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Validation of Satellite Rainfall Products for Western Uganda

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ABSTRACT

Central equatorial Africa is deficient in long-term, ground-based measurements of rainfall; therefore, the aim of this study is to assess the accuracy of three high-resolution, satellite-based rainfall products in western Uganda for the 2001–10 period. The three products are African Rainfall Climatology, version 2 (ARC2); African Rainfall Estimation Algorithm, version 2 (RFE2); and 3B42 from the Tropical Rainfall Measuring Mission, version 7 (i.e., 3B42v7). Daily rainfall totals from six gauges were used to assess the accuracy of satellite-based rainfall estimates of rainfall days, daily rainfall totals, 10-day rainfall totals, monthly rainfall totals, and seasonal rainfall totals. The northern stations had a mean annual rainfall total of 1390 mm, while the southern stations had a mean annual rainfall total of 900 mm. 3B42v7 was the only product that did not underestimate boreal-summer rainfall at the northern stations, which had ~3 times as much rainfall during boreal summer than did the southern stations. The three products tended to overestimate rainfall days at all stations and were borderline satisfactory at identifying rainfall days at the northern stations; the products did not perform satisfactorily at the southern stations. At the northern stations, 3B42v7 performed satisfactorily at estimating monthly and seasonal rainfall totals, ARC2 was only satisfactory at estimating seasonal rainfall totals, and RFE2 did not perform satisfactorily at any time step. The satellite products performed worst at the two stations located in rain shadows, and 3B42v7 had substantial overestimates at those stations.

1. Introduction

Central equatorial Africa is in need of rainfall data. It is a region with no definitive ground-based information on long-term trends in rainfall (Todd and Washington 2004; Trenberth et al. 2007), and modeling studies have

shown that rainfall in the region should decrease not only from an increase in carbonaceous aerosols from biomass burning in tropical Africa (Tosca et al. 2013) but also from a warming of the equatorial Indian Ocean (Hoerling et al. 2006). On the eastern edge of this region is the Albertine Rift, which Plumptre et al. (2007) define as a region extending from 30 km north of Lake Albert to the southern tip of Lake Tanganyika, including the valley, the flanks of the escarpment and associated protected areas, and the range of endemic species (Fig. 1). The Albertine Rift is a biodiversity

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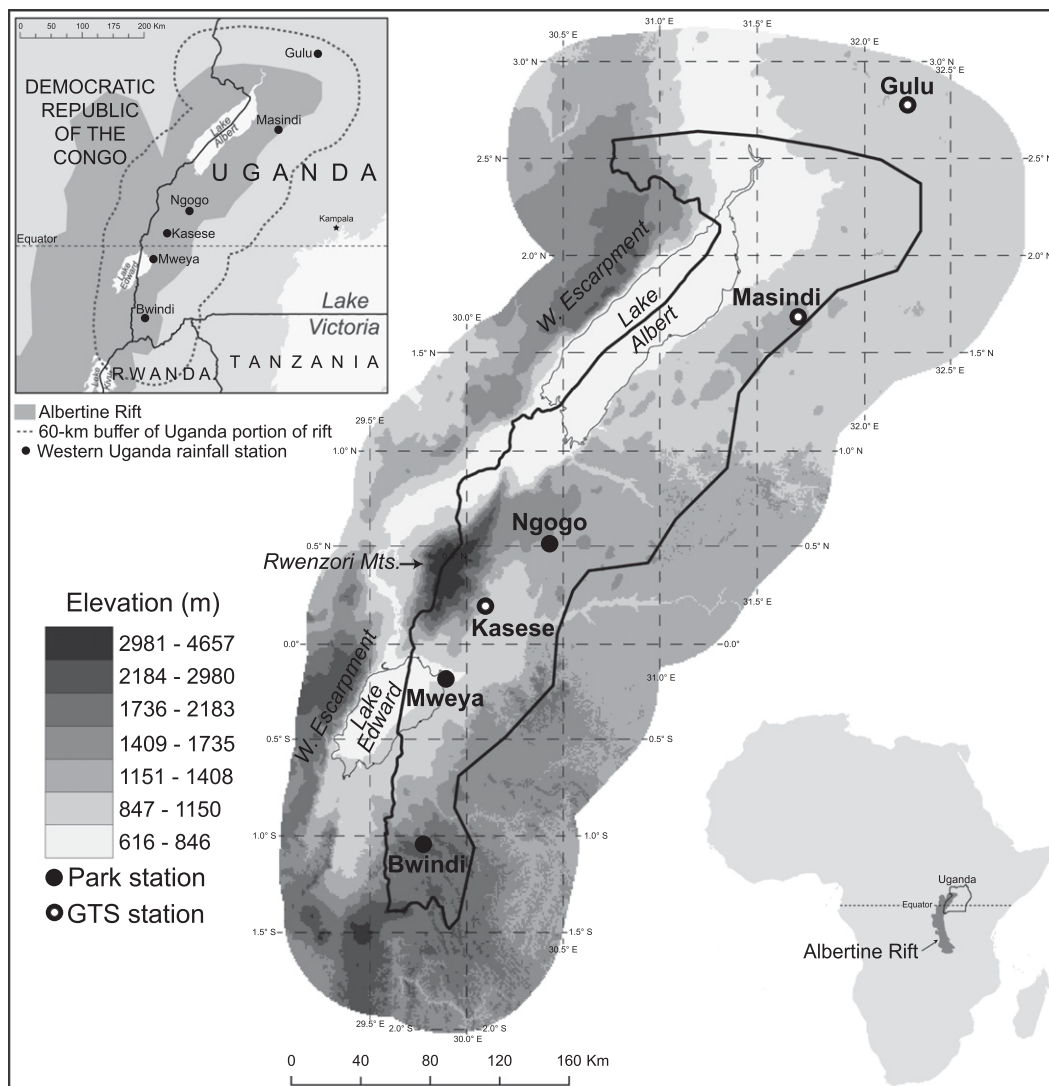


