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ORIGINAL PAPER

Validation of a new meteorological forcing data in analysis of spatial and temporal variability of precipitation in India

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Abstract During the past two decades, numerous datasets have been developed for global/regional hydrological assessment and modeling, but these datasets often show differences in their spatial and temporal distributions of precipitation, which is one of the most critical input variables in global/regional hydrological modeling. This paper is aimed to explore the precipitation characteristics of the Water and Global Change (WATCH) forcing data (WFD) and compare these with the corresponding characteristics derived from satellite-gauge data (TRMM 3B42 and GPCP 1DD) and rain gauge data. It compared the consistency and difference between the WFD and satellite-gauge data in India and examined whether the pattern of seasonal (winter, pre-monsoon, monsoon and post-monsoon) precipitation over six regions [e.g. North Mountainous India (NMI), Northwest India (NWI), North Central India (NCI), West Peninsular India (WPI), East Peninsular India (EPI) and South Peninsular India (SPI)] of India agrees well for the gridded data to be useful in precipitation variability analyses. The multi-time scale of precipitation in India was analysed by wavelet transformation method using gauged and WFD precipitation data. In general, precipitation from WFD is larger than that from satellite-gauge data in NMI and Western Ghats region whereas it is smaller in the dry region of NWI. Both WFD and satellite-gauge datasets underestimate precipitation compared to the measured data but the precipitation from WFD is better estimated than that from satellite-gauge data. It was found that the wavelet power spectrum of precipitation based on WFD is reasonably close to that of measured precipitation in NWI and NCI, while slightly different in NMI. It is felt that the WFD data can be used as a potential dataset for hydrological study in India.

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1 Introduction

Reliable observations of precipitation are important for hydrological science because it is crucial in applications such as water management for agriculture and drought and flood forecasting. In addition, current concerns about the possible consequences of climate change on spatial distribution of water resources have increased, which give rise to an ever increasing demand for information about whether precipitation characteristics more generally show evidence of changing spatial patterns and temporal distribution (Vincent et al. 2005). Therefore, estimation of precipitation characteristics in areas with low rain gauge densities and short length of records causes difficulties and uncertainties and this is one of the major concerns in hydrological sciences.

During the past two decades, numerous precipitation datasets have been developed, which might be the potential datasets for hydrological assessment and modeling including the Climate Research Unit (CRU 2000), the Tropical Rainfall Measuring Mission (TRMM) (Huffman et al. 2007), the Global Precipitation Climatology Project (GPCP) (Huffman et al. 2001), the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset (Kanamitsu et al. 2002). A new meteorological forcing data developed by the European Union funded Water and Global Change (WATCH) project (www.eu-watch.org), called the WATCH forcing data (WFD), has become available in August 2011 (Weedon et al. 2010, 2011). This dataset was derived from the re-analysis of the European Centre for Medium-Range Weather Forecasts (ERA40) (Uppala et al. 2005) for the period 1958–2001, and was bias corrected based on monthly observational data (Mitchell and Jones 2005).

Many studies have compared differences between the various precipitation datasets and rain gauge data as well as their impact on hydrological modelling (Fekete et al. 2004; Tian et al. 2007; Su et al. 2008; Biemans et al. 2009; Abdella and Alfredsen 2010; Clarke et al. 2011; Shen et al. 2010; Buarque et al. 2011; Li et al. 2012, 2013; Kizza et al. 2012; Parkes et al. 2013). Previous studies have shown that these precipitation datasets generally agree in their temporal trends and spatial distribution, but they often show remarkable differences at regional scales. Fekete et al. (2004) compared six monthly precipitation datasets to show that improving precipitation estimates in arid and semiarid regions is highly needed, where slight changes in precipitation can result in dramatic changes in the runoff response due to the nonlinearity of the runoff-generation processes. Biemans et al. (2009) compared seven global gridded precipitation datasets at river basin scale in terms of annual mean and seasonal precipitation. The study revealed that the representation of seasonality was similar for all the datasets but there were large uncertainties in the mean annual precipitation, especially in mountainous, arctic and small basins.

Adeyewa and Nakamura (2003) validated the TRMM precipitation radar data and TRMM-3B43 precipitation data with the Global Precipitation Climatology Center (GPCC) rain gauge data and showed significant seasonally and regionally dependent bias over land in Africa and TRMM-3B43 has the best agreement. Chiu et al. (2006) also found that merged satellite-gauge products (3B42 and 3B43) to be better correlated with Water District rain gauge data. Su et al. (2008) used TRMM Multisatellite Precipitation Analysis (TMPA) as forcing data to put into hydrological models in La Plata basin in South America and found a good agreement in reproduction of seasonal and inter-annual stream-flow variability, which shows that TMPA has potential for hydrologic forecasting in data-sparse regions. In addition, TMPA has been validated by more than 100 rain gauges in Thailand and result showed that the frequency distribution of daily TMPA rainfall is similar to the gauge data (Chokngamwong and Chiu 2008). Rahman and Sengupta (2007) compared the GPCP, TRMM 3B42-V5 and 3B42-V6 rainfall data with IMC gridded daily rainfall for the monsoon season. It showed that the spatial patterns of 3B42-V6 has the closest agreement with observed patterns except in certain places, i.e. Himalayan foothills, Gangetic plains and part of east central India. Nair and Nemani (2009) evaluated TRMM 3B42-V6 over western State of India and found that the TRMM 3B42-V6 retrieved the moderate rainfall best and mainly inaccurate in regions of sharp rainfall gradient. They believed that the TRMM 3B42-V6 data could have tremendous potential use for seasonal studies over most regions of western state of India. Some studies have shown that satellite-gauge precipitation products can be used as an alternative source of information but these need calibration and validation due to the indirect nature of the radiation measurements (Cheema and Bastiaanssen 2012; Tobin and Bennett 2010; Vila et al. 2009; Wilk et al. 2006).

As it is already known, satellite-gauge precipitation products, like TRMM and GPCP, are quite popular as they are updated regularly and closer to gauged data but have shorter periods starting from 1997. The WFD on the other hand, with a longer bias corrected record, is ideal for analysing the historical trends. Although some studies using WFD have shown that it improves simulations of river runoff in some regions (Hagemann et al. 2011; Piani et al. 2010; Li et al. 2013), its usefulness in many regions is yet to be analysed. In this study, the comparison of the precipitation characteristics in India derived from the WFD and rain gauge data is evaluated. The merged TRMM 3B42 and GPCP 1DD data (the satellite-gauge data) will be also used to compare the consistency and difference of spatial distribution of precipitation with WFD. It will be useful to explore how representative the WFD dataset is for India.

From the foregoing concerns, the paper aims to: (1) explore the precipitation characteristics of WFD data and compare these with the corresponding characteristics derived from satellite-gauge data and rain gauge data; and (2) examine whether the pattern of seasonal (winter, premonsoon monsoon and post-monsoon) precipitation over selected regions of India derived from WFD and rain gauge records agree well. The outcome of this study should be useful to the hydrology community and provide some insights on the selection and applicability of global weather datasets for research in India.

