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Comparison of global gridded precipitation products over a mountainous region of Africa

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ABSTRACT: Five gridded monthly precipitation products are evaluated using a gauge network over complex topography in Africa. The global gridded products considered are produced by the Global Precipitation Climatology Center (GPCC), NOAA Climate Prediction Center (NOAA–CPC), and the Climate Research Unit at the University of East Anglia (UEA–CRU). Three different products from GPCC are available at multiple spatial resolutions: 0.5, 1 and 2.5°; the NOAA–CPC product has a spatial resolution of 2.5° while that of UEA–CRU is 0.5°. Comparisons of the GPCC and UEA–CRU products are carried out at spatial resolutions of 0.5, 1 and 2.5°, while NOAA–CPC is compared with the other products only at 2.5° resolution. There is very strong agreement between the gridded global products and the reference raingauge data. Average correlation coefficients are about 0.95, 0.92, and 0.90 at 2.5, 1.0 and 0.5° spatial resolutions, respectively. Both systematic and random errors are reasonably low. The performance of these products is highest during the wettest season (Jun–Aug), and relatively poor during the dry season (Dec–Feb). The seasonal differences are more prominent at high resolution. These results are very encouraging, particularly, when considering the complex terrain of the validation site. Copyright © 2008 Royal Meteorological Society

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1. Introduction

Various global gridded datasets of monthly precipitation are available at diverse spatial resolutions. Examples include Legates and Willmott (1990), Xie *et al.* (1996), Dai and Del Genio (1997), New *et al.* (2000), Chen *et al.* (2002), Beck *et al.* (2005), and Mitchell and Jones (2005). Gauge observations used in the different products differ in numerous ways, including number, quality, and length of observations. The number of observations included in these products typically varies over the years and over different parts of the globe. Other differences may include quality checking and error correction procedures and the interpolation techniques implemented. These important nuances may lead to notable differences in the quality of the various products. Thus, evaluation of these products over different regions provides useful information both for the developers and users of these products. However, the number of such comparisons is very limited. The few comparisons that were performed (e.g. Rudolf *et al.*, 1994; Chen *et al.*, 2002; Qian *et al.*, 2006) were global in nature. Though global comparisons are important, evaluation of the products over specific geographic/climatic regions will help assess the performance of the global products under different circumstances.

This article compares five gridded products over a very complex topography in Africa. Three of these products are produced by the Global Precipitation Climatology Center (GPCC), one by the Climate Prediction Centre at the National Oceanic and Atmospheric Administration (NOAA–CPC), and another from the Climate Research Unit at the University of East Anglia (UEA–CRU) in the UK. The three GPCC products (Fuchs *et al.*, 2007) are the GPCC monitoring (GPCC-mon), full-data analysis (GPCC-ful), and the 50-year climatology (GPCC-clm). The monitoring product is available at 1 and 2.5° spatial resolutions, while GPCC-ful and GPCC-clm are produced at grid sizes of 0.5, 1 and 2.5°. The NOAA-CPC product (Chen *et al.*, 2002) has a spatial resolution of 2.5° while that of UEA–CRU (New *et al.*, 2000; Mitchell and Jones, 2005) is produced at 0.5° resolution. The gridded global products are evaluated against a reference gauge analysis, which is produced using a relatively dense station network over the Ethiopian highlands. The GPCC and UEA–CRU products are compared at spatial resolutions of 0.5, 1 and 2.5°, while NOAA–CPC is compared with the other products for 2.5° grids. Comparisons of the three GPCC products are also presented to show their relative performance.

The following Section describes the study region, raingauge data and products included in the comparison. Section 3 outlines the methodology adopted for evaluation of the products. Comparison between products and against reference data is presented and discussed in Section 4. Section 5 provides a summary of the results.

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2. Study region and data

2.1. Study region

The study region is located over the Ethiopian highlands (Figure 1). This region has a very complex terrain, with elevations varying from below sea level to 4620 m within a short distance. The central topographic feature of the country consists of a high plateau and mountain chains. The East African Rift Valley is a prominent feature that runs northeast to southwest through the country, creating a discontinuity of the central plateau. Topography plays a significant role in the climate of the country by creating diverse microclimates ranging from hot deserts over the lowlands to very cold temperature over the mountains. The main rainy season is from June to August, when most of the country receives its rainfall. The March–May season is the second wet season, but constitutes the main rainy season for the southern and southeastern parts of the country. The dry spell between these two seasons is limited to only a few weeks over some regions. The southern and southeastern regions also receive moderate rainfall amounts during the September–November season. December, January, and February are predominantly dry. Thus, some areas receive rainfall for extended periods of time, others for only a few months, while still others are characterized by two distinct rainfall seasons. Most of the rainfall is associated with the south–north movement of the Inter Tropical Convergence Zone (ITCZ). However, topography makes the spatial and temporal distribution very complex.

2.2. Reference raingauge data

The raingauge data used as a reference in this study is obtained from the National Meteorological Agency (NMA) of Ethiopia. About 150 stations were obtained from the NMA. Stations with time-series less than 15 years, stations located very closely to one another (<5 km), stations with excessive missing data, and stations whose seasonal patterns were significantly different from their closest neighbours, were removed. The reduced set includes 137 stations for the current analysis (Figure 1(b)). Figure 1(b) also indicates the specific stations used for the comparisons at different spatial resolutions. Stations in the four numbered boxes were used for comparison at 2.5° resolution, while those in larger grey box were used for evaluation at 0.5 and 1.0° resolutions. The four 2.5° boxes contain 22, 25, 37 and 23 gauges, respectively, while there are 74 stations in the larger grey box.

The gauge data used here have already undergone routine quality checks by NMA. However, rigorous quality checks were performed to further improve the quality of the data, and implemented in following three steps: First, plots of monthly means of each station and a maximum of five neighbouring stations within a radius of 150 km were inspected visually to determine if the climatology of a target station agrees with that of its neighbours. In the second step, temporal and spatial quality checks were performed as in Eischeid *et al.* (1995). The last part of the quality control procedure identifies and corrects inhomogeneities in station time-series.

The temporal check uses the interquartile range (IR), which is the difference between the 75th and 25th percentiles. A value is considered an outlier when

$$X_{\mathrm{i}} - \mathrm{q50} > f\mathrm{IR}$$

Where X_{i} is the monthly total of year i, q50 is the median, and f is the multiplicative factor.

