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RESEARCH ARTICLE

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Evaluation of evapotranspiration estimates from observed and reanalysis data sets over Indian region

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Abstract

In this study, we have computed the evapotranspiration (ET) from the input variables of India Meteorological Department (IMD) for different stations in Monsoon Core Region (MCR) of India and Indian Peninsular Region (IPR) and compared with the ERA Interim (ERA-I) and CRU ET data sets. While studying the discrepancies among the data sets, rainfall (source: IMD gridded), relative humidity (source: ERA Interim gridded), air temperature (source: IMD gridded) and soil moisture (source: TRMM/LPRM/TMI-Model) were made use to illustrate the ET variations. When compared with IMD ET, our results show the CRU ET is underestimated but maintained the close pattern over MCR and IPR during South West (SW) monsoon (June–September) and North East (NE) monsoon (October–December) period, respectively. ERA-I ET bounded to have mixed response over MCR and are higher than the IMD ET over IPR. Daily comparison of the IMD and ERA-I ET data sets shows a large bias during the beginning of SW monsoon (June month) compared to other months. Site wise correlations show the substantial positive correlations between IMD and CRU ET over MCR than IPR. Overall analysis shows the monsoon features were better explained by the variations in IMD ET compared to CRU and ERA-I ET data sets. The reported disparities among the data sets play an important role in the choice of selection for different applications such as water resource assessments, crop water requirements, monitoring of droughts etc.

KEYWORDS

CRU and India, ERA-I, evapotranspiration, IMD

1 | INTRODUCTION

Evapotranspiration plays a key role in the earth's hydrological cycle in linking the land surface and atmosphere through the transfer of moisture. The data of evapotranspiration is essential in many land surface and global hydrological models (Hanasaki *et al.,* 2008; Balsamo *et al.,* 2009; Zhang *et al.,* 2017; Tanguy *et al.,* 2018). There are several methods to estimate the evapotranspiration based on the availability of the data. Temperature based (Thornthwaite, 1948; Hargreaves and Samani, 1982) and micro meteorological methods (Penman, 1948; Monteith, 1965) are widely used to estimate the evapotranspiration. By making use of Penman–Monteith method and local moisture fluxes, global data sets of evaporation/evapotranspiration have been developed (e.g., MODIS ET, Climate Research Unit and ECMWF) with different grid resolutions. The Moderate Resolution Imaging Spectroradiometer (MODIS) global ET data sets are available with 0.5° × 0.5° grid resolution and reported as widely accepted remote sensing products (Miralles *et al.,* 2016; Wang *et al.,* 2017). The ET data sets developed by CRU (on monthly basis from 1901 to 2014) and ECMWF (1979 onwards) are used in many studies (Purnadurga *et al.,* 2017; Weiland et al., 2012; Uml *et al.,* 2017; Srivastava *et al.,* 2013; Romanou et al., 2010). These reanalysis data sets are developed based on the forecast models and data assimilation methods and proven as the best indicators of the weather and climate patterns (Saha *et al.,* 2006; Krogh *et al.,* 2015). Though they have been used in many studies, the work on the comparison among these data sets is very limited. Instantaneous and daily evaporation estimates obtained from EUMETSAT were compared with the ECMWF ET estimates in Africa and parts of South America and found high spatial correlation among them (Ghilain *et al.,* 2011). Mao and Wang, 2017 compared the ET estimates from ERA, modified Penman-Monteith and water balance approaches over continental China and found inconsistencies in ERA ET in showing the actual trends as observed by other data sets during 1997 to 2013. The uncertainties are reported as the uncertainties in simulating the precipitation that is used for the estimation of ET from reanalysis data sets. The results of the comparison of ET estimates from hydrological model PCR—GLOBWB and ERA Interim over African continent show that ERA ET is generally higher which could be explained by the assimilation of soil moisture (Trambauer *et al.,* 2014). Nkiaka *et al.,* 2017 reported that the utilization of input data in estimating the ET from different models used in reanalysis and other hydrological models influence the pattern and magnitudes of ET. Smith and Kummerow, 2013 used Max Plank Institute (MPI) ET and ERA ET data sets to study the water budgets over upper Colorado river basin and inferred the both data sets show interannual variability with different values. The reason being for this is that the reanalysis data have constraints as they were forced by the direct or remote observations which have limitations by model physics.

Many studies have been carried out on the estimates of ET from different equations (Kumar *et al.,* 1987; Nandagiri and Kovoor, 2006; Pandey *et al.,* 2016), trends and variability of ET (Verma and Jadhav, 2008; Jhajharia *et al.,* 2012; Lakshmi Kumar *et al.,* 2012; Goroshi *et al.,* 2017), quantification of ET during droughts for different crops (Madhu *et al.,* 2015; Zhang *et al.,* 2017) over India. Studies were also performed to delineate the calibration parameters among the different approaches for improving the accuracy of ET over India (Rao et al., 2012). Using the combination of rainfall and evapotranspiration, meteorological droughts were studied over Indian context and reported the drought occurrences based on the ET changes (Das *et al.,* 2016). Most of these studies use the ET estimated from IMD inputs, CRU, ERA data sets and satellite observations. However, there is no study on the comparison of the aforementioned data sets which is very important to know their applicability and capability in different applications.