Fig. 1. Location of the Albertine Rift in central equatorial Africa, the northern portion of the Albertine Rift, and the six rainfall stations within and proximate to the Uganda portion of the Albertine Rift (dark line in elevation map). Elevation is given as shading (m MSL). Gulu, Masindi, and Kasese are the three stations that are part of the GTS network.

hotspot (Cordeiro et al. 2007; Plumptre et al. 2007) with some of Africa’s fastest growing human populations (Fisher and Christopher 2007). Particularly in Uganda, where 80% of the land is used for rain-fed farming and the population growth rate is the second fastest in the world (Uganda Bureau of Statistics 2009; Population Reference Bureau 2012), the juxtaposition between biodiversity conservation and land-use intensification challenges local livelihoods. A lack of consistent, long-term rainfall data from ground-based gauges in the region makes rainfall studies very difficult (e.g., Kizza et al. 2009; Stampone et al. 2011; Harter et al. 2012).

Therefore, the aim of this study is to assess the accuracy of three high-resolution satellite-based rainfall products for the Uganda portion of the Albertine Rift from 2001 to 2010. The products are the recently completed African Rainfall Climatology, version 2 (ARC2); African Rainfall Estimation Algorithm, version 2 (RFE2); and the 3B42 product of the Tropical Rainfall Measuring Mission (TRMM), version 7 (3B42v7). ARC2 extends back to 1983 and is expected to be homogeneous over time; consequently, it might be useful for assessing rainfall trends (Novella and Thiaw 2013). RFE2 and 3B42 are included in the analysis because these products have been found to be the most accurate satellite-based rainfall

products for various river basins in tropical Africa (Thiemig et al. 2012).

2. Data and methods

a. Ground-measured rainfall data

Daily rainfall data from 2001 to 2010 were obtained for six rainfall stations (Gulu, Masindi, Ngogo, Kasese, Mweya, and Bwindi) within and proximate to the Uganda portion of the Albertine Rift (Fig. 1). As rain gauges are rare in western Uganda and records from gauges in the region are typically old and discontinued or new with only several years of quality data, it is remarkable that daily rainfall data were available from multiple stations in the region over the most recent decade. The 10-yr length of the dataset enables it to capture a robust amount of the variability of daily rainfall in the region. All rainfall measurements were made at 0500 or 0600 UTC. Data for Gulu, Masindi, and Kasese were acquired directly from the Uganda Department of Meteorology, Kampala. Data for Ngogo, located inside Kibale National Park, were collected by Drs. Jeremiah Lwanga, David Watts, and John Mitani of the Ngogo Chimpanzee Project. Data for Mweya, located in Queen Elizabeth National Park, were collected by the Uganda Wildlife Authority. Data for Bwindi, located in Bwindi Impenetrable National Park, were collected by the Institute of Tropical Forest Conservation.

