

A review of recent evaluations of TRMM Multisatellite Precipitation Analysis (TMPA) research products against ground-based observations over Indian land and oceanic regions

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सार – भारतीय भू-भाग और इससे सटे महासागरीय क्षेत्रों में हुई वर्षा की विश्वसनीय सूचना विभिन्न जल-मौसम विज्ञानिक कार्यों के लिए महत्वपूर्ण होती है। बहु-उपग्रहीय वर्षा के उत्पाद भूमंडलीय अथवा भूमंडलीय कल्प वर्षा मानचित्रों को नियमित अंतराल पर उपलब्ध कराते हैं और पृथ्वी-प्रेक्षण उपग्रहों के समूह पर लगाए गए सूक्ष्मतरंगीय संवेदकों तथा अवरक्त किरणों से सापेक्षिक लाभ भी मिलता है। उष्णकटिबंधीय वर्षा मापन मिशन (टी आर एम एम) उष्णकटिबंधीय बहु उपग्रह वर्षा विश्लेषण (टी एम पी ए) अनेक प्रकार के प्रयोगों में अधिकतर उपयोग किया जाने वाला क्वासी ग्लोबल उच्च विभेदन वर्षा उत्पाद है। टी एम पी ए उत्पादों के वर्तमान वर्जन 6 (वी6) कुछ अतिरिक्त इनपुट के साथ लगातार परिवर्तित हो रहे हैं और वर्ष 2012 के अंत में औपचारिक रूप से बाद का वर्जन 7 (वी7) डेटा सेट्स भी जारी कर दिए गए हैं। टी एम पी ए के इस नए वर्जन के व्यापक त्रुटि लक्षण इसकी व्यापक प्रयोज्यता के लिए एक शर्त है। इस शोध पत्र में भारतीय भू-भाग और महासागरीय क्षेत्रों में मौलिक प्रेक्षणों के विपरीत टी एम पी ए- 3बी42 और 3बी43 उत्पादों के वर्तमान मूल्यांकनों के परिणामों को उजागर किया गया है। अफ्रिकन-एशियाई-ऑस्ट्रेलियाई मॉनसून विश्लेषण के लिए रिसर्च मूअर्ड एरे से प्राप्त गौज प्रेक्षणों का उपयोग करते हुए टी एम पी ए डेटा सेट्स के दोनों वर्जन की तुलना की गई है और मासिक पैमाने पर पूर्वानुमान (आर ए एम ए) नौबंद बताते हैं कि अधिक वर्षा से संबंधित त्रुटियां V7 में कम हुई हैं, जबकि नए वर्जन में अपने पूर्ववर्ती वी6 की तुलना में समग्र पूर्वाग्रह और रूट मीन स्कवेयर एरर से पता चलता है। आर ए एम ए प्लावन प्रेक्षणों के विपरीत दैनिक पैमाने पर आठ वर्ष (2004-2011) की अवधि के टी एम पी ए वी7 उत्पाद का पुनः मूल्यांकन किया गया है जिससे पता चला है कि प्रेक्षणों की तुलना में टी एम पी ए वी7 में वर्षा अधिक आंकी गई है। हालांकि टी एम पी ए वी7 हल्की और भारी वर्षा की घटनाओं को कम आंकता है तथा अभिलाक्षणिक त्रुटियां ऋतुनिष्ठ भिन्नता अपेक्षाकृत कम दर्शाती हैं। भारत में वर्ष 1998-2010 की दक्षिण-पश्चिमी मॉनसून के ग्रीडेड गेज आधारित वर्षा डेटा सेट्स का टी एम पी ए डेटा सेट्स के दोनों वर्जनों के साथ तुलना करने से पता चला है कि वी6 से वी7 में थोड़ा सुधार हुआ है, विशेष रूप से पूर्वाग्रह वाली स्थिति में कमी आई है। जबकि भारत में अन्य समकालीन बहु उपग्रहीय वर्षा उत्पादों से टी एम पी ए वी7 बेहतर दक्षता को दर्शाता है और इसका उपयोग मॉनसून से संबंधित अध्ययन के लिए विश्वस्त होकर किया जा सकता है। अतः इसमें बहु-उपग्रहीय तथा स्थानीय गेज डेटा सेट्स के सम्मिलित क्षमता को वर्षा के बेहतर आकलन पर चर्चा की गई है और भविष्य में इसे भारतीय मॉनसून काल में इष्टतम वर्षा का आकलन करने के लिए अनुशंसा की जाती है।

ABSTRACT. Reliable information of rainfall over the Indian land and adjoining oceanic regions is crucial for various hydro-meteorological purposes. Multisatellite rainfall products provide global or quasi-global rainfall maps at regular interval and benefits from the relative advantages of infrared and microwave sensors onboard a constellation of Earth-observation satellites. The Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) is one of the most widely used quasi-global high resolution rainfall products for a variety of applications. The existing version 6 (V6) of TMPA products underwent substantial changes with additional inputs and consequently version 7 (V7) data sets were formally released in late 2012. The extensive error characterization of this new version of TMPA data sets is a prerequisite for its widest applicability. This paper highlights the results of recent evaluations of TMPA-3B42 and 3B43 products over the Indian land and oceanic regions against ground-truth observations. Comparison of both the versions of TMPA data sets over the Indian Ocean using gauge observations from the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) buoys at monthly scale shows that even though the error associated with higher rainfall is reduced in the V7, the new version shows overall larger bias and root-mean-

square error as compared to its predecessor V6. TMPA V7 product is further evaluated at daily scale for an eight-year period (2004-2011) against RAMA buoy observations which shows that TMPA V7 overestimates rainfall compared to observations. However, TMPA V7 underestimates light and heavy rainfall events and the error characteristics show a considerable seasonal variation. The comparison of both the versions of TMPA data sets against gridded gauge-based rainfall data sets over India for the southwest monsoon period of 1998-2010 shows a marginal improvement in V7 over V6, especially in terms of reduced bias. Moreover, TMPA V7 shows better skill than the other contemporary multisatellite rainfall products over India and can be used with higher confidence for monsoon-related studies. Finally, the potential of combined use of multisatellite and local gauge data sets for better rainfall estimation is discussed and the scope for optimal rainfall estimation over the Indian monsoon region in future perspective is recommended.

