Calibration of TRMM rainfall climatology over Saudi Arabia during 1998–2009

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ARTICLE INFO

Article history:
Received 13 May 2010
Received in revised form 9 November 2010
Accepted 9 November 2010

Keywords:
Rainfall climatology
Saudi Arabia
Arabian Peninsula
TRMM
Calibration

ABSTRACT

The short-term rainfall climatology regime over Saudi Arabia is obtained from the Tropical Rainfall Measuring Mission (TRMM) data for the period 1998–2009. The TRMM rainfall amounts are calibrated with respect to the rain-gauge data recorded at 29 stations across the country. Day-to-day rainfall comparisons show that the TRMM rainfall trends are very similar to the observed data trends, even if a general overestimation in the satellite products must be highlighted. Besides, especially during the wet season, some of the TRMM algorithm runs tend to underestimate the retrieved rainfalls. The TRMM rainfall data also closely follow the observed annual cycle on a monthly scale. The correlation coefficient for rainfall between the TRMM and the rain-gauge data is about 0.90, with a 99% level of significance on the monthly scale.

The spatio-temporal distributions of rainfall over Saudi Arabia are analyzed. Besides the four conventional seasons, this analysis considers the wet (November–April) and dry (June–September) seasons, based on the rainfall amounts recorded. Spring is the highest and winter is the second highest rainfall-occurring season, resulting in large amounts of rainfall during the wet season over most of the country. Regional variations in the rainfall climatology over Saudi Arabia are studied through defining four regions. The false alarm ratio, probability of detection, threat score, and skill score are calculated to evaluate the TRMM performance. The country’s average annual rainfall measured by the TRMM is 89.42 mm, whereas the observed data is 82.29 mm. Thus, the rainfall in Saudi Arabia is suggested as being the TRMM value multiplied by 0.93 plus 0.04. After this calibration, the TRMM-measured rainfall is almost 100% of the observed data, thereby confirming that TRMM data may be used in a variety of water-related applications in Saudi Arabia.

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1. Introduction

In arid and semi-arid areas, rainfall storms exhibit strong spatial variability, especially during heavy thunderstorms and localized torrential rainstorms (Habib and Nasrollahi, 2009; Alyamani and Sen, 1993). However, many of these areas worldwide suffer from limited surface rainfall monitoring stations (Ragab and Prudhomme, 2002). Alternative monitoring methods, such as those based on remote-sensing satellite techniques, can be a significant source of data collection in those regions. The purpose of this study is to assess the accuracy of one such remote sensing detector, the Tropical Rainfall Measuring Mission (TRMM), in estimating rainfall over Saudi Arabia.

Rainfall is a critical meteorological parameter and needs to be measured accurately; many applications of rainfall data can be studied in depth through knowledge of the actual distribution of rainfall. Additionally, the amount of rainfall received over an area is an important factor in assessing the amount of water available to meet the various demands of agriculture, industry, and other human activities. The Inter-Governmental Panel on Climate Change (IPCC) in 2007 concluded that more intense precipitation events would very likely occur in the future over many areas, and that these would thus cause increased flash-floods, landslides, soil erosion and avalanches (IPCC, 2007).
The study of the spatio-temporal distribution of rainfall is therefore very important for the welfare of a national economy. Reliable estimation of rainfall distribution in Saudi Arabia poses a great challenge, not only due to undulating surface terrain and complex relationships between land elevation and precipitation, but also due to the lack of a sufficient number of rainfall measurement points. The existing low-density rain-gauge network over the country (Fig. 1) is not adequate enough for obtaining accurate spatial distribution data of the rainfall. Installation and maintenance of a dense rain-gauge network would be difficult in hilly and remote desert areas. In this case, the utilization of remote-sensing technology is a better way of estimating rainfall for wide as well as for remote areas.

Abdullah and Al-Mazroui (1998) studied the rainfall in the south-western region of Saudi Arabia, and discussed the rainy seasons and the aridity of the area. Subyani (2004) studied the annual and seasonal mean rainfall patterns in south-western Saudi Arabia. Rehman (2010) analyzed rainfall for a single station (Dhahran), and reported a constant trend during the period 1970–2006. The monthly precipitation total for a 21-year period was analyzed by Abouammoh (1991) to compare the rainfall regimes at seven stations in order to determine the rainfall distribution in Saudi Arabia. Al-Jerash (1985) studied the climate of Saudi Arabia using Principal Component Analysis, and Ahmed (1997) used a multivariate technique, factor-cluster analysis, for a better understanding of Saudi Arabian climates. Abdurazzak et al. (1989) studied water balance conditions for Tabalah (Saudi Arabia). However, there has been no complete work dedicated to utilizing the TRMM data in order to estimate rainfall over Saudi Arabia, to develop rainfall climatology, or to study its distribution on regional and seasonal scales.