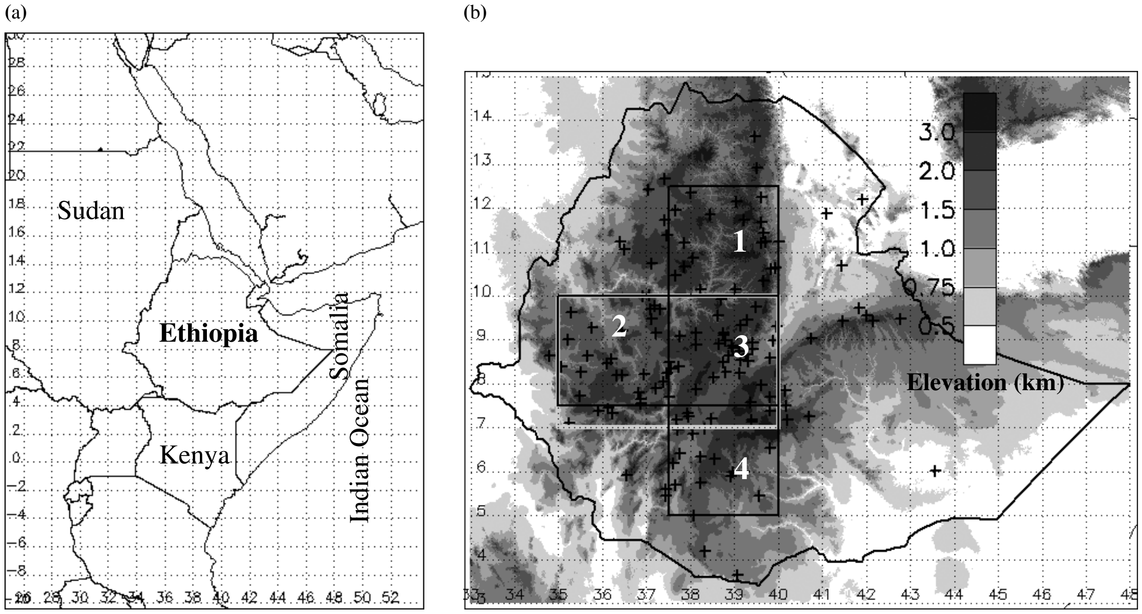

Figure 1. (a) Geographic location of Ethiopia; (b) Topography of the study region and raingauge distributions. The four numbered boxes are the 2.5° grid boxes used in the evaluation of the low-resolution products, while stations in the bigger grey box are used for evaluation of the high-resolution products.

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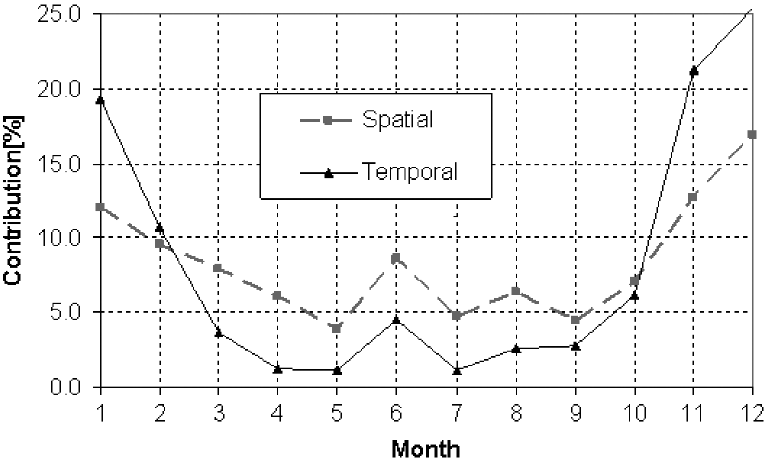

Figure 2. Contribution (%) of different months to suspected outliers identified by the spatial and temporal quality check procedures.

The value of the multiplicative factor in Eischeid *et al.* (1995) was $f = 4$. Here, different values were used for different seasons. Figure 2 compares the contribution of each month to the 'outlier' flag at $f = 4$. There is a disproportionately high (77%) contribution from the months of November, December, January, and February. This is due to untimely rains during the dry season, and is mainly associated with westward propagating storms/depressions from the Arabian Sea (Tadesse, 1994; Shanko and Camberlin, 1998). Since these months are normally dry, the occasional rains could be flagged as outliers. Thus, $f = 10$, selected subjectively, was used for the dry months. This reduced the contribution form the dry months to 37%.

The spatial quality check procedure compares the monthly values of a given station with values estimated from nearby stations. The estimates were computed using Shepard's interpolation method (Shepard, 1968); differences between the actual and estimated values at the station were then retained. The standard deviation (SD) of these differences was used to flag spatial outliers. Extreme values were removed from the differences before computing the SD for each month. A monthly value is flagged as an outlier if its difference from the estimated value over $\pm$ cSD; c is a multiplicative factor. As in the case of the temporal quality check, there were disproportionately high numbers of outliers during the dry season. However, the differences between months are not as large as for the temporal check case (Figure 2). In the spatial check case, the dry months contribute 51% at $c = 4$. Thus, c was set to 5, and 4 for the dry and wet months, respectively. The spatial quality check flags about 0.7% of the data as suspect. The suspect values from the temporal and spatial checks were combined. Some values were flagged as suspect by both checks. The total number of suspect values from the temporal and spatial checks was about 1.2% of the total data. These were set to missing values.

The homogeneity check aims at detecting and removing discontinuities in the monthly time-series. The first step involves creating a reference series (Peterson and Easterling, 1994). Here the reference series is obtained by interpolating the values of the surrounding stations at the location of the target station using Shepard's method (Shepard, 1968). A minimum of two and a maximum of five neighbouring stations were retained. Two main problems were encountered while creating the reference series. The first problem was missing data; some stations had missing values over a number of years. This could be a source of discontinuity by itself. The second problem was that some of the stations used for constructing the reference series could themselves have discontinuities. To alleviate the first problem, some of the missing values were replaced with estimates as in Mitchell and Jones (2005). Missing values that persisted over a long period of time were not replaced as this may create discontinuities. An iterative procedure was implemented to deal with the second problem. The major steps of the iterative procedure are as follows:

1. Cumulative sum plots (CUSUM), (Rhoades and Salinger, 1993) of the target station, and up to five neighbours (within a radius of 1.5°) were examined visually to identify possible discontinuities.
2. A reference series (Peterson and Easterling, 1994) was then created for each station, but stations identified as having discontinuities in step (1) were not used for constructing the first reference series. In addition, those stations used for constructing the reference series were required to satisfy the following conditions:
   - Must be within 100 km of the target station
   - Must have a correlation coefficient (climatological) above 0.70 with target station
   - Its time-series should overlap at least 70% of the target time-series
   - Its missing data should not exceed 25% of its time-series.
3. Discontinuities were determined objectively using Alexandersson's methods (Alexandersson, 1986) for each station, including those identified in step (1);
4. Identified discontinuities were corrected;
5. Steps (2) to (4) were repeated until no more discontinuities were detected.