Key words – TRMM multisatellite precipitation analysis, Buoy array, Rain gauge, Error characteristics, Indian monsoon.

1. Introduction

Accurate rainfall estimates at finer spatial and temporal scales over the Indian land and surrounding oceanic regions are very important for a wide range of applications, such as for food and water security, hydro-meteorological applications, model output verification and post-processing of numerical forecasts which would serve as a guidance for further advancement (Gadgil, 2003; Mitra *et al.*, 2003, 2009; Collins *et al.*, 2013). However, small-scale spatial and temporal variability of rainfall makes it difficult to measure adequately with ground-based observations at global scale whereas the rich constellation of Earth-observation satellites, alternatively, play a vital role in the global rainfall estimation at finer spatiotemporal scales. The requirement of stable and fine scale time-series of rainfall estimates at a uniform resolution is only possible by combining individual satellite-retrieved estimates using suitable techniques. Nowadays, several high-resolution multisatellite rainfall products are available to research and user community. The Tropical Rainfall Measuring Mission (TRMM) is one of the innovative satellite mission dedicated to study the tropical rainfall characteristics in more detail and advance our understanding of Earth's water and energy cycle. The precipitation radar (PR) onboard TRMM satellite is the first active spaceborne microwave radar which offers a unique opportunity to study the three-dimensional structure of rainfall. The TRMM has now a data record of more than 17 years (Liu *et al.*, 2012). The existing version 6 (V6) TRMM data products have gone through substantial changes and after retrospective processing with updated algorithm, new version 7 (V7) data sets were released in late 2012 which is supposed to be the final version of these products (Huffman and Bolvin, 2013; Wang *et al.*, 2014). Both the versions (V6 and V7) of TRMM-PR rainfall products were recently compared with ground-based observations over the Continental United States (Kirstetter *et al.*, 2013), Japan (Seto *et al.*, 2013) and South Asian land region (Prakash *et al.*, 2014b). These studies showed that V7 is superior to its predecessor V6 data sets; specifically bias against ground-based observations is reduced in the new version of data sets.

TRMM Multisatellite Precipitation Analysis (TMPA) product is one of the most widely used rainfall data sets for the various applications in hydrology and meteorology (Huffman *et al.*, 2010; Prakash *et al.*, 2014a). However, the precise skill assessment of this high-resolution multisatellite rainfall product at regional and seasonal scales is vital for its widest usage and applicability. The evaluation of TMPA V6 rainfall products over different parts of the globe (Huffman *et al.*, 2007; Sapiano and Arkin, 2009; Rahman *et al.*, 2009; Nair *et al.*, 2009; Scheel *et al.*, 2011; Kidd *et al.*, 2012; Prakash *et al.*, 2012; Karaseva *et al.*, 2012; Uma *et al.*, 2013) gave very encouraging feedback to the end users for their respective applications. These studies showed that TMPA products perform better than other contemporary multisatellite rainfall products and can be used with higher confidence for hydro-meteorological applications. The TMPA products were also used as a standard multisatellite rainfall data for the assessment of Kalpana-1 and other satellite-derived rainfall over the Indian monsoon region (Durai *et al.*, 2010; Prakash *et al.*, 2010; Mishra *et al.*, 2010, 2011; Roy *et al.*, 2012; Mahesh *et al.*, 2014). However, there were some limitations of this rainfall data set which is supposed to be rectified in the recent version (V7) of TMPA. The substantial changes in the recent V7 products are primarily due to incorporation of updated gauge analysis. Apart from that, V7 products comprise the changes in algorithm involve the radar reflectivity-rainfall rate relationship, surface clutter detection over high terrain, a new reference database for the passive microwave algorithm, latitude-band calibration scheme for all satellites, and use of larger volume of data from satellites and ground observations. A detailed description of the changes in V7 from V6 products is given by Huffman and Bolvin (2013). Recently, a number of studies have been done to evaluate this rainfall product against ground-based observations at different parts of the globe like over the tropical oceans (Prakash *et al.*, 2013; Yingjun *et al.*, 2013a; Prakash and Gairola, 2014), Australia (Yingjun *et al.*, 2013b), China (Sheng *et al.*, 2013a; Yong *et al.*, 2014), the United States (Sheng *et al.*, 2013b; Qiao *et al.*, 2014), the Andean-Amazon river basins (Zulkaflī *et al.*, 2014) and India (Prakash *et al.*, 2014a, 2015). All these studies reveal that the TMPA V7

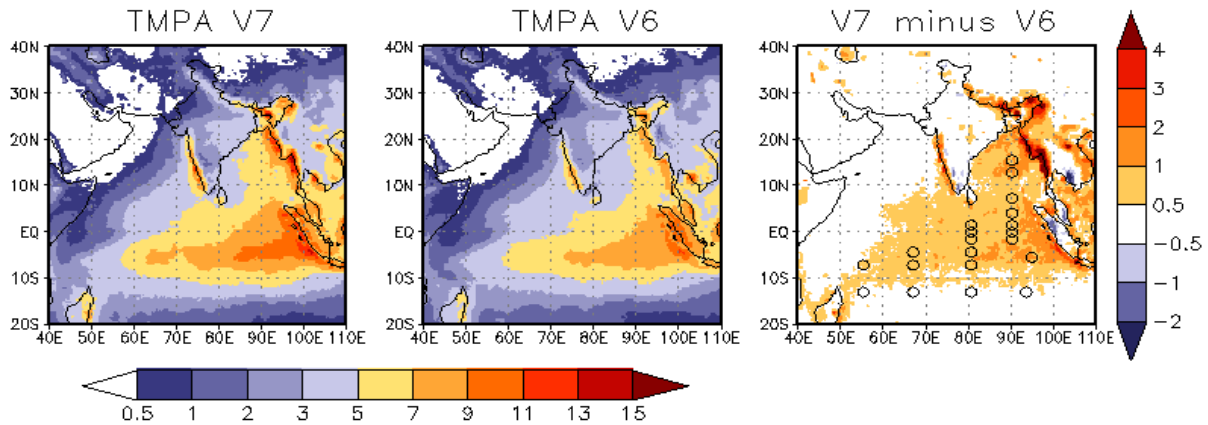


Fig. 1. Spatial distributions of mean rainfall rate (mm day^{-1}) over the Indian land and oceanic regions from TMPA V7 and V6 products for the period of January 1998 to December 2010 and their differences (mm day^{-1}). Locations of RAMA buoys are shown in the figure by open circles