Only one of the stations, Ngogo, was not missing any daily rainfall totals. Gulu, Masindi, Kasese, Mweya, and Bwindi were missing 3.4%, 5.8%, 1.7%, 18.3%, and 23.8% of the daily rainfall totals, respectively. With the exception of Bwindi, the missing data were restricted to only several months per station. Gulu was missing all daily totals for March 2002, September 2004, December 2007, and August 2008. Masindi was missing all daily totals for February 2004, May 2004, November 2005, September 2007, and September–November 2009. Kasese was missing all daily totals for October 2005 and November 2008. Mweya was missing daily totals for all of 2001 and January–October 2002. Bwindi was missing one or more days of data during a majority of the months in the dataset, and months with no rainfall totals included August–December 2005, August–December 2006, January–February 2007, May–October 2007, and January–February 2009.

b. Satellite rainfall products

Gridded rainfall estimates for 2001–10 from ARC2, RFE2, and 3B42v7 were obtained from the International Research Institute for Climate and Society at Columbia University and were compared with the gauge-measured totals using the point-to-pixel approach. The ARC2 and

RFE2 data, which are daily and pertain to 0600–0600 UTC, only apply to the African continent and have a spatial resolution of 0.10° . ARC2 and RFE2 are developed by the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA) for the Famine Early Warning Systems Network (FEWS NET). RFE2 data are produced from Global Telecommunication System (GTS) rain gauge reports, geostationary satellite thermal infrared data, and data from the Special Sensor Microwave Imager and Advanced Microwave Sounding Unit onboard polar-orbiting satellites, while ARC2 data are produced only from GTS gauge data and thermal infrared data (Love et al. 2004; Novella and Thiaw 2013). The 3B42v7 data have a spatial resolution of 0.25° , and the 3-hourly resolution of the data enabled the production of daily estimates pertaining to 0600–0600 UTC, thereby matching the ARC2 and RFE2 data. The 3B42v7 data, which are developed by the National Aeronautics and Space Administration, are produced from geostationary satellite thermal infrared data, precipitation-related passive microwave data collected by sensors on board a variety of satellites, and the TRMM Combined Instrument estimate, which employs data from both the microwave imager and precipitation radar instruments on board the TRMM satellite; the merged microwave and infrared estimates are adjusted based on analyses of monthly rainfall totals from the Global Precipitation Climatology Centre rain gauge database (Huffman et al. 2007).

c. Accuracy assessment

1) ASSESSMENT OF RAINFALL DAYS

False alarm ratio (FAR), probability of detection (POD), frequency bias (FB), and Heidke skill score (HSS) were used to assess the accuracy of the satellite products in identifying rainfall days (i.e., days with ≥ 1 mm). FAR, POD, FB, and HSS were calculated as follows:

$$\text{FAR} = \frac{B}{A + B}, \quad (1)$$

$$\text{POD} = \frac{A}{A + C}, \quad (2)$$

$$\text{FB} = \frac{A + B}{A + C}, \quad \text{and} \quad (3)$$

$$\text{HSS} = \frac{2(AD - BC)}{(A + C)(C + D) + (A + B)(B + D)}. \quad (4)$$

Variables A , B , C , and D in Eqs. (1)–(4) represent hits, false alarms, misses, and correct negatives, respectively (Table 1). FAR is the proportion of satellite-estimated rainfall days that did not actually occur. POD is the proportion of observed rainfall days that were identified

TABLE 1. Contingency table for comparing rain gauge measurements and satellite-based rainfall estimates.

	Gauge ≥ 1 mm	Gauge < 1 mm
Satellite ≥ 1 mm	A	B
Satellite < 1 mm	C	D

by the satellite product. FB, which ranges from 0 to ∞ , compares the rainfall-day detection frequency of the satellite estimates with that of the rain gauge: an FB less than (greater than) one indicates an underestimation (overestimation) of rainfall days. HSS, which ranges from $-\infty$ to 1, is a measure of the overall skill of the rainfall-day estimates accounting for matches due to random chance: an HSS less than zero indicates that random chance is better than the satellite product, an HSS of zero means the product has no skill, and an HSS of one indicates a perfect estimation of rainfall days by the product.

2) ASSESSMENT OF RAINFALL TOTALS

Error statistics were calculated for daily, 10-day, monthly, and seasonal rainfall totals. Rainfall totals for periods with at least 90% of days with nonmissing rainfall totals were upwardly adjusted to represent 100% of the days. This adjustment was done to increase the sample sizes at Bwindi, which was the only station with missing days that did not always constitute entire months. Percent bias P_{BIAS} and the Nash–Sutcliffe coefficient of efficiency E were calculated at the three time steps as follows:

