ORIGINAL PAPER

Soil moisture variations in remotely sensed and reanalysis datasets during weak monsoon conditions over central India and central Myanmar

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Abstract Variation of soil moisture during active and weak phases of summer monsoon JJAS (June, July, August, and September) is very important for sustenance of the crop and subsequent crop yield. As in situ observations of soil moisture are few or not available, researchers use data derived from remote sensing satellites or global reanalysis. This study documents the intercomparison of soil moisture from remotely sensed and reanalyses during dry spells within monsoon seasons in central India and central Myanmar. Soil moisture data from the European Space Agency (ESA)—Climate Change Initiative (CCI) has been treated as observed data and was compared against soil moisture data from the ECMWF reanalysis-Interim (ERA-I) and the climate forecast system reanalysis (CFSR) for the period of 2002–2011. The ESA soil moisture correlates rather well with observed gridded rainfall. The ESA data indicates that soil moisture increases over India from west to east and from north to south during monsoon season. The ERA-I overestimates the soil moisture over India, while the CFSR soil moisture agrees well with the remotely sensed observation (ESA). Over Myanmar, both the reanalysis overestimate soil moisture values and the ERA-I soil moisture does not show much variability from year to year. Day-to-day variations of soil moisture in central India and central Myanmar during weak monsoon conditions indicate that, because of the rainfall deficiency, the observed (ESA) and the CFSR soil moisture values are reduced up to 0.1 m^3/m^3 compared to climatological values of more than 0.35 m^3/m^3. This reduction is not seen in the ERA-I data. Therefore, soil moisture from the CFSR is closer to the ESA observed soil moisture than that from the ERA-I during weak phases of monsoon in the study region.

1 Introduction

The economy and livelihood of the population in India and its neighborhood largely depend on agriculture. Approximately 16 % of India's geographic area, mostly arid, semiarid, and subhumid is drought-prone. About 10 % of the total geographical area of Myanmar (mostly arid to semiarid zones of central Myanmar) is also drought-prone (Yi et al. 2013). Rainfall variability in monsoon months over India and Myanmar is the outcome of large-scale monsoon variability in seasonal to interannual timescales as well as intraseasonal oscillations. With wide variations in physiographic and climatic conditions in the region, various parts of the region (e.g., India and Myanmar) experience drought in some or other year with varying intensities. Previous studies of droughts based on observed rainfall data suggest that major drought events over the Indian region are due to large-scale negative rainfall anomalies (Guhathakurta 2003). The intraseasonal variability during monsoon season is broadly characterized by the active and break phases (Krishnamurthy and Shukla 2000). Active and break events are defined as periods during the peak monsoon months of July and August. The northward propagating convective anomalies lead to active and break phase of monsoon that occur in 30 to 60 day of periodicity. Kar et al. (1997) have found that the monsoon intraseasonal variability is closely linked to eastward propagating Madden Julian Oscillations (MJO).

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Rainfed agriculture in India and Myanmar region is largely dependent on soil type and available soil moisture. According to Kerr (1996), success of agricultural crop is dependent on precipitation since crops are rainfed in the Indian region. Variability of rainfall during monsoon affects the total crop yield and the economy of India (Wuttichai et al. 2011). Generally, black soil is available over central India and central Myanmar. The topography of both the study regions (central India and central Myanmar) is flat and soil moisture over central India ranges from 0.15 to 0.45 m^3/m^3 and over central Myanmar, it varies from 0.1 to 0.25 m^3/m^3 during summer monsoon season.

Soil moisture information is important for the climate statistics and prediction. Schreider et al. (1996) measured the drought frequency defined by a soil wetness index. Miralles et al. (2012) studied the use of satellite-derived soil moisture differences to explain temperature extremes. Many researchers have used soil moisture data in their study to understand the climate variability (e.g., Sun et al. 2005; Zhang and Zuo 2011). Soil moisture variability has been examined by both observational (Singh et al. 2005; Roxy et al. 2010) and modeling studies (Koster and Suarez 2001; Sun et al. 2005). Kar and Ramanathan (1990) have carried out sensitivity studies using various types of soil in the Indian region. Dutta et al. (2009) have simulated the impact of soil moisture and vegetation on monsoon rainfall using a regional model. Recent work by Ford and Quiring (2014) and Miralles et al. (2012) suggest a link between soil moisture and deficit rainfall in the tropics. Kar et al. (2014) have found that land surface processes, especially soil processes, play an important role in intraseasonal variability of monsoon rainfall over India. Remote sensing data is widely used by various researches for soil moisture analysis (Schreider et al. 1996; Koster and Suarez 2001; Sun et al. 2005; Roxy et al. 2010; Zhang and Zuo 2011; Ford and Quiring 2014). Remote sensing techniques offer an attractive alternative to straight measurement. Researchers have derived volumetric soil moisture using thermal infrared remote sensing and passive microwave remote sensing techniques (Ottl and Vidal-Madjar 1994 to approximate volumetric soil moisture contents.

In the recent years, several soil moisture datasets have been developed. These datasets are either from active or passive microwave satellite observations using data from Advanced Scatterometer (ASCAT), active microwave instrument—Windsat (AMI-WI), advanced microwave scanning radiometer—Earth observing system (AMSR-E), scanning multichannel microwave radiometer (SMMR), special sensor microwave imager (SSM/I), soil moisture and ocean salinity (SMOS), (Njoku et al. 2003; Bartalis et al. 2007; Mecklenburg et al. 2012; Parinussa et al. 2012). Intercomparisons of various reanalysis datasets for different parameters have been done by individual experiments to evaluate their accuracy (Loew et al. 2013. Mishra et al. 2012)

studied that the significant differences in the climatology over the Indian region of evaporation and soil moisture fields etc. They have found that the continental evaporation is significantly less in the National Center for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) compared to NCEP-Reanalysis-2 and Modern-Era Retrospective Analysis for Research and Applications (MERRA). Smith and Kummerow (2013) evaluated the surface and atmospheric water content using reanalysis, observed, and satellite-derived datasets. The reanalysis data they used included the European Center for Medium Range Weather Forecasting (ECMWF) Reanalysis-Interim (ERA-I), and the CFSR and they have found that all reanalysis data captured the seasonal cycle for each water content component.

Very few studies exist on the soil moisture variability over the Indian region and Myanmar, especially during break or weak phases of monsoon. There have been no studies to compare the remote sensing soil moisture data with other datasets (Table 1). In situ observations of soil moisture in India and Myanmar are only few. Therefore, reanalysis datasets have to be compared among each other and with satellite-derived soil moisture data over the regions of interest. It is also important to examine how the soil moisture varies during long dry spells during weak monsoon conditions. Two regions have considered. The first one is central India and the other is central Myanmar. Both the regions are in semiarid zones. Therefore, the main objective of this study is to document the intercomparison of soil moisture datasets over India and Myanmar and to examine soil moisture over the regions during weak monsoon conditions. The data used and methodology are presented in Sect. 2. Results are discussed in Sect. 3. The study is concluded in Sect. 4.