The main focus of this paper is to compare the ET estimates obtained from the independently derived data sets such as India Meteorological Department (IMD), Climate Research Unit (CRU) and ECMWF Interim over MCR and IPR of India. A thorough analysis has been carried out to bring a better understanding of inconsistencies and discrepancies as each data sets have intrinsic uncertainties in estimating the ET. The results of this work on validation will better serve the hydrology modellers for their operational assessments.

2 | DATA AND METHODOLOGY

We have used the meteorological data available from India Meteorological Department (IMD) for the estimation of evapotranspiration. The parameters such as maximum, minimum air temperature and relative humidity, wind information have been made use from 1979 to 2014 on daily basis for SW and NE monsoon period. The focus of this study is on the MCR (Rajeevan et al., 2008) during the SW monsoon period and the IPR (Rajeevan *et al.,* 2012) during the NE monsoon season. As the SW and NE monsoons are active over the respective MCR and IPR, these regions were chosen for the present study. The locations of the stations considered for the study are given in the Figure 1.

For the estimation of evapotranspiration, Penman-Monteith method (1965) was used and is given below. The full form of reference evapotranspiration can be expressed as

$$\mathrm{ET}=\frac{0.408\Delta(Rn-G)+\gamma\frac{900}{T+273}u2(es-ea)}{\Delta+\gamma(1+0.34u2)}, \tag{1}$$

where ET is reference evapotranspiration (mm day^{-1}), Δ is the slope of the saturation vapour pressure, T is the air temperature (°C). The net solar radiation (Rn) in W/m^2 is calculated based on the reflectivity (albedo) of the surface, that is, albedo for a reference crop 0.23 (FAO 56) and by using the extra-terrestrial radiations. The extra-terrestrial radiation is obtained from the source provided by Santa Clara University, USA, (http://www.engr.scu.edu/~emaurer/tools/calc_solar_cgi.pl). The ET has been estimated on daily basis and converted to monthly and seasonal basis for the analysis in the present study. We have selected 25 stations in the MCR and 17 stations in the IPR on the basis of continuous data availability.

The ECMWF reanalysis (ERA-I) data of ET with 0.25° × 0.25° grid resolution was obtained for the period

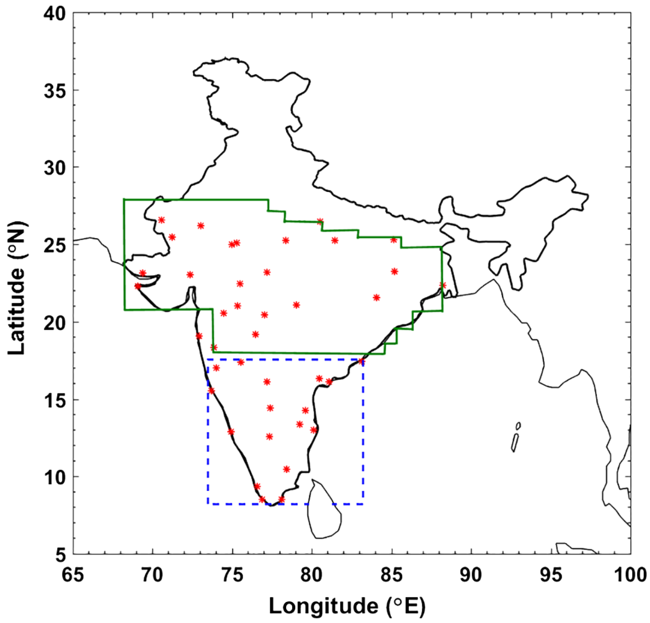

FIGURE 1 Map of India showing the Monsoon Core Region (MCR-solid line) and Interior Peninsular Region (IPR-dashed line) for the present study. The stars marked in figure depict the stations considered for the study [Colour figure can be viewed at wileyonlinelibrary.com]

1979 to 2014 on daily basis. The values were accumulated during the day hours (0530, 0830, 1130, 1430 and 1730 hr IST) and have been used in the present study for the comparison purpose. Furthermore, we have used the monthly mean ET, provided by the Climate Research Unit (CRU: https://crudata.uea.ac.uk/), on 0.5° × 0.5° resolution to compare the IMD and ERA-I data sets. In the analysis, we have also used the daily soil moisture provided by TRMM/LPRM/TMI-Model for the period 1998 to 2014. This model provides level 3 surface soil moisture on daily time scale which is derived from passive microwave remote sensing from Tropical Rainfall Measuring Mission (TRMM), Microwave Imager (TMI) using Land Parameter Retrieval Model (LPRM). The data is available globally at 0.25° × 0.25° grid resolution (https://giovanni.gsfc.nasa.gov/). In addition, gridded rainfall daily data (0.25° × 0.25°) of IMD developed by Pai *et al.* (2015), daily gridded air temperature data (1° × 1°) of IMD developed by Srivastava *et al.,* 2009 and daily relative humidity with the 0.25° × 0.25° grid resolution from ECMWF has been used in the present analysis.

