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Evaluation and bias correction of satellite rainfall data for drought monitoring in Indonesia

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Abstract

The accuracy of satellite rainfall data from different sources, TRMM 3B42RT, CMORPH and PERSIANN, was investigated through comparison with reliable ground station rainfall data in Indonesia, with a focus on their ability to detect patterns of low rainfall that may lead to drought conditions. It was found that all sources underestimated rainfall in dry season months. The CMORPH and PERSIANN data differed most from ground station data and are also very different from the TRMM data. However, it proved possible to improve TRMM data to yield sufficiently accurate estimates, both for dry periods (R^2 0.65–0.92) and annually (R^2 0.84–0.96), applying a single parameterized bias correction equation that is constant in space and time. It is proposed that these bias corrected TRMM data be used in real-time drought monitoring, in Indonesia and probably in other countries where similar conditions exist. This will yield major advantages, in terms of accuracy, spatial coverage, timely availability and cost efficiency, over drought monitoring with only ground stations.

1 Introduction

Indonesia is a tropical maritime country where most parts of it receive abundant annual rainfall, in excess of 2300 mm per year for instance over Java (Aldrian and Djamil, 2008). In large parts of the country, however, rainfall is highly seasonal, and sometimes erratic. This is the case particularly in areas furthest south of the Equator including the densely populated island of Java as well as the southern parts of Sumatra, Kalimantan and Papua (Aldrian and Susanto, 2003). In such regions, prolonged water deficits lasting several months occasionally cause failures of water supply systems and of rainfed and irrigated crops (Kirono and Tapper, 1999; Naylor et al., 2001), and frequently contribute to enhanced fire risk in forests and peatland areas (Field et al., 2004). Monitoring and understanding dry season rainfall patterns, in time and space, is therefore important for the country to be better prepared for drought conditions.

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Outside a few densely populated areas, rainfall monitoring using ground stations in much of Indonesia does at present not provide data with the speed, reliability and accuracy required for early warning of droughts. Moreover, ground stations are too scarce in most of the country to achieve the coverage needed for accurate analysis of rainfall patterns, especially as variability in rainfall is high in this vast country with thousands of islands and high mountain ranges. It would therefore be useful if satellite-based sensors could yield rainfall information that is available with very limited delay, has high accuracy and has full coverage of the entire country including the more remote areas.

Over the last decade, several remotely sensed rainfall estimate products have been developed that use data from several satellites, carrying different types of instruments. One of these satellites is the Tropical Rainfall Measuring Mission (TRMM), which carries a precipitation radar, similar to the radars used on the ground for measuring rain rates, and a microwave imager, which infers rain rates by analyzing the microwave backscatter from clouds (Huffman et al., 2007). Other satellite rainfall products are CMORPH (Joyce et al., 2004) and PERSIANN (Sorooshian et al., 2000). These products are all somewhat different in the satellite data they use, and how the data are processed. As they are available through the internet in near real-time, they are potentially suitable for use in operational early warning systems.

The time series of satellite rainfall data have only recently become long enough for confident analysis of their usefulness for water resources management. Understandably, national meteorological organizations will not adopt such data as a primary information source unless they are thoroughly evaluated for the specific conditions in their countries, based on a sufficiently long historical record covering the full range of climate conditions. A number of studies have been published that compared satellite data with ground station data, but these have mostly focused on potential use in river flow forecasting (Behrangi et al., 2011; Su et al., 2008), often with an emphasis on the ability to measure high rainfall amounts rather than low amounts. Most studies have concluded that TRMM data could be reasonably accurate at monthly timesteps,

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but less accurate on daily timesteps (Su et al., 2008). However no comprehensive study has been published to date on the suitability of satellite rainfall products specifically for use in drought monitoring for water resources management and agriculture in tropical countries, where rainfall data during dry periods are especially important. We have therefore investigated the accuracy of such products for Indonesia, and developed a simple method to correct TRMM data for bias in real-time to achieve a better fit with actual rainfall as measured by ground stations.

2 Methods and results

2.1 Selection and screening of ground station rainfall data

Validation areas were selected where sufficiently large numbers of stations produced data over the study period of 2003–2008 (Fig. 1). Having a relatively high station density was necessary to (i) allow inter-station data quality control, and (ii) to ensure that several stations are present in each of the TRMM grid cells covering the area. In practice, this meant that six clusters of rainfall stations on Java, Sumatra and Kalimantan were selected: around Jakarta, Bogor, Bandung, East Java, Lampung and Banjar Baru (Table 1).

Within the validation areas, monthly rainfall records (which were derived from daily measurements) were selected that had data coverage for over 75 % of the time during the study period. Subsequently, all periods of 2 months or longer in which rainfall amounts clearly deviated from all neighbouring stations, and from the pattern of the remainder of the station record, were excluded from further analysis as having a high likelihood of being incorrect. Data that appeared copied between stations or years were also excluded. After screening, a total of 76 stations were found suitable, with 10 to 15 stations selected for each of the six areas. The remaining data coverage was at least 67 % for all individual stations and 83 % to 99 % for each group of stations as a whole (Table 1).

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It is important to have more than one ground station in each satellite grid cell used for calibration and validation, because grid cells represent a measure of average rainfall over an area of 784 km^2 (grid cell resolution is 0.25° or approximately 28 km near the equator) which is much larger than can be represented by a single rainfall station. Tropical rainstorms as they occur in Indonesia tend to be localized, with heavy rainfall often affecting an area of less than 10 km across. This will result in random differences in rainfall rates over short distances, within satellite grid cells. Moreover, in a mountainous island country like Indonesia, many satellite grid cells are likely to cover different altitudes and different distances to the sea, which are likely to cause non-random differences in rainfall rates. An example of the differences between rainfall records from four reliable ground stations within a single satellite grid cell in the somewhat mountainous Bogor area is provided in Fig. 2. Combined data for more than one ground station will therefore be more representative of average rainfall in an area the size of a satellite grid cell. Average monthly ground station time series plots for each of the six validation areas are shown in Fig. 3. Different rainfall regimes are apparent in the different areas, but seasonality is largely the same with June-October usually being the driest months. Validating and bias correcting satellite data for these six areas, that are different in terms of distance to the coast, elevation, land cover (Table 1) and rainfall rates (Table 2), is meant to ensure that the resulting bias corrected rainfall data will be valid for the full range of conditions found in Indonesia.