There were a number of cases where the homogeneity check or adjustments were not possible. The former was not possible if there were no reference stations satisfying the conditions given in step (2) above. Twelve stations fell in this category; however, nine of these stations were outside the boxes delineated in Figure 1(b). Also, adjustments were not made if the discontinuity was at the beginning or at the end of the time-series (as in Alexandersson, 1986), or if the discontinuity was close to a series of missing values.

The quality controlled gauge observations were then interpolated onto a 0.1° × 0.1° grid. First, Kriging, with elevation as a co-factor, was used to interpolate mean monthly values. Then anomalies (ratios of monthly values to the climatological mean) were interpolated using angular distance-weighted interpolation as in New *et al.* (2000). The interpolation techniques used here were selected after experimenting with different approaches. All stations that passed the quality check were used for interpolation; however, only grids with a relatively dense station network were used for evaluation (Figure 1(b)). Since comparisons are done at spatial resolutions of 0.5, 1 and 2.5°, the 0.1° grids were aggregated to the coarser resolutions using simple averages.

2.3. Global gridded products

A brief description of the global products is provided here, with a summary given in Table I. The reader is referred to each product's relevant documents for more details. The three products from GPCC, i.e. the GPCC-mon, GPCC-ful, and GPCC-clm, are presented in Fuchs *et al.* (2007). The GPCC-clm is also discussed in more detail by Beck *et al.* (2005). GPCC-mon is based on SYNOP, and CLIMAT reports received by GPCC through the Global Telecommunication System (GTS) on near-real-time basis (Fuchs *et al.*, 2007). These data undergo quality checks and correction procedures before gridding. Reports from about 7500 stations are included in this product. The monitoring product is available within about 2 months following the observation month. This product starts from 1986 and is provided at spatial resolutions of 1.0 and 2.5°. The full-data product uses both near-real-time and non-real-time data from the GPCC database, and is thus, based on many more stations (10 000 to 43 000). The data used in GPCC-ful also demonstrate a higher quality as compared to those used in GPCC-mon. GPCC-ful is updated irregularly, and the current version (Version 3) covers the period from 1951 to 2004 at spatial resolutions of 0.5, 1.0 and 2.5°. The next version which will be based on significantly more observations, will be made available by the end of 2007 (Tobias Fuchs, personal communication.) The GPCC-clm is meant specifically for studies on climate variability and trends (Beck *et al.*, 2005; Fuchs *et al.*, 2007) This product is based on stations whose time-series is at least 90% complete. This is a very restrictive criterion as only a limited number of stations may satisfy it. As a result, GPCC-clm uses fewer observations than other products. The current version (Version 1.1) uses a total of 9343 stations and covers the period 1951–2000. GPCC-clm is available at 0.5, 1.0 and 2.5° spatial resolutions.

Table I. Summary and comparison of the rainfall products.

Product	Spatial resolution (deg)	Period
GPCC-mon	1.0, 2.5	1986–present
GPCC-ful	0.5, 1.0, 2.5	1951–2004
GPCC-clm	0.5, 1.0, 2.5	1951–2000
UEA-CRU	0.5	1901–2002
NOAA-CPC	2.5	1948–present

The Climate Research Unit at UEA produces gridded products for nine climate variables and precipitation among them, at a spatial resolution of 0.5°. For this comparison, we used CRU TS 2.1 (Mitchell and Jones, 2005), which covers the period from 1901 to 2002. The gridded products are based on data from many different sources, and were subjected to rigorous quality checking procedures. The number of stations used varies significantly over the years and across different regions of the world. The number of precipitation stations used for the Africa region is under 500 in the early 1900s, close to 2000 during 1960s and 1970s, and falls below 500 during the most recent years (Mitchell and Jones, 2005).

The NOAA–CPC product (Chen *et al.*, 2002) employs over 17 000 stations and is available starting from 1948, running up to the present, at a spatial resolution of 2.5°. The observations used in this product come from two sources: the Global Historical Climatology Network (GHCN; Vose *et al.*, 1992) and the Climate Anomaly Monitoring System (CAMS; Ropelewski *et al.*, 1985). This product is known as PREC/L (precipitation reconstruction overland), however the NOAA–CPC nomenclature is chosen for consistency with other products studied here, referring to their origin.

3. Evaluation method

The following statistics were used to evaluate the products: linear correlation coefficient (CC), mean error (ME), mean absolute error (MAE), efficiency score (Eff), and bias.

$$\mathrm{ME} = \frac{1}{N}\sum(G - R) \tag{1}$$

$$\mathrm{MAE} = \frac{1}{N}\sum|(G - R)| \tag{2}$$

$$\mathrm{Eff} = 1 - \frac{\sum(G - R)^2}{\sum(R - \overline{R})^2} \tag{3}$$

$$\mathrm{Bias} = \frac{\sum G}{\sum R} \tag{4}$$

where R = reference raingauge observation, $\overline{R}$ = average of the reference data, G = global gridded product, and

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N = number of data pairs. ME and MAE are in mm while Eff and Bias are unit-less. Here MAE is used instead of RMS to avoid the effect of large outliers (Legates and McCabe, 1999, and references therein). The efficiency, also know as coefficient of efficiency (Nash and Sutcliffe, 1970; Legates and McCabe, 1999), shows the skill of the estimates relative to a reference (in this case, the mean of the reference data). It varies from minus infinity to one, one representing perfect skill. A negative value implies that the reference mean (climatology) is a better estimate than the global products, zero indicates that the climatology is as good as the global products, and positive values show good skill. The efficiency statistic is considered to be 'the most appropriate relative error or goodness-of-fit measures available' owing to its straightforward physical interpretation (Legates and McCabe, 1999).