$$P_{\text{BIAS}} = 100 \frac{\frac{1}{N} \sum (S - G)}{\bar{G}} \quad (5)$$

and

$$E = 1 - \frac{\sum (G - S)^2}{\sum (G - \bar{G})^2}. \quad (6)$$

Variable G is a rainfall total at a gauge, \bar{G} is the mean observed rainfall total at a gauge, S is a rainfall total for a satellite product, and N is the number of data pairs. The average tendency of estimated totals to be larger or smaller than the observed totals is given by P_{BIAS} . In this paper, a positive (negative) P_{BIAS} indicates overestimation (underestimation), and E ranges from $-\infty$ to 1, with higher values indicating better agreement between observations and estimates (Nash and Sutcliffe 1970; Legates and McCabe 1999). In the case of the satellite-based rainfall products, negative E values indicate that the mean observed value (i.e., the null model) is a better estimate for all cases than are the estimated values from a product, while a value of zero indicates that the product is only as accurate as the null model (Legates and McCabe 1999; Moriasi et al.

2007). Correlation coefficients were not used in the rainfall totals assessment, because coefficients can be large even if the observations and predictions differ considerably in magnitude and variability (Legates and McCabe 1999).

3) CALCULATION OF ALTERNATIVE ERROR VALUES AT GTS STATIONS

Alternative values of FAR, POD, FB, HSS, P_{BIAS} , and E were calculated for ARC2 and RFE2 at the GTS stations only using days where data at those stations were not used in the creation of the daily ARC2 and RFE2 data. Gulu, Masindi, and Kasese are listed as GTS stations by NOAA and thus may have had ARC2 and RFE2 rainfall estimates that were less independent of observed rainfall totals than were rainfall totals at Ngogo, Mweya, and Bwindi. Nonreporting days (i.e., days where a 24-h rainfall total was not reported at 0600 UTC) were identified using NOAA's Global Surface Hourly dataset, and the percentage of nonreporting days at Gulu, Masindi, and Kasese were 83%, 85%, and 81%, respectively. Reporting days at those stations were biased toward rainfall days: 65%, 70%, and 58% of the reporting days were rainfall days at Gulu, Masindi, and Kasese, respectively, despite just 35%, 33%, and 29% of all days being rainfall days at those respective stations. Therefore, to eliminate the associated bias toward nonrainfall days among the nonreporting days, 489, 591, and 715 nonrainfall days at Gulu, Masindi, and Kasese, respectively, were selected randomly and removed from the sample of nonrainfall days used to calculate the alternative values of FAR, POD, FB, HSS, P_{BIAS} , and E .

3. Results and discussion

a. Mean annual, seasonal, and monthly rainfall totals

Annual rainfall totals and intra-annual behavior of rainfall differed markedly between the northern and southern stations (Fig. 2). The northern stations (i.e., Gulu, Masindi, and Ngogo) had a mean annual rainfall total of 1390 mm, while the southern stations (i.e., Kasese, Mweya, and Bwindi) had a mean annual rainfall total of 900 mm. Kasese and Mweya had rainfall totals less than 900 mm, and these relatively low rainfall totals are most likely due to rain shadows (Bahati et al. 2005; Orlove et al. 2010): the stations are at relatively low elevations (i.e., < 1000 m MSL) in the rift valley and are thus thousands of meters lower than the peaks of the nearby Rwenzori Mountains and the western escarpment of the Albertine Rift on the western side of Lake Edward (Figs. 1 and 2). All stations had rainfall controlled strongly by the intertropical convergence zone (Nicholson 1996), with rainy seasons typically occurring during boreal