2.2 Comparing satellite with ground station rainfall data

In this study we used the real-time products TRMM 3B42RT (Huffman et al., 2007), CMORPH (Joyce et al., 2004) and PERSIANN (Sorooshian et al., 2000) which are all available on a 0.25 × 0.25° spatial resolution and a 3-h temporal resolution. Rainfall estimates derived from the TRMM satellite have been collected since 1998 and are available as a real time product since early 2002, whereas CMORPH and PERSIANN data are available since 2003 and 2000, respectively. The TRMM Multisatellite Precipitation Analysis (TMPA) 3B42 Real Time (RT) product (hereafter referred to as TRMM)

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produces precipitation estimates by converting data from the TRMM Microwave Imager (TMI), Special Sensor Microwave/Imager (SSM/I) and the real time data from the Advanced Microwave Scanning Radiometer for the Earth Orbiting System (AMSR-E). Calibration is performed using the TMI sensor (Huffman et al., 2007). The Climate Prediction Center morphing (CMORPH) method from Joyce et al. (2004) estimates precipitation using only microwave data. PERSIANN (Precipitation Estimation from Remotely Sensed Information Using Neural Networks) uses infrared data as input to artificial neural networks (ANNs), and when available, ground based data to update the ANNs (Hsu et al., 1997).

To assess the accuracy of these remote sensing products, comparisons were performed between rainfall that has been measured on the ground, and rainfall which was estimated by the different satellite rainfall products. Since all three satellite products have real-time data since 2003, and ground station data after 2008 are incomplete, the selected study period was 2003 to 2008, 6 full years. Over this period, the data were aggregated to monthly totals, for all grid cells that cover Indonesia's land area (as well as the neighbouring countries of Malaysia, Singapore and Brunei, which are in the same rectangular frame; Fig. 1a). The monthly satellite data for the grid cells covering the validation areas were then averaged, weighted for the number of stations in each TRMM grid cell (Fig. 1b). Figure 4 shows the double mass curves for each of the individual validation areas, one for each satellite product investigated. It is evident that most products have a considerable bias although this bias is not always consistent between the individual validation areas. Overall, PERSIANN has the highest positive bias (overestimate) whereas CMORPH has the highest negative bias (underestimate). The TRMM bias is smallest in most cases, being either somewhat positive of somewhat negative in different areas. In each of the double mass curves a breaking point in the TRMM line is seen at approximately 4000–5000 mm which coincides with early 2005. This may be explained by the incorporation of additional rainfall intensity estimates, as derived from the AMSU-B and AMSR-E satellite instruments, from February 2005 onwards (Huffman and Bolvin, 2010). Although the validation period is too short to confidently quantify this change, it appears that TRMM data have become more accurate since 2005.

The annual and dry season relative bias (Eq. 1) for each of the products as well as rainfall total is shown in Tables 2 and 3. While different definitions of "dry season" exist in Indonesia (Wyrtki, 1956; Aldrian and Susanto, 2003), for different regions and purposes, we have defined it as June–October for the current study, the period over which the six validation areas had average monthly rainfall rates below 100 mm, which defines "dry" conditions *sensu* (Brünig, 1969; Oldeman et al., 1979, 1980). Relative bias on an annual basis varies between −12.8 to 12.6 for TRMM, −42.6 to 2.6 for CMORPH and −1.4 to 63.5 for PERSIANN (Table 2). Dry season relative bias is greater compared to the annual relative bias, ranging from −55.1 to 1.0 for TRMM, −55.6 to 8.7 for CMORPH and −63.7 to 9.5 for PERSIANN (Table 3).

$$\text{Relative bias (bias)} = \frac{\sum_{i=1}^{N} P_{\text{groundst.}(i)} - P_{\text{satellite}(i)}}{\sum_{i=1}^{N} P_{\text{groundst.}(i)}} \times 100 \quad (1)$$

where N is the number of months.

2.3 Spatial comparison of average annual rainfall from satellite products for Indonesia

For the Indonesian archipelago, maps of annual rainfall were generated using the three different satellite rainfall products. The relative differences between these maps are shown in (Fig. 5). Consistent difference patterns are evident when comparing TRMM and CMORPH. Near the coastlines, CMORPH underestimates precipitation by up to 50 % (decreasing with distance from the coast), as compared to TRMM, whereas further inland CMORPH overestimates precipitation by up to 50 % (especially in the mountainous area of Papua, Fig. 5a). Major differences are also evident when comparing

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TRMM and PERSIANN (Fig. 5b). However, in this case no consistent patterns are evident. It appears that PERSIANN greatly overestimates rainfall in Sumatra when compared with TRMM, whereas difference patterns elsewhere appear to be almost random.

2.4 Determining a bias correction equation for TRMM rainfall data

Comparison with ground station measurements showed the TRMM real time product to be the most accurate satellite rainfall product (Tables 2 and 3). Moreover, comparison with other satellite sources revealed large differences between the sources. The TRMM data were identified as the most suitable source of satellite rainfall information. However, there were differences with ground station data that may be reduced. We therefore obtained a bias correction equation to achieve a closer fit between monthly TRMM and ground station averages. A non-linear power function was applied in which each average monthly rainfall amount (P) is transformed into a bias corrected amount P^* using:

$$P^* = a \cdot P^b \tag{2}$$

The parameters a and b were derived by minimizing both the annual and dry season sum of average monthly differences between bias corrected and ground station measurements for all 6 validation areas together. The generalized reduced gradient algorithm (Fylstra et al., 1998) was used to obtain an optimized value of 3.20 for a and 0.79 for b. The distribution of average monthly rainfall over the year for ground station data and uncorrected and bias corrected TRMM data is shown in Fig. 6, and the monthly time series in Fig. 7. The average difference, relative bias, RMSE and correlation coefficients of the bias corrected TRMM rainfall are given in Tables 4 and 5 for each of the individual validation areas. The bias corrected TRMM data have a better fit with ground station data, with R^2 varying from 0.84 for both the Jakarta and Bogor area to 0.96 for East Java on an annual basis and improved RMSE in all cases, by 6 % for Banjar Baru to 24 % for Lampung (Table 4). For the dry season RMSE improved for

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4 of the 6 validation areas, by 12 to 26 % with R^2 ranging from 0.65 for Jakarta to 0.92 for East Java (Table 5).