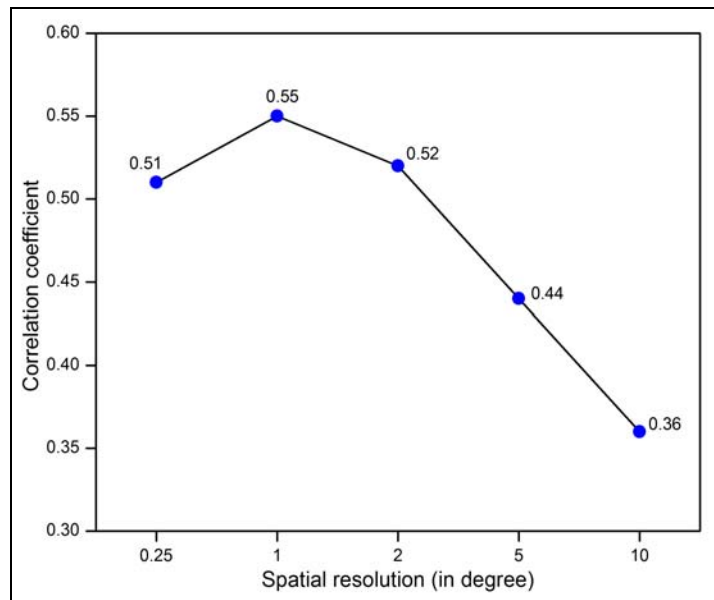
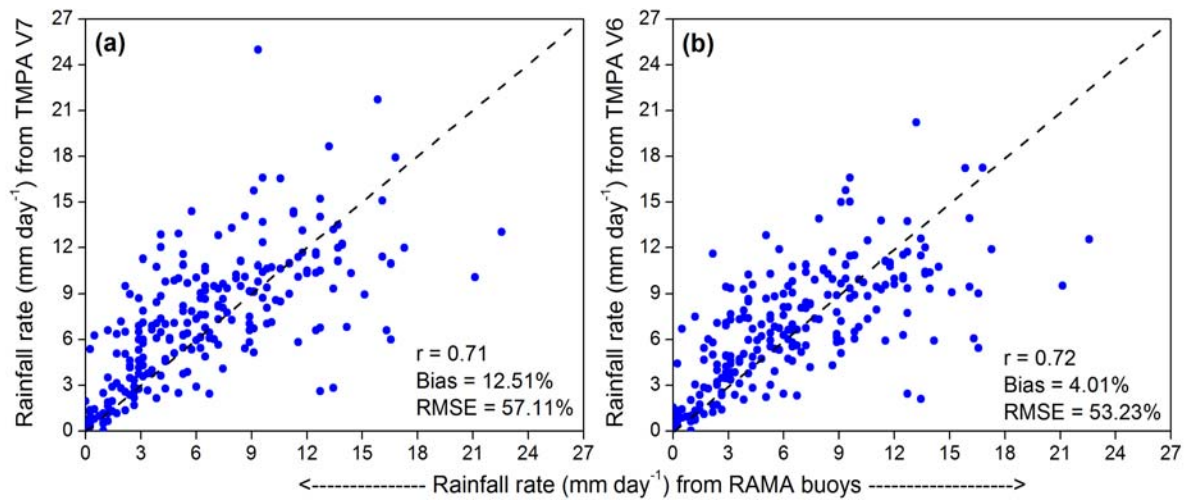


Fig. 2. Variation of correlation coefficient between TMPA V7 and RAMA buoys daily rainfall (2004-2011) at different spatial resolutions over the tropical Indian Ocean

is improved over its predecessor V6 in terms of reduced bias. However, considerable seasonal and regional variations in error characteristics were observed in the new version of rainfall data set.

India is a unique region due to its high rainfall variability at various time scales such as at intraseasonal, seasonal and interannual scales accompanied with varied topographic features (Gadgil, 2003). The country receives about 60-80% of its annual rainfall from the southwest monsoon spanning from June to September.

The reliable rainfall information over this agrarian country is vital. Hence, the evaluation of the recent version of TMPA products over the Indian monsoon region has great importance. Recently, some studies have documented the capability of TMPA V7 products over this region using ground-based observations. This paper is intended to highlight the status of TMPA V7 products over the Indian land and oceanic regions, and also deals with the scope of further advancements in multisatellite rainfall products especially over these regions.



Figs. 3(a&b). Scatter plots of TMPA V7 and V6 with RAMA buoy monthly rainfall rate (mm day^{-1}) over the tropical Indian Ocean for the period of January 1998 to December 2010. Dashed lines show 1:1 line and correlation coefficient (r), bias and RMSE are also given in each plot