In this study, we compared the value ET obtained for a grid box covering the station with the ET of the respective station. In addition, there are other methods in the comparison of grid data of ET with the station data when the grid resolution is coarse as suggested by (Mooney *et al.,* 2011) where they have used a grid resolution of 2.5° for the evaluation ET data sets. The other methods make use of area weighted averages in comparing the station data and this issue arises mainly when the station is located not in the middle of the coarse grid. Since, we have used the high resolution data sets of ET in the present study, direct comparison of ET of grid and station would serve the purpose. It is also reported that the ET values vary spatially during the coarsening of grid resolution if there are topographic changes and high spatial variability of rainfall exists within the gird are considered (Mo *et al.,* 2009; Shrestha *et al.,* 2018). The present study area does not possess the rapid changes of topography and no rainfall variations within the grid resolution considered and hence the comparison of gridded ET with the station ones can be carried out.

To obtain the overall time series of ET over MCR and IPR, we have averaged the ET values of all stations/ grids covering the stations data for IMD/CRU & ERA-I data sets. As the test stations are wide spread, the overall time series provides the better representation of overall study area.

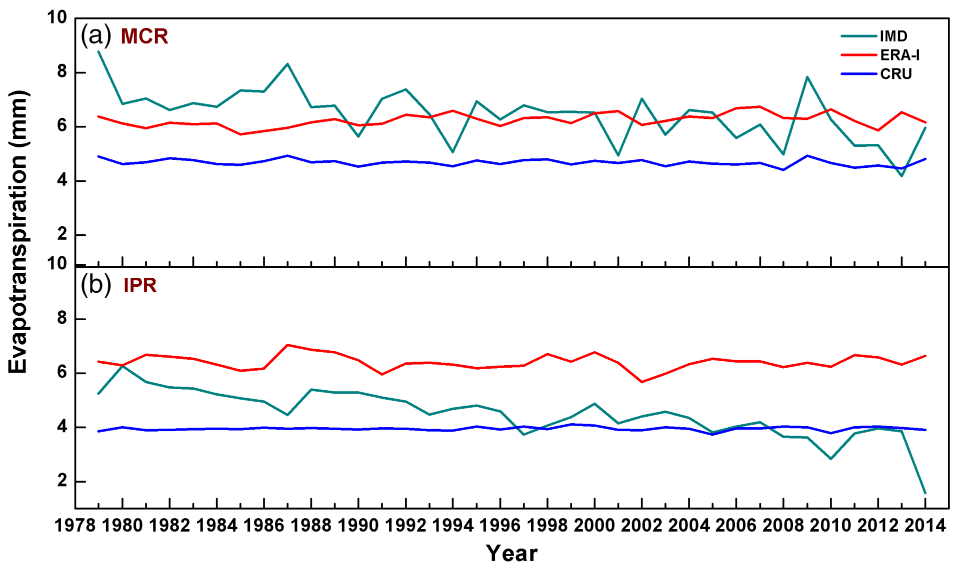

FIGURE 2 (a, b) Mean seasonal ET over (a) MCR (b) IPR during SW and NE monsoon seasons of India from 1979 to 2014 obtained from IMD, ERA-I and CRU data sets [Colour figure can be viewed at wileyonlinelibrary.com]

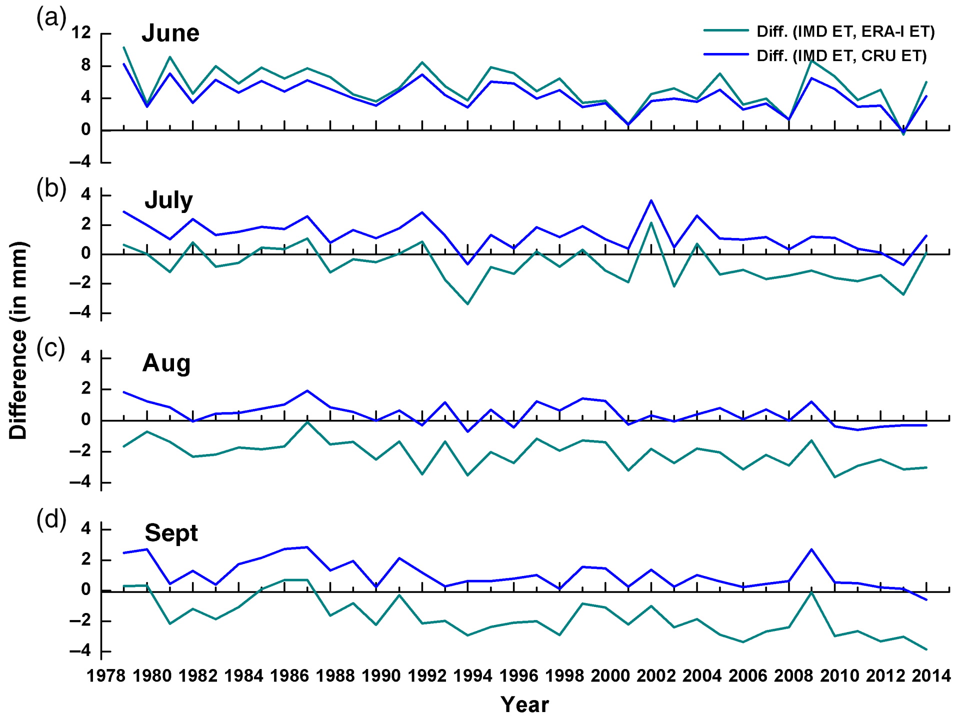

FIGURE 3 (a–d) Difference (in mm) between IMD ET and ERA-I ET, CRU ET data sets over MCR of India for (a) June (b) July (c) August and (d) September of 1979–2014 [Colour figure can be viewed at wileyonlinelibrary.com]

Daily/monthly time series thus computed from IMD and ERA-I/CRU has been converted to seasonal mean to obtain seasonal time series.