2 Study area and data

2.1 Study area

India lies to the north of the equator between 6°44′ and 35°30′ north latitude and 68°7′ and 97°25′ east longitude and has a large variation in climate from region to region, due to its vast size. India experiences four major climate groups based on Köppen climate classification (Köppen 1936; Peel et al. 2007), including tropical rainy, dry, humid sub-tropical and mountain. The different regions used for comparison are shown in Fig. 1. Six regions over India, i.e., North Mountainous India (NMI), Northwest India (NWI), North Central India (NCI), West Peninsular India (WPI), East Peninsular India (EPI) and South Peninsular India (SPI) were chosen based on the consideration that the seasonal and annual precipitation data within each of these six zones is homogeneous (Sontakke et al. 2008). The mean monthly, seasonal and annual precipitation of the six regions in India is shown in Table 1.

The NMI region is in the Himalayan Mountain which consists of steep valleys where topographic elevations go up to 7,000 m. Mean annual precipitation is 1,336 mm, of which monsoon season accounts for nearly 72 %. The NWI region is in the arid and semi-arid climate zone, where the Great Indian Desert, the Thar Desert is located. Mean annual precipitation is 775 mm with monsoon accounting for 88 % of it. The NCI region contains the foothills of the Himalayan and fertile Indus-Gangetic alluvial plains adjacent to the Himalayas. Climate here is humid sub-tropical type with dry winters. This area has very high population density and is called as the "food bowl" of India. Mean annual precipitation is 1,212 mm (85 % falls in monsoon). The mean annual precipitation for WPI, EPI and SPI regions is 1103, 1162 and 1555 mm, with nearly 85, 73 and 60 % falling in monsoon season, respectively. In this study, data of all the regions except NEI are used for comparison (Sontakke et al. 2008).

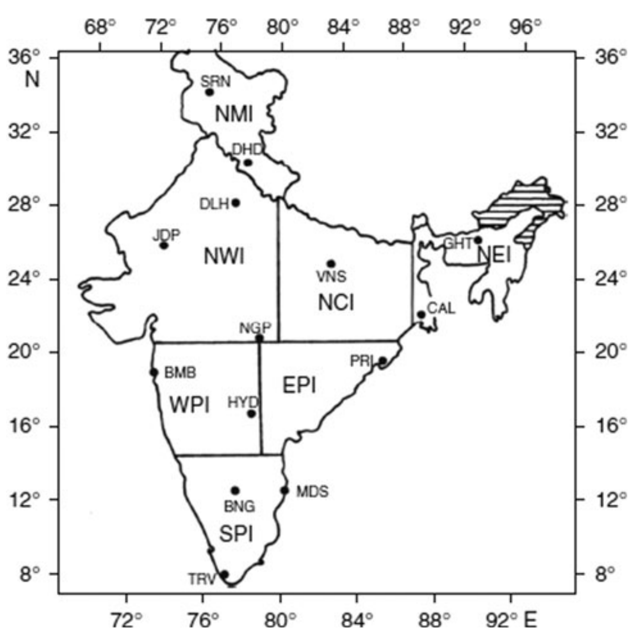

Fig. 1 The Boundary of homogeneous region zone of India including North Mountainous India (NMI), Northwest India (NWI), North Central India (NCI), West Peninsular India (WPI), East Peninsular India (EPI), South Peninsular India (SPI) and Northeast India (NEI) (From Sontakke et al. 2008) (the *shading area* is Arunachal Pradesh which is disputed area by China and India)

2.2 Data

Two global precipitation datasets and an observed rain gauge dataset were used in the study. The 0.5° × 0.5° gridded daily precipitation dataset from 1958 to 2001 has been developed by the Water and Global Change (WATCH) project (Weedon et al. 2010, 2011) as inputs for large-scale land-surface and hydrological models. The WFD consists of meteorological variables needed for running hydrological models derived from ERA-40 reanalysis (Uppala et al. 2005). The data are derived from the ERA-40 reanalysis product (www.ecmwf.int/research/era/do/get/era-40) via sequential interpolation to half-degree resolution, elevation correction and monthly-scale adjustments based on CRU-TS2.1 (corrected-temperature, diurnal temperature range, cloud-cover) (www.cru.uea.ac.uk/~timm/grid/CRU_TS_2_1.html; Mitchell and Jones 2005) and the Global Precipitation Climatology Centre Full data product v4 (GPCCv4) (http://orias.dwd.de/GPCC/GPCC_Visualiser; Rudolf and Schneider 2005; Schneider et al. 2008) monthly observations combined with separate precipitation gauge corrections for rainfall and snowfall.

A satellite-gauge estimates from 1997 to 2009 was constructed by combining a 0.25° and a 1° datasets: the TRMM 3B42-V6 dataset (Huffman et al. 2007), which has a coverage between 50°S and 50°N, and the GPCP 1DD dataset (Huffman et al. 2001) which covers the whole globe. The combined precipitation was rescaled to 0.5° through linear interpolation (Gong et al. 2011). GPCP 1DD is a merged dataset based on gauge measurements and satellite estimates of precipitation. TRMM uses a combination of microwave and infrared sensors to improve accuracy, coverage and resolution of its precipitation estimates. However, lower skill still remains in correctly specifying moderate and light rain rates on short time intervals (Michaelides et al. 2009). In common with the GPCP products, TRMM was designed to combine precipitation estimates from satellite with land surface gauges (Huffman et al. 2007). The monthly TRMM and merged

Table 1 The mean monthly and annual precipitation of the six zones NMI, NWI, NCI, WPI, EPI, SPI and India (IN) for the data period 1848–2006 (Unit: mm)

Precipitation	NMI	NWI	NCI	WPI	EPI	SPI	IN
Jan	60.8	8.2	11.4	4.8	9.6	10.2	10.8
Feb	77.4	9.2	11.4	4.6	27.7	14.9	14.7
Mar	82.1	7.2	14.0	3.1	9.5	9.5	15.2
Apr	67.9	9.4	20.9	11.9	31.6	64.5	32.5
May	83.4	26.4	60.2	47.9	45.4	117.0	70.0
Jun	173.8	116.5	195.7	228.1	164.1	254.7	189.1
Jul	340.7	245.8	336.3	267.1	220.7	265.6	287.1
Aug	300.6	178.5	294.3	253.3	248.8	204.5	241.3
Sep	147.2	113.2	220.9	167.9	196.6	177.0	173.4
Oct	41.9	42.3	76.1	113.3	136.0	232.2	98.5
Nov	28.9	7.7	15.0	19.7	52.8	146.6	33.9
Dec	25.4	10.9	11.6	12.0	15.6	69.6	19.2
ANN	1430.1	775.3	1267.9	1133.9	1158.4	1566.4	1185.4
Winter	138.2	17.4	22.8	9.5	37.4	25.2	25.5
Pre-monsoon	233.4	43.0	95.2	62.9	86.5	191.1	117.6
Monsoon	962.3	654.0	1047.3	916.5	830.3	901.7	890.8
Post-monsoon	96.2	60.9	102.7	145.0	204.3	448.4	151.5

Winter is from January to February, pre-monsoon is from March to May, monsoon is from June to September and post-monsoon is from October to December

estimate are produced by merging the TRMM adjusted Geostationary Observational Environmental Satellite (GOES) precipitation index (AGPI) with information of rain gauges which is from the GPCP (Rudolf 1993). de Goncalves et al. (2006) found that the TRMM 3B42 underestimates overall precipitation in South America.