Gridded Ethiopian raingauge data from 1981 to 2000 were used as a reference for comparison of the global products. The use of these observations as a reference may require some justification. One advantage of the reference data is that the number of observations used to generate the reference grids is much greater than those used in the global products (Figure 3. There have been efforts to determine the number of stations required per 2.5 × 2.5° box to attain 10% sampling error in the spatial averages. Some suggested figures include five (Xie and Arkin, 1995), from 8 to 16 (Rudolf *et al.*, 1994) and from 15 to 20 (Ali *et al.*, 2005). The number of gauges per 2.5° grid used here ranges from 22 to 37. Though these numbers are relatively high, this alone may not be enough to justify the use of this data reference. Additional factors that justify the use of the gauge data as a reference include the following:

- The monthly rainfall totals were constructed from daily values, and monthly totals with too many missing days were set to missing values. This is in contrast to the global products, which incorporate monthly totals. The SYNOP reports may contain numerous missing days, but that information is likely not available for the global products. According to Rudolf *et al.* (1994), incomplete coverage of the monthly period by SYNOP reports is the main source of errors in the GPCC data.
- The reference data is of higher quality because it is obtained directly from NMA, as compared to the global products, which use different sources. The reference data also eliminates other errors associated with transmitting the data through GTS and other channels.
- The reference data has undergone routine manual quality checking procedures at the source.
- Rigorous quality checking procedures similar to those used in the products have been used here to further improve the quality of the reference data. Local knowledge, which may not be available to the global products, was incorporated into the quality control procedures.
- Since the reference data stations are relatively few, as compared to the huge number of stations used by the global products, visual comparison of each station with its closest neighbours was possible.
- Only 1° boxes containing at least three gauges, and 0.5° boxes with at least one gauge were used to create the reference data.
- The interpolation errors of the reference data were compared with jack-knife errors from GPCC-clim for 0.5° grid boxes. The reference data shows much smaller errors as compared to that of GPCC-clm (Figure 4), with mean errors at −1.5 and 3.0 mm, respectively. The mean root mean square error is 25 mm for the reference and 65 mm for GPCC-clm, a significant difference. However, it should be noted that GPCC-clm is a product with the minimum number of observations (Figure 3), its use is included

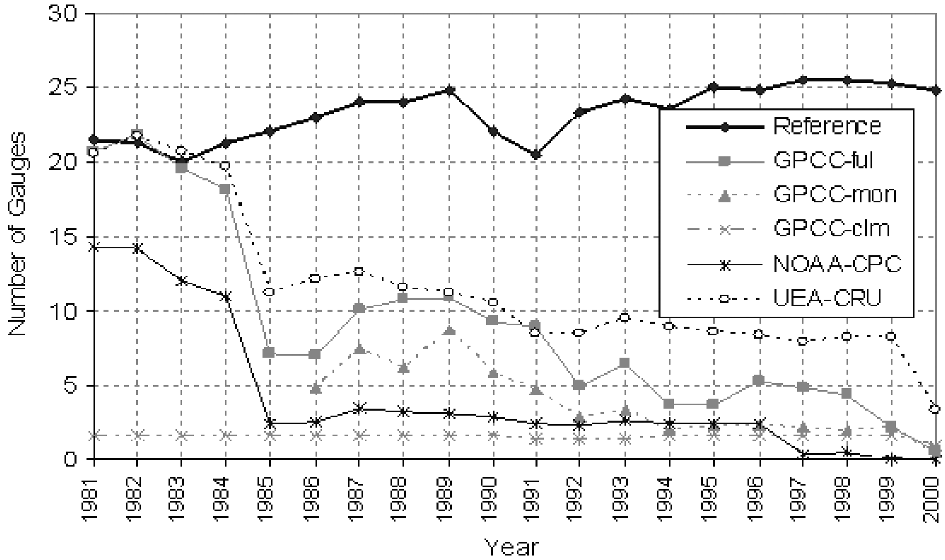

Figure 3. Average number of gauges per 2.5° grid box for reference data and the different global products. The averages are taken over the four boxes in Figure 1(b), and over 12 months for each year.

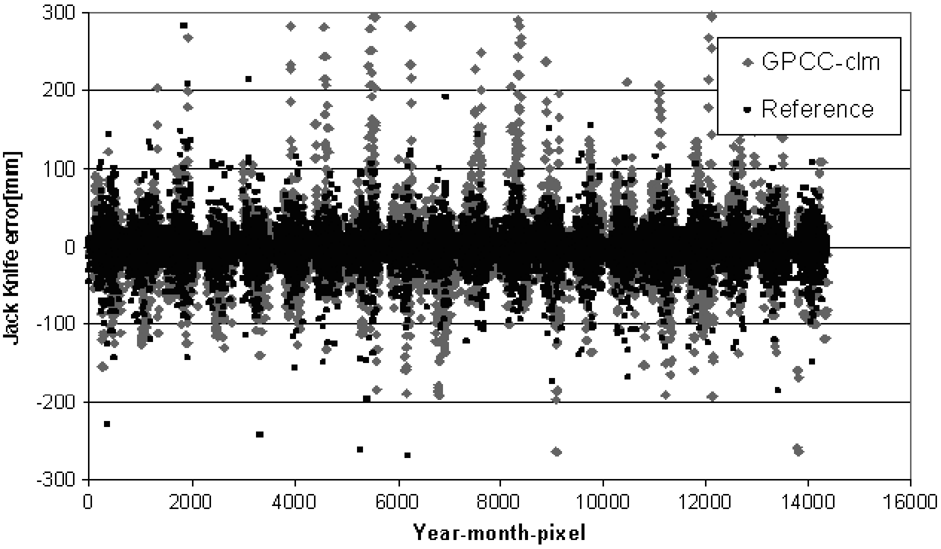

Figure 4. Jack-knife errors for the reference data and the GPCC-clm product. The X-axis gives pixels for each of the 12 months during 1981–2000.

Table II. (a) Comparison of gridded gauge products at a spatial resolution of 2.5° N = number of data pairs. (b) Comparison of gridded gauge products for two 5-year periods: 1981–1985, and 1996–2000. There are much more observations used in the analyses of the global products during the first period as compared to the second one (Figure 3).

(a)

$N = 960$	NOAA–CPC	UEA–CRU	GPCC-ful	GPCC-clm
CC	0.95	0.94	0.96	0.94
Eff	0.89	0.88	0.92	0.88
Bias	1.04	1.03	1.00	1.00
ME (mm)	4.4	2.9	0.5	−0.3
MAE (mm)	17.6	21.3	15.6	20.3

(b)

$N = 240$	NOAA–CPC		UEA–CRU		GPCC-ful		GPCC-clm	
Period	1981–1985	1996–2000	1981–1985	1996–2000	1981–1985	1996–2000	1981–1985	1996–2000
CC	0.97	0.88	0.95	0.92	0.98	0.91	0.96	0.94
Eff	0.94	0.76	0.91	0.84	0.94	0.83	0.92	0.88
MAE (mm)	14.1	26.6	17.8	25.0	13.8	22.1	16.3	23.2

here, strictly because it is the only product for which jack-knife errors are available.