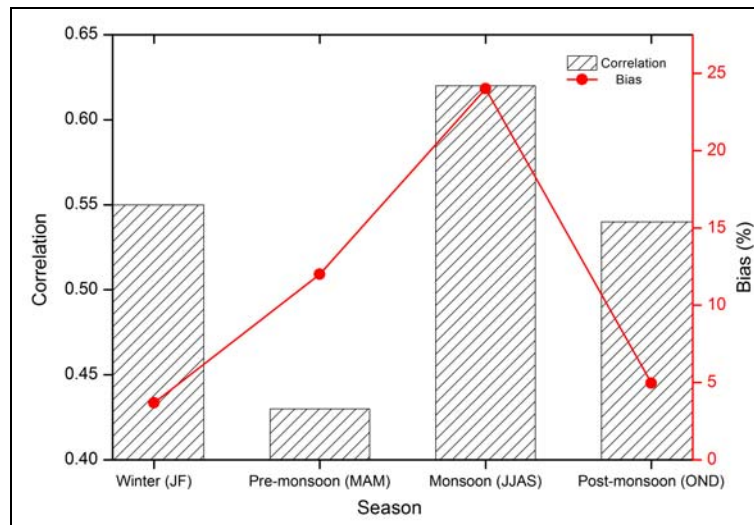


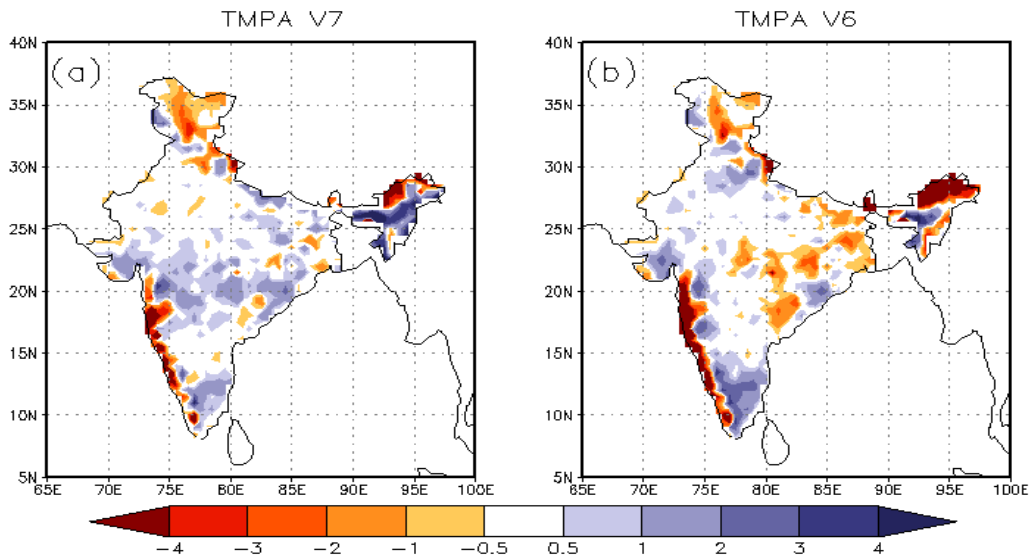
Fig. 4. Seasonal variations of correlation coefficient and bias of TMPA V7 daily rainfall against RAMA buoy observations in the tropical Indian Ocean for the period of 2004 to 2011

2. Rainfall data sets

2.1. Multisatellite products

TMPA products are developed by the combined use of infrared and microwave observations from geostationary and low-Earth orbiting satellites, and also use available rain gauge data over the land to take the relative advantages of the satellite-borne sensors and *in situ* observations (Huffman *et al.*, 2007, 2010). The gauge-based rainfall products, known as research-quality products, are different from the real-time products

which do not use the gauge information. Another difference between both the products is related to their calibrations, the former products are calibrated against TRMM Calibration Instrument (TCI) whereas the real-time products are calibrated against TRMM Microwave Imager (TMI) with some climatological adjustments (Huffman *et al.*, 2010). The TMPA products are available at three different temporal scales such as three-hourly (3B42), daily (3B42) and monthly (3B43) and at 0.25° latitude/longitude resolution. The TMPA research products V7 are released after retrospective processing of the various inputs with the new version



Figs. 5(a&b). Bias (mm) of daily TMPA V7 and V6 with respect to gauge-based rainfall data over India for the southwest monsoon season of 1998-2010

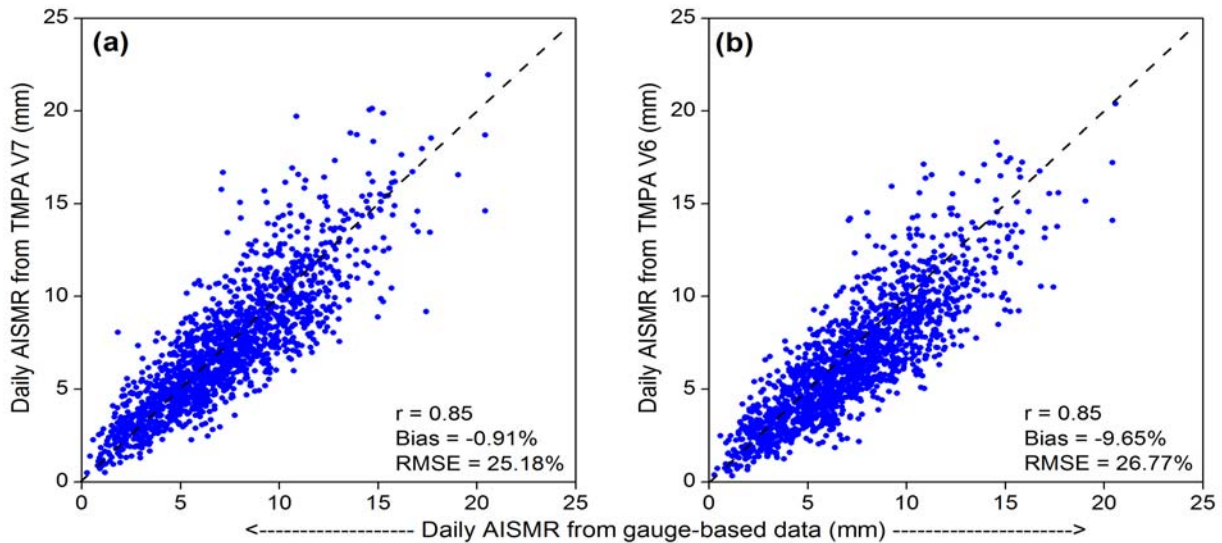
algorithm which replaced the existing V6 products. V7 products are supposed to be better than V6. The relevant data are obtained from the TRMM Online Visualization and Analysis System (TOVAS; <http://disc2.nascom.nasa.gov/Giovanni/tovas/>) created and supported by the Goddard Earth Sciences Data and Information Services Center (GES DISC).