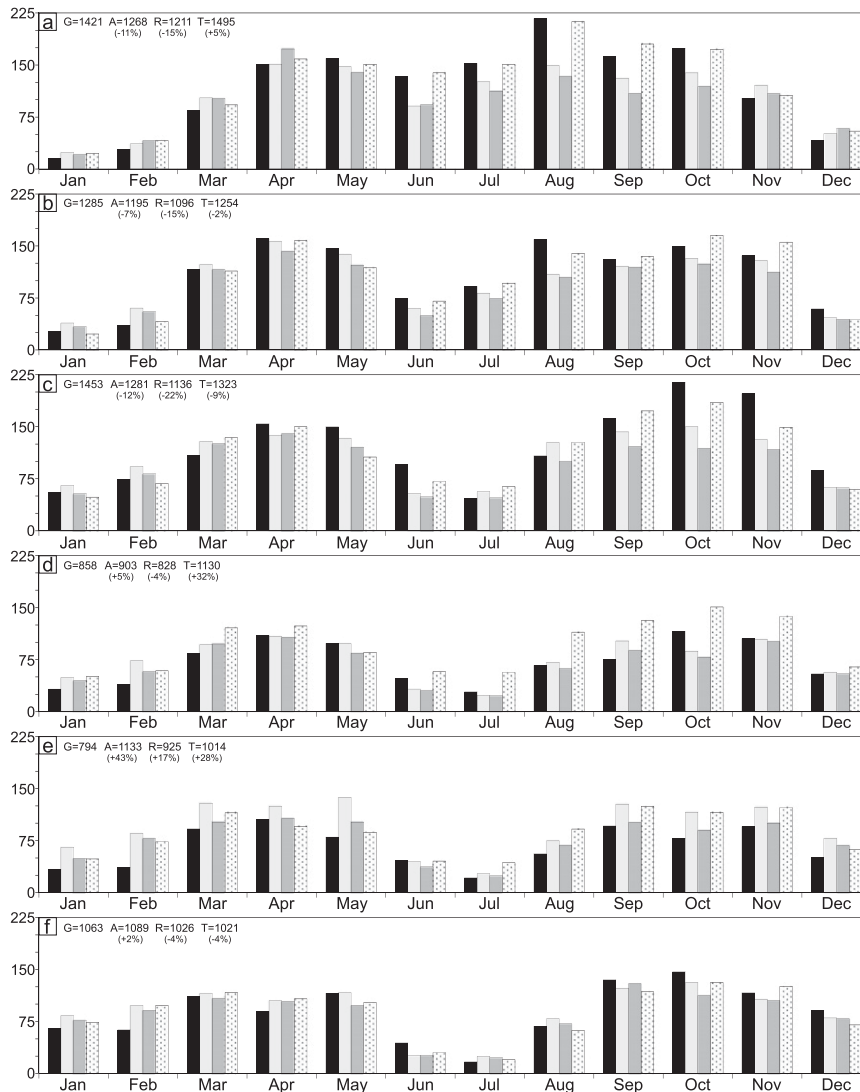


Fig. 2. Mean monthly rainfall totals (mm) during 2001–10 at (a) Gulu, (b) Masindi, (c) Ngogo, (d) Kasee, (e) Mweya, and (f) Bwindi from gauges (black columns), ARC2 (light gray columns), RFE2 (dark gray columns), and 3B42v7 (spotted column). Rainfall totals are on the y axis, and months are on the x axis. Annual rainfall totals (mm) from gauges (G), ARC2 (A), RFE2 (R), and TRMM (T; i.e., 3B42v7) are provided; P_{BIAS} is shown in parentheses below the rainfall totals.

spring and autumn (Basalirwa 1995; Hartter et al. 2012). The main difference in intra-annual rainfall between the northern and southern stations was that the northern stations had nearly 3 times more rainfall during boreal summer than did the southern stations. Therefore, rainfall at the northern stations was more similar to rainfall in central Africa (i.e., Democratic Republic of the Congo) than in East Africa (e.g., Nicholson 2000; Herrmann and Mohr 2011; Liebmann et al. 2012).

All products estimated mean monthly and annual rainfall totals reasonably well (Fig. 2). The products tended to underestimate rainfall at the wetter stations and overestimate rainfall at the drier stations. In addition,

3B42v7 did not underestimate boreal-summer rainfall at the northern stations like ARC2 and RFE2 did.

b. Rainfall-day errors

All three products had at least 30% of the identified rainfall days as false alarms, and the products rarely correctly identified more than 80% of the observed rainfall days (Table 2). As should be expected when up to 19% of the days at the GTS stations were reporting days, alternative FAR values at Gulu, Masindi, and Kasee were slightly higher than the original values, and alternative POD values were slightly lower than the original values. All three products had the smallest FAR values at Gulu

TABLE 2. FAR and POD for ARC2, RFE2, and 3B42v7 at the six stations over the 2001–10 period. The number of days is N . The values in parentheses for ARC2 and RFE2 at the GTS stations (i.e., Gulu, Masindi, and Kasese) were calculated using only the nonreporting days at those stations.

Station	N	FAR			POD		
		ARC2	RFE2	3B42v7	ARC2	RFE2	3B42v7
Gulu	3529 (2434)	0.29 (0.33)	0.33 (0.36)	0.33	0.72 (0.65)	0.79 (0.75)	0.79
Masindi	3440 (2330)	0.35 (0.40)	0.40 (0.43)	0.36	0.69 (0.67)	0.78 (0.77)	0.72
Ngogo	3652	0.37	0.39	0.32	0.69	0.81	0.72
Kasese	3591 (2207)	0.42 (0.48)	0.46 (0.50)	0.60	0.61 (0.49)	0.69 (0.60)	0.70
Mweya	2983	0.60	0.61	0.63	0.67	0.81	0.53
Bwindi	2783	0.43	0.45	0.35	0.61	0.76	0.63

and Ngogo. RFE2 had the highest FAR values, and that was associated with the highest POD values. FAR values were extremely high (e.g., ≥ 0.60) at Mweya for all products.