2 Data and methodology used

High-resolution observational datasets are available for soil moisture and precipitation. These observations help to understand ground conditions of soil moisture and precipitation. The India Meteorological Department (IMD) is responsible for collection of observational precipitation in India. Remotely sensed daily soil moisture data from European Space Agency (ESA) Climate Change Initiative (CCI) has been used in this study as proxy of observation data. ESA-CCI has made available soil moisture data from various sensors, i.e., SMMR, SSM/I, TMI, AMI-WS, ASCAT, AMSR-E, WindSat, AMSR2, etc. The data sets have been developed following procedure described in Christopher et al. (2011), Parinussa et al. (2012); Liu et al. (2011, 2012); and Wagner et al. (2012). The merged products present volumetric soil moisture (m^3/m^3) at a spatial resolution of 0.25° by 0.25°. In the following text, observed soil moisture and ESA soil moisture have been interchangeably used.

Table 1 Description of datasets

Parameter	Data Source	Resolution	Availability	Data used	Type
Rainfall	IMD/NCMRWF	1.0°	Daily (1998–2011)	2002–2011 (Jun-Sept)	Observed
Soil moisture	ESA	0.25°	Daily (1979–2013)	2002–2011 (Jun-Sept)	Observed (remotely sensed)
Soil moisture	CFSR v1 and v2	0.50°	Daily (1979-present)	2002–2011 (Jun-Sept)	Reanalysis
Soil moisture	ERA-I	0.25°	Daily (1979-present)	2002–2011 (Jun-Sept)	Reanalysis

Two different reanalysis soil moisture datasets have been use in the present study. These are from the CFSR and ERA-I for the monsoon period. These data are based on data assimilation systems that assimilate a huge amount of in situ and observations of satellite in the system with either three-dimensional variational analysis (CFSR) or a four-dimensional variational analysis (ERA-I) 4-D variation (Saha et al. 2010; Dee et al. 2011). Daily mean of soil moisture data used in the study that have been taken from the ERA-I archive. The data at 0.25° spatial resolution have been used in this study from year 2002 to 2011. The National Center for Environmental Prediction (NCEP) provides the CFSRv1 and CFSRv2 data (Saha et al. 2010). CFSRv1 is available from 1979 to 2010 and the availability for CFSRv2 is from 2011 to present. The temporal resolution of CFSR is 6 h that has been converted into daily mean. CFSR data sets available at 0.5° resolution have been used in this study. This study uses the Indian Meteorological Department (IMD)/National Centre for Medium Range Weather Forecasting (NCMRWF) daily gridded rainfall at 1° resolution (Mitra et al. 2013). The IMD/NCMRWF merged product available for each day for the period from 1998 to 2011. This IMD/NCMRWF product combines Tropical Rainfall Measuring Mission (TRMM) and Multisatellite Precipitation Analysis (TMPA) rainfall assessments with gauge statistics from IMD gridded data.

Monthly and seasonal mean total soil moisture and its interannual variability (standard deviation) have been computed for both reanalysis and observation. The root mean squared differences between observation and reanalysis data have been computed for the climatological mean and the interannual variability. Relationship between soil moisture and

Table 2 Weak monsoon phases over central India and central Myanmar

Light or no rainfall phases over central India				
2002	02 to 11 July	21 to 31 July	13 to 28 September	
2003	19 to 22 June	29 to 31 July	19 to 21 August	
2004	20 to 25 June	09 to 14 July	19 to 24 July	24 to 30 August
2005	07 to 14 August	23 to 30 August		
2006	06 to 11 September	25 to 30 September		
2007	18 to 23 July	11 to 18 September		
2008	13 to 16 June	18 to 24 August	21 to 30 September	
2009	23 July to 07 August	11 to 24 September		
2010	24 to 26 June	21 to 24 August	21 to 29 September	
2011	30 June to 03 July	20 to 23 August	18 to 21 September	
Light Rainfall Phases over central Myanmar				
2002	20 to 25 July	30 August to 02 September		
2003	25 July to 01 August	16 to 20 July	27 August to 02 September	
2004	18 to 26 June	15 to 20 July		
2005	02 to 07 June	24 Jun to 11 July	02 to 11 August	
2006	04 to 15 June	29 Jun to 03 July	02 to 10 September	21 to 27 September
2007	13 to 19 June	28 Jun to 19 July	18 to 23 September	
2008	29 June 05 July	21 to 26 August	08 to 30 September	
2009	06 to 16 June	18 to 27 June	07 to 12 July	18 to 30 July
2010	13 to 21 June	03 to 17 July	29 August to 08 September	16 to 24 September
2011	08–23 June	04 to 08 July		

rainfall has been established by computing correlation coefficients. The reanalysis and observed soil moisture values for 2002 to 2011 on daily basis during June, July, August, and September (JJAS) have also been used in the study. Data at various horizontal resolutions have been brought to the same grid (0.5° × 0.5°) by regridding the data using bilinear interpolation. During break phases of monsoon or during weak monsoon conditions, very less or no rainfall occurs over central parts of India and Myanmar. Such weak phases of JJAS rainfall during 2002 to 2011 over central India and central Myanmar have been identified from the last day of rain and to the day during which no rainfall or very light rainfall (0 to 3 mm/day) is observed. The IMD has defined rainfall up to 2.4 mm/day as very light rainfall and rainfall from 2.4 to 15.5 mm/day as light rainfall for a station. In this study, rainfall of up to 3 mm/day has been used as very light rainfall as gridded rainfall data has been used. However, the results based on selection of days as weak phases of monsoon for the study region does not change if rainfall amount of 2.4 mm/day is the threshold value. The list of such phases is provided in Table 2 for which composite analysis has been made.