3 Discussion

3.1 Comparison of different satellite rainfall estimates over Indonesia

Satellite rainfall products before bias correction tend to overestimate intense precipitation events quite significantly (Behrangi et al., 2011). It is therefore not surprising that uncorrected satellite data overestimate rainfall in almost all validation areas in the wet season, compared with ground station measurements, as is shown for TRMM in Fig. 7. The underestimation of the dry season estimates for TRMM may be explained by the difficulty of the precipitation radar in observing very low rainfall amounts, especially from high cirrus type clouds (Franchito et al., 2009). The spatial differences between the different satellite rainfall products are striking, but the underlying reasons for this have not been further explored as this was outside the scope of this study. All comparisons have shown the TRMM data to be more accurate than the two other products evaluated.

3.2 Suitability of bias corrected TRMM data for monthly rainfall monitoring

Although patterns in uncorrected TRMM rainfall closely resemble patterns in ground station rainfall in Indonesia, they consistently underestimate rainfall in dry periods (Table 3). When uncorrected TRMM data would be used for water resources management purposes, this underestimation of rainfall would introduce an overestimation of water deficits. After bias correction on a monthly basis, rainfall difference in ground station measurements and TRMM data over the dry season was greatly reduced for 5 out of 6 areas, which was reflected by an improved RMSE and higher correlation coefficients (Table 5). The bias correction has reduced the average difference between

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ground station and TRMM rainfall over the June–October "dry season" period from 83 to 18 mm, or only 4 mm month^{-1} on an average monthly rainfall amount of 77 mm. This is a distinct improvement, although greater deviations remain for individual areas: from 111 mm in Bogor to −89 mm for Banjar Baru. However on a monthly basis the latter deviations are still within 25 mm month^{-1}, which is tolerable in most water resources management applications especially if no superior dataset would be available locally.

On an annual basis, the bias reduction has removed the difference between ground station and TRMM rainfall as averaged over all areas. However, significant differences remain for individual areas, ranging from 287 mm yr^{-1} in East Java to −254 mm yr^{-1} in Lampung (Table 4). This is up to 15 % of the ~2000 mm yr^{-1} rainfall that these locations receive. For some water resources management applications, a smaller deviation would be preferable. However, it should be considered that for much of Indonesia, the low spatial coverage and variable quality of ground station records will not allow a better measurement of average rainfall over large areas. Moreover, we tentatively observed that TRMM rainfall estimates in the wet season seem to have much improved since 2005. We would therefore suggest that TRMM rainfall data may also be used for applications around the year, including the wet season, unless a superior set of ground station records is locally available.

It is recognised that the ground stations used in this validation do not cover all climatic regions of Indonesia (Aldrian and Susanto, 2003) and there is a structural undersampling in higher and forested areas. The latter is due to the simple fact that rainfall in Indonesia (but in other data sparse countries as well) is mainly measured in densely populated and deforested areas. Romilly and Gebremichael (2011) found that in some rainfall regimes encountered in six river basins of Ethiopia, satellite rainfall estimates depended on the elevation. Using a similar approach we find no apparent relationship between the bias ratio (TRMM precipitation estimate divided by average annual gauge precipitation, calculated for each individual measurement station) and elevation (Fig. 8, $R^2 = 0.0001$). Additionally, an independent check with measurements of the SACA dataset (Klein Tank et al., 2011) in the Northern Territory of Australia, shows that our

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bias correction also improved monthly (and annual) precipitation estimates (Fig. 9) in that region, which enhance additional confidence that the derived bias correction is applicable to the more remote areas of Indonesia and probably elsewhere in tropical South East Asia as well.

Maps of average annual and dry season rainfall, generated using bias corrected TRMM data, are presented in Fig. 10. This clearly shows the large spatial and temporal variation in rainfall that exists in Indonesia, with annual rainfall rates varying from above 3000 to below 1500 $mm\,yr^{-1}$, and with even greater relative differences in the dry season. The latter is even more apparent when comparing a relative wet dry season month (October 2007) with the same month in the 2006 El Niño year (Fig. 10c,d). Clearly such major variations necessitate the use of accurate and real time rainfall information in water resources management and crop planning. Moreover the availability of up-to-date maps of rainfall patterns will allow better long-term planning of activities. Examples are the optimization of reservoir dimensions and the location planning of agricultural activities that are very sensitive to drought. After all, the limited spatial coverage of ground stations, and the existence of climate change, does not allow us to assume that existing rainfall distribution maps based on historical ground station rainfall data are entirely accurate. It would be best to enhance such maps using up-to-date and accurate satellite data.

In addition to the bias correction of the TRMM data, it may be worthwhile to include remotely sensed soil moisture estimates (AMSR-E, ASCAT) to filter out any additional errors using for instance a data assimilation approach as discussed in Crow and Ryu (2009).

4 Conclusions

It was demonstrated that TRMM 3B42RT satellite rainfall data, after bias correction on a monthly basis, are sufficiently accurate to be used for real-time monitoring of rainfall in periods of potential drought, in support of water resources management, agriculture and fire prevention. A Drought Early Warning System (DEWS) for Indonesia is now being developed on this basis, which will produce data in the public domain. We propose that use of this data, after bias correction, may also benefit other countries that are prone to periodic water shortages and where a high spatial variation in rainfall rates can not be sufficiently monitored by ground stations alone.