The primary function of the TRMM (Kummerow et al., 2000; Simpson et al., 1988) Ground Validation (GV) program at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) is to provide ground-based surface rainfall estimates for validating satellite-derived precipitation retrievals from the TRMM (Wolff et al., 2005; Robinson et al., 2000). Besides this GV program, the TRMM rainfall is calibrated with rain-gauge data from different Asian countries; India (Brown, 2006), Thailand (Chokngamwong and Chiu, 2006), Bangladesh (Islam and Uyeda, 2007), and Nepal (Islam et al., 2010). Habib and Nasrollahi (2009) used the TRMM Multi-Sensor Precipitation Product (TMPA-3B42) across several arid and semi-arid areas over the western coast of Saudi Arabia, the Sinai Peninsula in Egypt, and Yemen. They found that there are considerable discrepancies between the gauge measurements and the TMPA estimates at the daily scale. However, monthly comparisons between the two sources show a better correlation and probability of detection.

Most parts of Saudi Arabia are classified as hot and dry (Köppen, 1936), where rainfall is irregular and the climate is characterized by high temperatures (Al-Jerash, 1985; Al-Tahir, 1994). However, the south-western region of the country is classified as semi-arid (Köppen, 1936). This region is characterized by having rainfall throughout the year, where the topography enhances local convective rain (Al-Mazroui, 1998; Abdullah and Al-Mazroui, 1998).

Occasional heavy rainstorms occur on only a few days in a year and only in some parts of the country. This seldom-received rain makes Saudi Arabia one of the driest countries in the world. The Rub Al-Khalii (Empty Quarter) is the largest continuous expanse of sand desert in the world (Atlas, 1984), and is located in the eastern and south-eastern parts of Saudi Arabia. With the exception of the south-western coast, the Saudi Arabian climate is characterized by extreme heat during the day, an abrupt drop in temperature at night, and slight, erratic rainfall. However, because of the influence of the regional subtropical high-pressure system, and the many fluctuations in elevation, there are considerable variations in temperature and humidity across Saudi Arabia.

The two main extremes in climate are felt between the coastal lands and the interior. The south-western region is subject to the influence of the Indian Ocean monsoons, usually occurring between October and March. An average of 300 mm of rainfall occurs during this period, which is 60% of the annual total (Climate, 2010). Additionally, in this region, condensation caused by the higher mountain slopes contributes to the total precipitation. For the rest of the country, rainfall is low and erratic. The rainfall usually consists of one or two high-intensity, short-duration thunderstorms. Even a small storm with little precipitation can produce flash flooding because the Saudi Arabian desert soil does not soak up water very easily. Dry wadis (ravines) can quickly turn into raging rivers during and after heavy rains.

In the cities, low points in roads and highways can quickly fill with floodwaters, trapping unsuspecting motorists, for example, the historically severe flooding that occurred in Jeddah on 25th November, 2009 (GES, 2009). Although the mean annual rainfall is 79 mm (Qureshi and Khan, 1994), whole regions of the country may not experience rainfall for several years. When such droughts occur, affected areas may become incapable of sustaining either livestock or agriculture. With limited natural water resources, the country has had no choice but to resort to drilling wells for underground water and to desalinating seawater in order to provide its increasing
population with the water they need. In such a situation, the ability to estimate rainfall throughout the country, in the different seasons and regions, would be very useful for agriculture, infrastructural development, and water resource management.

In this paper, efforts have been made to utilize remote-sensing technology in order to estimate the rainfall over Saudi Arabia. This work is conducted through calibrating the TRMM rainfall with reference to the observed data, for utilization in application-oriented tasks. This study also illustrates how satellite data can be used to observe changes in the seasonal and regional climate in dry regions, such as Saudi Arabia, where traditional measurement instruments are sparse.

2. Data and methods

2.1. Data used

Daily rainfall data collected by the Presidency of Meteorology and Environment (PME) at 29 stations over Saudi Arabia are used in this study. The rain-gauge station names, together with latitude, longitude, altitude (m) and annual rainfall amount (mm), are presented in Table 1. The rain-gauge network over the country is displayed in Fig. 1. The asterisks represent the locations of the rain gauges, and the numbers are serial as per Table 1. The data for one station (No. 25, Table 1) are not used due to 100% missing values during the study period (1998–2009).