3 Results and discussions

3.1 Climatology and interannual variability of soil moisture

Figure 1 shows the monthly mean climatological features of soil moisture (for June, July, August, and September for the period from 2002 to 2011) from ESA (observed). In June, observed soil moisture over west and central India is less and values range from 0.05 to 0.15 m^3/m^3. Over the remaining regions in India, the soil moisture values vary from 0.2 to 0.3 m^3/m^3. Observed soil moisture values over Myanmar ranges from 0.1 to 0.25 m^3/m^3. In July, as the frequency and magnitude of summer monsoon rainfall increases, the observed soil moisture values have increased with values reaching up to 0.4 m^3/m^3 in some parts of west and central India. The soil moisture value of central Myanmar has also increased up to 0.35 m^3/m^3. There is no large difference in soil moisture between July and August months. In September, the soil moisture values have reduced over the north central part of India but no large reduction is seen over south peninsular
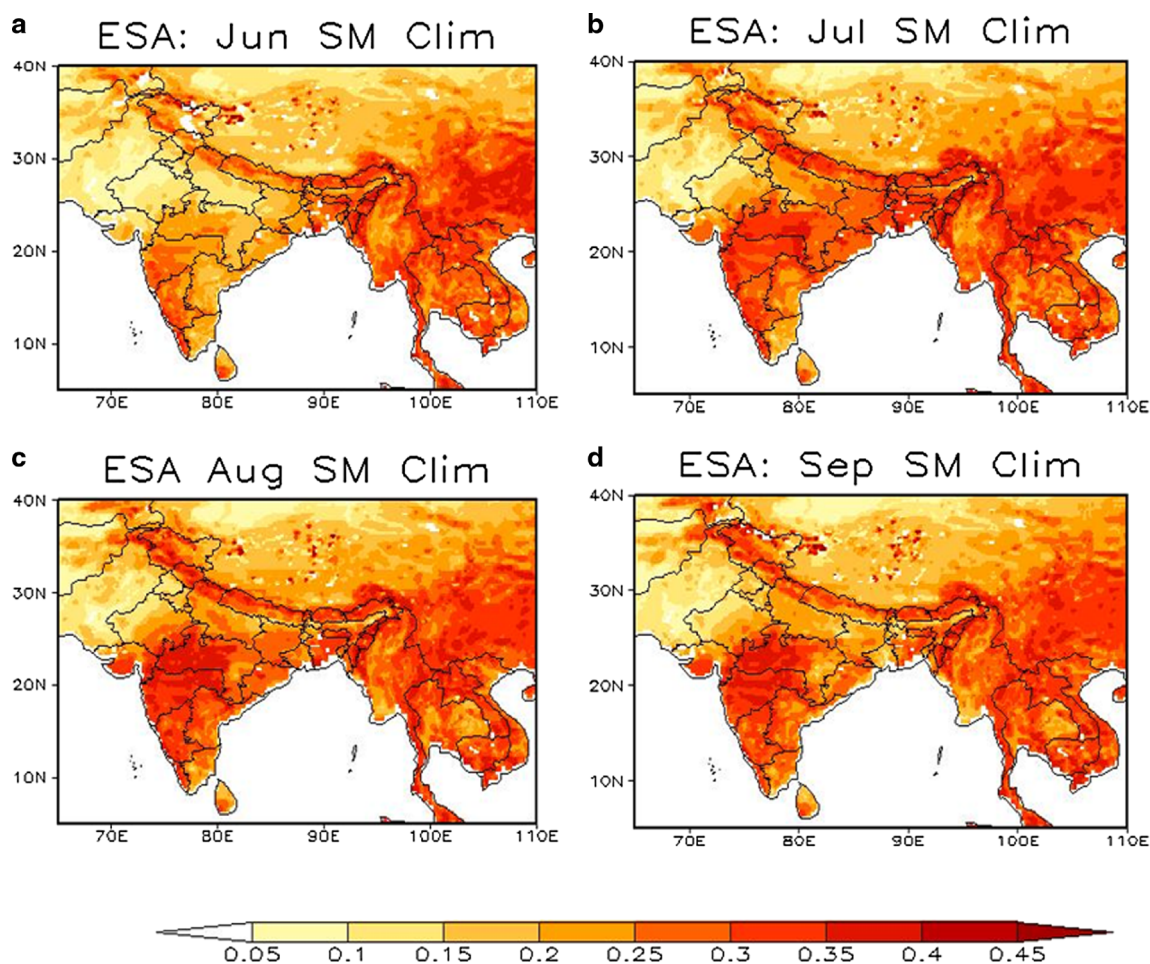

Fig. 1 Climatology of monthly mean observed (ESA) soil moisture (m^3/m^3) in **a** June, **b** July, **c** August, and **d** September

India. The soil moisture values over Myanmar have also reduced. Monthly mean climatological soil moisture values from reanalysis datasets from CFSR and ERA-I have also been examined (figures not shown). ERA-I soil moisture has higher values of soil moisture compared to that of ESA. In June, the soil moisture values are 0.2 to 0.35 m³/m³ over India and 0.5 to 0.6 m³/m³ over Myanmar. In July, the values have increased and it reflects more soil moisture compared to the observations. In Myanmar, the soil moisture values do not have large month-to-month variation. Moreover, ERA-I data has high amount of soil moisture (0.5 to 0.65 m³/m³ or more) in this region. CFSR soil moisture values are less than observations over the Indian region and more over Myanmar. Over both India as well as Myanmar, the soil moisture has increased in July compared to June as observed and values are 0.2 to 0.35 m³/m³.

Figure 2a shows the seasonal mean climatological features of soil moisture for June, July, August, and September (JJAS) for the period from 2002 to 2011 from ESA (observed). The

soil moisture has large variations from region to region in India, Bangladesh, Bhutan, Nepal, and Myanmar. The ESA has observed soil moisture from 0.05 to 0.4 m³/m³ during summer monsoon over India and surrounding region. The amount of soil moisture over western India is 0.1 to 0.2 m³/m³, central and southern India is 0.3 to 0.4 m³/m³, and over Bangladesh, Bhutan, Nepal and Myanmar, it varies from 0.3 to 0.4 m³/m³. The soil moisture increases from west to east and north to south over India and its surrounding region. The central part of India (drought-prone area) has soil moisture content of about 0.3 to 0.35 m³/m³. The soil moisture content is less (range is 0.25 to 0.3 m³/m³) over the central part (drought-prone area) of Myanmar. However, higher amount of soil moisture content over the western and northern parts of Myanmar is observed. Figure 2b, c shows the difference JJAS mean climatology of soil moisture of ERA-I from ESA and CFSR from ESA respectively over the Indian subcontinent. The ERA-I overestimates the soil moisture content over India and surrounding regions. The values of soil moisture from ERA-I during the JJAS reaches up to 0.65 m³/m³. Soil moisture content in this dataset does not vary from region to region over Myanmar. ERA-I
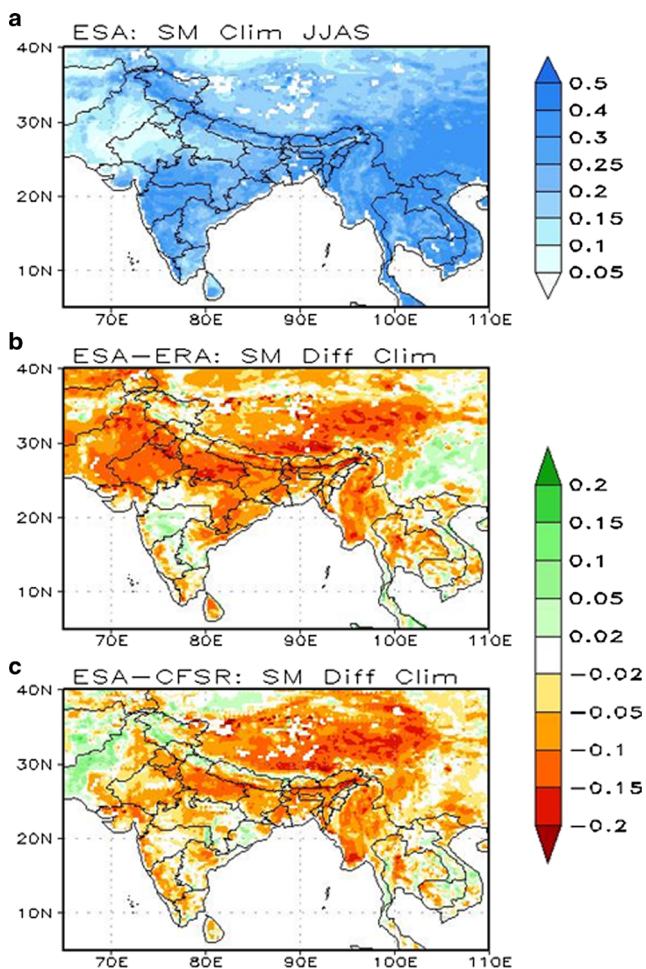

