increases, which mirrors the results of the original satellite data comparison. The individual *R* curves for each site show a similar pattern, although the site offset is not zero in all cases, and in some cases the maximum correlation is not very large. Table 2 shows the individual results. Even though the site offset is non-zero for all but one of the sites, all sites have an offset smaller than the 3-hour resolution of the 3B-42 data. Therefore, there is confidence in the TBG timestamps.

3. DUAL GAUGE COMPARISONS

The tipping bucket gauges at Hanan, Niue and Port Vila, Vanuatu are co-located with standard manual-read gauges and have coincident observation periods. This provides an opportunity to examine the accuracy of the tipping bucket gauge relative to the traditional manual gauge. The length of the of coincident observation periods for both locations is limited to 11 months for Port Vila and only 30 days for Nikao, so the following results are not definitive. The manual gauge data are daily observations made at 0900 local time; multi-day accumulations due to missed observations are excluded from the analyses. The TBG data were converted to daily accumulations by summing the tips in each 24-hour period, starting at 0900 to mimic the manual observation day. This results in a maximum possible error of ±0.254 mm/day for the TBG accumulations.

As expected, there is a high correlation between the manual and tipping bucket gauges at both locations (see Figure 3). While numerous studies have shown that tipping bucket gauges underestimate rainfall for various reasons, the slopes of the trend lines show a positive bias for

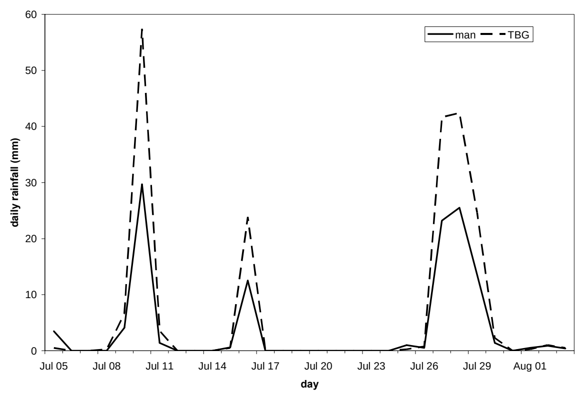

FIGURE 4. Time series for Hanan for all coincident data (July 5 - August 3, 2006). Solid line is the manual gauge and dashed line is the tipping bucket gauge.

the tipping bucket gauge for both sites. A possible reason for this is double tipping at high rainfall rates, which is where the tipping mechanism is moving so fast that it bounces off the mechanical stop and records an additional tip. Cursory analysis shows that the Hanan gauge may be especially susceptible to this.

The time series for both sites also show the high correlation and positive TBG bias. Figure 4 shows the time series for Hanan for the entire comparison period. The mean absolute error for Hanan is 3.2 mm for all days and 6.0 mm when excluding zero/zero days (no rainfall reported by either gauge). Figure 5 shows the time series for Port Vila; for illustrative purposes, only April 2005 is shown. The mean absolute error for Port Vila for the entire comparison period is 1.5 mm for all days and 2.8 mm when excluding zero/zero days.

There is a notable discrepancy between the two Port Vila gauges for April 13-14, and the hourly TBG data offer a possible explanation for