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Table 1. Descriptive characteristics of the validation areas. Ground station data coverage for the period 2003–2008. Elevation determined from SRTM 90 m resolution (Jarvis et al., 2008). Forest and urban cover determined from GlobCover v2.2 regional land cover map over Southeast Asia (ESA, 2008). * including degraded forest and plantation forest.

Validation region	No. of grid cells	No. of ground stations	Ground station coverage	Avg. ground station elev.	Avg. area elev.	Distance from coast	Forest cover*	Urban cover
			% time	m	m	km	%	%
Jakarta	3	10	89	13	8	0–30	2.1	31.8
Bogor	4	10	99	354	331	30–90	25.7	10.6
Bandung	4	13	96	978	1050	30–90	40.1	9.1
East Java	6	15	91	492	619	0–60	29	0.5
Banjar Baru	6	15	83	19	52	90–180	51.2	0
Lampung	5	13	90	83	120	0–60	15.3	0.4

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Table 2. Average annual precipitation (P, in mm) and relative bias over the period 2003–2008 for ground stations, and satellite products TRMM 3B42RT, CMORPH and PERSIANN.

Validation region	Ground stations	TRMM		CMORPH		PERSIANN	
	P	P	rel. bias	P	rel. bias	P	rel. bias
Jakarta	2010	1865	−7.2	1155	−42.6	2524	25.5
Bogor	3056	2944	−3.7	2246	−26.5	3087	1.0
Bandung	1723	1936	12.3	1690	−1.9	2806	62.9
East Java	2106	1835	−12.8	1417	−32.7	2077	−1.4
Banjar Baru	2208	2217	0.4	2264	2.6	2783	26.1
Lampung	1946	2191	12.6	1695	−12.9	3182	63.5

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Table 3. Average dry season (June–October) precipitation (*P*, in mm) and relative bias over the period 2003–2008 for ground stations, and satellite products TRMM 3B42RT, CMORPH and PERSIANN.

Validation region	Ground stations	TRMM		CMORPH		PERSIANN	
	P	*P*	rel. bias	*P*	rel. bias	*P*	rel. bias
Jakarta	319	276	−13.5	261	−18.1	349	9.5
Bogor	715	539	−24.6	400	−44.1	375	−47.5
Bandung	286	204	−28.7	169	−41.1	207	−27.5
East Java	166	75	−55.1	74	−55.6	60	−63.7
Banjar Baru	462	467	1.0	502	8.7	423	−8.5
Lampung	367	255	−30.3	237	−35.4	377	3.0

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Table 4. Annual ground station and TRMM precipitation (P, in mm), average difference, relative bias (to observations), RMSE and correlation coefficients before and after bias correction of TRMM 3B42RT precipitation estimates over the period 2003–2008.

Validation region	Gr. st.	TRMM					TRMM bias corr.				
	P	P	Avg. diff.	rel. bias	RMSE	R^2	P	Avg. diff.	rel. bias	RMSE	R^2
Jakarta	2010	1865	145	−7.2	83.8	0.84	1918	92	−2.2	78.2	0.84
Bogor	3056	2944	112	−3.7	94.9	0.83	2845	211	−4.6	79.8	0.84
Bandung	1723	1936	−213	12.3	85.8	0.84	1965	−242	16.9	71.6	0.86
East Java	2106	1835	271	−12.8	56.0	0.95	1819	287	−11.5	49.3	0.96
Banjar Baru	2208	2217	−9	0.4	59.6	0.84	2303	95	7.0	56.0	0.85
Lampung	1946	2190	−244	12.6	83.8	0.89	2200	−254	15.9	63.6	0.90
Avg. total	2175	2165	10				2175	0			

Table 5. Dry season (June–October) ground station and TRMM precipitation (*P*, in mm), average difference, relative bias (to observations), RMSE and correlation coefficients before and after bias correction of TRMM 3B42RT precipitation estimates over the period 2003–2008.

Validation region	Gr. st.	TRMM					TRMM bias corr.				
	P	*P*	Avg. diff.	rel. bias	RMSE	R^2	*P*	Avg. diff.	rel. bias	RMSE	R^2
Jakarta	319	276	43	−13.5	50.5	0.62	340	−21	6.6	51.2	0.65
Bogor	715	539	176	−24.6	72.9	0.78	604	111	−15.4	64.1	0.79
Bandung	286	204	82	−28.7	33.9	0.87	265	21	−7.3	29.7	0.87
East Java	166	75	91	−55.1	31.8	0.91	114	52	−31.3	23.6	0.92
Banjar Baru	462	467	−5	1.0	36.0	0.85	551	−89	19.3	40.2	0.85
Lampung	367	255	121	−30.3	39.9	0.71	336	31	−8.4	32.2	0.77
Avg. total	386	303	83				368	18			

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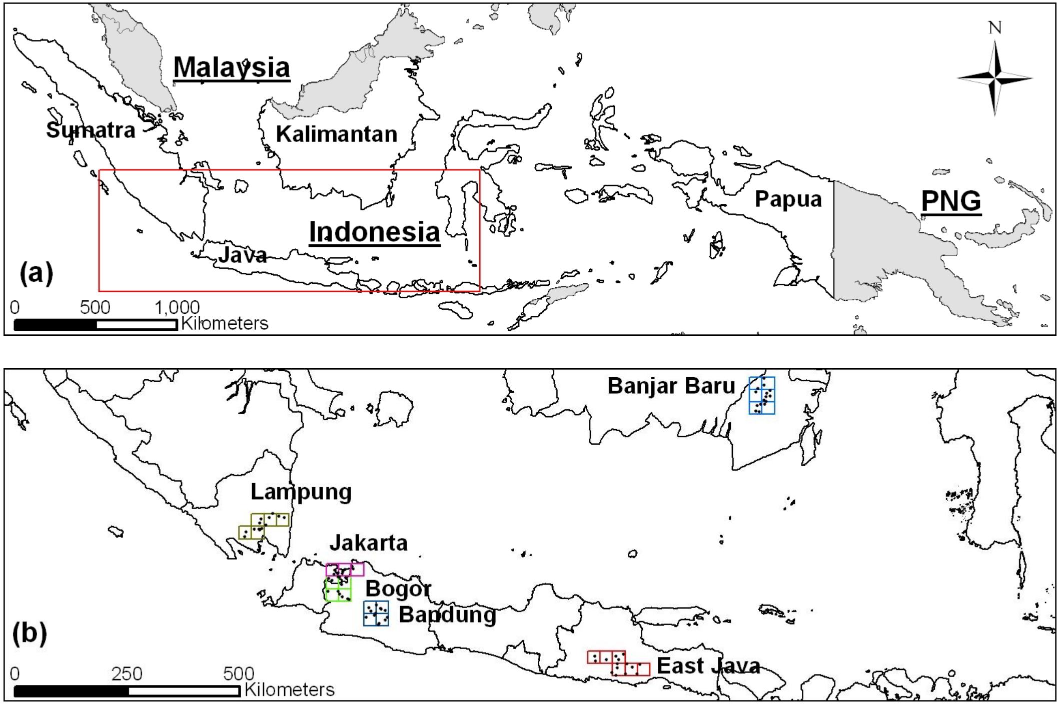