The TRMM is a joint US–Japan satellite mission for monitoring tropical and subtropical precipitation, and for estimating its associated latent heat. The TRMM was successfully launched on 27th November, 1997 from the Tanegashima Space Center in Japan (Kummerow et al., 1998). The TRMM includes a number of precipitation-related instruments, such as a precipitation radar, a visible and infrared sensor (VIRS), and a SSM/I-like TRMM microwave imager (TMI) (Kummerow et al., 2000). The purpose of the 3B42 class of algorithm (Huffman et al., 2007) is to produce TRMM-adjusted merged-infrared (IR) precipitation and root-mean-square (RMS) precipitation-error estimates.

The algorithm consists of two separate steps. The first step uses the TRMM VIRS and the TMI orbit data (TRMM products 1B01 and 2A12), and the monthly TMI/TRMM Combined Instrument (TCI) calibration parameters (from TRMM product 3B31) to produce monthly IR calibration parameters. The second step uses these derived monthly IR calibration parameters to adjust the IR precipitation data, which consists of GMS, GOES-E, GOES-W, Meteosat-7, Meteosat-5, and NOAA-12 data. The final gridded Version 6 of the 3B42 product (henceforth referred to simply as TRMM) is a 0.25° grid-mesh dataset based on multi-satellite precipitation analysis (Huffman et al., 2004). Details of the algorithm can be found in Huffman and Bolvin, 2009; Iguchi et al., 2009; Huffman et al., 2007; and Dinku and Anagnostou, 2006. The TRMM spatial coverage extends from 50° S to 50° N.

2.2. Analysis procedure

Among the interpolation methods described in the literature, ordinary Kriging and modified residual Kriging are attractive because of their simplicity and ease of use (Prudhomme and Reed, 1999). However, there are only 29 stations over the varied topographic variations of Saudi Arabia (Fig. 1), and so none of them are useful in gridding rain-gauge rainfall. This is the reason that rainfall data obtained from the TRMM near the closest point to a station’s location in a 25 km grid box are compared with the data from that same rain gauge. The rain gauge situated in a grid box represents the observed amount corresponding to the TRMM measured rainfall in that grid. A comparison of the TRMM day-to-day rainfall with the rain-gauge data for each observation site is then carried out. Following this, the monthly, seasonal, annual and long-term amounts obtained from both the data sources are compared.

Regression analysis is performed using the TRMM and observed data on a daily basis. Regression slopes and constants are useful for calibration purposes. The Pearson correlation coefficient is obtained for the rainfall measured by the TRMM and each rain gauge. The performance of the TRMM algorithm is characterized into three basic categories (Brown, 2006): underestimation, overestimation and approximately equal (within ±10%). To understand the TRMM performance, the following performance-indices are also calculated for all the stations mentioned in Table 1:

\[
FA = \frac{FA}{H + FA}
\]

(1)

\[
POD = \frac{H}{H + M}
\]

(2)

\[
TS = \frac{H}{H + FA + M}
\]

(3)

\[
SS = \frac{(Z^*H - FA*M)}{(Z + FA)*(M + H)}
\]

(4)

Table 1

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<th>No.</th>
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<th>Altitude (m)</th>
<th>Annual Rainfall (mm)</th>
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where $FAR$ is the false alarm ratio, $POD$ is the probability of detection, $TS$ is the threat score, and $SS$ is the skill score. The $FA$ is the number of false alarms, $H$ is the number of hits, $M$ is the number of misses, and $Z$ is the number of zeros (Barros et al., 2000; Islam et al., 2010). The days with rainfall $\geq 1$ mm are defined as rainy days. The traces in the observed data are not considered as rainy days, and rainfall $0.1$ mm/day measured by both data sources are excluded because the rain-gauge data use a minimum value of 0.1 mm/day for observations.

Three-month averages for meteorological parameters such as temperature and rainfall are used to define the seasonal climate (AMS, 2001) for the various regions of Saudi Arabia. Accordingly, four seasons are defined as follows: the winter is December through February (DJF); the spring is March through May (MAM); the summer is June through August (JJA); and the autumn is September through November (SON). Almazroui (2006) defined only two seasons based on the synoptic conditions in Saudi Arabia. He defined the wet and dry seasons from October through May, and from June through September, respectively. In the study area, rainfall mainly occurs during the wet season, whereas the dry season is almost entirely rainless except for the south-western part of the country.

Thus, in this work, six seasons are considered: the conventional four seasons (Winter, Spring, Summer and Autumn), and the wet and dry seasons. Due to the few rainfall events occurring in October and May, these months are considered here as transition months, from the dry to the wet, and from the wet to the dry seasons, respectively. Therefore, the wet season is defined here as being only from November through April.