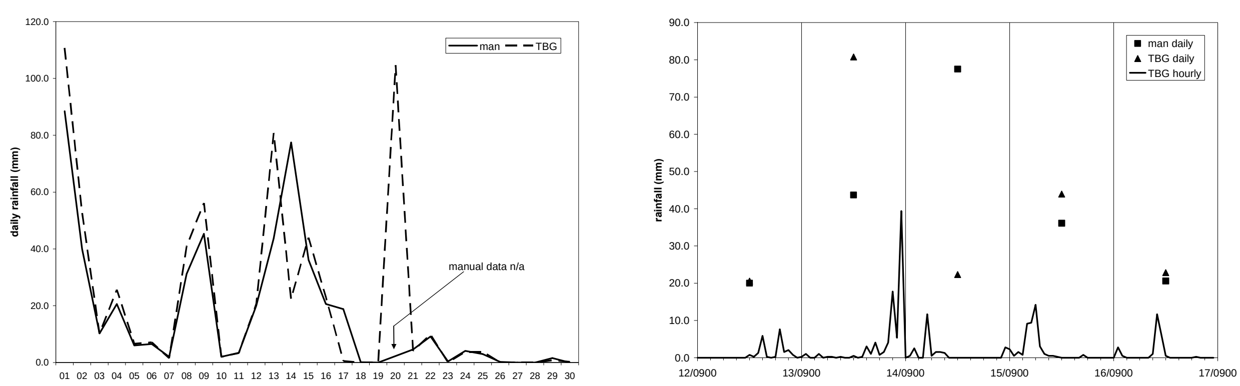

FIGURE 5. Time series for Port Vila for April 2005. The left panel is for the entire month. Solid line is the manual gauge and dashed line is the tipping bucket gauge; the manual observation for April 20 was not available. The right panel focuses on April 12-17. Squares are the manual observations, triangles are the TBG daily totals, and solid line shows the TBG hourly totals.

Hanan		manual	
		wet	dry
TBG	wet	15	1
	dry	0	14

Port Vila		manual	
		wet	dry
TBG	wet	127	8
	dry	35	149

FIGURE 6. Contingency tables for Hanan and Port Vila. Categories refer to days with and without recorded rainfall for each gauge.

this (Figure 5, right panel). A significant amount of rainfall was recorded by the tipping bucket gauge immediately before the nominal 0900 manual observation time on April 14. If the observation for that day was made early, some portion of this rainfall would not have been recorded until the April 15 observation, and would have been incorrectly attributed to the 24-hour period beginning on April 14 instead of April 13. The effect of this would be a deficit for the manual gauge for April 13 and a corresponding surplus for April 14, which is the observed pattern for these two days.

Any ambiguity with the April 14 observation time is irrelevant if the total rainfall for 0900 on April 13 to 0900 on April 15 is considered. The manual gauge total for this period is 121.2 mm, and the TBG total is 103.1 mm; this 15% difference is typical of the difference between the two gauges for the entire comparison period. Therefore, an early manual observation is a plausible explanation for the April 13-14 discrepancy. This example shows that differences between the manual and TBG data can be due to interpretation errors and not just measurement errors.

An obvious requirement of any rain gauge is the detection of rainfall event, defined as an observation day with recorded rainfall in this case. While this is a very coarse test, it can be valuable. Figure 6 shows a contingency table (Wilks, 1995) for each site that provides a concise picture of any discrepancies between the manual and tipping bucket gauge. The table for Hanan shows perfect agreement between both gauges except for one “false alarm” for the tipping bucket gauge. The raw TBG data show that this is an isolated tip between rain events.

Spurious isolated tips are often an artifact of the finite size of the measuring bin, i.e. the “tipping bucket”. The end of a rain event is not likely to coincide with the complete filling of a bin, leaving a partially full bin. A small amount of additional moisture or even collected debris will be enough to cause a tip, possibly during the middle of a dry period. The tipping mechanism is obviously sensitive to movement, so any jostling of the gauge might also cause erroneous tips.

For Port Vila there are 8 false alarms and 35 missed events for the tipping bucket gauge. Three of the false alarms appear to be due to isolated tips, but five appear to be missed rainfall days by the manual gauge rather than any problem with the tipping bucket gauge. For 25 of the missed events in the TBG record the manual gauge recorded an amount of 0.2 mm or less, meaning that even if the same amount was collected by the tipping bucket gauge a tip would not have been recorded. For 5 more of the missed events the amount recorded by the manual gauge was no more than 0.4 mm, so even a small difference in the rainfall collected by the tipping bucket gauge might result in a partially full bin and no tip. The remaining 5 missed events should have conceivably been recorded by the tipping bucket gauge, but it is currently unknown why they were missed.

In addition to Hanan and Port Vila, Afiamalu, Samoa; Fua’amotu, Tonga; and Funafuti, Tuvalu have had both types of gauges in operation, but the periods of record do not overlap at the latter three sites (the manual gauge record ends before the TBG record begins). Nevertheless, the TBG data should share the same distribution as the manual data for each of these sites absent any climatological shift in the local rainfall. Table 3 shows some statistical parameters for the entire periods of record for both the manual and tipping bucket gauges.