Moreover, three contemporary multisatellite rainfall products, namely the Climate Prediction Center Morphing (CMORPH) Version 1.0, Naval Research Laboratory (NRL)-blended, and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) are used for their comparison with TMPA V7 products over the Indian monsoon region. All the three rainfall products use distinct algorithms. CMORPH uses motion vectors derived from the geostationary satellite IR images to propagate the global rainfall estimates by adjacent passive microwave measurements (Joyce *et al.*, 2004). The NRL-blended satellite rainfall technique is primarily based on real-time, underlying correction of time and space-matching pixels from all operational geostationary infrared imagers calibrated with TRMM-PR over the tropics and with Special Sensor Microwave Imager (SSM/I) over the extra-tropics and low-Earth orbiting passive microwave imagers (Turk and Miller, 2005). This rainfall product also uses model winds at 850 hPa and topographic information to correct the orographic effects. PERSIANN product uses an artificial neural network technique to estimate rainfall from infrared measurements calibrated with passive microwave data (Hsu *et al.*, 1997).

2.2. Ground-based data

For the evaluation of the TMPA rainfall data sets over India, rain gauge-derived daily gridded rainfall data developed by the India Meteorological Department (IMD) are used. This gridded rainfall data set is developed using rainfall observations collected from a dense network of gauges well spread across India followed by proper quality-check and interpolated into a regular grid of 0.5° latitude/longitude (Rajeevan and Bhate, 2009). Although rain gauges used for the preparation of these data are not uniformly distributed in both space and time, it is assumed to be more realistic representative of ground-truth and hence widely used for various meteorological and climatological applications.

Furthermore, the gauge-based rainfall data from the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) buoys in the tropical Indian Ocean are used. RAMA buoy array is dedicated to provide measurements in the historically data-sparse Indian Ocean for the advancement of monsoon research and forecasting (McPhaden *et al.*, 2009). The RAMA buoy started to disseminate data since late 2004; however the number of buoys was very few during the initial years. The relevant rainfall data from 20 buoy locations (Fig. 1) are obtained from the Tropical Atmosphere Ocean (TAO) Project Office of the National Oceanic and Atmospheric Administration - Pacific Marine Environmental Laboratory (NOAA/PMEL; <http://www.pmel.noaa.gov/tao>).



Figs. 6(a&b). Scatter plots of daily TMPA V7 and V6 with gauge-based rainfall over India for the southwest monsoon season of 1998-2010. Dashed lines show 1:1 line and correlation coefficient (r), bias and RMSE are also given in each plot

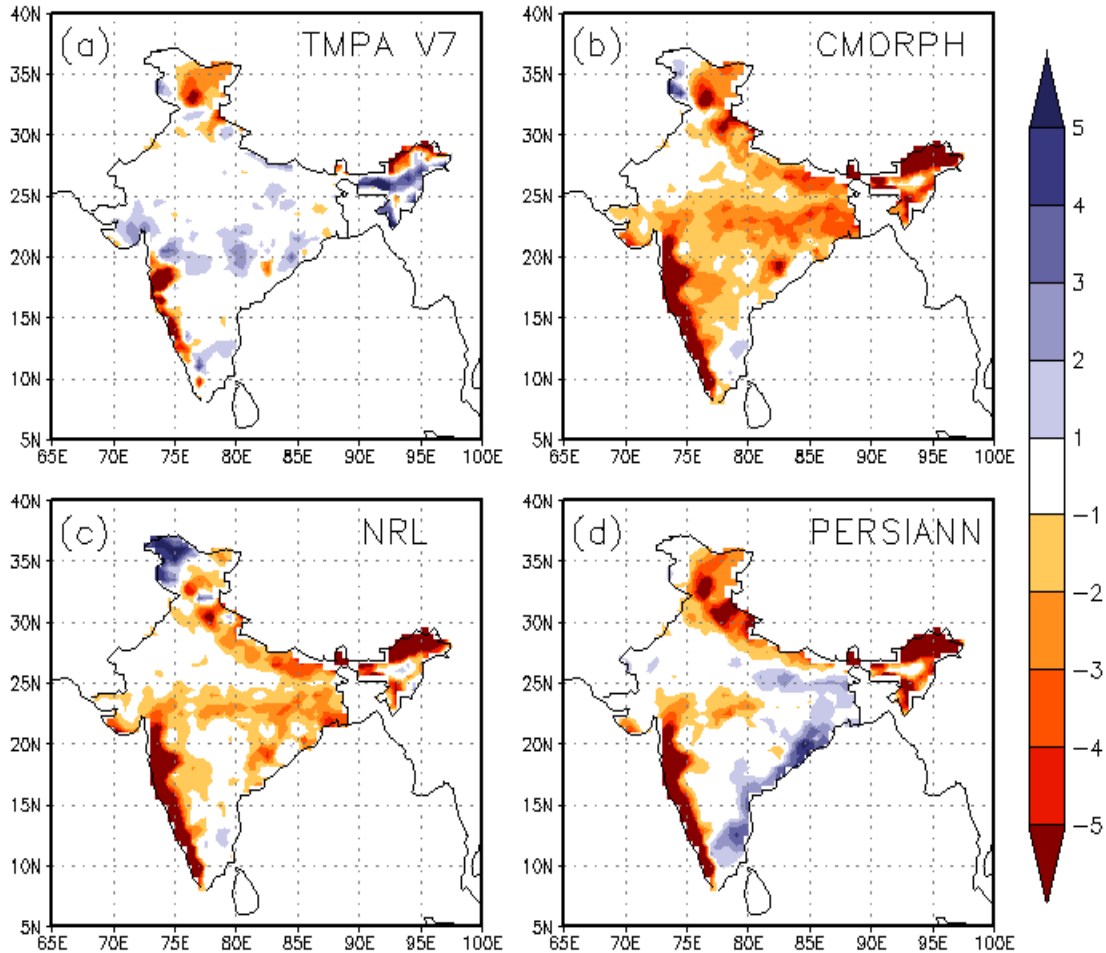
3. Evaluation of TMPA products over the tropical Indian Ocean