3. Results

3.1. Spatio-temporal distribution of rainfall over Saudi Arabia, as observed from the TRMM

3.1.1. Monthly rainfall distribution over Saudi Arabia

The spatial distribution of monthly rainfall (mm) in and around Saudi Arabia is displayed in Fig. 2a. The rainfall is obtained from the TRMM data, averaged over 1998–2009. The rainfall observed in the northern regions occurred during November through April; these are wet months, as defined above in this analysis. The rainfall observed in the southern regions occurred during June through September; these are dry months.
During the wet season, events sometimes also prevail from the southwest (e.g. January and April, Fig. 2a). However, during the dry season, there is no rain-producing system to the north. To confirm this observation, the January and July rainfall distribution data for three consecutive years from 1998 are presented in Fig. 2b. In January, rainfall occurred in the southern regions in 1998 and 1999, however there was no rain in 2000. On the other hand, July shows no rain in the northern regions for all three years.

3.1.2. Seasonal rainfall distribution over Saudi Arabia

The rainfall distribution data for the winter, spring, summer, autumn, dry and wet seasons are displayed in Fig. 3. The summer and dry seasons show similar characteristics; there is no rain over Saudi Arabia except in the south-western regions, which is due to the strong south-westerly low-level winds, and to strong orographic effects (Atlas, 1984). During the winter, spring and autumn seasons, rainfall occurred in most parts of the country, which contributed towards the rainfall pattern in the wet season. In this season, the rainfall is enhanced by the moisture advected from both the Red Sea and Arabian Sea (Almazroui, 2006). Study of the development of precipitation systems is outside the scope of this paper; here we examine the performance of a remote-sensing data collecting device in documenting the short-term rainfall climatology over the country.

3.1.3. Annual rainfall distribution over Saudi Arabia

In general, the annual rainfall varies from year to year and from place to place. As an example, Fig. 4a displays the annual rainfall (mm) distribution for three consecutive years from 2006. The rainfall occurred all over the country in 2006, even though in some places the amounts were too small for this study. In 2007, the western regions of Saudi Arabia were dry, and in 2008 no rain was observed in the eastern regions, which is climatologically typical in this country. The spatial distribution of the rainfall (mm) over Saudi Arabia, averaged over 1998–2009, is displayed in Fig. 4b. It is clear that the rainfall amounts are large in two regions of the country; one is in the south-western zone along the coast of the Red Sea, and the other is from the northern Arabian Gulf down to the central parts of Saudi Arabia.

Two dry zones are very clear; one in the eastern part, and another is located in the north-west. Some pockets of large amounts of rainfall were identified by TRMM in various parts of the country, but which were not detected using rain gauges. However, the performance of the TRMM in estimating rainfall over Saudi Arabia must be verified before utilizing it in any application, which is performed in Subsection 3.4.2.

3.1.4. Comparison of the day-to-day rainfall

The comparison of the daily rainfall (mm/day) obtained from the TRMM and rain gauges averaged over 1998–2009 is displayed in Fig. 5. The patterns are well matched with each other.

Fig. 3. The spatial distribution of seasonal rainfall (mm) obtained from the TRMM data in left to right panels are for winter (DJF), spring (MAM), summer (JJA), autumn (SON), as well as for the wet (NOV–APR) and dry (JUN–SEP) seasons, averaged over 1998–2009.
other, even though the TRMM underestimated the rainfall on some days and overestimated on others.

Overall, the TRMM can detect most of the rainy days with reference to the observed data on a country-wide scale. To assess the level of missing and false detection data recorded by the TRMM sensor and the algorithm, an inspection of the rainfall measuring instruments in some selected stations was considered necessary. Examples of the comparison of the daily rainfall obtained from the TRMM and from the observed data over different sites of the country (at a coastal station, a high-elevation station, and a station on the plains) are discussed in the following paragraphs.

Al-Jouf Observatory (station No. 4, Table 1; Fig. 1) is located in the NW region at an altitude of 670 m above mean sea level (msl). In this region, the Mediterranean disturbance brings rainfall during wet season. In 2000, the rain gauge

Fig. 4. a. The spatial distribution of annual rainfall (mm) obtained from the TRMM data for the years 2006, 2007 and 2008. b. The distribution of annual rainfall (mm) obtained from the TRMM and averaged for the analysis period 1998–2009.