A complete statistical analysis to determine if each pair of data sets are similar has not yet been completed, but some general trends can be noted. It is expected that the maximum value in the long-term manual data should be greater or equal to—again, ignoring any long-term trends—the maximum value in the much shorter-term TBG data, and this generally holds true. The TBG maximum for Fua’amotu is slightly greater than the manual gauge maximum, but it is not clear that is not simply due to measurement differences between the two gauges rather than a significant event. However, the TBG period of record was clearly influenced by one or more very heavy rainfall events. Relative to the manual gauge, the overall distribution skews drier but the mean rainfall is larger.

Site	n	μ	σ	1st Q	med	3rd Q	max
Hanan, NU	6051	5.05	15.01	0.00	0.00	2.80	270.50
	30	6.88	15.14	0.00	0.25	1.97	57.40
Afiamalu, WS	4589	13.87	27.75	0.00	2.50	14.90	293.00
	21	98.58	80.34	54.10	82.80	126.75	278.64
Fua'amotu, TO	8496	4.71	14.27	0.00	0.00	2.00	203.00
	827	4.99	17.29	0.00	0.00	0.64	204.72
Funafuti, TV	11719	9.28	17.42	0.00	2.10	10.30	232.90
	136	7.03	14.33	0.00	0.25	7.62	98.04
Port Vila, VU	5531	5.12	14.51	0.00	0.20	3.40	199.50
	319	4.79	15.54	0.00	0.00	2.29	154.43

TABLE 3. Statistical parameters for the entire manual gauge and TBG periods of record for sites where both types of gauge have been in operation, but not necessarily at the same time. For each site, the top row is for the manual gauge and the bottom row is for the tipping bucket gauge. Parameters are mean, standard deviation, 1st quartile, median, 3rd quartile, and maximum; all units are mm.

SAMPLE RESEARCH

The high temporal resolution of TBG data make them invaluable for a wide range of applications in hydrometeorology. One such application is the development of high-resolution statistical rainfall models. Morrissey (2008) used the TBG data from Fua'amotu, Tonga to add a skewness component to a point process tropical rainfall (TR) model. Skewness, the third statistical moment, is an increasingly important descriptor of rainfall as the temporal resolution increases, especially for the high rainfall intensities observed in the tropics.

The modified TR (MTR) model is essentially the same as the TR model; the difference is that the skewness of the training data is explicitly considered when calculating the model parameters. This does result in a better fit to the skewness of the verification data, but at the expense of the first two moments (mean and variance) relative to the TR model. For applications where the skewness is particularly important, though, the MTR model is an improvement.

FUTURE WORK

These preliminary analyses of the TBG data collected so far will form the basis of a quality control (QC) scheme to indentify errors in the TBG data set. Some QC techniques for use in locations where manual gauge data are also available have been introduced, and these need to be expanded upon. For example, statistical tests need to be developed to compare the similarity of the TBG data to the manual gauge data. Significant differences may indicate a problem with the tipping bucket gauge.

One of the purposes of the TBG network is to allow gauges to be installed where it has not been practical to install a manual gauge in the past, so the dual-gauge comparisons described here will have limited utility as more and more remote sites come online. Nearest-neighbor techniques are also unsuitable when the nearest neighbor may be hundreds of kilometers distant. Others have developed techniques for detecting errors using data from a single tipping bucket gauges (e.g. Upton and Rahimi, 2003), and these will be explored.

Research activities will be expanded as more data become available. In particular, high-resolution rainfall modeling requires the high-resolution data that tipping bucket gauges proved. The TBG network will also be more useful for large scale climatological research as the spatial coverage increases. Of interest is trends in extreme rainfall events, which have been predicted to increase as a consequence of global warming.

SUMMARY

PACRAIN and PI-GCOS are working to develop a tipping bucket rain gauge network in the tropical Pacific. Data from these gauges are being added to the PACRAIN database, and work has begun to assess the quality of the data. Comparison with satellite data suggests that there are no gross errors in the reported TBG time stamps. Analyses at two sites with co-located manual and tipping bucket gauges show that the manual and TBG data are highly correlated, and that the tipping bucket gauges have a positive bias, possibly due to double tipping at high rainfall rates. Further analysis is possible at these sites and three others where manual gauge data are available. New techniques will need to be developed for sites where the tipping bucket gauge is the sole source of data. An example of research being done with the TBG data is the improvement of a high-resolution statistical rainfall model, and more research will be possible as more data is collected.

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