Fig. 1. (a) Map of Indonesia (and Malaysia, Brunei, Singapore, Papua New Guinea (PNG) and East Timor, grey areas). The red box is shown in more detail in **(b)**. **(b)** TRMM validation areas indicated in different colours. Each square represents one satellite grid cell of 0.25 × 0.25°. The black dots are the locations of the ground stations.

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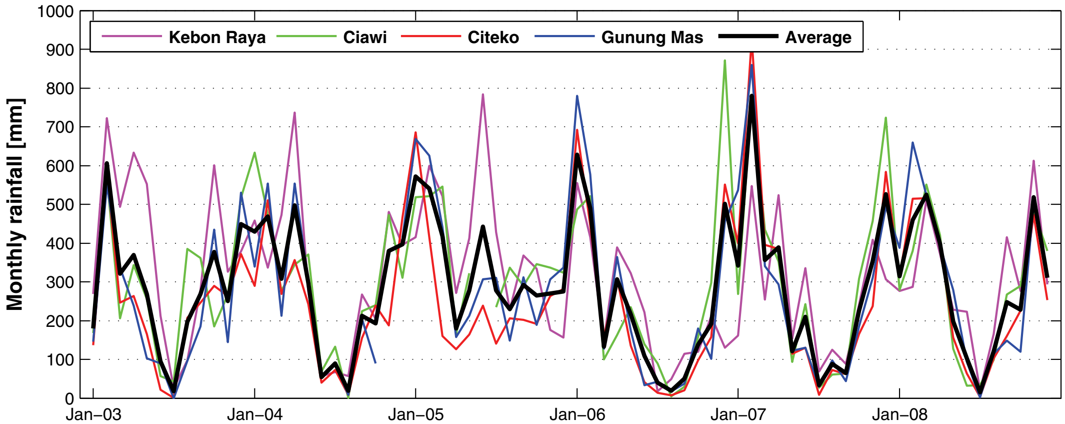

Fig. 2. Monthly ground station rainfall records for the period 2003–2008 in a single satellite grid cell, around Bogor.

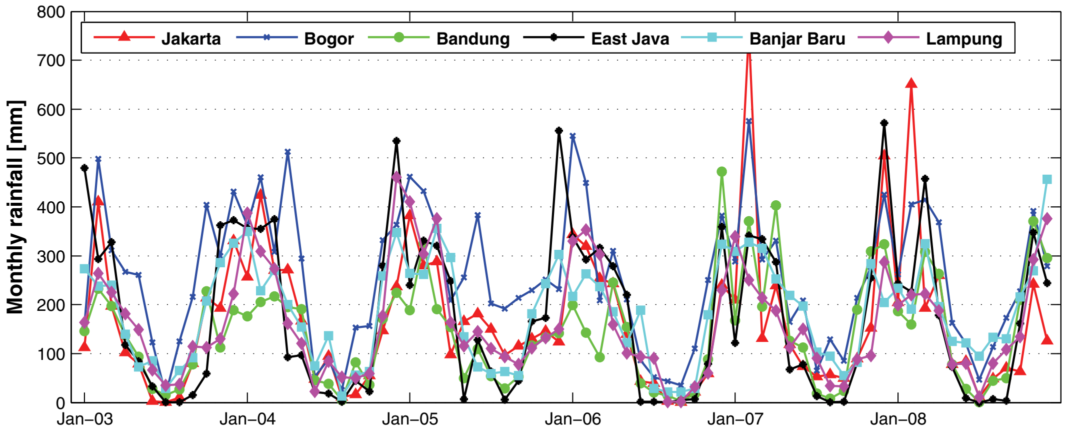

Fig. 3. Average monthly ground station rainfall for the six validation areas for the period 2003–2008.