Fig. 5. Day-to-day comparison of rainfall (mm/day) obtained from the TRMM and observed data. The rainfall is averaged on each day during 1998–2009 from all analyzed stations.
recorded 14 rainy days, and of those, 11 had rainfall $\geq 1$ mm/day and 3 days had $<1$ mm/day (Fig. 6a). This year, the TRMM detected 14 rainy days, of which 5 had $<1$ mm/day. The TRMM detection of rainy days matched rain-gauge data on most of these days, however the TRMM missed 2 days and falsely detected 1 day. The TRMM also failed to quantify the large amount of rainfall on 17th October 2000.

Al-Qaysumah (station No. 7, Table 1; Fig. 1) is located in the NE region at an altitude of 360 m above msl. The rainfall of this region is influenced by the Arabian Gulf. In 2000, the TRMM detected 15 rainy days ($\geq 1$ mm/day) out of 17 recorded by the rain gauge (Fig. 6b). On most of the rainy days, both the data sources are overlapping except for a few mismatches.

Fig. 6. The comparison of the daily rainfall (mm/d) at a) Al-Jouf in 2000, b) Al-Qaysumah in 2000, c) Sharurah in 2003, d) Jeddah in 2003, e) Khamis Mushait in 2006 and f) Wadi-Alwasser in 2006. The TRMM rainfall extracted at the selected sites are used in this comparison.
Sharurah (station No. 29, Table 1; Fig. 1) is located in the SE region at an altitude of 727 m above msl. In reality, the characteristics of rainfall at Sharurah are similar to those in the SW region (see Table 1). In these regions, rainfall occurs during both the wet and dry seasons. Therefore, this station is to be considered in SW even though it is located in SE for the purposes of this analysis. In 2003, the TRMM detected 10 rainy days ($\geq 1$ mm/day) out of the 12 recorded by the rain gauge (Fig. 6c). Again, on most of the rainy days, both measurements could be overlapped except for a few mismatches.

Jeddah (station No. 19, Table 1; Fig. 1) is located on the coast of the SW region at an altitude of 18 m above msl. The rainfall in the Jeddah area is heavily influenced by the Red Sea. In 2003, the rain gauge recorded 5 rainy days ($\geq 1$ mm/day) and the TRMM also reported the same days, though some days with rainfall of $< 1$ mm/day (Fig. 6d). The TRMM hugely underestimates the rainfall on 7th November 2003.

Khamis Mushait (station No. 26, Table 1; Fig. 1) is a high-altitude station (2047 m) compared to Jeddah but is also located in the SW region. The Indian Ocean monsoon influences the rainfall of this region. In 2006, the TRMM measured a rainfall amount $\geq 1$ mm/day on 24 days, and the rain gauge recorded the same for 25 days (Fig. 6e). On some days, the TRMM measured rainfalls do not match with the observations, and the TRMM hugely underestimates the rainfall on 30th July 2006.

Wadi Aldawasser (station No. 24, Table 1; Fig. 1) is located in a valley of the SW region at an altitude of 617 m above msl.

In 2006, the TRMM measured a rainfall amount of $\geq 1$ mm/day on 5 days, whereas the rain gauge recorded the same for 3 days (Fig. 6f).

In general, this comparison of the daily rainfall data obtained from the TRMM and the rain gauges at the different locations shows that most of the rainy days are common to both measurement tools, with some missing values and false detections. As the TRMM data are extracted from a 25 km grid box (the one nearest to the observation site), some mismatches are expected to occur between the two data sources. Also, the TRMM algorithm may suffer from problems related to microwave signals over sandy desert areas (Habib and Nasrollahi, 2009). Moreover, the retrieval algorithm may not be sufficient to filter out any emissivity over the bare stone hills and sandy coastal areas of Saudi Arabia. Details of the TRMM performance and the false detections are discussed in Subsection 3.4.2.

### 3.1.5. Comparison of the monthly rainfall

The monthly rainfall (mm) obtained from the TRMM data is compared with the rain-gauge data (Fig. 7). The rainfall of each month is averaged over 1998–2009, both from the TRMM data and from all the analyzed stations. The TRMM follows the annual cycle well, with overestimations during...
February through October and underestimations during November through January. These results are consistent with the overestimations of rainfall in the dry season and underestimations in the wet season in Bangladesh, even though the months are different for the wet and dry seasons (Islam and Uyeda, 2007). On the annual scale, the rain-gauge value is about 6.56 mm/month, whereas the TRMM measured about 7.35 mm/month, an error of 12.05%.

The correlation coefficient ($r$) of the rainfall between the TRMM and the rain-gauge data obtained each month is displayed in Fig. 8. The correlation coefficient is significant ($>0.4$) for all months; it lies between 0.53 and 0.96, and on average it is about 0.83. This indicates that there is good linkage between the two data sources, even though the TRMM overestimates the amount of rainfall for 9 months out of 12 (Fig. 7).