All three products tended to overestimate rainfall days at all stations (Table 3). ARC2 and RFE2 had the lowest and highest bias, respectively, among the three products. The largest overestimates occurred at Mweya for ARC2 and RFE2 and at Kasese for 3B42v7: the FB values equaled or exceeded 1.68. Those overestimates were connected to relatively large FAR values (Table 2).

There was little difference in HSS values among the three products (Table 3). The HSS values among the products and stations ranged from 0.22 to 0.50, and all values for the northern stations equaled or exceeded 0.40. All three products performed worst at either Kasese or Mweya.

The original HSS values at all three GTS stations were inflated, just as the original POD values also were inflated and the original FAR values were deflated (Table 3). Alternative HSS values equaled or exceeded 0.43 at Gulu and Masindi and ranged from 0.31 to 0.33 at Kasese. Alternative HSS values for ARC2 at Gulu, Masindi, and Kasese were 0.08, 0.07, and 0.12 lower, respectively, than the original values, and the values for RFE2 were 0.06, 0.04, and 0.09, lower, respectively. HSS values decreased the most at Kasese for two reasons: Kasese had a higher percentage of reporting days than did the other two GTS stations, and it was more difficult for the satellite products to identify rainfall days at Kasese compared to the northern stations.

c. Rainfall total errors

There were large differences in P_{BIAS} among the products and the stations (Tables 4 and 5). As one might expect, P_{BIAS} did not change appreciably with an increase in time step (i.e., from daily to seasonal totals). 3B42v7 was by far the least biased product at the northern stations, with P_{BIAS} ranging from -9% to 6% . ARC2 and RFE2 underestimated rainfall totals at all northern stations, and underestimates at Gulu and Masindi by ARC2

and RFE2 were even larger when reporting days were excluded from the analysis. Therefore, the most valid P_{BIAS} values at the northern stations ranged from -17% to -12% for ARC2 and approximately -23% for RFE2. 3B42v7 greatly overestimated rainfall totals at Kasese (i.e., P_{BIAS} values equaled or exceeded 30%). ARC2 and RFE2 actually had underestimates at Kasese (Table 4); adjusted P_{BIAS} for ARC2 and RFE2 were 12% – 13% lower than the original values. All three products, especially ARC2, greatly overestimated rainfall totals at Mweya: P_{BIAS} values ranged from 16% to 43% . Finally, there was minimal bias at Bwindi, the southernmost station.

The products in general were more accurate at estimating rainfall totals at the northern stations compared to the southern stations (Tables 4 and 5). The E values for all three products tended to increase with an increase in time step, and this has been observed in other studies (e.g., Cohen Liechti et al. 2012). Product 3B42v7 was superior to ARC2 and RFE2 at estimating rainfall totals at the northern stations. For example, seasonal E values for 3B42v7 at the northern stations approached or exceeded 0.70. Alternative daily E values for ARC2 at Gulu and Masindi were 0.15 and 0.07 lower, respectively, than the original, biased values. Therefore, valid seasonal E values for ARC2 at Gulu and Masindi were probably around 0.50, which was equivalent to the E value at Ngogo. The corresponding values for RFE2 were slightly lower. The alternative daily E values for RFE2 at Gulu and Masindi were 0.17 and 0.07 lower, respectively, than the original values; thus, the valid seasonal E values were most likely lower than the E values for ARC2. Kasese and Mweya had the smallest seasonal E values, with none of the values exceeding 0.33. The alternative daily E values for ARC2 and RFE2 at Kasese were 0.14 and 0.18 lower, respectively, than the original values. Therefore, RFE2 may have had the largest seasonal E value at Kasese, but it probably did not exceed 0.30. All three products had relatively high seasonal E values at Bwindi, but the relatively low sample size (i.e., 20) reduces the robustness of the results.

TABLE 3. FB and HSS for ARC2, RFE2, and 3B42v7 at the six stations over the 2001–10 period. The number of days is N . The values in parentheses for ARC2 and RFE2 at the GTS stations (i.e., Gulu, Masindi, and Kasese) were calculated using only nonreporting days at those stations.