4. Results

4.1. Comparison of the global products at 2.5° spatial resolution

Figure 5(a) compares the performance of GPCC-clm, GPCC-ful, UEA-CRU, and NOAA-CPC relative to the reference data. The monthly rainfall totals of the global products generally agree very well with the reference data, however, there are also some obvious distinctions. The first, though only for a few pixels, is the overestimation by the two GPCC products at low and high rainfall amounts. The other discrepancy is the overestimation of moderate rainfall amounts (100–200 mm) by the UEA–CRU product. Table II compares the error statistics for these products. Again, all the products indicate strong agreement with the reference data. Correlation coefficients are above 0.94, while efficiency values range from 0.88 to 0.92; biases are very low for all products. The differences in statistics among products are also small. The GPCC-ful product has the best overall statistics followed by NOAA-CPC, GPCC-clm, and UEA-CRU.

The above comparisons are based on data taken from all months. However, evaluation of the performance of the global products across different seasons also proves to be very important. Table III compares the products for different seasons, indicating very good overall performance. The best results are observed during the wettest season (JJA) with very high correlation coefficients and efficiency values. Comparatively, the performance during the driest season (DJF) is relatively poor. The seasonal effects vary slightly for different products.

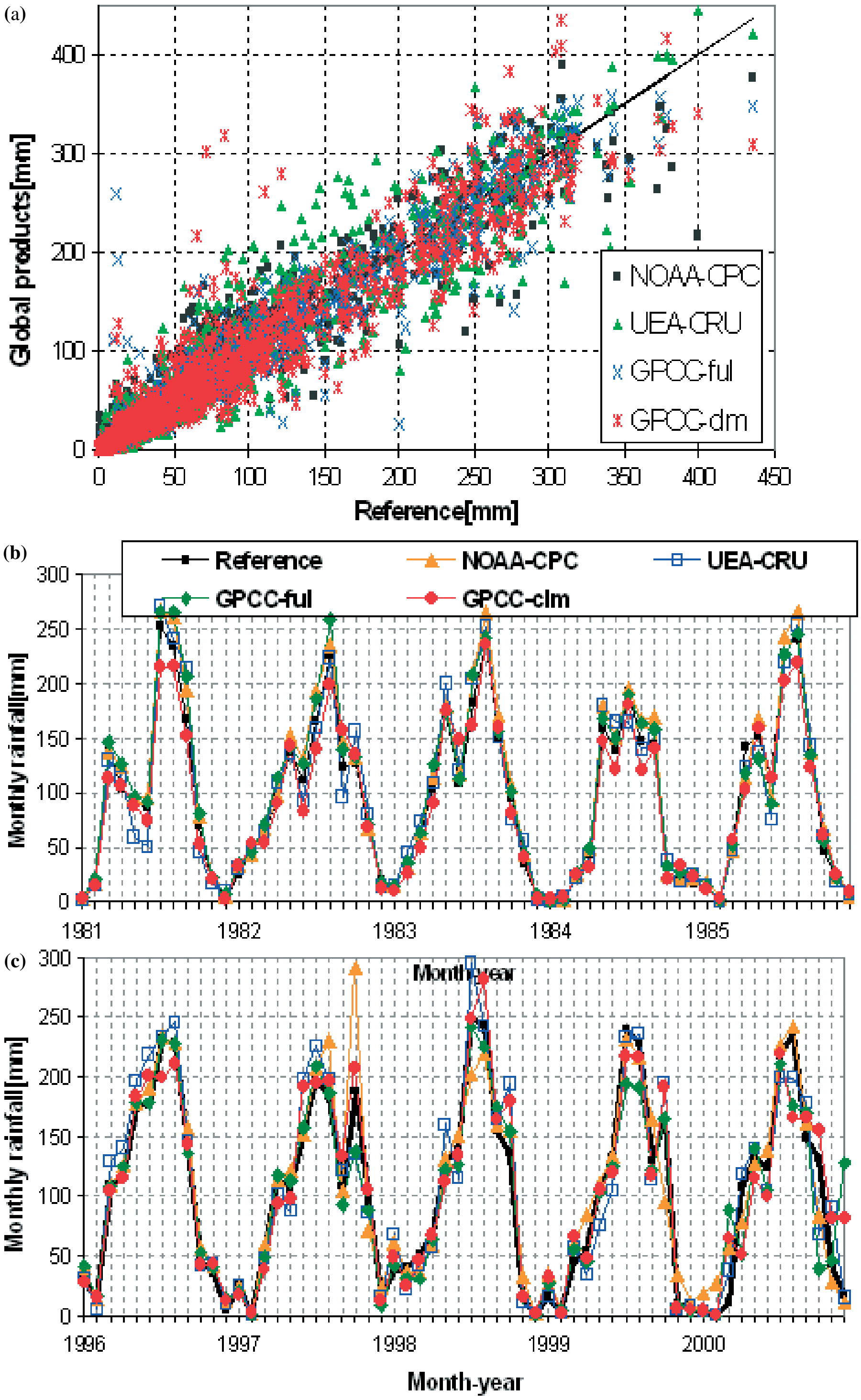

Figure 5. (a) Scatter plot comparing the performance global gridded products with respect to the reference data at a spatial resolution of 2.5°, (b) and (c) time-series of the different products during two different periods. The number of gauges used by the global products is much higher in (b) as compared to (c).

Figure 5(b) and (c) compare the time-series of monthly rainfall for the reference data and the global products. This time-series is constructed from the average of the four 2.5° pixels in Figure 1(b). Figure 5(b) is for the period 1981–1985, while Figure 5(c) is for 1996–2000. There is strong agreement between the reference data and the global products, particularly during 1981–1985. However, there are some discrepancies, particularly during the second period. The UEA–CRU product overestimates the summer rains in most of the cases, GPCC-clm underestimates rainfall most of the time, and NOAA–CPC also shows some discrepancies. The most consistent product seems to be GPCC-ful.

The two time-series in Figure 5(b) and (c) represent extreme cases in terms of the number of raingauges utilized in the different products. Many more stations

Table III. Same as Table II, but for different seasons.