The third dataset of area-averaged monthly precipitation used in this study came from monthly gauge precipitation data, the longest instrumental precipitation series of the Indian regions covering the period from 1813 to 2006 (Sontakke et al. 2008). This data can be downloaded from the web site (http://www.tropmet.res.in) of the Indian Institute of Tropical Meteorology (IITM). Highly quality-controlled data from a widespread network of 316 rain gauge stations over whole India was used to retrieve and interpolate to form the area-averaged monthly, seasonal and annual precipitation series of seven homogeneous zones in India from 1813 to 2006. Put together, these zones have a network of 306 stations over 30 meteorological subdivisions and cover about 2,880,000 km^2, which is about 90 % of the total area of India.

The overlapping period of bias corrected reanalysis precipitation data products (WFD) and the satellite-gauge data was 1997–2001. The characteristics of WFD and the satellite-gauge data are compared over India and also compared with gauge precipitation for quality control.

3 Methods

The consistency and differences between the two global precipitation datasets, i.e., WFD and the satellite-gauge datasets were compared by several statistical and hypothesis testing methods in this study, including Kolmogorov–Smirnov (K–S) test for checking whether the two datasets have the same distribution pattern (Xu 2001; Li et al. 2013), and student's t test and F test for checking the equality of mean value and variance between the two global datasets respectively (Zhang et al. 2012). A 5 % significance level was used for the above tests. The details of methods can be seen in Chu et al. (2010) and Li et al. (2013). Furthermore, the continuous wavelet transform (CWT) technique (Farge 1992; Torrence and Compo 1998; Grinsted et al. 2004; Mishra et al. 2011), as a tool for analysing localized variations of power within a time series, was applied in the study. The concept and procedure of the wavelet method are discussed by Torrence and Compo (1998).

4 Results

As discussed in Sect. 2.2, the time intervals of global gridded precipitation and gauge precipitation datasets are different. The former is daily and the latter is monthly. For the sake of comparison, monthly sums of various datasets are used.

4.1 Spatial distribution and areal mean

The difference in mean annual precipitation between the WFD and satellite-gauge datasets from 1997 to 2001 is shown in Fig. 2. From the figure, we can see that (1) in general, the spatial distributions of annual precipitation from 1997 to 2001 derived from the two datasets are quite

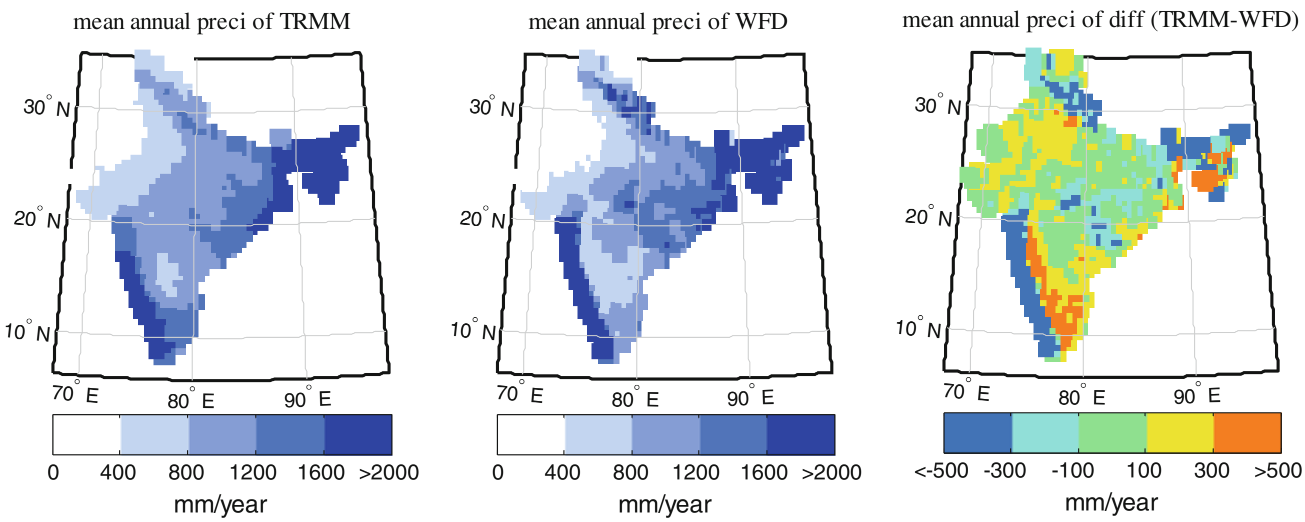

Fig. 2 Comparison of spatial distribution of mean annual precipitation in India between WFD and satellite-gauge data (TRMM) (1997–2001). (diff. = satellite-gauge data − WFD)

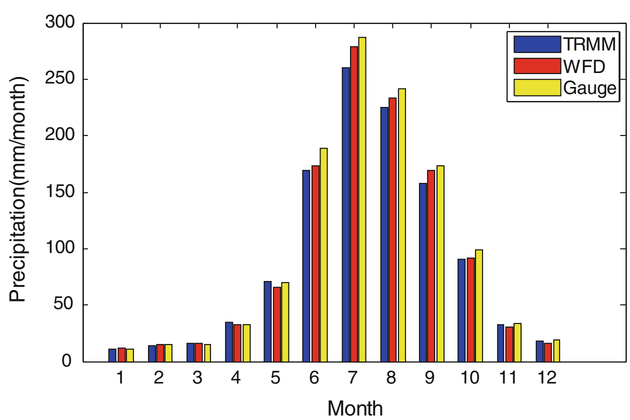

Fig. 3 Mean monthly precipitation in India from WFD, satellite-gauge data (TRMM) and rain gauge (1997–2001)

similar. Mean annual precipitation in India ranges from 400–1,200 mm/a in the northwest to over 1,600 mm/a in the northeast and also in the west coast of Indian peninsula; (2) the difference in mean annual precipitation between the satellite-gauge and WFD datasets is around −300 to 300 mm/a in the NWI, NCI and EPI regions whereas the differences are larger (from 100 to 500 mm/a) in the NMI, SPI and west coast regions; (3) the difference between the two datasets has a clear geographic pattern. The precipitation derived from the satellite-gauge data is considerably less than that from WFD in the NMI and Western Ghats region. In NWI region and on east side of Western Ghats which are the dryer regions, the precipitation derived from the satellite-gauge data is larger than that from WFD; and (4) the total annual precipitation derived from the satellite-gauge data (1,101 mm) is slightly less than that from WFD (1,133 mm). This can be graphically confirmed by Fig. 3, which shows a quantitative comparison of mean monthly precipitation from the WFD and satellite-gauge datasets over India during 1997–2001. It can also be seen from Fig. 3 that compared to the rain gauge data, both the satellite-gauge and WFD datasets underestimate precipitation amount, especially in monsoon period from June to September.