The scatter plot in Fig. 9 displays the linear relationship between the TRMM and the rain-gauge data for the rainfall (mm/day). Statistically, the regression procedure may be utilized to calibrate an unknown parameter in reference to a known one. The general regression equation has the form $y=c+mx$, where the $m$ and $c$ represent for slope and constant, respectively. For the estimation of the rainfall from the satellite, the regression equation is:

$$RF_{\text{Estimated}} = c_{RF} + m_{RF}(RF_{\text{TRMM}}) \quad (5)$$

where $RF_{\text{Estimated}}$ is the rainfall to be estimated, $m_{RF}$ is the slope, $c_{RF}$ is a constant, and $RF_{\text{TRMM}}$ is the TRMM-detected rainfall. The rainfall is averaged for 365 individual days over 12 years; $m_{RF}$ and $c_{RF}$ are 0.726 and 0.046, respectively, with $r=0.76$ and the coefficient of determination $R^2=0.581$, at a 97% level of significance. If the rainfall is averaged for individual months over 12 years ($12 \times 12 = 144$ months), $m_{RF}$ and $c_{RF}$ are 0.927 and 0.041, respectively, with $r=0.90$ and $R^2=0.816$, at a 99% level of significance. These indicate that monthly averages from daily data enhance the relationship between the TRMM and the rain-gauge data, i.e. the average data for a month reduces the difference between the two measurements. The slopes and constants obtained through Eq. (5) on different days and months for each station are useful in calibrating the TRMM rainfall at the station level. The implications of these values in estimating the rainfall over Saudi Arabia from the TRMM dataset are discussed in Section 4.

### 3.1.6. Comparison of the seasonal rainfall

The comparison of the TRMM rainfall with the observed data for the different seasons is presented in Fig. 10. The TRMM measured rain amounts are quite similar to the observed data during the winter (DJF) and autumn (SON) seasons, whereas in spring (MAM) and summer (JJA) an evident overestimation can be registered. Furthermore, from the same figure, it appears that the two datasets could be ably overlapped during the wet season, while throughout the dry season the TRMM overestimates the rainfall. The observed (TRMM) data measurements in millimeters are 25.81 (25.27), 29.76 (35.74), 9.21 (12.85), 14.10 (14.33), 59.09 (59.90) and 10.42 (14.75) during the winter, spring, summer, autumn, wet and dry seasons, respectively.

### 3.1.7. Comparison of the annual rainfall

The time sequences for the annual rainfall obtained from the TRMM and the rain gauges are presented in Fig. 11. The TRMM overestimated the rainfall in all years except for 1998, 2000, 2001 and 2002. There is no particular trend in over- or underestimation. The bias (TRMM value minus observed value) is positive in some years and negative for others. Therefore, the regression equation (Eq. (5)) can provide estimations for the annual rainfall from the TRMM data, as will be discussed in Subsection 4.2.

### 3.2. Variation of rainfall with altitude

Variation of rainfall with altitude is examined in this section because, in some Saudi Arabian regions, topographic variation can be quite marked (Fig. 1). The upward trend of rainfall with altitude is presented in Fig. 12. The altitude of the Najran station is 1213 m, however rainfall there is low (No. 28, Table 1). The rain-shadow effect may be responsible for reducing the amount of rainfall in this location as it is on the leeward side of a mountain (No. 28, Fig. 1). Other elevated stations, such as Taif, Al-Baha, Khams Mushait and Abha receive large amounts of rainfall (Nos. 20, 22, 26 and 27). The elevation of Gizan is only 4 m above msl, however it receives a large amount of rainfall. It is located on the windward side of the SW tip, through which precipitation systems approach Saudi Arabia during both the wet and the dry seasons. Al-Qaysumah (No. 7), Hafer-Albaten (No. 8) and...
Gassim (No. 10), also receive large rainfall amounts due to their locations, through which systems approach Saudi Arabia during the wet season.

In general, the rainfall increases with the increases in altitude. This characteristic is opposite to the rainfall variation with altitude in Nepal (Islam et al., 2010). The rate of increase is slightly lower for the TRMM rainfall data (1.17 mm/m) compared to the observed data (1.93 mm/m). Hence, it is clear that in Saudi Arabia rainfall at the higher elevations is heavier than at the lower elevations, and this is reflected in the small amounts of rainfall in the eastern parts of the country (Fig. 4b). Additionally, very little or no rain at all fell in the Rub Al-Khali.