In this section, TMPA rainfall products are evaluated at daily and monthly scales over the tropical Indian Ocean using RAMA buoy data. As the V6 products are available till June 2011, the mean rainfall from January 1998 to December 2010 from both the versions of TMPA rainfall products and their difference are shown in Fig. 1. Large-scale rainfall features are similar in both the versions of TMPA product qualitatively. Higher rainfall over the eastern equatorial Indian Ocean, along the Arakan Yoma mountains chain and west coast of India are observed in both the version of datasets. However, V7 shows higher magnitude of rainfall by about 2-4 mm day⁻¹ than V6 over the high rainfall regimes. The difference plot clearly shows that V7 enhanced rainfall amount over the central and eastern Indian Ocean and along the mountainous regions as compared to V6. To investigate whether V7 improved over V6 or not, rainfall over the oceanic region is evaluated against RAMA buoy data at monthly scale without employing wind-loss corrections for the period 1998-2010 by Prakash *et al.* (2013).

As the buoys and satellites measure rainfall based on different principles, the validation were done at each buoy location. For this purpose, the knowledge of optimum spatial resolution for validation is required because buoys provide rainfall measurements at specific point location whereas TMPA provides gridded rainfall. The correlation coefficients between rainfall estimates from both the sources are plotted against different spatial resolutions for the study period (Fig. 2), which revealed that the optimum

spatial resolution for validation is 1° latitude/longitude (Prakash and Gairola, 2014). Hence, the validation was carried out at 1° latitude/longitude resolution. Figs. 3(a&b) show the scatter plots of TMPA V7 and V6 rainfall estimates with RAMA buoys observations. It can be seen that the bias and root-mean square error (RMSE) are unexpectedly increased by about 8% and 4% in V7 data set as compared to V6 over the tropical Indian Ocean. This analysis shows that V7 product is not improved over V6 in the tropical Indian Ocean, in general. But, the bias and RMSE are considerably improved for the higher rainfall rates when compared for different rainfall rate ranges (Prakash *et al.*, 2013). Even though the buoys represent open-ocean conditions and provide accurate rainfall measurements, their sparseness and intermittent sampling lead to some limitations.

Furthermore, TMPA V7 products were validated with RAMA buoy observations at daily scale for an eight-year period ranging from 2004 to 2011 by Prakash and Gairola (2014). They showed that the linear correlation coefficient and RMSE between two rainfall estimates had large ranges from 0.40 to 0.89 for correlation and 1 to 22 mm day⁻¹ for RMSE. Even the TMPA V7 overestimates rainfall over the Indian Ocean in general; it underestimates light and heavy rainfall events. Fig. 4 shows the seasonal variations of correlation and bias of TMPA V7 with RAMA buoy observations. The error characteristics show a pronounced seasonal variation with the largest correlation and bias during the southwest monsoon season (June-September). The lowest correlation is observed in the pre-monsoon season (March-May).



Figs. 7(a-d). Bias (mm) of daily TMPA V7, CMORPH, NRL and PERSIANN rainfall products with respect to gauge-based data over India for the southwest monsoon season of 2004-2009

4. Evaluation of TMPA products over India during the southwest monsoon season

In this section, the results of evaluation of TMPA-3B42 V7 products over India are discussed. As India receives about 60-80% of its annual rainfall from the southwest monsoon season, the evaluation is restricted for the monsoon season spanning from June to September. The daily gridded gauge-based rainfall data (Rajeevan and Bhate, 2009) were used as reference for the comparison. As the gauge-based data accumulates daily rainfall ending at 0300 UTC, daily rainfall from TMPA products were also computed at 0300 UTC using three-hourly data sets for comparison. The comparison was done at 0.5° latitude/longitude resolution for the period 1998 to 2010. Large-scale monsoon rainfall features were well-captured

by both the versions of TMPA product (Prakash *et al.*, 2015). The bias in V7 and V6 products against gauge-based rainfall data set is shown in Figs. 5(a&b). It can be seen that V6 considerably underestimates rainfall over the northeast and eastern India and along the west coast and the foothills of the Himalayas whereas it overestimates rainfall over the southeast peninsular and northwest India. The magnitude of bias is higher (more than 4 mm day⁻¹) along the west coast and over the northeast India which is reduced in the V7 estimates. Overall, the bias is noticeably reduced in V7 as compared to V6 data set. However, V7 shows positive bias over the central India which was negative in the V6 data set. Similarly, the areal spread of positive bias is relatively larger in V7 over the northeast India. The scatter plots of all-India summer monsoon rainfall (AISMR) from both the versions of TMPA

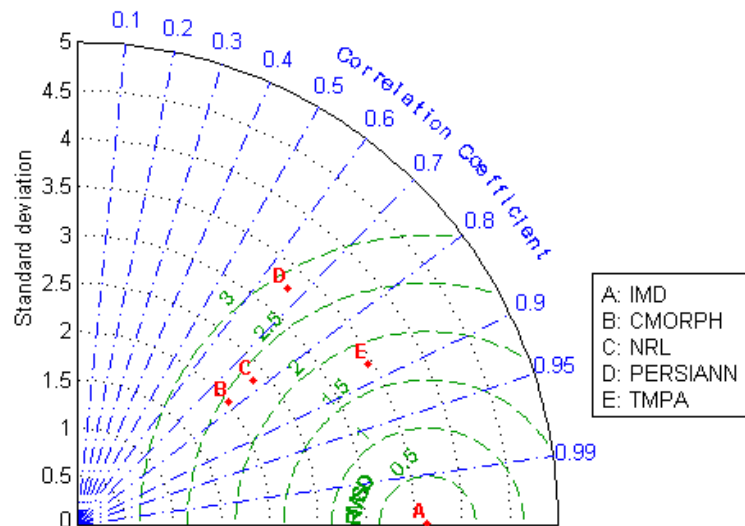


Fig. 8. Taylor diagram of daily CMORPH, NRL, PERSIANN and TMPA V7 rainfall with respect to IMD gauge-based data over India for the southwest monsoon season of 2004-2009. The units of standard deviation and centered root-mean-square difference (RMSD) are mm day^{-1}