		NOAA–CPC	UEA–CRU	GPCC-ful	GPCC-clm
DJF	CC	0.96	0.94	0.95	0.93
	Eff	0.92	0.86	0.89	0.87
	Bias	1.06	1.12	1.13	1.01
MAM	CC	0.98	0.97	0.98	0.97
	Eff	0.96	0.94	0.96	0.94
	Bias	1.05	1.00	1.04	0.93
JJA	CC	0.99	0.98	0.99	0.99
	Eff	0.97	0.96	0.97	0.97
	Bias	1.08	0.99	1.06	0.91
	CC	0.98	0.96	0.98	0.97
SON	Eff	0.95	0.90	0.95	0.94
	Bias	1.13	1.06	1.11	1.02

were used during 1981–1985 compared to the period 1996–2000 (Figure 3). However, the number of gauges used by the reference data over the same years remains practically unchanged. Thus, comparison of Figure 5(b) and (c) may help understand the significance of the number of stations used on the accuracy of the products. There are larger discrepancies between the products and the reference data in Figure 5(c) as compared to Figure 5(b). However, these differences are not as significant as the difference in the number of stations used in the different products. This can also be observed from Table II(b), which compares select validation statistics for the two periods. Biases are small for both periods, and therefore, not shown. The statistics for the first period are definitely stronger than those for the second period. The differences are more significant for NOAA–CPC and GPCP-ful. This corresponds to the large fall in the number of stations (Figure 3) for those two products during 1996–2000. However, the statistics for the second period still indicate high correlation and efficiency values. This illustrates the lack of any linear relationship between the number of stations used and the accuracy of the grid average relative to the reference data. To further elaborate this point, Figure 6 compares the MAE statistics for the different products for each year. There is an increasing trend in the MAE over the years with very high values during 2000. The increase in MAE does correspond to the decrease in the number of observations over the years. However, the rate of increase in the error is much less than the rate of fall in the number of stations used. Thus, a limited number of stations may suffice to represent monthly rainfall totals in a 2.5° grid box. This is very good news as it implies that these global products could be useful over most parts of Africa where raingauge distribution is very sparse. Of course, this depends on the specific application of the product. This finding is somewhat similar to that of Rudolf *et al.* (1994), who showed that areal means from different methods agree well as long as there are at least five stations per every 2.5° grid. They also stated that the accuracy of the areal mean rainfall may not depend on the analysis method as long as there are sufficient data, but more on the density, location, and quality of the data. What makes the current results significant and interesting is the complex terrain with high spatial variation of precipitation.

Figure 6 also compares the performance of the different products over the years 1981–2000. GPCC-ful has consistently lower errors over the years, while GPCC-clm and UEA–CRU have relatively high errors. Considering the fact that the UEA–CRU product uses the most number of gauges (Figure 3) and the fact that it employs elaborate quality checking schemes, it is expected to perform as well as or better than the other products. However, its performance is sometimes similar to that of GPCC-clm, which includes the least number of gauges. One possible explanation could be that UAE–CRU uses elevation as a factor in the interpolation of the climatological values. The use of elevation in interpolation may not be a problem by itself, but may become one when monotonous

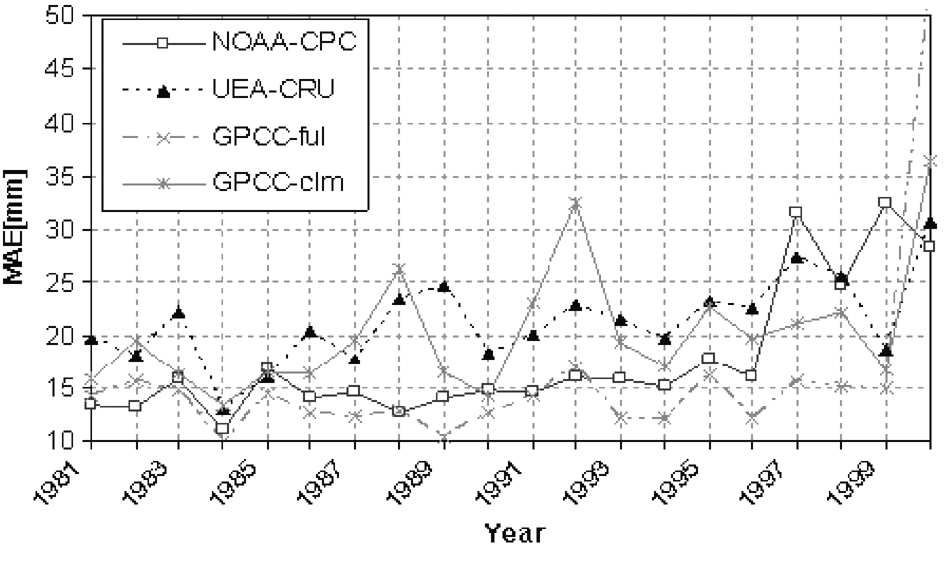

Figure 6. Comparison of the mean absolute error (MAE) for the global products for each year. The number of data-points used for each year is 48 (4 pixels × 12 months).

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increase of rainfall with elevation is assumed. Analysis done using the reference data (not shown) has shown that rainfall over the Ethiopian highlands increases up to an elevation of about 2000 m, and then begins to decrease with elevation. This may consequently lead to an overestimation, as observed for the UEA–CRU product.

4.2. Comparison of UEA–CRU, GPCC-ful and GPCC-clm at 1 and 0.5° spatial resolutions

Figure 7 and Table IV compare the three products at a spatial resolution of 1°. (The NOAA–CPC product, available only at a spatial resolution of 2.5°, is omitted from this section.) Figure 7 shows a good agreement between the global products and the reference data, although, the GPCC products overestimate low and high rainfall amounts, while UEA–CRU shows some overestimation at moderate rainfall amounts. The error statistics in Table IV, however, show that the performance of the three products is still very good: correlations are above 0.9 while Eff values are above 0.8, and bias is still very small. The GPCC products have slightly better statistics.

The evaluations at 0.5° spatial resolution are given in Figure 8 and Table V. Figure 8 is somewhat similar to the scatters at 1.0 and 2.5° resolutions, except for the wider scatter owing to the higher spatial resolution. The overestimation of low rainfall amounts by the GPCC products is again evident. There is some underestimation of rainfall of about 200 mm, particularly by GPCC-ful. However, the number of these outliers for the GPCC products is very small as compared to the whole data. For instance, the cases where the reference rainfall is less than 10 mm and GPCC-ful is above 150 mm represent only 0.2% of the total data. Additionally, this is limited to box 2 in Figure 1(b), and could be a product of error in the input data. Thus, even at this relatively high resolution, the overall performance of these products is very encouraging. This is also evident from Table V where the correlations are still about 0.9, Eff values are about 0.8, and there are no biases. Again GPCC-clm has slightly better statistics, but the differences are minimal.

The performance of the global products across different seasons is also investigated at a spatial resolution of 0.5°, presented in Table VI. Considerable differences are observed among correlation and efficiency values for the different seasons. Correlation coefficients and efficiency values are smallest for the dry season (DJF), and highest for the wettest season (JJA). These differences are much greater than the corresponding differences at the lower spatial resolution of 2.5°. The poor performance of the global products during the dry season is largely because the occurrence of rainfall during this season is limited both in space and time; as a result, a denser station network is needed to capture the structure of the rainfall.

Table IV. Comparison of gridded gauge products at a spatial resolution of 1.0°.