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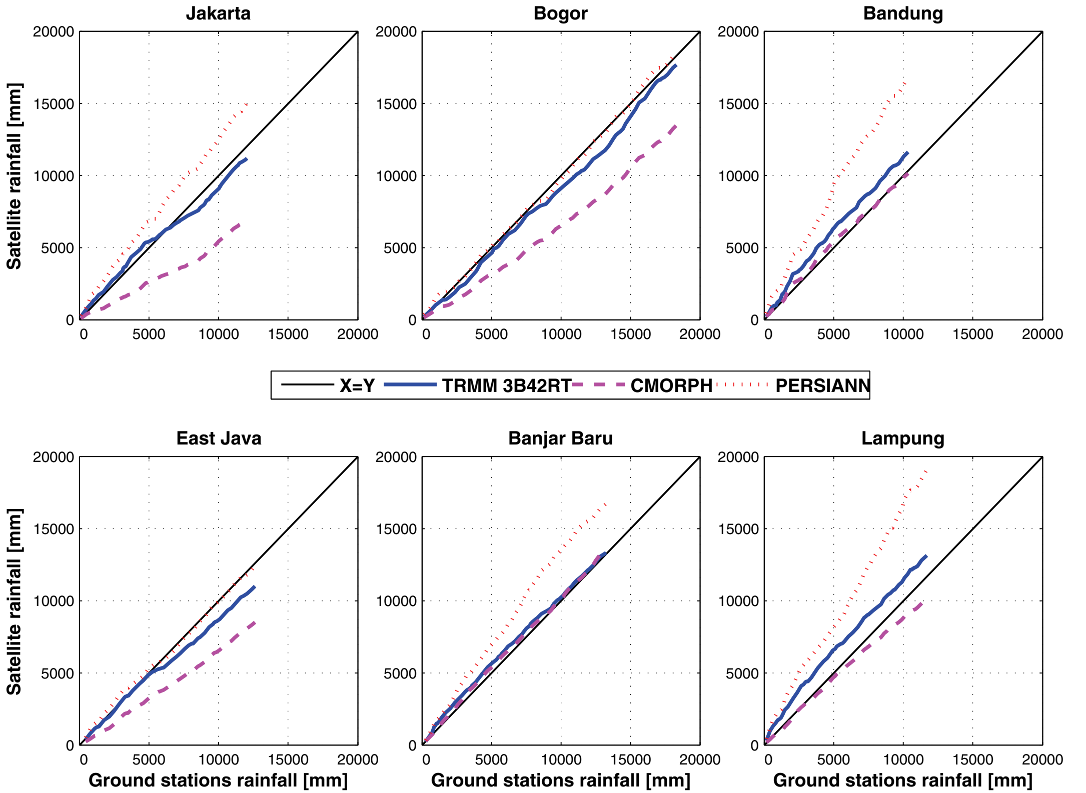

Fig. 4. Double mass curves showing the accumulated amount of rainfall of the observations against the satellite estimates (TRMM 3B42RT, CMORPH and PERSIANN) for each of the six validation areas for 2003–2008.

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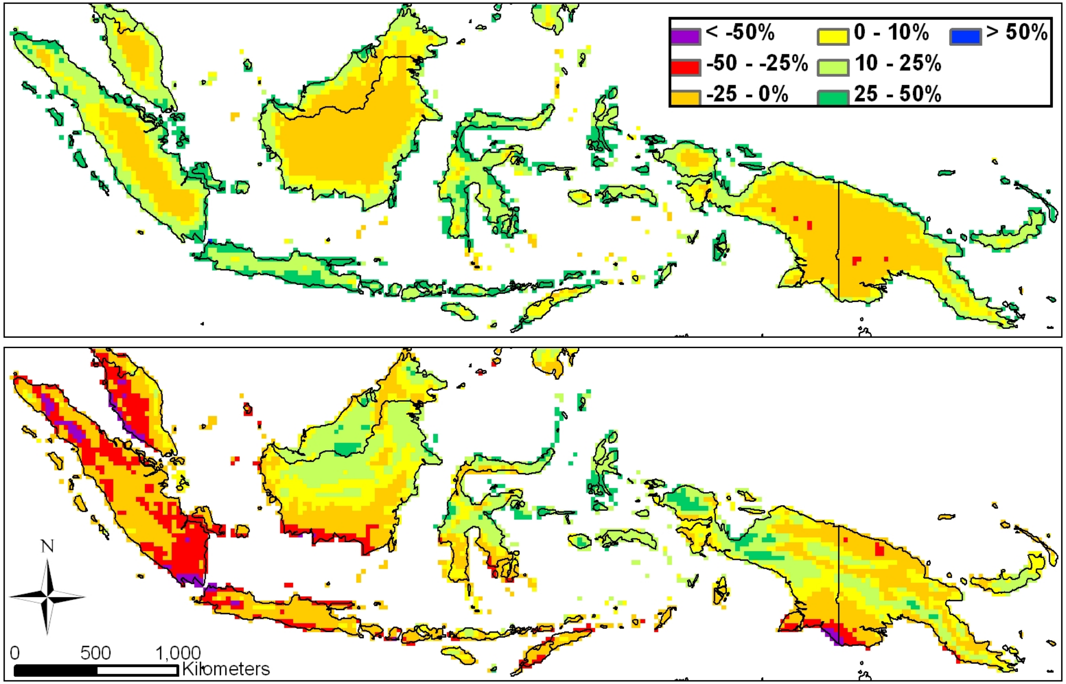

Fig. 5. Relative difference in annual average rainfall over the period 2003–2008 between TRMM 3B42RT and CMORPH (top panel) and TRMM 3B42RT and PERSIANN (lower panel).

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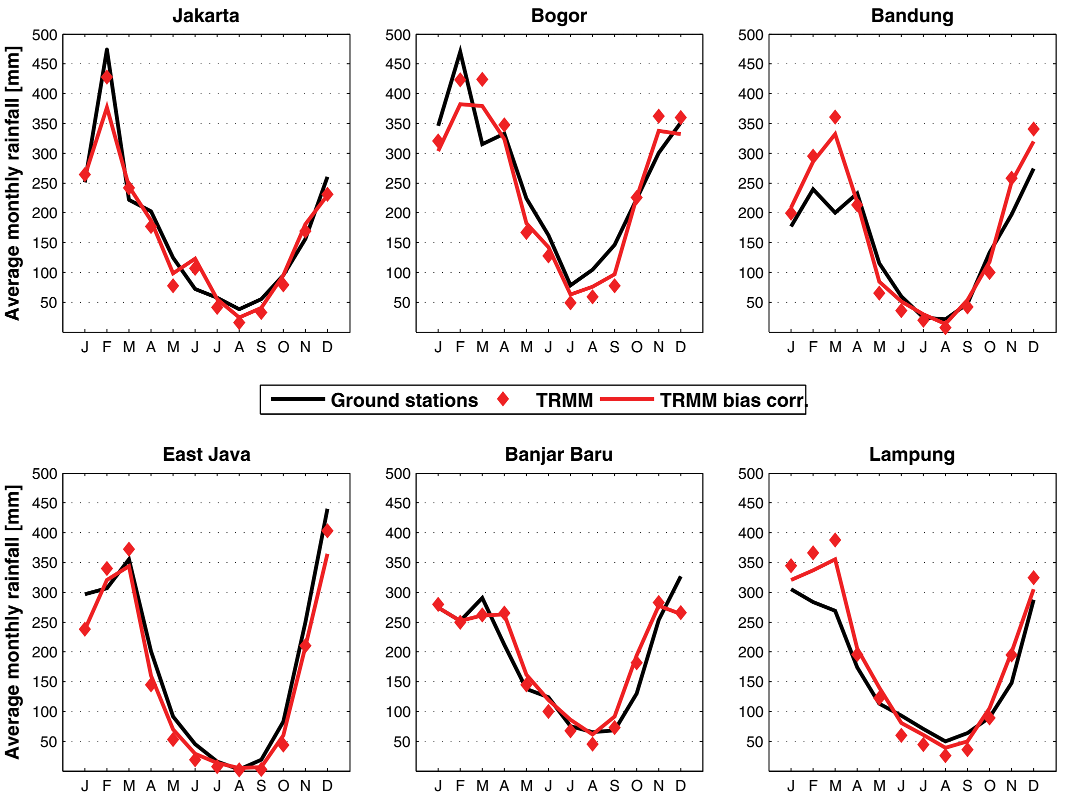