3 | RESULTS AND DISCUSSION

Monthly mean seasonal ET obtained from IMD, ERA-I and CRU data sets for the period 1979 to 2014 shows the IMD ET yielded to higher intra-annual variability compared to other data sets (Figure 2a,b). The variability was found to be very less in CRU and maintained almost around 4.68 ± 0.12 mm during the study period over MCR and 3.95 ± 0.07 mm during the NE monsoon period of IPR. The impact of global teleconnections such as El Niño and La Niña are conspicuous in IMD data sets. For example, in the El Niño year 1987, Indian subcontinent experienced −18% of deficit rainfall. During this year, the IMD ET is higher than the preceding and succeeding years. The higher ET (8 mm) is the result of more atmospheric demand of moisture from the surface due to the higher temperatures during El Niño (Revadekar *et al.,* 2009). Similarly the years, 2002, 2009 showed a similar variation as it shown in the year 1987. These features are not well depicted in the ERA-I and CRU data sets. The overall mean monthly seasonal ET over

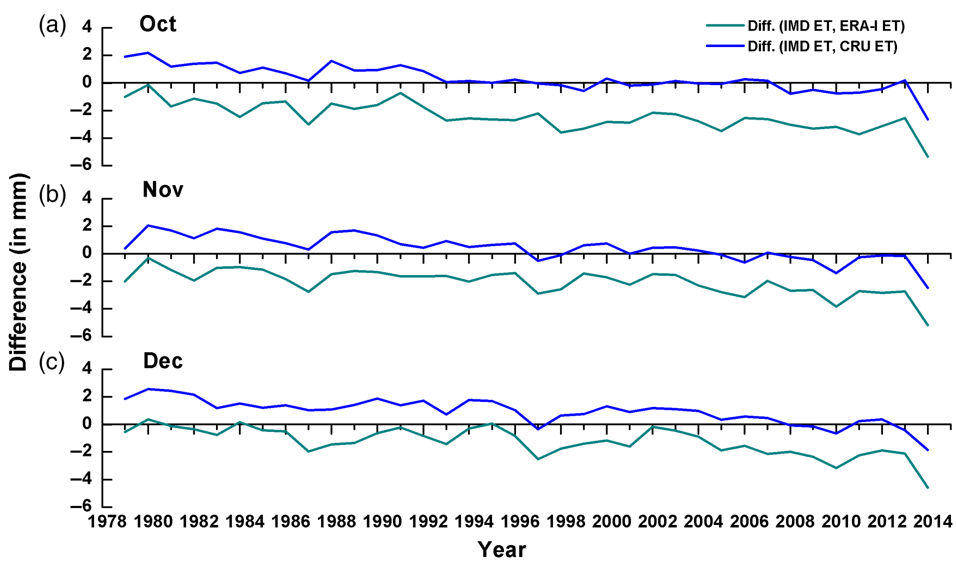

FIGURE 4 (a–c) Difference (in mm) between IMD ET and ERA-I ET, CRU ET data sets over IPR of India for (a) October (b) November and (c) December of 1979–2014 [Colour figure can be viewed at wileyonlinelibrary.com]

MCR during the SW monsoon from IMD, ERA-I and CRU data sets are 6.47, 6.25 and 4.68 mm, respectively. Similar situation was observed during the NE monsoon of IP region and the mean monthly ET from IMD, ERA-I and CRU are 4.51, 6.41, 3.95 mm, respectively.

The monthly difference of ET of ERA-I and CRU data sets with reference to IMD (IMD value minus ERA-I/ CRU value) are given in the Figures 3a–d and 4a–c over MCR and IPR, respectively. It can be seen from Figure 3a–d, that the ERA-I ET has shown higher positive difference in the month of June and during the months of July, Aug and Sept, the difference is mostly negative. This infers that ERA-I ET during the June month is lower than the IMD ET whereas in other months it is found to be high compared to the IMD ET values. Contrasting to this, the CRU data sets have underdone positive magnitude of difference which means the CRU ET is less compared to the IMD ET during all the months of SW monsoon. During the NE monsoon over the IP region, the CRU ET is found to be underestimated and lower than IMD (most of the cases) which is displayed by positive/no difference during the Oct, Nov and Dec months of the study period.

We have carried out the correlation analysis between IMD ET and ERA-I, CRU ET data sets for the study period on seasonal basis for different stations falling in the study regions. Tables 1 and 2 show the station name, Pearson correlation between ET of IMD and ERA-I and IMD and CRU along with the statistical significance levels. The gaps in the Table 2 represent the non-availability of CRU data sets for those stations. We can see from Table 1 that all the stations showed substantial significant correlation between IMD and CRU where as a mixed response is seen between IMD ET and ERA-I ET. Six stations viz BRM, KOL, MMB, NGP, RCH and SKT have showed positive correlations between IMD ET and ERA ET which led to the proportionate relation between them. The other stations have shown negative correlations leading to the inverse relation between IMD ET and ERA-I ET. Based on the correlations obtained and the bias, we can infer the pattern of CRU ET followed IMD but not on the estimates whereas ERA-I ET pattern is same as IMD ET in a few stations only. Table 2 provides the same information but for the NE monsoon season over IPR. Here, among 17 stations, 8 stations viz CHN, KTM, MNG, MPT, NLR, TPT, TRV and VZG have yielded to significant positive correlations (.24, .35, .78, .39, .36, .29, .50 and .37) which refer the similar ET pattern between IMD and ERA-I over these stations. However, the other stations maintained the negative correlations between IMD and ERA-I ET interestingly. Though the positive correlations were found between IMD and CRU ET, the values of the correlations are lesser compared to that of the MCR of SW monsoon period. The negative and poor positive correlations among these data sets need to be critically examined by considering the site specific conditions.