Station	N	FB			HSS		
		ARC2	RFE2	3B42v7	ARC2	RFE2	3B42v7
Gulu	3529 (2434)	1.01 (0.97)	1.19 (1.16)	1.19	0.56 (0.48)	0.56 (0.50)	0.45
Masindi	3440 (2330)	1.06 (1.12)	1.30 (1.35)	1.13	0.50 (0.43)	0.48 (0.44)	0.50
Ngogo	3652	1.10	1.34	1.06	0.41	0.44	0.40
Kasese	3591 (2207)	1.04 (0.95)	1.28 (1.21)	1.76	0.43 (0.31)	0.42 (0.33)	0.22
Mweya	2983	1.68	2.07	1.34	0.28	0.29	0.35
Bwindi	2783	1.07	1.39	0.97	0.35	0.38	0.45

d. Overall performance of the products

3B42v7 and ARC2 were the two best products at the northern stations, and RFE2 was the most versatile product throughout the entire study region. Following the performance ratings for watershed models described in Moriasi et al. (2007), a product in this study had a satisfactory performance if the P_{BIAS} was between approximately -20% and 20% and the E value was greater than 0.50. None of the products performed satisfactorily at estimating daily and 10-day rainfall totals at any of the stations and estimating monthly and seasonal rainfall totals at the southern stations. Only 3B42v7 performed satisfactorily at estimating both monthly and seasonal rainfall totals at all northern stations. ARC2 likely performed satisfactorily at estimating seasonal rainfall totals at all three northern stations. RFE2 did not perform satisfactorily at any of the stations; nevertheless, it also did not perform poorly at the seasonal scale at any of the stations. All three products might have performed satisfactorily at the seasonal scale at Bwindi; however, data for more years are needed to determine this. Finally, since HSS and E have the same upper and lower bounds, an HSS exceeding 0.50 might be a reasonable expectation for satisfactory performance by a product. Therefore, the three products are borderline satisfactory at identifying rainfall days at the northern stations and unsatisfactory at the southern stations, with the possible exception of Bwindi.

The satellite products performed the best at stations with the least complex topography and the worst at stations that appear to be affected by nearby mountains. Gulu, Masindi, and Ngogo have much less complex landscapes than do Kasese, Mweya, and Bwindi. Dinku et al. (2008) note that the relatively flat landscape of Zimbabwe contributes to the better performance of rainfall products there compared to the Ethiopian highlands. As noted earlier, both Kasese and Mweya have relatively low rainfall totals due to rain shadows; the stations are located in the rift valley, and Mweya is surrounded by mountainous terrain (Fig. 1).

The locations of Kasese and Mweya in rain shadows caused all three products to perform unsatisfactorily at those stations. The products struggled to either identify rainfall days or estimate rainfall totals or both at Kasese and Mweya. And the large overestimation of rainfall by 3B42v7 also has been observed for the 3B42 product in other rain-shadow regions (Nair et al. 2009). Therefore, the products also are likely to perform unsatisfactorily in other anticipated rain-shadow areas in the northern portion of the Albertine Rift, including Lake Edward and Lake Albert and nearby low-elevation areas.

Previous research (Dinku et al. 2007, 2008, 2011) shows that nearly every rainfall product, including ARC, RFE2, and 3B42, underestimates rainfall in the highlands of Ethiopia, where the warm orographic rain process dominates. The products did not underestimate rainfall at Bwindi, which is located at 2355 m MSL in the

TABLE 4. Evaluation statistics at the six rainfall stations over 2001–10 for daily rainfall totals. The sample size is N . Positive (negative) P_{BIAS} (%) are overestimates (underestimates). The coefficient of efficiency between observed totals and predicted totals is E .

	Product	N	P_{BIAS}	E
Gulu	ARC2	3529 (2434)	-11 (-17)	0.17 (0.02)
	RFE2	3529 (2434)	-15 (-23)	0.23 (0.06)
	3B42v7	3529	4	0.06
Masindi	ARC2	3416 (2330)	-7 (-15)	0.09 (0.02)
	RFE2	3416 (2330)	-15 (-23)	0.13 (0.06)
	3B42v7	3416	-3	0.07
Ngogo	ARC2	3626	-12	-0.04
	RFE2	3626	-22	0.07
	3B42v7	3652	-9	0.05
Kasese	ARC2	3591 (2207)	6 (-7)	-0.07 (-0.21)
	RFE2	3591 (2207)	-3 (-15)	0.10 (-0.08)
	3B42v7	3591	32	-0.10
Mweya	ARC2	2983	43	-0.43
	RFE2	2983	17	-0.10
	3B42v7	2983	25	-0.08
Bwindi	ARC2	2783	3	-0.41
	RFE2	2783	-3	-0.11
	3B42v7	2783	-1	-0.20

TABLE 5. Evaluation statistics at the six rainfall stations over 2001–10 for 10-day, monthly, and seasonal rainfall totals. The sample size is N . Positive (negative) P_{BIAS} (%) are overestimates (underestimates). The coefficient of efficiency between observed totals and predicted totals is E . Italicized P_{BIAS} and E values are artificially closer to 0 and 1, respectively, because of reporting days included in the calculations.