Fig. 6. Average monthly bias corrected TRMM data over 2003–2008, compared with ground station and uncorrected TRMM data.

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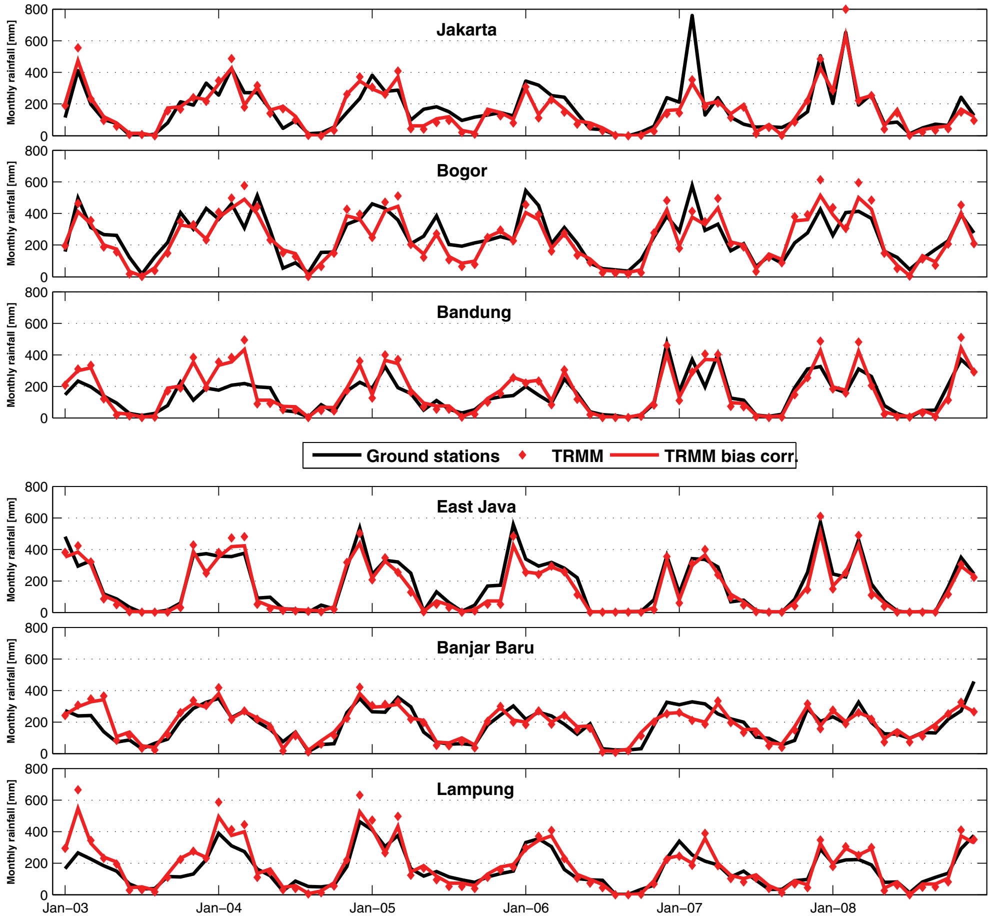

Fig. 7. Comparison of average monthly ground station rainfall with bias corrected and uncorrected TRMM 3B42RT for the individual validation areas.

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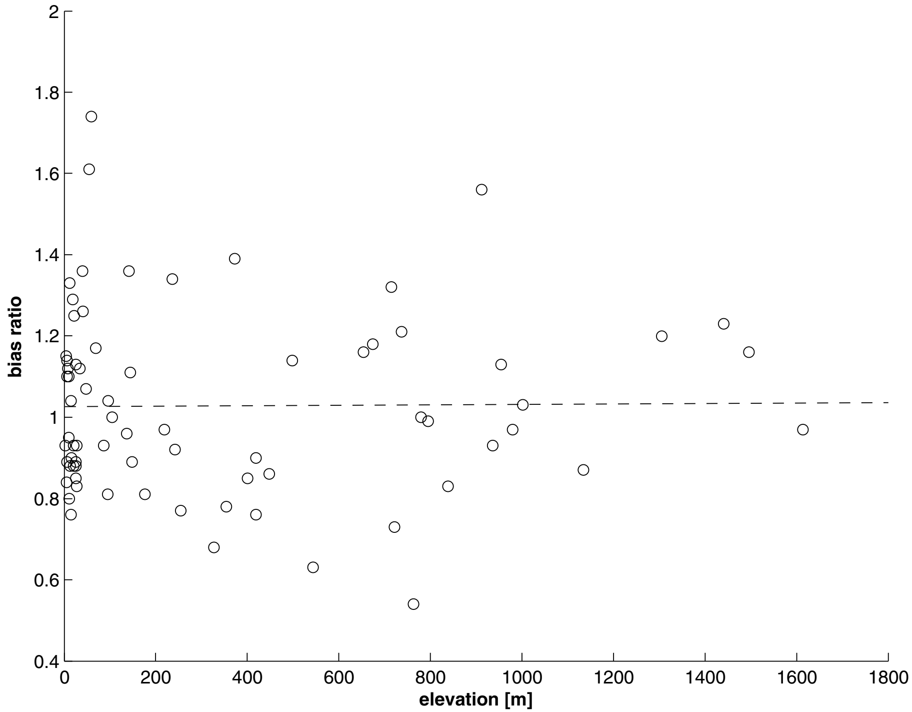