Fig. 2 Climatology of seasonal mean observed and reanalysis soil moisture (m³/m³) for JJAS **a** observed (ESA); **b** difference of soil moisture between ERA-I and ESA and (**c**) difference between CFSR and ESA
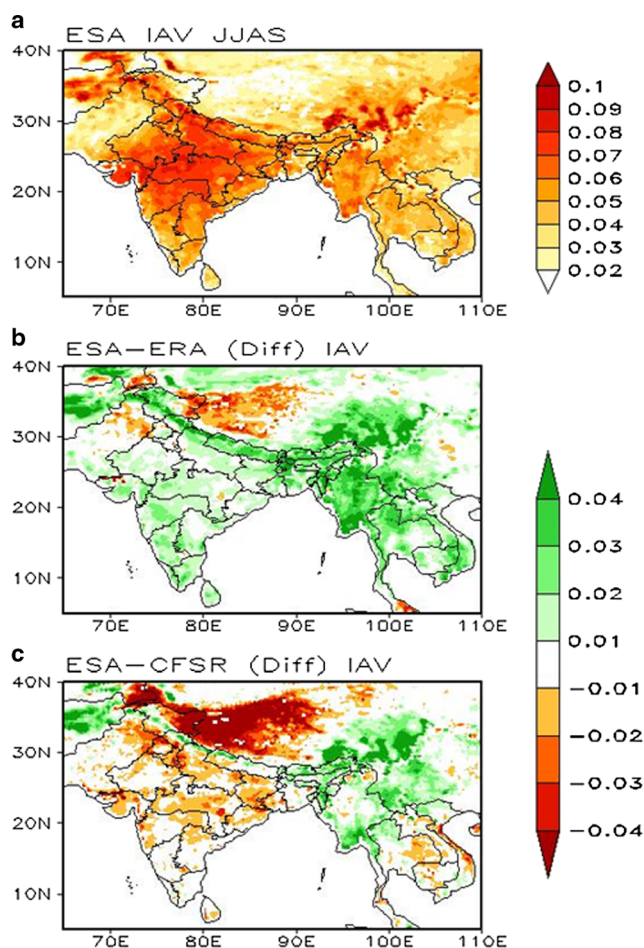

Fig. 3 **a** Interannual variability (IAV) of observed (ESA) and reanalysis soil moisture (m³/m³) for JJAS; **b** difference of IAV between ESA and ERA-I and (**c**) ESA and CFSR for JJAS

estimates almost a constant amount of soil moisture during summer monsoon for Myanmar region. The CFSR values match well with that from ESA over the western, central, and southern parts of India and central part of Myanmar. The CFSR overestimates soil moisture over northeast India, Bangladesh, and some parts of Myanmar as seen in the difference plots.

3.2 Interannual variability of soil moisture

In the present study, observational (remotely sensed) and re-analysis datasets have been used to investigate interannual variability of soil moisture over India and its neighborhood during summer monsoon season. Figure 3a shows the interannual variability (IAV) of observed soil moisture (from ESA). Figure 3b, c shows the difference of JJAS IAV between ESA and ERA-I and ESA and CFSR respectively over India and neighboring countries. In the observed ESA dataset, soil moisture shows considerable interannual variability during JJAS. All the three datasets show large variability (about 1 m^3/m^3) over the central parts of India. The magnitude of IAV in CFSR is maximum while ERA-I does not show large variability. Therefore, over most parts of India and its neighborhood, difference of ESA and ERA-I IAV is positive. In ESA data, IAV ranges from 0.4 to 0.6 m^3/m^3 in southern peninsula. In Myanmar, the soil moisture variability ranges from 0.4 to 0.6 m^3/m^3 in ESA and CFSR. ERA-I data shows very less variability (about 0.2 m^3/m^3) in the same region. IAV of soil moisture in monthly scale has also been examined. The volumetric soil moisture content varies

from 0.02 to 0.06 m^3/m^3 over India during the months of June, July, August, and September (figures not shown). In July and September, more variability is seen compared to August. Over central India, the soil moisture content variability is larger in July and September than in June and August. The central dry zone of Myanmar does not show large variability in volumetric soil moisture contents during JJAS compared to other parts of Myanmar. It may be noted that the ERA-I uses observed climatology in place of missing values. Therefore, it may be concluded that ERA-I underestimates IAV in soil moisture over India and neighboring countries, whereas CFSR overestimates it. The underestimation of IAV of soil moisture by ERA-I is larger over the Myanmar region. CFSR shows higher IAV of soil moisture over central India, northern India, and associated Himalayan region as compared to observations.

3.3 Root mean square difference of soil moisture

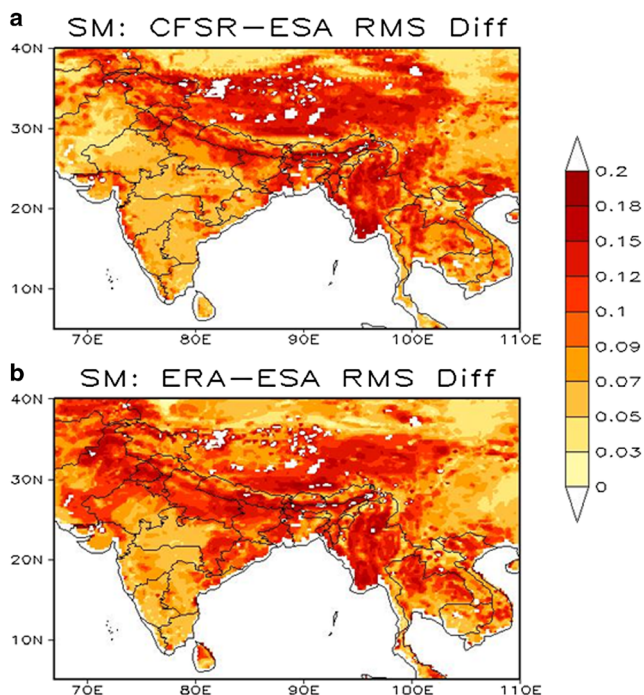Figure 4 shows the root mean square (RMS) differences of soil moisture between observed ESA and ERA-I and between