product with respect to gauge-based data for the study period are shown in Figs. 6(a&b). The bias and RMSE are marginally improved in V7 over V6 whereas the correlation is maintained. Prakash *et al.* (2015) extensively compared both the versions of TMPA rainfall estimates with gauge-based data at all-India and sub-regional scales. They showed that V7 marginally improved over V6 across the scales. The bias in the frequency of occurrence of light rainfall is also improved in V7, although it still differs from the observations. Moreover, both the V6 and V7 showed similar kind of intraseasonal rainfall variability. Overall analysis suggested that V7 is improved over V6 in terms of bias, but the results are almost equivalent as far as correlation and RMSE is concerned. The results finally suggest that the main improvement in V7 is due to the upgraded gauge analysis, even though the individual rainfall events are driven by the satellite measurements.

Furthermore, the capability of TMPA-3B42 V7 was also evaluated against other contemporary multisatellite rainfall products over the Indian monsoon region. For this purpose, four high resolution multisatellite rainfall products namely, TMPA V7, CMORPH, NRL-blended and PERSIANN were validated against IMD gauge-based gridded rainfall data set at daily scale. This study was done for a six-year southwest monsoon period from 2004 to 2009 and at 0.5° latitude/longitude resolution (Prakash *et al.*, 2014a). The bias in each multisatellite rainfall products is shown in Figs. 7(a-d). All the four rainfall products show notable negative bias along the west coast

of India and over the northeast India, but the magnitude of bias is relatively smaller for the TMPA V7 estimates. CMORPH, NRL and PERSIANN show negative bias along the foothills of the Himalayas and over the northwest India, whereas the bias is very small or negligible in TMPA V7 product. PERSIANN shows an overestimation of rainfall along the east coast of India which makes it different from the other estimates. These results show that the TMPA V7 is relatively closer to the ground-truth as compared to the other multisatellite rainfall products, possibly due to incorporation of rain gauge data in it. Prakash *et al.* (2014a) compared these four rainfall products at all-India and sub-regional scales with gauge-based data. They showed that even though all the four rainfall estimates were able to capture the prominent monsoon rainfall characteristics such as intraseasonal (active/break spells) and interannual (excess/deficient) variability well, TMPA V7 is comparatively closer to the ground-truth observations. They also investigated the rain detection capability of these rainfall products and showed that all the four multisatellite rainfall estimates exhibited high probability of detection, low false alarm ratio, and high threat score in detection of rainfall events over most parts of India, however these products had some difficulties in rainfall detection over the rain-shadow region of the southeast peninsular India, semi-arid northwest parts of India, and hilly northern parts. The Taylor diagram (Taylor, 2001) of daily AISMR for the study period is presented in Fig. 8 which shows the correlation, standard deviation (SD) and centered root-mean square difference (RMSD) of each V7

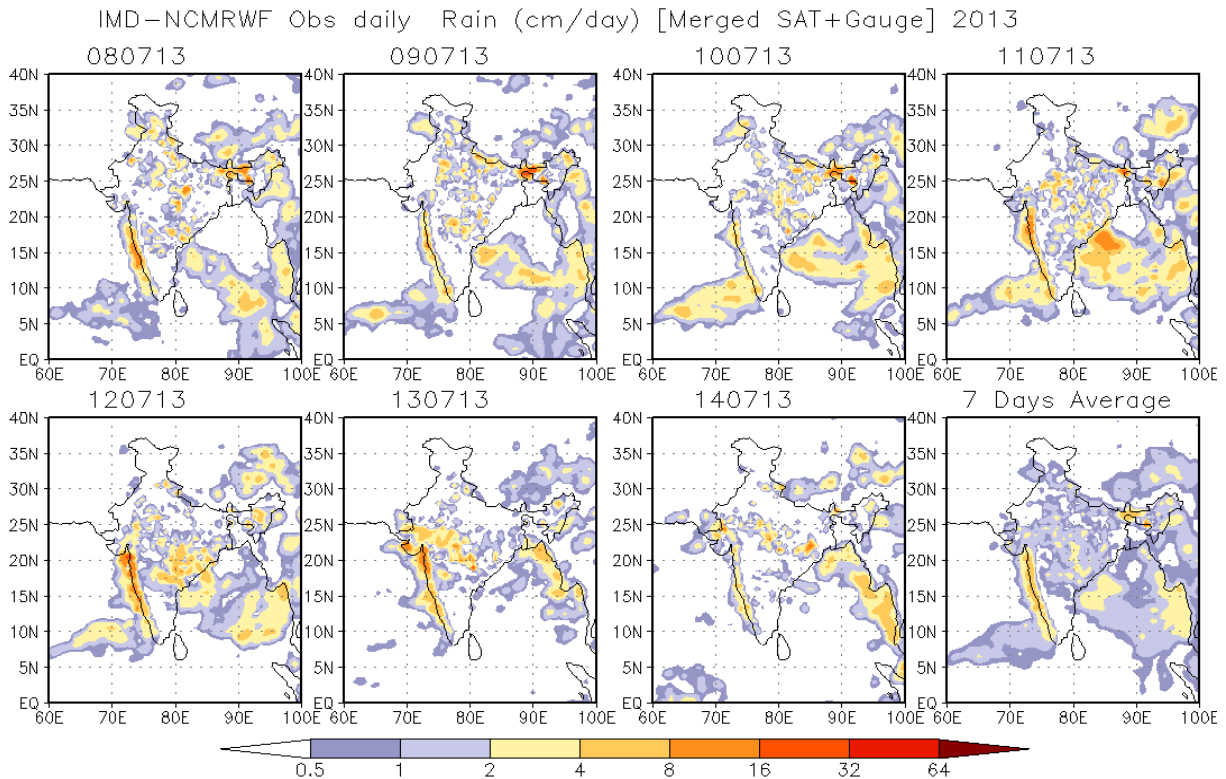


Fig. 9. Spatial distributions of daily and weekly rainfall (cm day^{-1}) from NMSG rainfall product for the period of 8 - 14 July, 2013

rainfall estimates in a single diagram. TMPA V7 has the largest correlation, the least RMSD and SD closer to observations. PERSIANN shows SD closer to observations, but it has the least correlation and the largest RMSD. Hence, the Taylor diagram also shows that TMPA is the best among the four multisatellite rainfall products at all-India scale. Finally, it can be concluded that TMPA can be used with higher confidence as compared to other multisatellite rainfall products for the monsoon studies, particularly over the Indian land region.