Fig. 8. Bias ratio vs. elevation for the individual ground stations in the six validation areas ($R^2 = 0.0001$, $n = 73$; of the 76 available stations (Table 1), 3 did not have any full year of validated observations).

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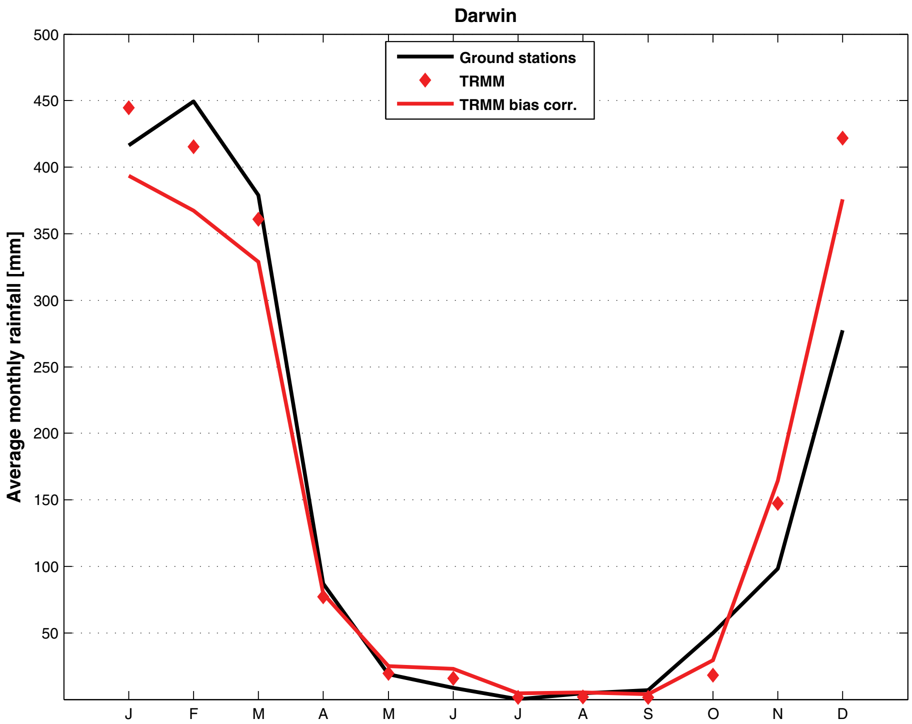

Fig. 9. Average monthly corrected TRMM data over 2003–2008, compared with ground station and uncorrected TRMM data for a TRMM grid cell in the Northern Territory (Darwin), Australia. Average annual precipitation 4 ground stations (Darwin airport, Karama, Leanyer and Shoal Bay) = 1797 mm, average annual uncorrected TRMM = 1926 mm and average annual bias corrected TRMM = 1801 mm. R^2 uncorrected TRMM = 0.90; R^2 bias corrected TRMM = 0.91; RMSE uncorrected TRMM = 94.8; RMSE bias corrected TRMM = 85.6.

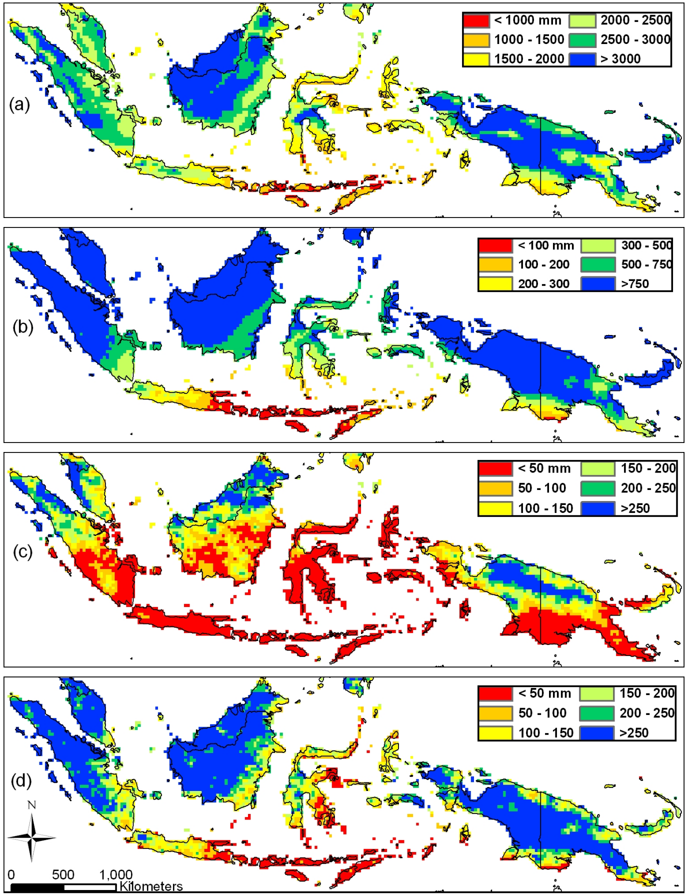

Fig. 10. **(a)** Average annual and **(b)** dry season (June–October) rainfall as determined from monthly bias corrected TRMM 3B42RT over 2003–2008 as well as **(c)** October 2006 and **(d)** October 2007 bias corrected TRMM 3B42RT rainfall.

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