4.2 Seasonal precipitation

There are four seasons in India: winter (from January to February), pre-monsoon (from March to May), monsoon (from June to September) and post-monsoon (from October to December). In this section, the spatial distributions of seasonal precipitation derived from WFD and satellite-gauge datasets are compared. In addition, the interannual variation of four seasonal areal mean precipitations over six regions of India is analyzed. The seasonal (winter, pre-monsoon, monsoon and post-monsoon) 1997–2001 precipitation over India based on the WFD and satellite-gauge datasets is shown in Fig. 4. From this figure, we can see that (1) in general, the spatial distributions of mean seasonal precipitation from the WFD and satellite-gauge datasets are similar in four seasons during 1997–2001; (2) in the winter season, the mean monthly precipitation ranges from 0–8 mm/month in the south and the west to over 16 mm/month in the north, the east and south coast area. The differences of precipitation between the two datasets are between −2 and 2 mm/month at most areas of India, except NMI where the difference is −10 to 10 mm/month; (3) in the pre-monsoon season, the mean monthly precipitation are from 0 to 40 mm/month at the most areas of India; and over the narrow strip of Western Ghats and in the northeast area, it is over 80 mm/month. The biggest

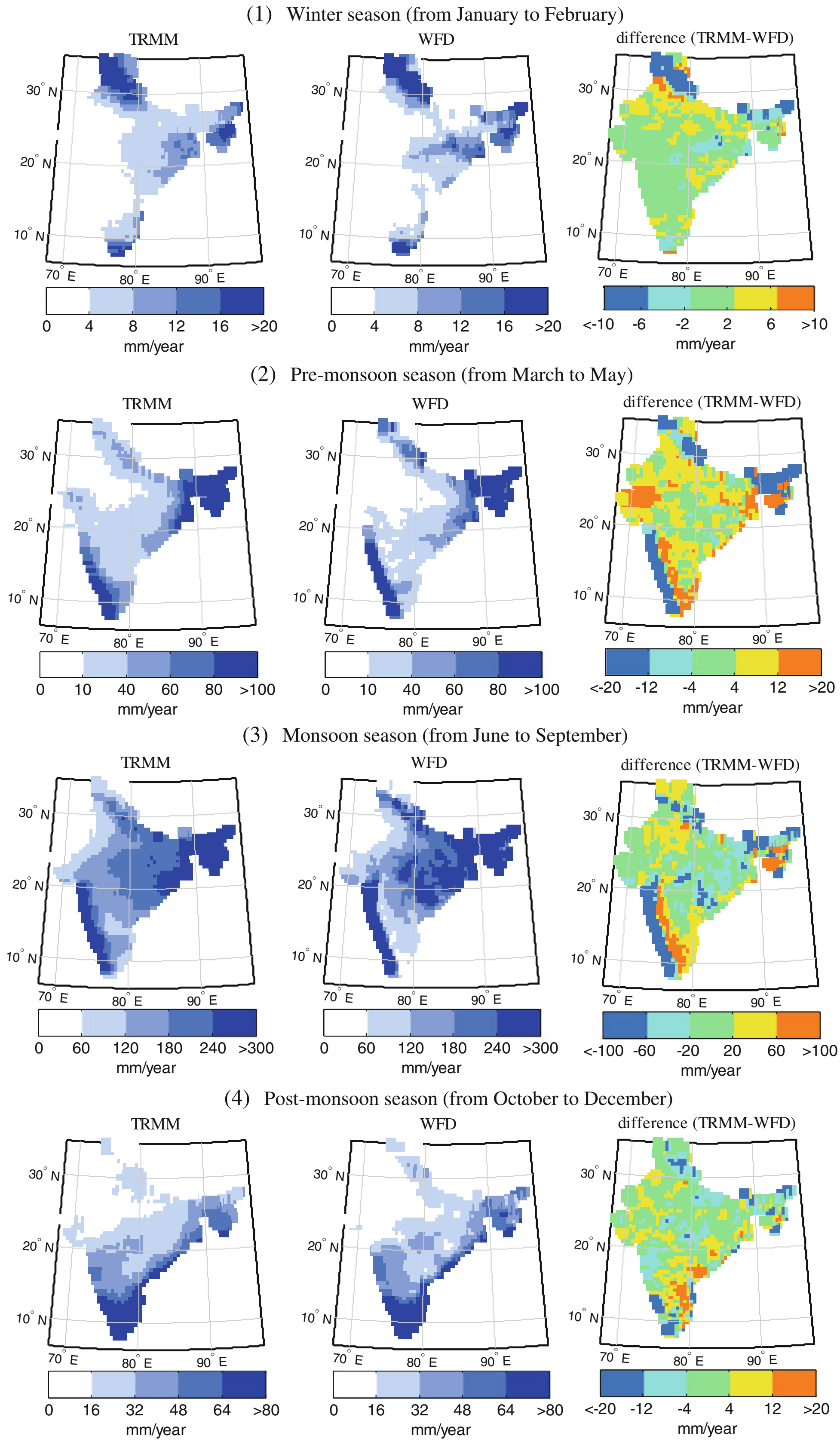

Fig. 4 Comparison of average monthly precipitation from WFD and satellite-gauge data (TRMM) in four seasons (1997–2001). Notice the difference of value scales

difference between the satellite-gauge data and the WFD are larger than 12 mm/month in northeast, the narrow strip of Western Ghats and north mountainous area; (4) in the monsoon season, the mean monthly precipitation is over 240 mm/month in the north mountainous, the east and the Western Ghat area. The highest difference of the two datasets is in the north mountainous and Western Ghat area and it is over 60 mm/month; and (5) in the post-monsoon season, the precipitation is 0–32 mm/month over most areas while the precipitation is over 64 mm/month in both datasets only in the south and Eastern Ghat area.

The interannual variation of seasonal areal mean precipitation over India in 1997–2001 is shown in Fig. 5, which shows a quantitative comparison of the spatial average of the seasonal precipitation over India from WFD, satellite-gauge data and gauge data from 1997 to 2001. It is seen that both WFD and satellite-gauge datasets overestimated the precipitation in pre-monsoon season while underestimated the precipitation in monsoon season. It is also shown that the precipitation from WFD is closer to gauge precipitation than TRMM. However, it’s hard to say which global gridded dataset is closer to gauge precipitation from this figure. While drawing conclusions from the results of this section, it must be noted that these are based on 5 years of data.

4.3 Regional precipitation

In order to examine the datasets more clearly, Fig. 6 shows the mean monthly precipitation from 1997 to 2001 in the six different regions of India based on the WFD, satellite-gauge data and rain gauge dataset. It can be obviously seen that (1) the precipitation from gauge dataset are higher than those from global gridded datasets, i.e. WFD and satellite-gauge data, especially in NMI; (2) the precipitation from gauge data is larger than that from gridded data in NMI, NWI and SPI regions especially in monsoon season; (3) the precipitation of WFD, satellite-gauge data and gauge are close at most areas of India, while the precipitation from WFD and satellite-gauge datasets show high mismatch with rain gauge records in NMI region, especially in pre-monsoon and monsoon periods; (4) the precipitation of WFD agree better with gauge precipitation than that from the satellite-gauge data especially in NMI region. Figure 7 shows the areal mean monthly precipitation (mm/month) from satellite-gauge data, WFD and gauge over the six regions of India from 1997 to 2001. We can see from the figure that (1) the precipitation of WFD and satellite-gauge datasets are close to that from rain gauge in all the regions except NMI; (2) In NMI region, both WFD and satellite-gauge datasets captured the variation of precipitation in all years but obviously underestimated the volume of rain, especially in monsoon period; (3) WFD data is closer to rain gauge than the satellite-gauge data for all the six regions of India. This can be confirmed by Table 2 which shows the results of RMSE and bias of WFD and the satellite-gauge data validated by rain gauge. It indicates that RMSE of precipitation from WFD is smaller than that of satellite-gauge data at most areas of India, except EPI