3.3. Variation of the rainfall in different regions

To understand the rainfall variation in the different parts of the country, four regions, named NE, NW, SE and SW, are defined in Fig. 1. All the stations located in each region are utilized for the analysis of regional rainfall, with the exception of one station in the SE region (No. 29, Fig. 1), which may not sufficiently represent a region like Rub Al-Khali; its data are removed from the regional analysis.

In the NE region, the TRMM overestimates the calculated rainfall in all seasons except autumn (Fig. 13a). In this region, rainfall mainly occurs during winter (DJF) and spring (MAM), which results in large amounts of rainfall in the wet season (~95%) compared to only a few millimeters of rain in the dry season (~2%).

In the NW region, the TRMM overestimated the rainfall (Fig. 13b). In this region, the influence of the different seasons is similar to the NE region; the wet and the dry seasons receive about 82% and 4% of the total amount, respectively.

The rainfall characteristics in the SW region differ from the other regions: all seasons contribute in the total amount of this region’s rainfall (Fig. 13c). The TRMM overestimated the rainfall in each of the four seasons except winter, which was influenced by an underestimation for the wet season. Also, it overestimated the rainfall in the dry season. These wet season underestimations and dry season overestimations in the rainfall are consistent with the results of Islam and Uyeda (2007), who calibrated the TRMM rainfall over Bangladesh. However, in all seasons, the amounts calculated by the TRMM follow the trends of the observed data. In this SW region, the TRMM (observed) data measured 13.12 (18.43), 43.0 (42.83), 25.98 (20.97), 17.91 (17.78), 49.56 (58.26) and 30.36 (23.88) as percentages of the annual total during the winter, spring, summer, autumn, wet and dry seasons, respectively.

Overall, the NE region received the largest amount of rainfall in the wet season (~95%), and the SW region received the largest amount in spring (~43%). The observed (TRMM) data for the annual rainfall is as follows: 32.58 (33.39), 21.95 (22.18) and 45.47 (44.43)% in the NE, NW and SW regions, respectively.

3.4. The TRMM performance in detection of rainy days

3.4.1. Approximate under-detection and over-detection of rainfall by the TRMM

The performance of the TRMM is summarized in Table 2 for the period 1998–2009. To find the distribution of the analyzed 29 stations in these 12 years, 348 (=29×12) individual stations are to be considered in Saudi Arabia. The values in each row under each year in Table 2 display the number of stations that represent either under-detection, over-detection, or approximately equal detection (vis-à-vis the ground stations’ observed rainfall values) recorded by the satellite measurement tool in the different years. Station-wise, the TRMM data were accurate (to within 10%) only about 12% of the time. By expanding the definition of acceptable accuracy to be ±25% of observed precipitation (Brown, 2006), the TRMM data was accurate for about 33% of the ground station locations. These results differ for Bangladesh (Nepal), which are 38% (19%) and 72% (57%) for ±10% and ±25%, respectively (Islam and Uyeda, 2007; Islam et al., 2010). The topography and climate of Saudi Arabia are different from Bangladesh and Nepal, which may be the cause of these differences. For the satellite data, under-detection and over-detection were 37% and 51%, respectively. Hence, it is clear that the TRMM over-detects rainfall over Saudi Arabia. It overestimated rainfall in dry areas more so than in wet areas (Islam and Uyeda, 2007). However, for daily rainfall estimates, the satellite data are essential, especially for flood monitoring and measurement of rainfall in remote regions. Therefore, the TRMM data products are now further studied in order to evaluate the instrumental performance in estimating rainfall in Saudi Arabia.
3.4.2. False-, missing- and exact-detection of rainy days by the TRMM

As discussed above, the measurement of rainfall by the TRMM was mostly over-detection (51%), while under-detection was 37%, and approximately equal was 12%. The detection of false alarms and the failure to detect rainy days, as determined by the ground-observed data, are used to assess the performance of the TRMM sensors. Performance-indices, such as false alarm ratio (FAR), probability of detection (POD), threat score (TS) and skill score (SS) as defined in Section 2.2, are calculated and are presented in Fig. 14. It can be seen that FAR is lowest at Madina (altitude 630 m) and highest at Jeddah (altitude 18 m). FAR is high on the westward-facing slopes, down from the hilly regions along the Red Sea coast, where Jeddah is located i.e. at coastal stations with low altitudes. The POD is fairly good for all high- and low-altitude stations. The values for TS are between 0.07 and 0.44, which are small, for the low-altitude coastal stations. The values for SS are between 0.24 and 0.65. On average, TS and SS are 0.25 and 0.41 respectively, which are low compared to the same calculations over Nepal (Islam et al., 2010). Thus, there is no particular trend in the performance-indices with respect to altitude in Saudi Arabia.