TABLE 1 Station-wise Pearson correlation (*r*) between the IMD ET with ERA-I and CRU ET during SW monsoon season over a MCR of India

Station name	Correlation (*r*) between IMD & ERA-I ET	Correlation (*r*) between IMD & CRU ET
Ahmedabad (AHM)	−.56*	.92*
Akola (AKL)	−.44*	.80*
Allahabad (ALB)	−.33*	.63*
Barmer (BRM)	.40*	.71*
Bhopal (BHP)	−.53*	.93*
Bhuj (BHJ)	−.47*	.76*
Dhule (DHL)	−.40*	.73*
Fatehpur (FTP)	−.35*	.79*
Indore (IND)	−.47*	.91*
Jaisalmer (JSM)	−.46*	.82*
Jalgaon (JLG)	−.55*	.87*
Jhansi (JHN)	−.11*	.88*
Jharsuguda (JRG)	.00	.90*
Jodhpur (JDP)	−.29*	.85*
Kolkata (KOL)	.41*	.76*
Kota (KTA)	−.56*	.91*
Lucknow (LKN)	−.36*	.88*
Mumbai (MMB)	.30*	.69*
Nagpur (NGP)	.22**	.55*
Okha (OKH)	−.35*	.82*
Parbhani (PRB)	.03	.85*
Patna (PTN)	−.25*	.79*
Pune (PNE)	−.19***	.79**
Ranchi (RCH)	.13	.67*
Shantiniketan (SKT)	.28*	.52*

Note: *, ** and *** indicate .01, .02 and .05 level of significance.

Many studies report that the ET increases/decreases with the rainfall increase/decrease (Reynolds *et al.,* 2000; Zhang *et al.,* 2013; Yang *et al.,* 2016; Kundu *et al.,* 2017). This relation mainly depends on the teleconnections, air-sea interactions and solar activity (Zhang *et al.,* 2013). But, however, during the rainy season, higher relative humidity levels suppress the evaporative ability from land to atmosphere than in other seasons. The cloud cover during the rainy season moderates the latent heat energy required for evapotranspiration. It is also reported the temperature and radiation play a key role in ET magnitudes (Armstrong *et al.,* 2015). During the initial conditions of SW monsoon over India, due to higher temperatures and high direct radiation (low cloud cover),

TABLE 2 Station-wise Pearson correlation (r) between the IMD ET with ERA-I and CRU ET during NE monsoon season over an IPR of India

Station name	Correlation (r) between IMD & ERA-I ET	Correlation (r) between IMD & CRU ET
Anathapur (ANT)	−.19	.41*
Banglore (BNG)	−.48*	.36*
Chennai (CHN)	.24*	.48*
Gannavaram (GNV)	−.24*	−.20***
Kottayam (KTM)	.35*	—
Kolhapur (KLP)	−.34*	—
Manglore (MNG)	.78*	—
Machilipatnam (MPT)	.39*	−.14
Nellore (NLR)	.36*	.49*
Panjim (PJM)	.07	—
Rayachur (RCH)	.00	−.10
Solapur (SLP)	−.26*	.00
Trichurapalli (TCP)	−.17***	.51*
Tirupati (TPT)	.29*	.40*
Trivendrum (TRV)	.50*	—
Tuticorin (TTC)	−.17***	—
Visakhapatnam (VZG)	.37*	—

Note: *, ** and *** indicate .01, .02 and .05 level of significance.

more energy is available to evaporate the surface water and hence, higher ETs result in. As the monsoon advances, though excessive soil moisture is available, the moist weather conditions inhibit the vaporization of water from the surface. Hence, in these conditions, the ET shows negative relation with rainfall over the SW monsoon period of India (Madhu *et al.,* 2015). In the present study, we have plotted the scatter plots between rainfall and ET of all data sets during study period (Figure 5a–f). The response of rainfall to the ET is different for the three data sets. Seasonal mean daily rainfall was correlated with seasonal mean daily ET for study period 1979 to 2014. The scatter plots for MCR (Figure 5a–c) and IPR (Figure 5d–f) have shown that IMD ET and CRU ET are inversely correlated with the rainfall which infers that higher rainfall causes lower ET values which becomes possible with the monsoon activity (Figure 5a–f). But the correlation between ERA-I ET and rainfall is +.41 which is statistically significant at .01 level. In IP region, the relation between CRU ET and rainfall is strong compared to the relation between IMD ET and ERA-I ET with rainfall. The negative relation between IMD ET and rainfall over MCR can also be analysed based on the monsoon mechanism. As the study period over MCR is the SW monsoon season, the rainfall mechanism during this period is strati-form where the moist winds advect from Arabian Sea (Lakshmi Kumar *et al.,* 2014). Hence, the role of local evaporation will be less over this region. The role of advection is vital as the rainfall increases (active monsoon) and hence the inverse relation between IMD ET and rainfall.