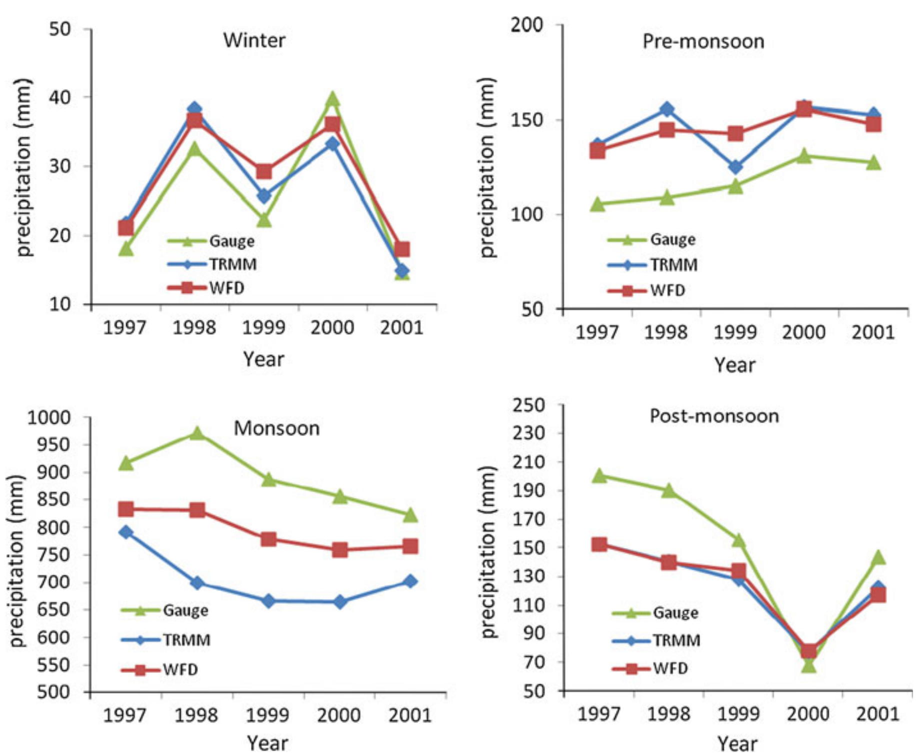

Fig. 5 Interannual variation of seasonal areal mean precipitation in India. Notice different scales in subfigures

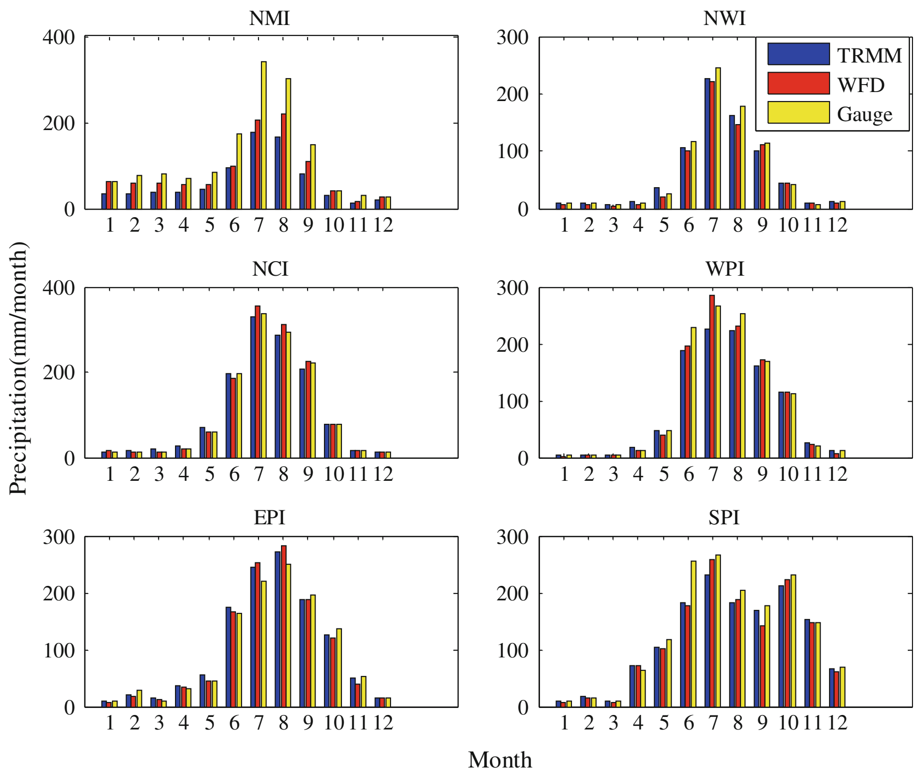

Fig. 6 Mean monthly precipitation in different regions of India derived from WFD, satellite-gauge data (TRMM) and Gauge datasets (1997–2001). Notice the Y-axis difference of value scales

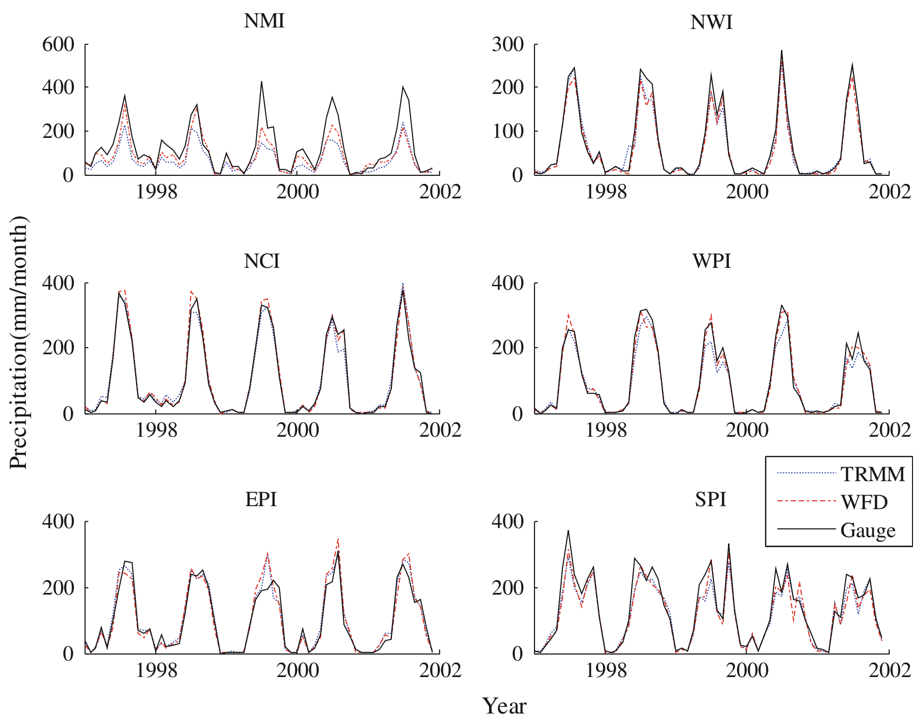

Fig. 7 Monthly areal mean precipitation (mm/month) over six regions of India based on WFD, satellite-gauge data (TRMM) and Gauge datasets. Notice different scales in subfigures

and SPI, where the RMSE of precipitation from WFD is slightly larger. The bias from WFD is smaller than that from the satellite-gauge data only in NMI, WPI and EPI regions. In SPI region, although the RMSE and bias from WFD is larger than those from the satellite-gauge data, the differences are quite small. The monthly rain gauge analysis by the GPCC (Rudolf 1993) was used for correction in the TRMM 3B42, while both the CRU number of "wet" days and the monthly precipitation of GPCCv4 (Rudolf and Schneider 2005) have been used for bias correction in

Table 2 The RMSE and bias of monthly precipitation from WFD and satellite-gauge data as compared with observed gauge data at six zones NMI, NWI, NCI, WPI, EPI, SPI and India (IN) for the data period 1997–2001 (Unit: mm)

Index	Datesets	IN	NMI	NWI	NCI	WPI	EPI	SPI
RMSE	Satellite-gauge	29.2	79.2	15.9	16.3	24.0	23.5	30.0
	WFD	24.2	61.7	15.5	14.7	18.8	26.8	31.4
Bias	Satellite-gauge	22.3	55.6	3.6	−0.4	9.2	−4.1	13.5
	WFD	19.7	35.7	8.3	−3.3	3.3	−1.8	14.3

WFD. In general, the precipitation from WFD is closer to gauge precipitation than that from the satellite-gauge dataset in India, especially in NMI regions.