Fig. 4 RMS difference between observed and reanalysis soil moisture (m^3/m^3) for JJAS a CFSR and ESA and b ERA-I and ESA
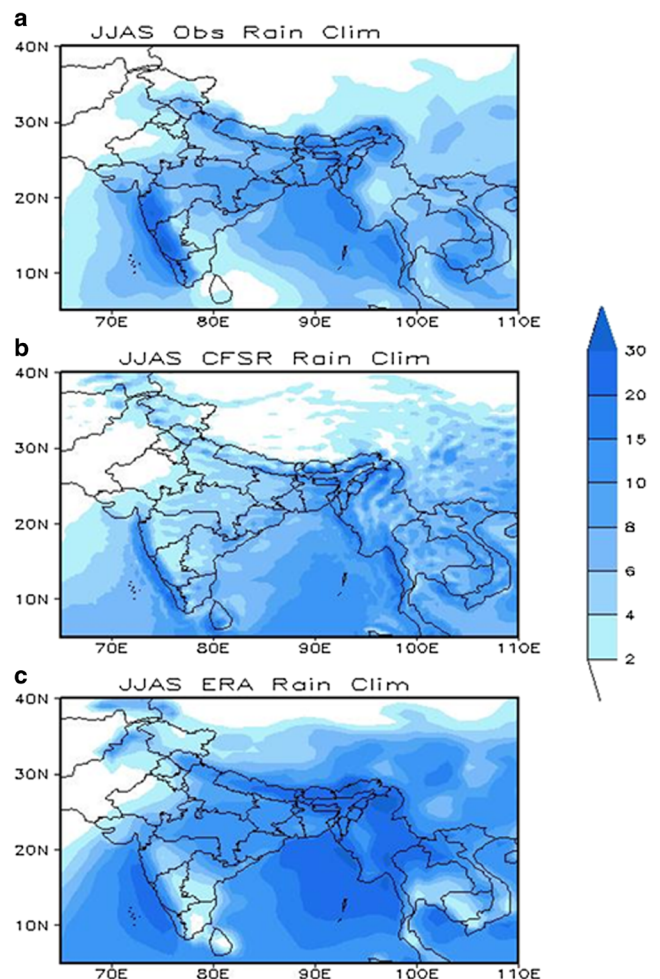

Fig. 5 Climatology of seasonal mean (JJAS) rainfall (mm/day) from a observed (IMD/NCMRWF), b CFSR, and c ERA-I

Table 3 Correlation between various data sets

Rainfall	Soil moisture	Correlation for Madhya Pradesh	Correlation for Myanmar
Correlation of soil moisture with rainfall			
NCMRWF (1°)	ESA (0.25°)	0.459	0.024
NCMRWF (1°)	ERA-I (0.25°)	0.471	0.235
NCMRWF (1°)	CFSR v1 and v2 (0.5°)	0.500	0.393
Intercorrelation of soil moisture			
ESA (Observed)	ERA-I	0.894	0.335
ESA (Observed)	CFSR v1 and v2	0.856	0.231
ERA-I	CFSR v1 and v2	0.940	0.212

observed ESA and CFSR reanalysis for JJAS. The RMS differences have been computed using monthly data for JJAS. The difference between CFSR reanalysis and ESA observed soil moisture shows that over the western, southern, and central parts of India, soil moisture difference is very less (0.05 m^3/m^3) difference. Whereas, the northern and eastern parts of India and the western, northern, southwestern, and central parts of Myanmar have very large (0.1 to 0.15 m^3/m^3) differences. The ERA-I

reanalysis and ESA observed difference is lesser (0.05 to 0.07 m^3/m^3) at southern and some parts over central India. The difference is very high (0.15 to 0.2 m^3/m^3) with the observed soil moisture over all Indian subcontinent. The difference of ERA-I and ESA observed ranges from 0.15 to 0.2 (m^3/m^3) at almost all Indian subcontinent. It shows that CFSR is closer to the ESA observed soil moisture than ERA-I. It may be noted here that in situ observations are very few and not available in
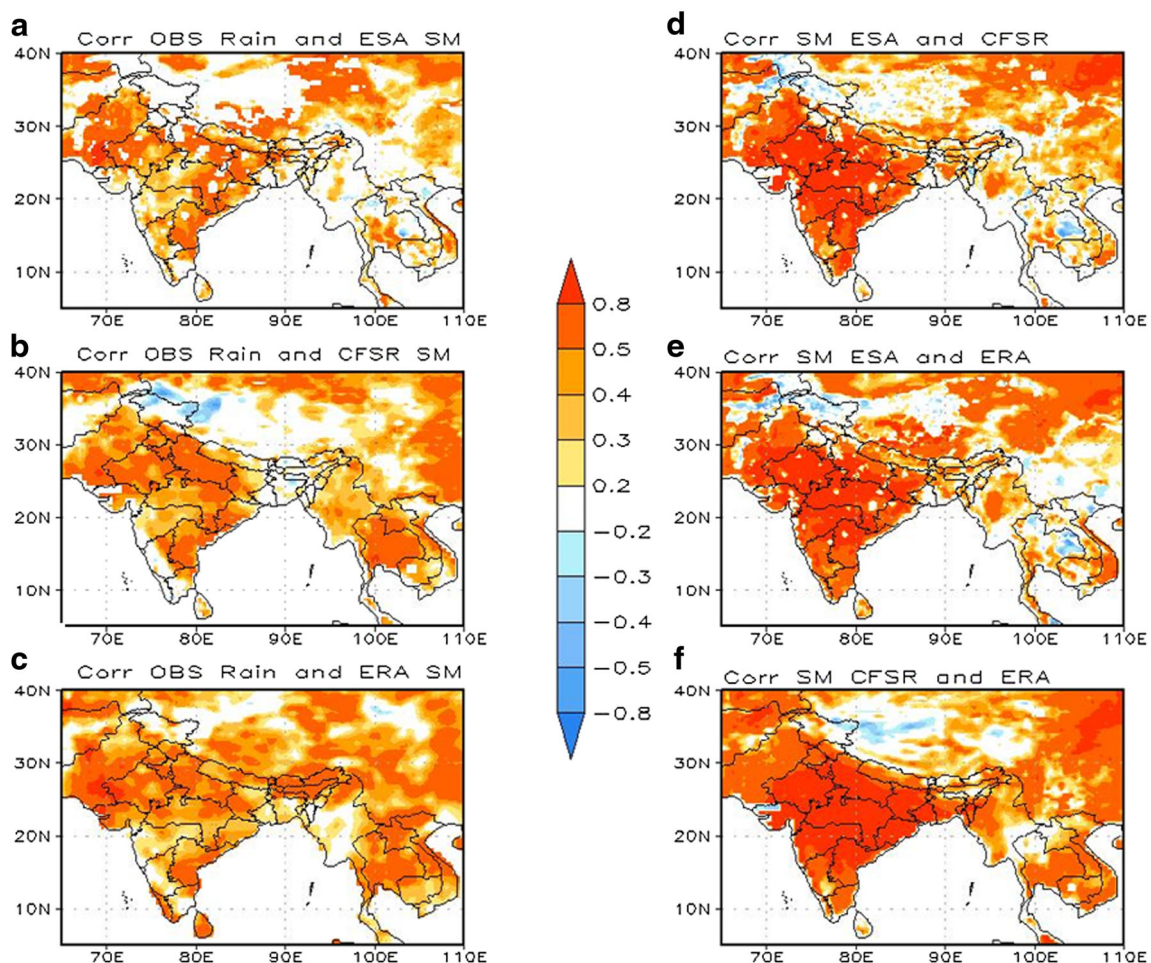