$N = 2640$	UEA–CRU	GPCC-ful	GPCC-clm
CC	0.91	0.92	0.92
Eff	0.81	0.84	0.85
Bias	1.02	0.99	1.00
ME (mm)	2.5	−1.2	−0.2
MAE (mm)	28.3	21.9	24.9

Table V. Comparison of gridded gauge products at a spatial resolution of 0.5°.

$N = 13440$	UEA–CRU	GPCC-ful	GPCC-clm
CC	0.89	0.90	0.90
Eff	0.78	0.80	0.81
Bias	1.01	0.99	0.99
ME (mm)	1.8	−0.7	−1.2
MAE (mm)	32.3	27.1	29.1

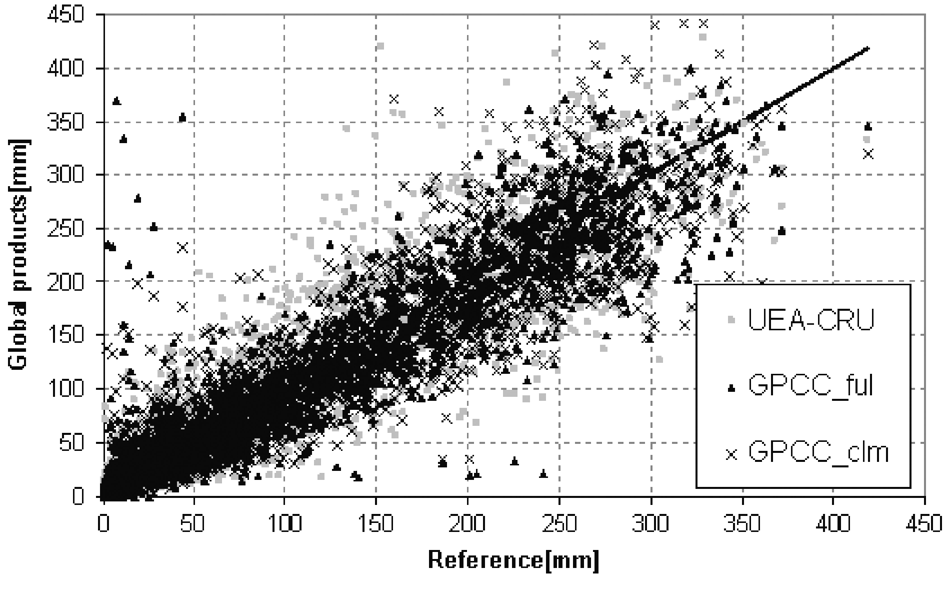

Figure 7. Scatter plot comparing the performance of global gridded products with respect to the reference data at a spatial resolution of 1.0°.

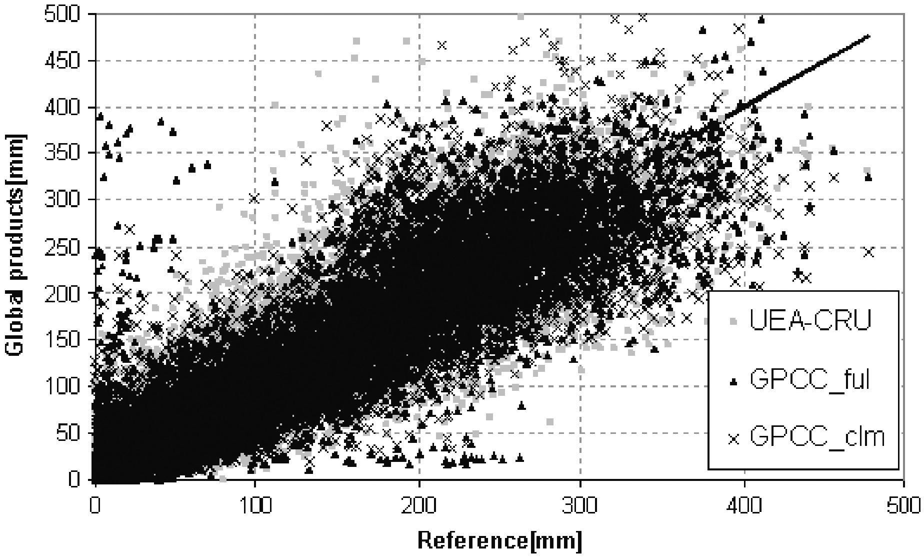

Figure 8. Scatter plot comparing the performance global gridded products with respect to the reference data at a spatial resolution of 0.5°.

Table VI. Comparison of gridded gauge products at a spatial resolution of 0.5° for different seasons.

		UEA–CRU	GPCC-ful	GPCC-clm
DJF	CC	0.80	0.73	0.78
	Eff	0.59	0.40	0.59
	Bias	1.07	1.11	1.02
MAM	CC	0.92	0.92	0.93
	Eff	0.83	0.84	0.86
	Bias	1.03	1.00	0.95
JJA	CC	0.96	0.96	0.96
	Eff	0.91	0.92	0.91
	Bias	1.00	0.98	0.98
	CC	0.92	0.95	0.96
SON	Eff	0.84	0.91	0.91
	Bias	1.01	0.98	1.03

4.3. Inter-comparison of GPCC products

The three GPCC products (GPCC-mon, GPCC-ful, and GPCC-clm) are also compared to one another over 1986–2000. The three products are each constructed using a different number of stations with dissimilar quality levels (Fuchs *et al.*, 2007). The monitoring product uses stations whose data is available within a month after the observation month, and most of the data is transmitted through GTS. As a result, the quality of these data may not be as robust as the other two products. GPCC-clm uses stations whose time-series is at least 90% complete, with rigorous quality checking. As a result, this product uses fewer stations with relatively higher quality. For instance, there are a maximum of two gauges per 2.5° grid box for the current study area. The full-data product uses a large number of quality controlled gauges. For the current study region, the number of stations per 2.5° used by GPCC-ful varies from 1 to 22 (Figure 3) with an overall average of nine stations per grid. Therefore, the comparison of these three products provides further insight into the effects of number and quality of stations on the quality of the products. Although this effect has already been discussed in Section 4.1, it is revisited here since the GPCC products use the same interpolation scheme, and thus, differences in performance may be ascribed simply to differences in the number and quality of the gauge data used.

As the monitoring product is available only at 1.0 and 2.5° spatial resolutions, the three products were compared at these two resolutions. Figures 9 and 10 present scatter plots comparing the products with the reference data at spatial resolutions of 2.5 and 1.0°, respectively. Despite the difference in the quality and number of stations used, the performance of the three products is quite similar. It is interesting to note that GPCC-mon does not have the outlier pixels observed for GPCC-ful and GPCC-clm. The error statistics for the three products (Tables VII and VIII) are also similar, with GPCC-ful showing a relatively stronger overall performance. The monitoring product has a higher bias while GPCC-clm has a higher random error as evidenced by low efficiency values and higher MAE. The higher random error may be associated with those outlying pixels at lower and higher rainfall amounts (Figures 9 and 10.)