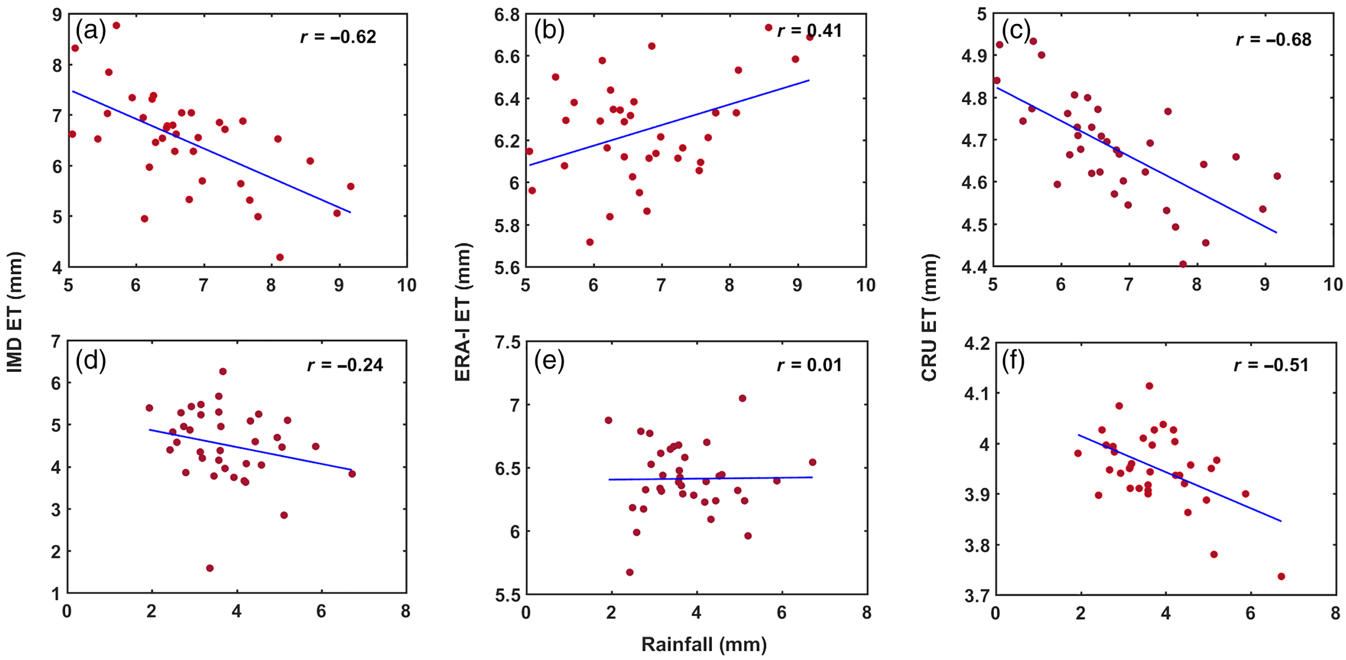

FIGURE 5 (a–f) Scatter plots along with the correlation between rainfall and ET of IMD, ERA-I and CRU over (a–c) MCR and (d–f) IPR of India for 1979–2014 [Colour figure can be viewed at wileyonlinelibrary.com]

During NE monsoon period of IPR, the negative relation between IMD ET and rainfall is less than that of during SW monsoon period of MCR. As the NE monsoon is mainly convective nature, the role of ET will be more in this region than over the SW monsoon of MCR.

In order to understand more about the behaviour of IMD and ERA-I ET data sets, we have analysed the daily time series for the study period. The daily averaged ET of two data sets over MCR for the SW monsoon and IPR for NE monsoon period are plotted in the Figures 6a and 7a along with the mean daily IMD gridded rainfall and TRMM/LPRM/TMI-Model soil moisture (Figures 6b and 7b), ERA-I relative humidity and IMD gridded mean temperature (Figures 6c and 7c) respectively. In the beginning of June month, the IMD ET is 15 mm/day and slowly decreased as the monsoon progresses. Analogous to ET variations the rainfall and soil moisture showed minimum values which portrayed the initial phase of monsoon and gradually increased and attained peak during July and August months. The temperature is high during the beginning of monsoon with lower values of relative humidity. From these variations, we understand that, due to higher temperatures (associated by low cloud cover and less scattered radiation) the water acquires enough latent heating to evaporate. At this stage, the relative humidity also showed lower values indicating the dry weather conditions. As the monsoon progresses, due to higher rainfall activity, relative humidity also shown higher values which means that the atmosphere is getting saturated and not conducive to hold the evaporative moisture. This is well reflected in IMD ET values showing low values during July, August and September months. Contrary to this, ERA-I ET did not maintain much variation during the SW monsoon period. IMD ET is completely lesser than ERA-I ET over IPR during NE monsoon period. The mean daily ET of IMD and ERA-I are 4.50 ± 0.27 mm and 6.41 ± 0.36 mm, respectively. In most of the days, the rainfall and soil moisture has showed inverse relations with IMD ET during the monsoon season. Correspondingly, humidity has no much variation during the monsoon season as it varies from 80 to 75% which is conspicuous in IMD ET