Fig. 6 Spatial correlation between observed rainfall and soil moisture from **a** ESA, **b** CFSR, and **c** ERA-I for the JJAS season. Spatial correlation between soil moisture from **d** ESA and CFSR, **e** ESA and ERA-I, and **f** CFSR and ERA-I

real time in the Indian region for assimilating those into the models or data assimilation systems in real time. In the absence of in situ data, assimilation systems such as that of ERA-I and CFSR either use only model forecasts as true soil moisture or use some or other satellite-derived soil moisture. As mentioned earlier, when soil moisture values are missing, ERA-I uses climatology.

3.4 Rainfall climatology and relationship with soil moisture

Figure 5 shows the climatology of rainfall over the Indian subcontinent during summer monsoon (JJAS) for the period of 2002–2011. The climatology has been plotted using IMD/ NCMRWF (observed) and CFSR and ERA-I reanalysis rainfall. The observed rainfall climatology over the Indian

subcontinent shows that the Western Ghats gets between 20 to 30 mm/day rainfall and rainfall amount over Bhutan, northeast India, eastern parts of Bangladesh and Arakan Mountains in between 15 and 25 mm/day during JJAS. The central India and Nepal gets 8 to 10 mm/day rainfall during summer monsoon. The western, northern India, and central Myanmar gets 4 to 6 mm/day rainfall during summer monsoon. The rainfall pattern over northern, western India, and central Myanmar is well captured by the CFSR data. However, the CFSR underestimates the rainfall over Western Ghats and central India. ERA-I overestimates the rainfall over the Indian subcontinent. The amount of rainfall over the Western Ghats, central India, Nepal, Bhutan, Bangladesh, and whole of Myanmar is very high as compared to the observed. Therefore, a comparison of rainfall from observation, ERA-I, and CFSR leads to the conclusion that the CFSR rainfall matches rather well with

Fig. 7 **a** Study areas *A* over central Madhya Pradesh (India) and *B* over central Myanmar, **b** monthly rainfall anomaly (mm/day) for June, July, August, and September, and **c** seasonal anomaly of rainfall (mm/day) for JJAS mean over the two boxes in (**a**)
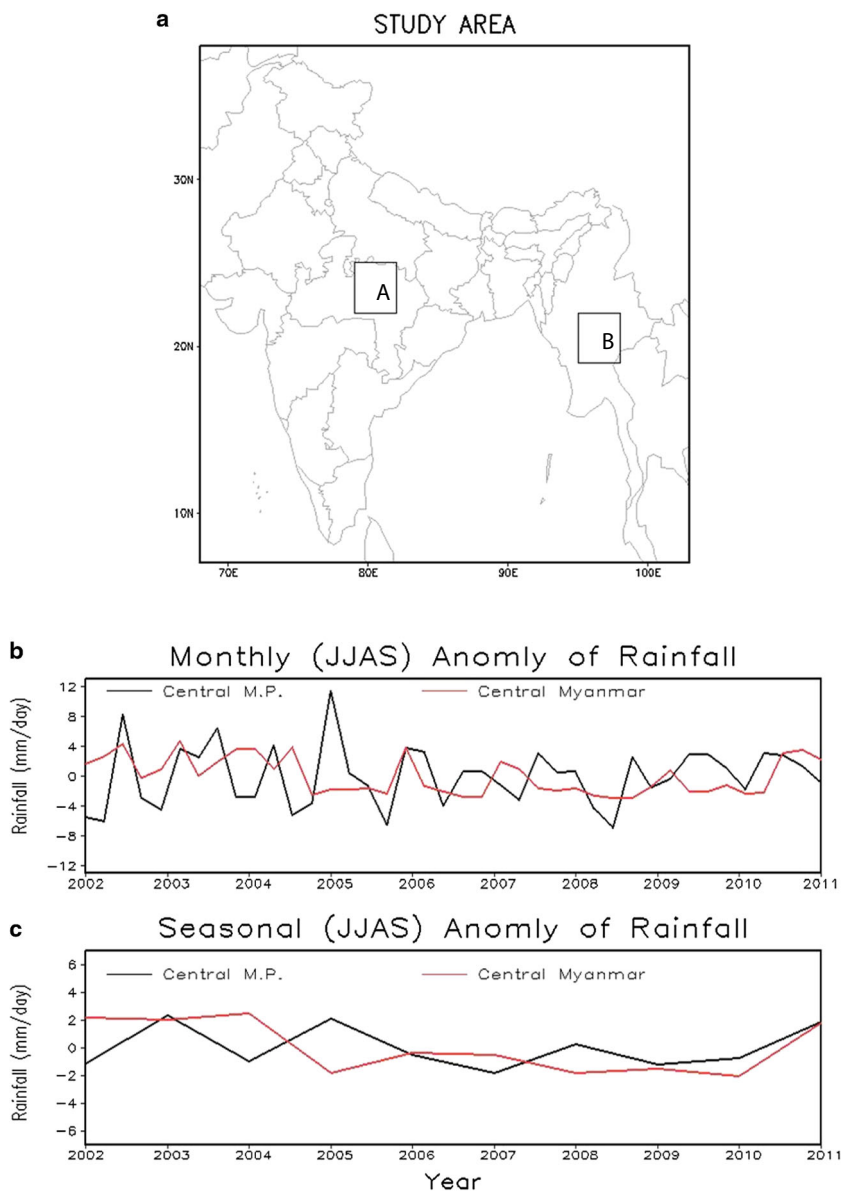
observations (with underestimation in east and central India) than the ERA-I rainfall over the Indian subcontinents during JJAS.

There is a significant relationship between the observed rainfall and soil moisture for Madhya Pradesh as shown in Table 3. This table also shows the correlation values for Myanmar. The correlation between the observed rainfall and ESA soil moisture over Madhya Pradesh is 0.459. The correlation between soil moisture from ERA-I and rainfall is 0.471, and that between CFSR and rainfall is 0.509. The relationship between the rainfall and reanalysis soil moisture is less as compared to the observed. It shows that the variation in reanalysis soil moisture does not match well with the actual observation. The intercomparison between reanalysis and observed datasets of soil moisture has been studied. It found that the correlation between observed soil moisture and ERA-I is 0.894, observed and CFSR is 0.856, and CFSR and ERA-I is 0.940. Similar correlation values have been computed for Myanmar (also shown in Table 3), which indicate that these correlation coefficients are statistically not significant.