5. Development of new merged gauge-satellite rainfall product for Indian region

The evaluation results of TMPA V7 over the Indian monsoon region showed that even though TMPA is the best available multisatellite rainfall product, it has some region-specific bias as reported by other researchers for other parts of the globe. One of the possible ways to further improve TMPA products is to merge additional local rain gauge observations in it using proper technique. TMPA uses the gauge information from the Global Precipitation Climatology Center (GPCC), having data record mainly exchanged through the World

Meteorological Organization (WMO). The potential of synergism of additional local gauge data and TMPA V6 product over the Indian region was demonstrated by Mitra *et al.* (2003, 2009). They used successive correction method for merging and showed that the new rainfall product benefits from the relative merits of TMPA and local gauge information. This objectively analyzed rainfall product is supposed to be optimal. Using these assumptions, Mitra *et al.* (2013) developed a new gridded daily rainfall data set over the Indian monsoon region at 1° latitude/longitude resolution for the period of 1998 to 2011 which combines near-real time TMPA rainfall estimates with IMD gauge-based gridded rainfall data. This merged gauge-satellite rainfall data set is termed as NCMRWF (National Centre for Medium Range Weather Forecasting) merged satellite gauge (NMSG) rainfall and is superior to other daily global rainfall data sets. This daily gridded rainfall product is freely available in near-real time at IMD, Pune and at NCMRWF. One example of daily and weekly rainfall from NMSG product during 8-14 July 2013 is shown in Fig. 9. During this period, the monsoon was active over India. Most parts of India received fairly good amount of rainfall and this rainfall distribution from the NMSG appears realistic.

Now, upgraded daily gridded gauge-based rainfall data over India are available at 0.25° latitude/longitude resolution after retrospective processing with more number of local gauges (Pai *et al.*, 2014). Hence, the combined use of near-real time TMPA V7 and improved gauge-based rainfall data would essentially provide more accurate merged rainfall analysis at finer spatial scale and for longer time period which is under development.

6. Conclusion and future scope

Rainfall, an integral component of the global water cycle, is one of most complex atmospheric parameters. Accurate estimates of rainfall have large socio-economic impacts. Precise information of rainfall over India is vital for a number of applications related to hydrology, meteorology, agriculture, water resource management and numerical model output verification for its further advancement. Multisatellite rainfall products play a key role in study of rainfall variability at global or quasi-global scale and take the relative advantages of infrared and microwave sensors embedded at various Earth-observation satellites. The TMPA research product is one of the widely used multisatellite rainfall products over different parts of the globe for various hydro-meteorological applications. The existing V6 of TMPA products underwent major revisions and consequently V7 data sets were formally released in late 2012 which are supposed to be the final version of TRMM products.

In this paper, the results of evaluation of TMPA-3B42 and 3B43 V7 product over the Indian land and oceanic regions against ground-truth observations were highlighted. Evaluation of V6 and V7 data sets over the tropical Indian Ocean using gauge observations from the RAMA buoy array without employing wind-loss corrections at monthly scale for 2004-2010 showed that RMSE associated with higher rainfall was reduced in the V7. However, overall results suggested that the new version slightly degraded from its predecessor V6 data sets. In addition, TMPA V7 product was further compared at daily scale for an eight-year period (2004-2011) with RAMA buoy observations which showed an overestimation of rainfall by TMPA V7 as compared to observations. The error characteristics showed a seasonal variation with the largest correlation during the southwest monsoon season. The comparison of both the versions of TMPA-3B42 estimates against gridded gauge-based rainfall data sets over India for a thirteen southwest monsoon period (1998-2010) showed an overall improvement in bias in V7 over V6, but the results were equivalent in terms of correlation and RMSE. Furthermore, four contemporary high resolution multisatellite rainfall products like TMPA-3B42 V7,

CMORPH, NRL-blended and PERSIANN were evaluated against IMD gridded gauge-based observations over India for the southwest monsoon season which showed that TMPA has better skill than the other three products, possibly due to incorporation of gauge information. Overall, TMPA V7 is one of the best multisatellite rainfall products for monsoon-related studies, but it has still some biases. Following the launch of the Global Precipitation Mission (GPM) Core Observatory (Hou *et al.*, 2014) in February 2014, a new very high-resolution (at 0.1° grids and half-hourly) merged rainfall product namely, Integrated Multi-satellitE Retrievals for GPM (IMERG) is released recently. The extensive evaluation of the IMERG product over the Indian monsoon region would essentially help users to utilize this data set for their specific applications over this region.

One of the possible ways to reduce bias from TMPA data set is to combine it with local gauge data sets. The potential of synergism of TMPA and local gauge data over the Indian monsoon region using successive correction method was also discussed. The new gridded rainfall product namely, NMSG uses this approach and benefits from the relative advantages of TMPA and local gauge information. Recently, upgraded daily gridded gauge-based rainfall data at 0.25° latitude/longitude resolution with more number of rain gauges are released. Hence, the combined use of near-real time TMPA V7 and upgraded gauge-based rainfall data would certainly enhance the value of NMSG rainfall product at finer spatial scale which is under development. The synergism of advanced rainfall estimates from the GPM and more ground-based observations from rain gauges, automatic weather stations (AWS), automatic rain gauges (ARG) and weather radars would further enhance the quality of the NMSG rainfall product.

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