4. Discussion and conclusions

Through this analysis, it has become clear that the TRMM overestimates the rainfall in some seasons and areas, and underestimates in other seasons and areas for Saudi Arabia. Nevertheless, the employment of remote-sensing data devices in estimating the rainfall in uninhabitable but vast areas remains important.

The scatter plot of the TRMM-uncalibrated rainfall data and the ground-observed data shows overestimation of the TRMM values on a monthly scale, with r = 0.95 and R² = 0.91, at a 94% level of significance (Fig. 15). However, the correlation coefficient is improved to 0.95 from 0.90 (Fig. 9b) when averaged month-wise over 12 years.

On average, the TRMM (observed) data measured 12.38 (13.02), 5.93 (5.03), 10.98 (10.29), 15.86 (13.53), 8.93 (5.88), 2.39 (1.07), 3.54 (2.27), 6.91 (5.83), 1.90 (1.21), 4.61 (3.46), 7.81 (9.41) and 6.98 (7.74) mm of rainfall, respectively, for the period January through December in Saudi Arabia (Fig. 16a). On the annual scale, the TRMM and the observed data measured 88.22 mm and 78.73 ± 10 mm, respectively, with an error of 12.05%. After using the calibration factors from Fig. 13. The comparison of the TRMM and the observed rainfall (mm) in the different seasons for a) NE region, b) NW region, and c) SW region.

Table 2

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<td>29</td>
<td>29</td>
<td>28</td>
<td>348</td>
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</tbody>
</table>
Eq. (1), the TRMM estimated rainfall is 78.7316 mm, which is almost the same (100%) as the observed data.

This indicates that very similar amounts to the observed rainfall are extractable using the TRMM data, with the help of the calibration factors discussed above. The calibrated TRMM rainfall in the different months for the different regions is shown in Fig. 16(b–d). This analysis reveals the complete distribution of rainfall for the whole of Saudi Arabia, irrespective of season. Therefore, using the calibration factors suggested in this study, one may conclude that the TRMM data can be utilized to determine the rainfall climatology over Saudi Arabia.

Thus, using the Tropical Rainfall Measuring Mission (TRMM) 3B42 dataset, the short-term rainfall climatology over Saudi Arabia has been obtained for the period 1998–2009. The TRMM rainfall is extracted and calibrated with reference to the observed data for 29 stations across the country. The TRMM data display patterns of annual rainfall cycles that are mostly similar to those based on the rain gauges throughout the country.

The monthly comparisons between the two data sources show the best correlations ($r = 0.90$), which is statistically significant at the 99% level. The day-to-day comparisons revealed some discrepancies between the gauge measurements and the TRMM estimates at the station level, but very good matching for the country on average. The wet (November–April) and dry (June–September) seasons are defined based on the monthly distribution of rainfall, considering October and May as transition months. For the regional rainfall analysis, the country is divided into four regions based on rainfall climatology and topography.

The seasonal rainfall patterns obtained from the TRMM data are mostly similar to those based on the observed data across the country, as well as in the different regions. This analysis reveals that spring is the highest (38.93%) and winter is the second highest (32.51%) as rainfall occurring seasons. These contribute significantly towards the large amounts of rainfall that occur during the wet season (75.39%) over the country as a whole. Only small amounts of rainfall are observed during the summer (11.46%) and in the dry season (12.94%), whereas autumn received about 17.09% of the total annual rainfall. The SW region receives rainfall in all seasons, with a maximum in spring (44.29%), whereas the NW and NE regions receive very small amounts of rainfall in summer (~2%). The SE region is almost totally dry. Over Saudi Arabia, false alarm ratio, probability of detection, threat score and skill score are found to be 0.61, 0.44, 0.25, and 0.41, respectively.

In general, rainfall increases with rising altitude, at a rate of ~1.93 mm/m in Saudi Arabia. The TRMM data overestimated the rainfall over Saudi Arabia irrespective of region or season except winter. However, after calibration, the TRMM-measured rainfall is almost the same (100%) as the ground-observed data, encouraging its utilization (in various application purposes) where conventional measurement tools are few or unavailable.

Acknowledgements

The author would like to acknowledge the Presidency of Meteorology and Environment (PME) of Saudi Arabia for providing the rain-gauge data. The TRMM data were acquired from their website at http://trmm.gsfc.nasa.gov. The TRMM is an international project jointly sponsored by the Japan Aerospace Exploration Agency (JAXA) and the U.S. National
Aeronautics Space Administration (NASA), Office of Earth Science. The helpful comments of the anonymous reviewers are highly appreciated.

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