	Product	10 Days			Monthly			Seasonal		
		N	P_{BIAS}	E	N	P_{BIAS}	E	N	P_{BIAS}	E
Gulu	ARC2	349	-9	<i>0.38</i>	113	-11	<i>0.53</i>	35	-10	<i>0.62</i>
	RFE2	349	-13	<i>0.43</i>	111	-15	<i>0.50</i>	35	-14	<i>0.54</i>
	3B42v7	349	6	0.51	113	4	0.72	35	5	0.77
Masindi	ARC2	339	-7	<i>0.36</i>	109	-7	<i>0.49</i>	34	-8	<i>0.59</i>
	RFE2	339	-15	<i>0.36</i>	108	-15	<i>0.49</i>	34	-15	<i>0.50</i>
	3B42v7	339	-2	0.39	109	-3	0.67	34	-4	0.71
Ngogo	ARC2	365	-12	0.29	121	-12	0.38	39	-12	0.50
	RFE2	365	-22	0.29	119	-22	0.27	39	-22	0.28
	3B42v7	365	-9	0.45	121	-9	0.51	39	-9	0.67
Kasese	ARC2	358	6	<i>0.08</i>	118	6	<i>0.16</i>	37	5	<i>0.31</i>
	RFE2	358	-3	0.22	116	-3	0.32	37	-2	0.47
	3B42v7	358	32	-0.02	118	32	0.18	37	30	0.13
Mweya	ARC2	297	43	-0.21	98	43	-0.22	32	43	-0.58
	RFE2	297	16	0.08	96	17	0.19	32	17	0.33
	3B42v7	297	25	0.06	98	25	0.05	32	24	0.12
Bwindi	ARC2	252	3	0.04	76	5	0.25	20	5	0.44
	RFE2	252	-2	0.15	76	-2	0.24	20	0	0.58
	3B42v7	252	0	0.16	76	-5	0.07	20	0	0.46

highlands of southwestern Uganda; therefore, it appears that the Bwindi rain gauge is not in a location dominated by warm orographic rains. Nevertheless, the products are expected to perform poorly in the Rwenzori Mountains, an approximately 100-km tract of the most mountainous part of the study region with peaks exceeding 5000 m MSL and annual rainfall exceeding 2000 mm (Osmaston 1989; Eggermont et al. 2009). Over the 2001–10 period, the maximum mean annual rainfall totals in the Rwenzori Mountains from ARC2, RFE2, and 3B42v7 were just 1350, 1010, and 1330 mm, respectively.

4. Conclusions

The purpose of this study was to assess the accuracy of ARC2, RFE2, and 3B42v7 for estimating rainfall days and rainfall totals at six stations in the Uganda portion of the Albertine Rift, which is on the eastern edge of central equatorial Africa, for the period 2001–10. The products performed best at identifying rainfall days at the three northern stations, but all three products tended to overestimate rainfall days at all stations. Both 3B42v7 and ARC2 were satisfactory products for estimating seasonal rainfall totals at the northern stations, with 3B42v7 being more accurate than ARC2. 3B42v7 also was accurate at estimating monthly rainfall totals at the northern stations, and it was the only product not to underestimate boreal-summer rainfall at the northern stations. None of the products performed satisfactorily at the two southern stations in rain shadows. The products were borderline

satisfactory at estimating rainfall at the southernmost station, located in the highlands of southwestern Uganda. Finally, the products greatly underestimate rainfall in the Rwenzori Mountains, the largest mountain range in the study region. Consequently, the rainfall products are not useful for estimating rainfall in rain shadows and possibly other valley locations of the rift and in mountainous areas where the warm orographic rain process dominates.

Much more validation work is needed not only in low- and high-elevation areas of western Uganda, but also southward throughout the rest of the Albertine Rift and westward into the rest of central equatorial Africa. The major obstacle to proper validation work in the region is the lack of high-quality, daily, ground-measured rainfall totals over multiple years. Additional validation studies are especially important with respect to ARC2: that product extends back to 1983 and thus might be useful for rainfall-variability analyses in gauge-deficient regions, such as the rest of central equatorial Africa.

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