5. Conclusion

Five global gridded monthly raingauge products from GPCC, NOAA–CPC, and UEA–CRU are evaluated

Table VII. Comparison of the different GPCC products at a spatial resolution of 2.5°.

$N = 720$	GPCC-mon	GPCC-ful	GPCC-clm
CC	0.95	0.95	0.93
Eff	0.91	0.91	0.86
Bias	0.95	0.98	1.01
ME (mm)	−4.4	−1.5	1.3
MAE (mm)	17.4	16.2	21.6

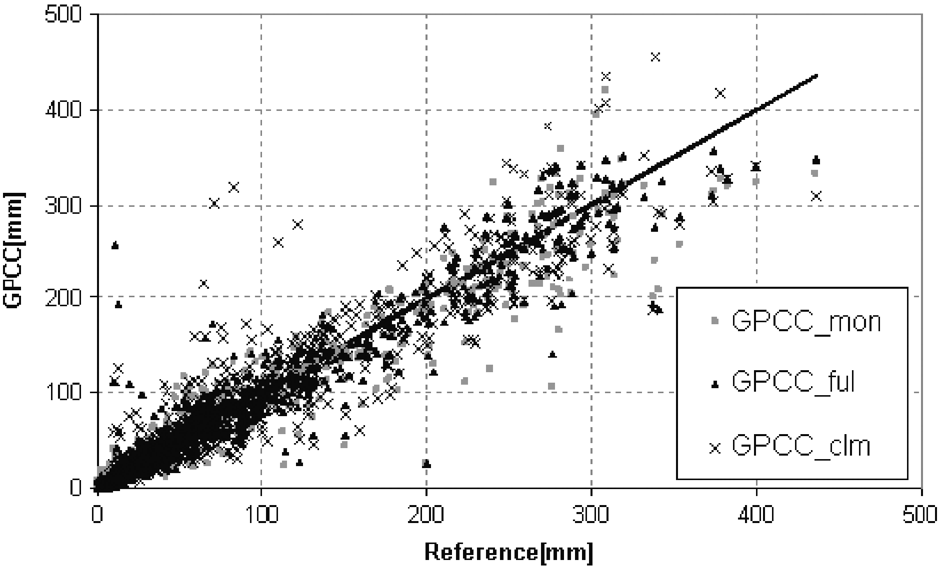

Figure 9. Comparison of the three GPCC products at spatial resolution of 2.5°.

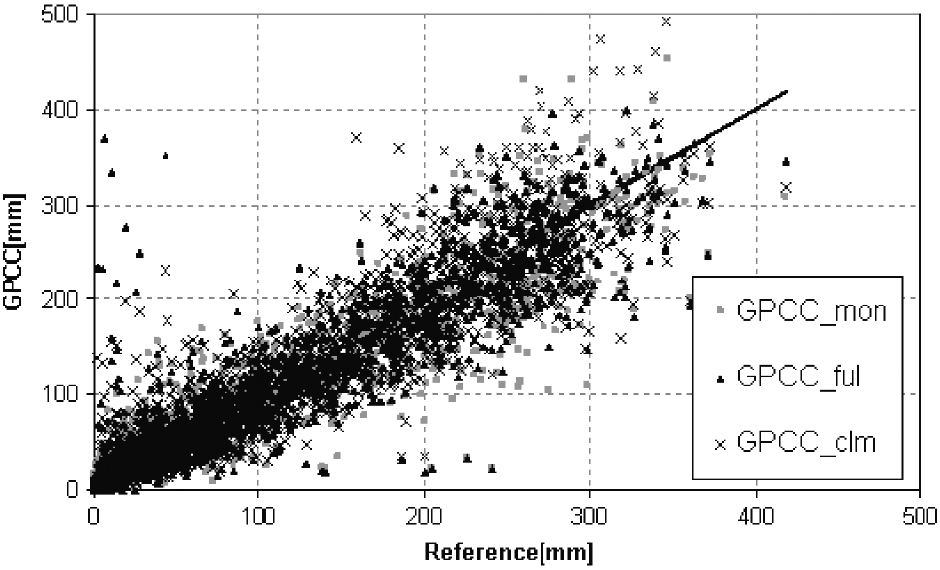

Figure 10. Same as Figure 9, but at 1.0°.

Table VIII. Comparison of the different GPCC products at a spatial resolution of 1.0°.

$N = 1980$	GPCC-mon	GPCC-ful	GPCC-clm
CC	0.93	0.92	0.92
Eff	0.86	0.85	0.84
Bias	0.96	0.98	1.01
ME (mm)	−4.2	−2.5	1.7
MAE (mm)	23.4	22.9	25.8

using a gauge network over a complex topography in Africa. These products are compared at grid sizes of 2.5, 1.0 and 0.5°. There is very good agreement between the global products and the reference data at all spatial resolutions. Comparison among products shows that there are some relatively small differences in the performance of the different products. The GPCC-ful has been found to be the best product for the current validation region, followed by NOAA–CPC, UEA–CRU, and GPCC-clm. The relatively poor performance of GPCC-clm is related to the small number of stations included in this product. On the other hand, the UEA–CRU product employs a larger number of stations than do other products, but this is not reflected in its performance; this is mainly attributable to the use of elevation in constructing the climatological values used in this product. The performance of the products across different seasons is also evaluated at grid sizes of 2.5 and 0.5°. The strongest agreement between the global products and the reference data is observed during the wettest season, while the performance during the dry season is poor. These seasonal differences are more significant at the higher spatial resolution.

The effect of the number of gauges on the quality of the products is also investigated. Two approaches are undertaken. In the first approach, the time-series of the products are compared for two different periods. The number of gauges used during the first period is much higher than those used during the second period. Though there are visible difference in the performances of the products during the two periods, the differences are not as significant as the differences in the number of gauges. In the second approach, the three GPCC products, which use a different number and quality of gauges, are compared. Again, though there are clear differences among the three products, they are not as significant as the differences in the number and quality of the gauges.

The overall strong performance of these products, even those with the least number of gauges, is very encouraging, particularly considering the complex terrain of the validation site. The spatial variation of rainfall over this region is very high because of the complex topography. Yet all the products are able to capture the variability of the monthly rainfall reasonably well. This indicates that these products may provide reliable information, depending on the application, even over data sparse regions. The next steps in this investigation include evaluating these products over other parts of Africa.

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