Therefore, enough caution should be taken while using reanalysis soil moisture data while developing application systems such as crop modeling etc.

Figure 6a, b, c show the spatial correlation between observed rainfall and soil moisture from ESA, CFSR, and ERA-I respectively over the Indian region for the JJAS season. All the soil moisture products have positive correlation with rainfall. It is seen that the correlation of soil moisture from CFSR with observed rainfall (0.6 to 0.8 or more) is stronger than that with observed rain and ERA-I (0.5 to 0.7) soil moisture over the Indian region. However, the ESA and ERA-I relationship with rainfall is poor over Myanmar region. The CFSR has correlation values of 0.3 to 0.5 over Myanmar and it is better than ERA-I. Figure 6d, e, f show the spatial correlation between observed and reanalysis soil moisture (m^3/m^3) for these months. While both CFSR and ERA-I are highly correlated with the ESA soil moisture over India, the CFSR is less correlated with ESA over Myanmar. Both CFSR and ERA-I intercorrelation is also very high over the Indian region.
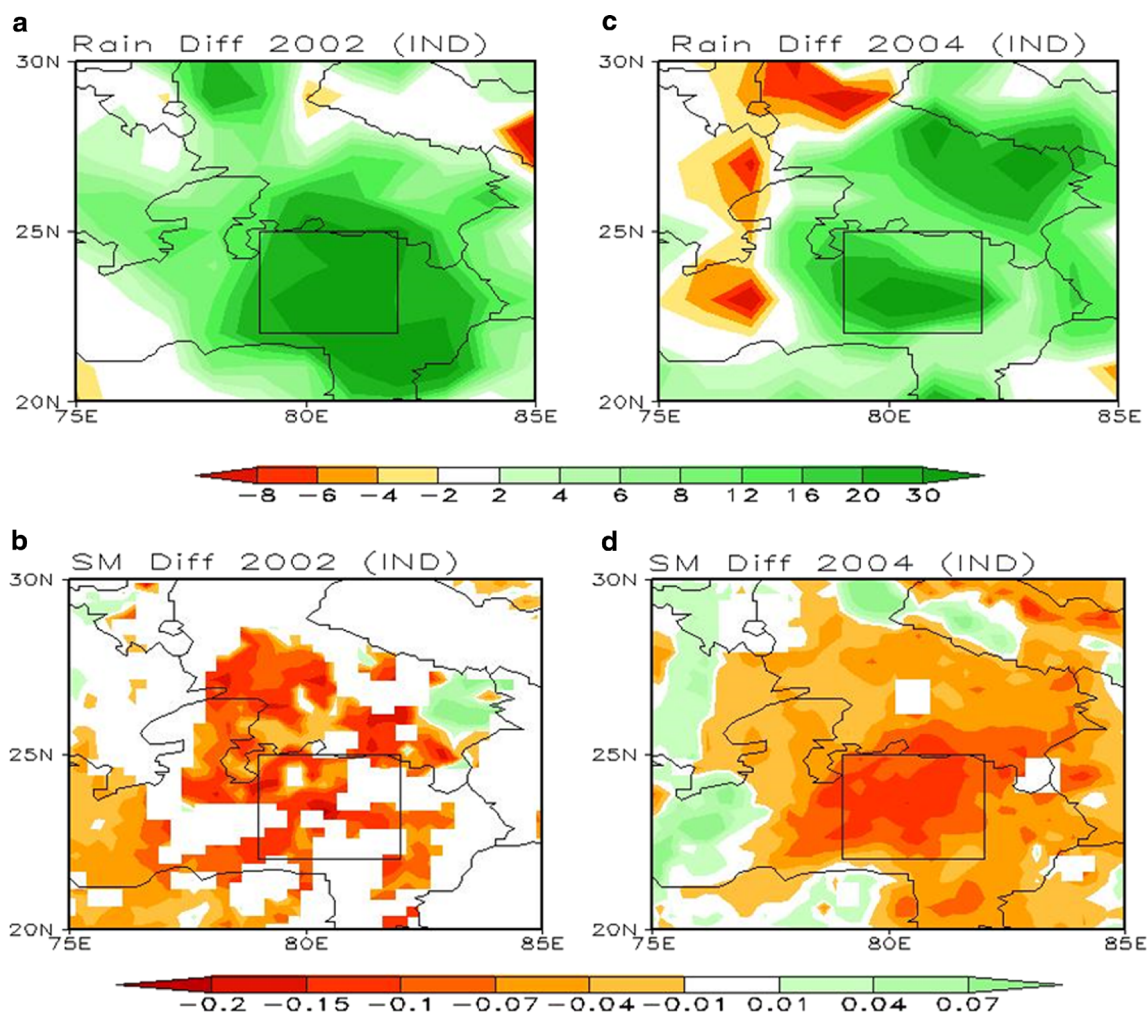

Fig. 8 Rainfall and soil moisture differences between an active rainfall day followed by weak monsoon phase for the selected region in India a rainfall in 2002; b soil moisture in 2002; c for rainfall in 2004; d soil moisture in 2004

3.5 Soil moisture during weak monsoon phases

Day to day variations of soil moisture in central parts of India and central parts of Myanmar have been examined during weak monsoon conditions. During last 10 years, the semiarid zone of central India has faced about three severe droughts. Similarly, the central semiarid zone of Myanmar has faced around four severe droughts during the last 10 years. The study regions are shown in Fig. 7a. The latitudinal and longitudinal extents of the semiarid zone of central India are 79°–82° E and 22°–25° N (IND) and that of the semiarid zone of central Myanmar are 95°–98° E and 19°–22° N (MN), respectively. The regions for which soil moisture evolution during weak phases of monsoon are discussed here are marked as boxes in the figure. Results discussed in this section describe the impact of rainfall over soil moisture during JJAS in the study domains. Figure 7b shows the monthly rainfall anomaly (mm/day) for June, July, August, and September, and Fig. 7c has the seasonal anomaly of rainfall (mm/day) for JJAS mean over the two boxes (study regions). The weak rainfall phases in the study areas have been identified from observed IMD/

NCMRWF datasets for each year. As mentioned earlier, Table 2 shows the low rainfall phases from 2002 to 2011 over central India and central Myanmar. Based on these low rainfall phases, the composite analysis of rainfall and soil moisture have been made. For each year, two to four such phases have been selected. Each phase has rainfall less than 3 mm/day. The differences have been calculated between the rainfall for the last day of rainfall and the period of no rainfall (0 to 3 mm/day). The difference of soil moisture is also plotted based on no rainfall (0 to 3 mm/day) phases.