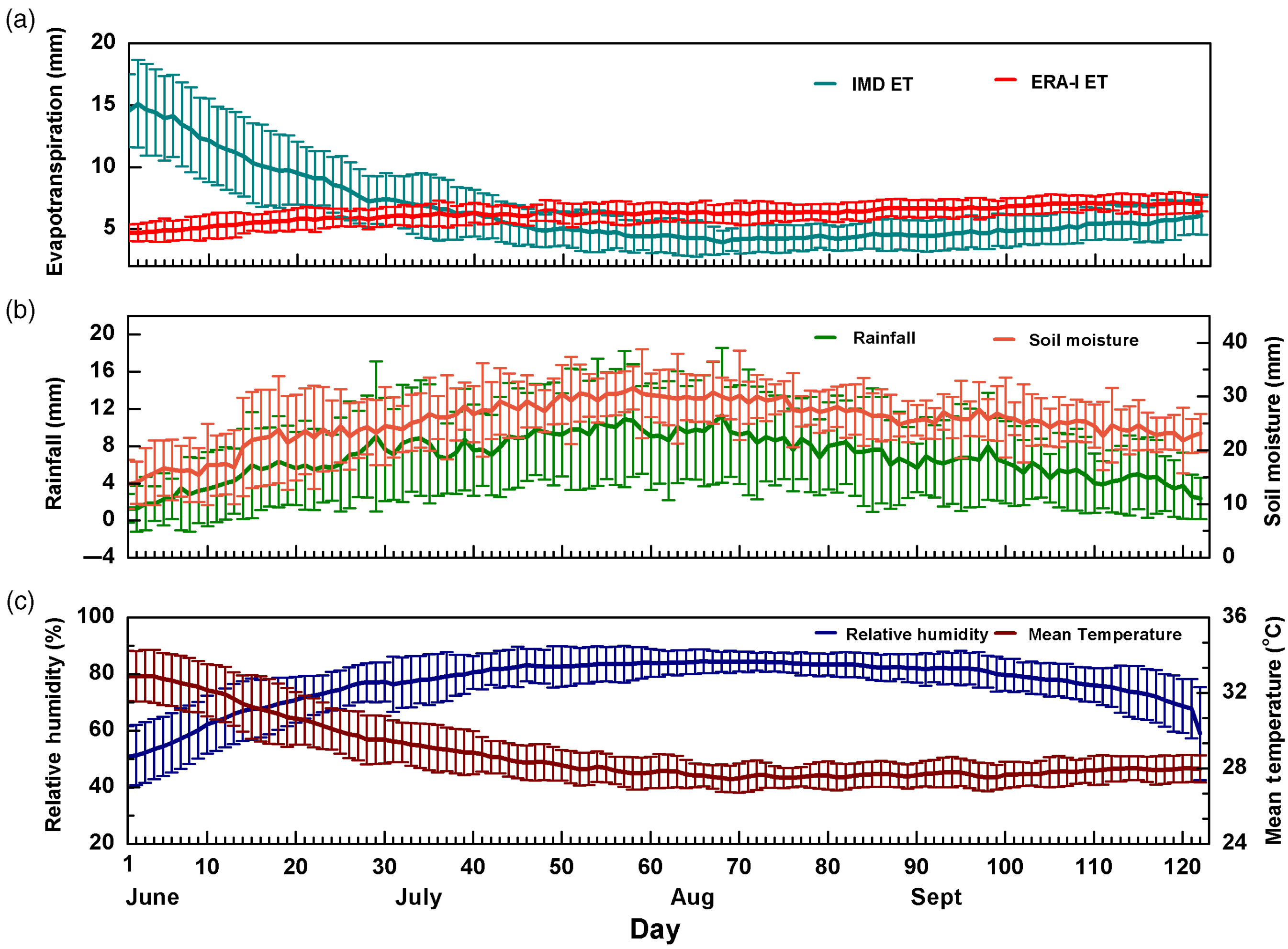

FIGURE 6 (a–c) Mean daily variation of (a) IMD ET and ERA-I ET, (b) rainfall and soil moisture and (c) air temperature and relative humidity over MCR during the SW monsoon period [Colour figure can be viewed at wileyonlinelibrary.com]