4.4 Temporal distribution

The results of the correlation of the two global precipitation datasets on daily time step are shown in Fig. 8, which indicates that the correlation coefficient of WFD and satellite-gauge datasets are around 0.2–0.5 in most areas in India which is quite weak but significant. In the west part of NWI, correlation coefficient between WFD and satellite-gauge datasets is close to zero. The results of the consistency test of the WFD and satellite-gauge precipitation datasets in terms of their distribution patterns (KS test), long-term mean values (t test) and variances (F test) are shown in Fig. 9 and Table 3. It is seen from Fig. 9 that (1) the hypothesis of the daily data belonging to the same distribution is rejected at 5 % significance level all over India in general; (2) in NWI, NCI and EPI long-term mean values of the two datasets are statistically equal at 5 % significance level while this is just opposite in large parts of NMI and SPI and Western Ghats; and (3) the hypothesis that the variances of each pair of the two grid datasets are equal is rejected at 5 % significance level in the majority of the regions in India. These results are summarized in Table 3, which shows percentage of areas which satisfies the hypothesis of equality according to six regions of India, which quantitatively confirms the results from Fig. 9. The area of the same variance at 5 % significance level based on satellite-gauge and WFD datasets is <25 % in all regions, which means that the variability of precipitation from WFD and satellite-gauge datasets are quite different.

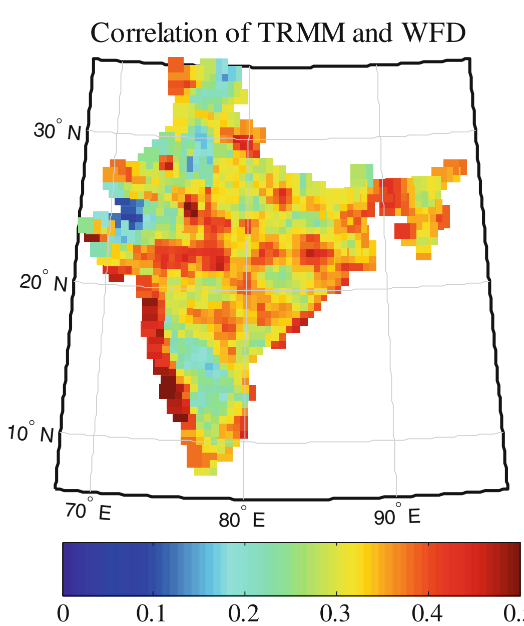

Fig. 8 Comparison of spatial distribution of correlation for daily precipitation between WFD and satellite-gauge data (TRMM) in India (1997–2001)

4.5 Long term comparison in volume and variability

The results presented in previous sections are based on the common period among the three datasets. In this section the difference in long-term trend and variability between gridded datasets and the observed gauge data is investigated separately, because the overlapping period between WFD and observed gauge data (1997–2006) and between satellite-gauge data and observed gauge data (1958–2001) is different. The comparison between areal monthly precipitation over India computed from WFD and satellite-gauge data and observed gauge data is shown in Fig. 10. It is seen that both reanalysis data (WFD) and satellite-gauge data (TRMM) are very close with monthly gauge precipitation over India. However, some differences are seen if the comparison is made on different regions (Fig. 11). In general, the mean annual precipitation of WFD and satellite-gauge datasets are close to that of observed gauge data in most of the regions except NMI. In NMI region, although WFD data are slightly better than satellite-gauge data, both WFD and satellite-gauge datasets obviously underestimated the annual precipitation as compared with gauge data. This can be seen more clearly in Table 4, which shows the RMSE and bias of WFD (1958–2001) and the satellite-gauge data (1997–2006) validated by rain gauge, separately. It indicates that (1) except NMI, the RMSE and bias of WFD over India range from 7.9–31.9 to −7.4 to 17.5 mm/month, respectively; (2) the bias of WFD in NMI region is 38.3 mm/month, while the bias of satellite-gauge data is 53.1 mm/month; (3) the RMSE values of WFD and satellite-gauge are close, around 76 mm/month; (4) the precipitation from WFD and satellite-gauge datasets in NWI, NCI and WPI regions have equal performance in terms of bias and RMSE; and (5) WFD is slightly better in bias and RMSE than satellite-gauge data. The monthly gridded datasets highly correlated with gauge precipitation.

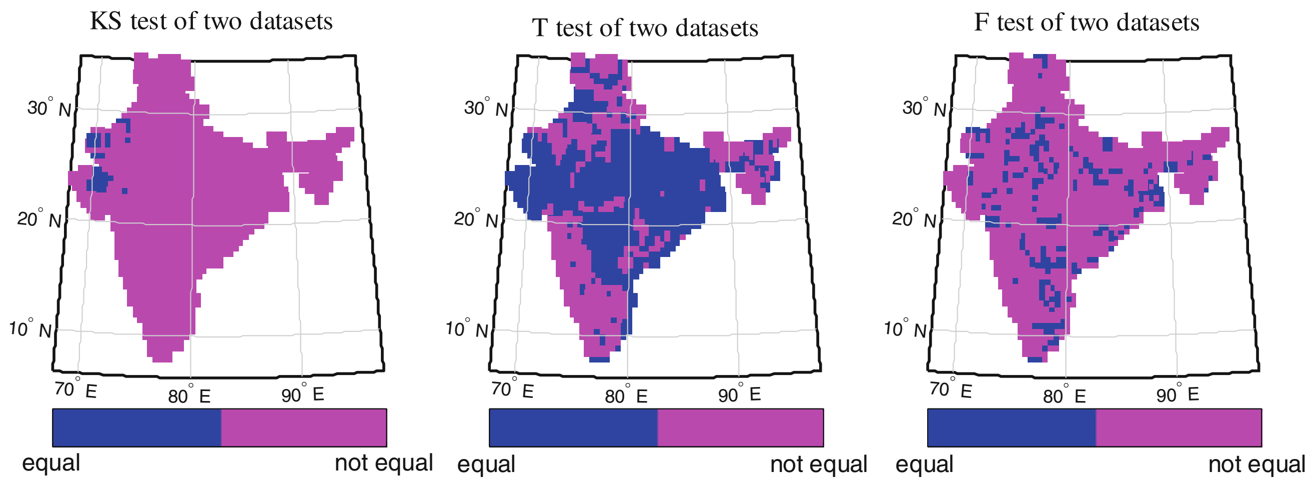

Fig. 9 Comparison of spatial distribution of general pattern by KS test, mean by student t-test and variance by F test of daily precipitation between WFD and satellite-gauge data (TRMM) in India (1997–2001)