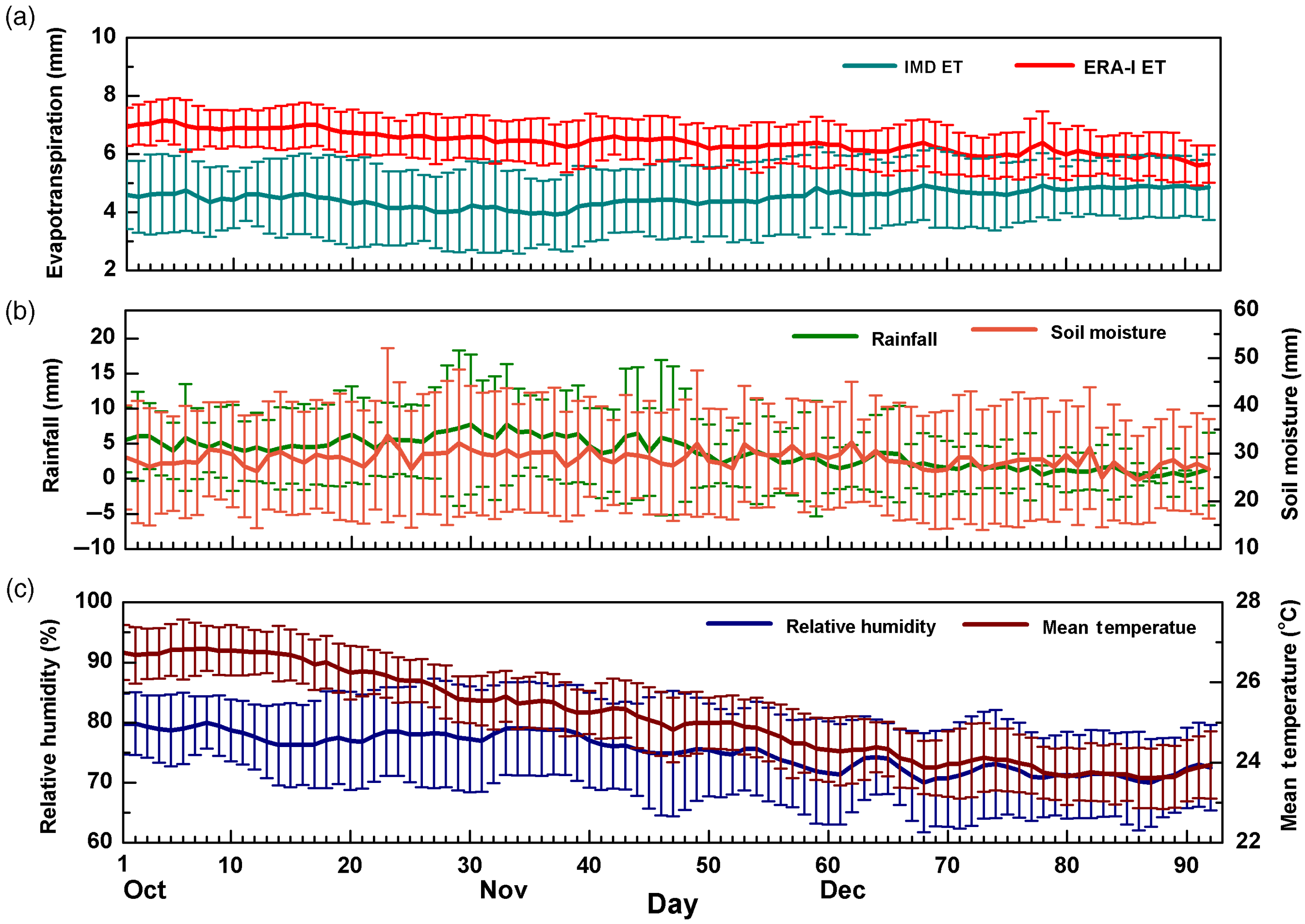

FIGURE 7 (a–c) Mean daily variation of (a) IMD ET and ERA-I ET, (b) rainfall and soil moisture and (c) air temperature and relative humidity over IPR during the NE monsoon period [Colour figure can be viewed at wileyonlinelibrary.com]

as it has also not undergone many variations. Overall daily analysis of IMD and ERA-I ET, IMD ET has shown the intra seasonal variability and varied from 15 to 6.8 mm from SW monsoon to NE monsoon. But ERA-I ET did not show variability during the two monsoon seasons.

The overall analysis portrays the regional comparison of ET from different approaches which are treated as the bench mark data sets and the disparities among them. As reported by Massonnet *et al.,* 2016 that due to the uncertainties in parameterization schemes and the model physics, the values of ET estimated from the above methods have inherent complications. Since the key drivers of ET are rainfall and soil moisture, the association of ET of the above mentioned data sets varies among the data sets. The main controlling factor for these biases would be the variations in the radiation values as we have taken the extra- terrestrial radiation to estimate the net radiation for IMD ET. Contribution of differences in temperature data also play role and is reported up to 20 to 30% between ERA Interim and World Climate (Zomer *et al.,* 2008). The inconsistencies among the ET products obtained from different reanalysis were also reported and found the global reanalysis ET show higher magnitudes. In the present study, it is very difficult to conclude the best performing method and accurate data sets and the end choice depends on the data availability, type of application and the environmental setting.

4 | CONCLUSIONS

In this study, the performance of three data sets viz, evapotranspiration (ET) estimates from IMD, ERA Interim and CRU are examined in light of their seasonal, monthly and daily variations. Variations in ET of these data sets are studied in relation to the key drivers of ET such as rainfall, air temperature, relative humidity and soil moisture. Disparities are witnessed among the data sets and IMD ET found to be satisfying the ET variability in the context of south west monsoon performance. CRU ETs are underestimated than IMD ET over MCR/IP of SW/NE monsoon seasons. The pattern of CRU ET is highly coincides with the IMD ET on seasonal basis evidenced by substantial correlations during

SW monsoon season of MCR. ERA-I ETs are underestimated during June month and completely overestimated than IMD ET in July to September of SW monsoon over MCR and during the NE monsoon over IPR, they are overestimated. Overall analysis of this comparison of ET data sets poses the utmost care to be taken in the selection of data sets as they suffer from uncertainties.

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CONFLICT OF INTEREST

The authors have no conflict of interest in submitting this paper to the International Journal of Climatology.

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