Table 3 The percentage of areas where the test hypothesis is accepted based on WFD and satellite-gauge data at six zones NMI, NWI, NCI, WPI, EPI, SPI and India (IN) (Unit: %)

Methods	Hypothesis	Percentage of area						
		IN	NMI	NWI	NCI	WPI	EPI	SPI
Kolmogorov–Smirnov test	The same distribution	4.3	0	4.3	0	0	0	0
Student' *t* test	The same mean	58.1	29.5	73.9	95.2	57.2	71.2	21.8
F test	The same variances	16.3	2.6	18.3	16.2	19.9	17.8	22.7

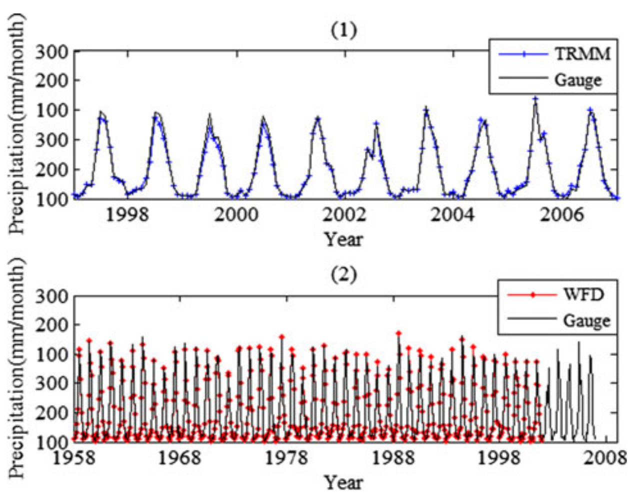

Fig. 10 Comparison between areal monthly precipitation in India computed from satellite-gauge data (TRMM) and Gauge data (1997–2006) and from WFD and Gauge data (1958–2006)

The lowest correlation is in NMI for both WFD and satellite-gauge data, which are 0.94 and 0.95, respectively.

Continuous wavelet transform technique (Torrence and Compo 1998) was used to study the periodicity properties and abrupt behaviors of precipitation variations. It has been widely used in hydrological studies and a detailed introduction has been presented by Zhang et al. (2007). Three typical regions were chosen for analysis in this part: NMI, NWI and NCI, which represent the mountain climate, the arid and semi-arid climate and the humid sub-tropical climate, respectively. The wavelet power spectra of the monthly precipitation for the period 1958–2001 based on Gauge and WFD in these three regions are shown in Figs. 12, 13 and 14. The wavelet power spectra of the monthly precipitation changes of three typical regions in India demonstrate pronounced annual and sub-annual cycles of the precipitation changes. Figure 12 shows that the wavelet power is relatively broadly and uniformly distributed in the 1/4- to 1-year band, but the 1/2- and 1-year bands were much more prevalent. There is a difference between the wavelet power spectrum of precipitation based on the Gauge and WFD datasets. More significant wavelet power spectrum appeared at the bands of 1-year and 1/2-year at the gauge data than that of WFD dataset. However, both graphs show that the annual cycle of the precipitation series was removed during 1981–1984 and 1990–1993. There is no annual cycle during 1973–1976 based on the WFD dataset while significant annual cycle is identified based on the gauge data. The precipitation at NMI is reflected mainly by intermittent periodicity after 1980.

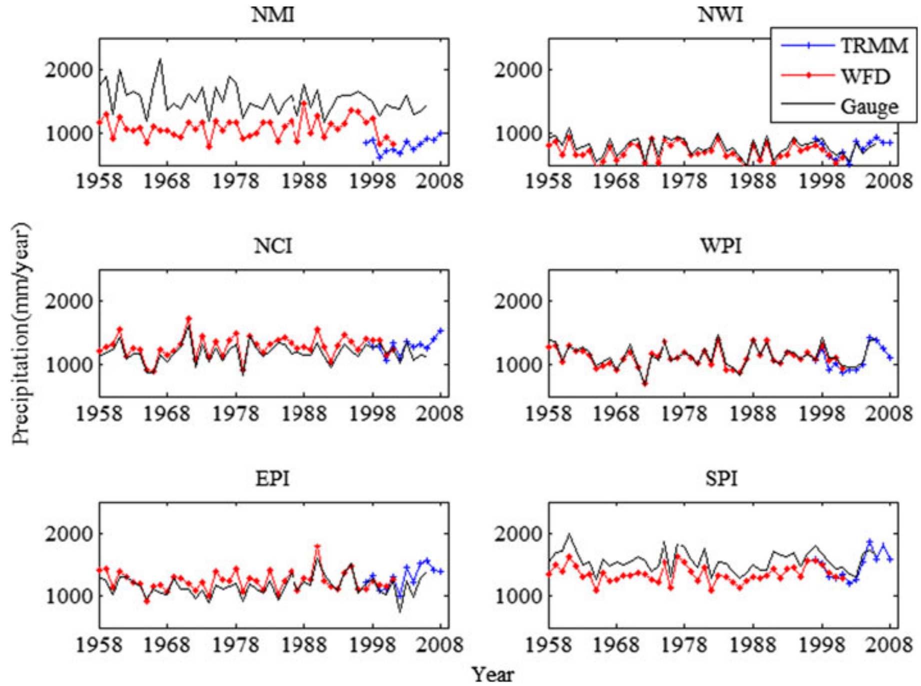

Fig. 11 Annual precipitation over six regions of India based on WFD, satellite-gauge data (TRMM) and observed gauge datasets

Table 4 The comparison of RMSE, bias and correlation coefficient of monthly precipitation from reanalysis data WFD (1958–2001) and satellite-gauge data (1997–2006) as compared with observed gauge data at six zones NMI, NWI, NCI, WPI, EPI, SPI and India (IN) (Unit: mm/month for RMSE and Bias)

Index	Datesets	IN	NMI	NWI	NCI	WPI	EPI	SPI
RMSE	Satellite-gauge	12.4	76.2	14.7	17.9	24.0	31.6	27.3
	WFD	7.9	76.9	15.0	18.3	15.0	26.1	31.9
Bias	Satellite-gauge	3.1	53.1	0.2	−5.2	5.3	−11.4	8.6
	WFD	1.5	38.3	6.6	−7.4	1.9	−5.9	17.5
Correlation coefficient	Satellite-gauge	0.99	0.95	0.99	0.99	0.98	0.96	0.97
	WFD	1.0	0.94	0.99	0.99	0.99	0.98	0.98

Figure 13 clearly shows that the prominent 1-year and 1/2 year bands dominate the whole monthly precipitation series at NWI based on both datasets. The interannual variation in the precipitation series are significant at >95 % confidence level. Visual comparison between Fig. 13a and b indicates that the difference mainly lies in the shorter periodic components, i.e. the period of 1/2-years. Significant 1/4-year band is sparsely distributed along the whole precipitation series. The removals of the annual cycle of the precipitation at NWI based on two dataset are quite similar. Figure 14 also indicates a significant half annual and annual cycle at NCI region based on the two datasets. However, the half-annual cycle was not persistent, especially after about 1987. Comparing the Fig. 12 with Fig. 14, the shorter period components of precipitation become more significant from the NMI region to the North plains region (NWI and NCI).

5 Discussion and conclusion

The precipitation from a new global meteorological forcing data WFD has been compared with the satellite-gauge data and both of the gridded precipitation datasets have also been validated against monthly rain gauge data obtained from IITM over six regions covering almost all of India. If we look at the spatial distribution of mean annual precipitation on the common period of the three datasets, the WFD and satellite-gauge datasets are quite similar, while the values of mean annual precipitation are different. The total precipitation derived from WFD is larger than that from satellite-gauge data in India, which is closer to the gauge precipitation, especially in the NMI region.

The difference between the two gridded datasets has a clear geographic pattern. The precipitation derived from WFD is considerably higher than that from satellite-gauge

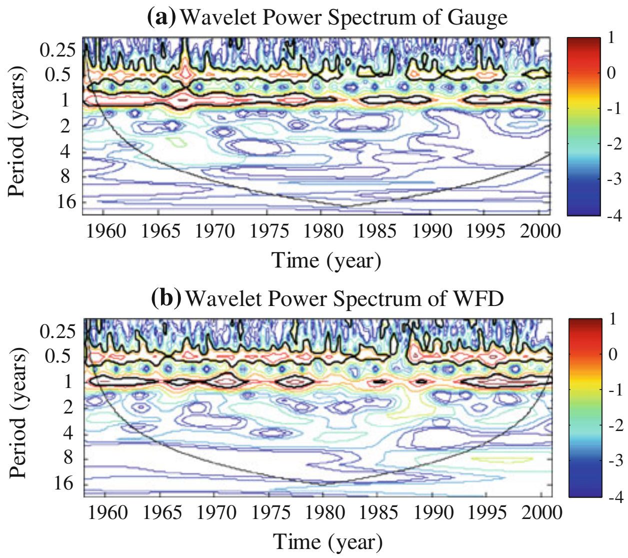

Fig. 12 Wavelet power spectrum of the monthly precipitation based on **a** Gauge and **b** WFD in North Mountainous India (NMI). The 5 % significance level against red noise is shown as *thick black contours*

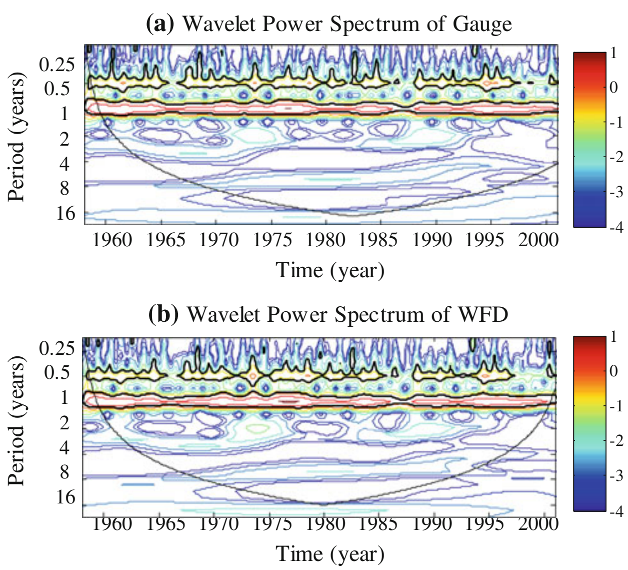

Fig. 13 Wavelet power spectrum of the monthly precipitation based on **a** Gauge and **b** WFD in Northwest India (NWI). The 5 % significance level against red noise is shown as *thick black contours*

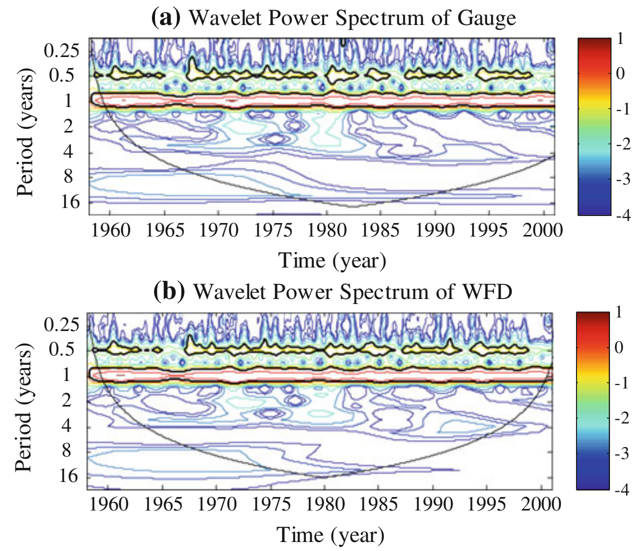

Fig. 14 Wavelet power spectrum of the monthly precipitation based on **a** Gauge and **b** WFD in North Central India (NCI). The 5 % significance level against red noise is shown as *thick black contours*

data in the north Himalaya mountainous region and Western Ghat area. However, in the NWI, on the east side of Westen Ghats and southeast SPI regions, the precipitation derived from satellite-gauge data is larger than that from WFD. Both WFD and satellite-gauge datasets underestimate precipitation amount compared with observed precipitation from gauge data, especially in monsoon period from June to September while overestimate pre-monsoon precipitation in 1997–2001. This has also been confirmed in a previous research by Rahman et al. (2009). These two gridded datasets are close to the observed precipitation at NWI, NCI and EPI regions, while they highly mismatched the records from gauge in the NMI region, especially in pre-monsoon and monsoon periods in 1997–2001. The precipitation of WFD is closer to gauge precipitation than that of satellite-gauge data in 1997–2001. The long-term period comparison of WFD (1958–2001) and satellite-gauge data (1997–2006) with gauge precipitation has the similar results as in common period of 1997–2001. The monthly precipitation from WFD and satellite-gauge data in most regions of India are quite close to the gauge precipitation in terms of trend, variation and volume, except in NMI region. WFD, which has longer period, is slightly better in terms of bias and RMSE than satellite-gauge data.

The spatial–temporal precipitation variations (1990–2001) between WFD and satellite-gauge datasets in India have been compared by using three statistical testing methods, which include the KS test, the student's *t* test and the *F* test. There are large differences between the two datasets in terms of their variances than their mean values and spatial patterns. The mean values of the two datasets are statistically equal at 5 % significance level in NWI, NCI and EPI while this is contrary in large parts of the NMI, WPI and SPI regions. Furthermore, the correlation coefficient of precipitation between WFD and satellite-gauge datasets during 1997–2001 is around 0.2–0.5 at daily time step, which is quite weak, but significant. The smallest correlations are located at the eastern NMI and the western NWI. The correlation coefficients between the gridded datasets and the observed gauge data are high at monthly time step with the value of 0.95–0.99 between TRMM and gauge data (1997–2006) and 0.94–1.0 between WFD and gauge data (1958–2001).

The wavelet power spectrum of precipitation in 1958–2001 based on gauge and WFD is broad and uniformly distributed in the 1/2- and 1-year bands in NMI, NWI and NCI. Furthermore, the wavelet power spectra of precipitation based on WFD are reasonably close to that of observed precipitation from gauge data in NWI and NCI, while slightly different in NMI during 1958–2001.

The WFD compared with the satellite-gauge datasets, i.e. TRMM 3B42, has shown to have better potential to be used for variability and seasonal studies and might be a good potential dataset for hydrological assessment and modeling in India. However, more attention should be paid in NMI region, where both satellite-gauge data and reanalysis data poorly performed in terms of mean value and variance of monthly precipitation.

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