Figure 8 shows the rainfall and soil moisture differences between an active rainfall day followed by a weak monsoon phase for 2002 and 2004 for the selected region in India. Similar figures for 2005 and 2009 are shown in Fig. 9. Plots for the other years (normal years) are not shown in the figure for brevity. It may be noted that the years 2002, 2004, 2007, and 2009 were drought years in central India. During these drought years, the rainfall anomalies are rather very high than during normal years. The relationship between the rainfall and soil moisture also appears to be stronger during these years. In 2002, there were three long weak rainfall
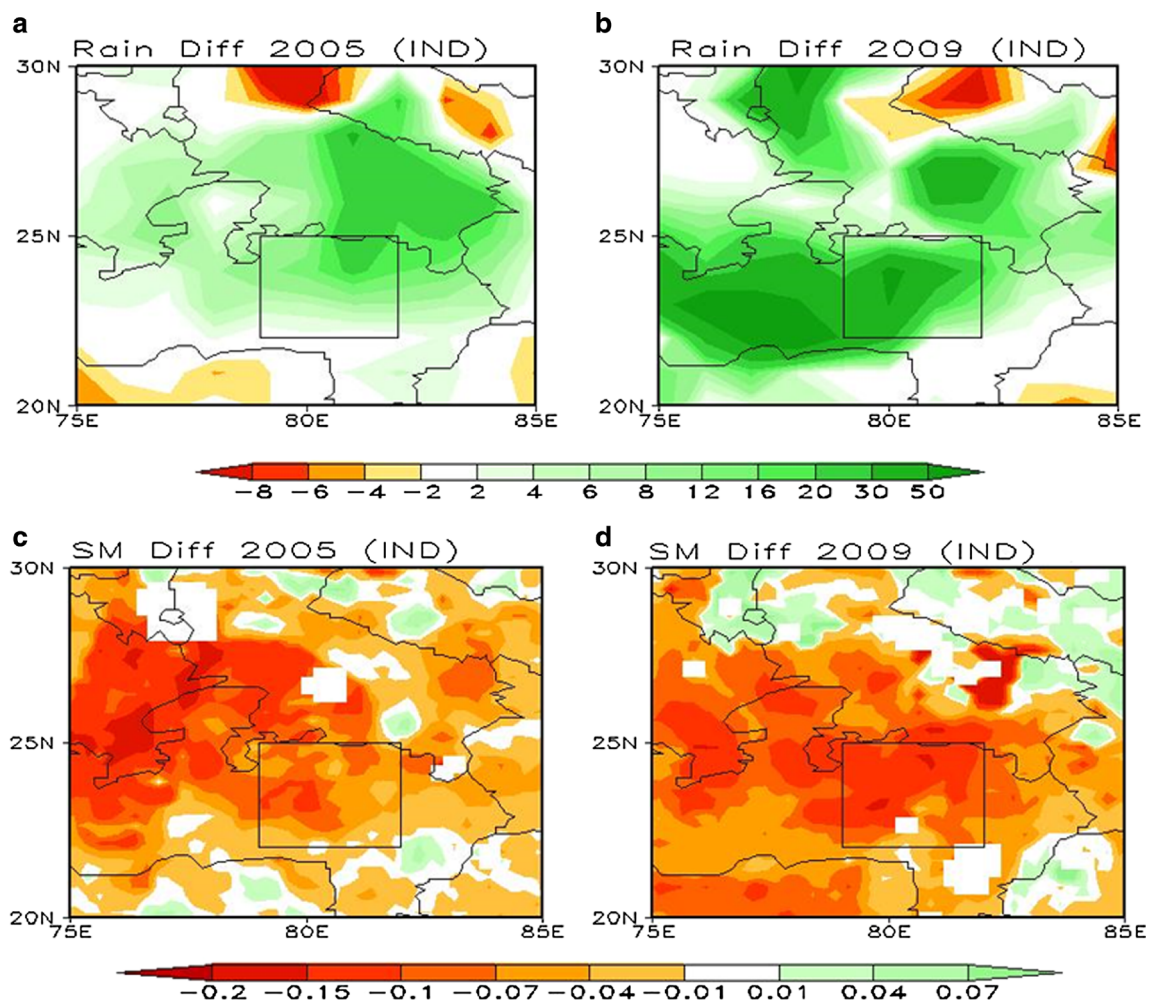

Fig. 9 Same as Fig. 8 but for **a** rainfall in 2005; **b** soil moisture in 2005; **c** for rainfall in 2009; and **d** soil moisture in 2009

phases. These phases are during 02 to 11 and 21 to 31 July and 13 to 28 September. After the rainy phase, which ended on July 01, for about 10 days, there was no rainfall in the area of interest. As a result, large deficit in rainfall occurred over eastern Madhya Pradesh. Because of the rainfall deficiency, soil moisture values have also decreased up to 0.1 (m³/m³) or less as seen in Fig. 8b. In 2003, three no rainfall phases were observed during 19 to 22 June, 29 to 31 July, and 19 to 21 August. These phases were not as long as in 2002. Therefore, very less difference has been noticed in the rainfall and soil moisture. The difference in rainfall is about 5 to 7 mm/day and soil moisture difference is 0.03 to 0.05 (m³/m³), not shown in figure. In Madhya Pradesh, 2004 was a drought year and several weak or no rainfall phases occurred during 20 to 25 June, 09 to 14 July, 19 to 24 July, and 24 to 30 August. Moreover, long phases with no rainfall affected the soil moisture over Madhya Pradesh in this year. As a result, the rainfall difference reached up to 15 to 20 mm/day or more and the soil moisture difference reached up to 0.08 to 0.15m³/m³ as seen in Fig. 8b. In 2005, two dry events occurred from 07 to 14 August and 23 to 30 August. After the dry spell began, soil

became too dry and soil moisture reduced by more than 0.1 m³/m³ as seen in Fig. 8c. The drought year of 2009 had also two very long dry spells (23 July to 07 August and 11–24 September). Before the dry spell began, there was good amount of rainfall in July (more than 20 mm/day). However, prolonged dry spell reduced the soil moisture by more than 0.15 m³/m³.

Figure 10 shows the composite of rainfall and soil moisture over the semiarid zone of central Myanmar for 2002 and 2006. Similar plots for 2007 and 2011 are shown in Fig. 11. The composite plots show the relationship between rainfall and soil moisture over central Myanmar during the study period. The rainfall difference in the central zone of Myanmar reduced by 10 to 15 mm/day, then the soil moisture difference reached up to 0.08 m³/m³. The impact of rainfall over soil moisture is more over the central Myanmar region where small difference in rainfall caused large changes in soil moisture. In all the years considered, the soil moisture over central Myanmar reduced by 0.08 to 0.1 m³/m³ during dry spells notably in the years shown in Fig. 10 and Fig. 11. The years 2002 and 2007 are noteworthy when large-scale soil moisture
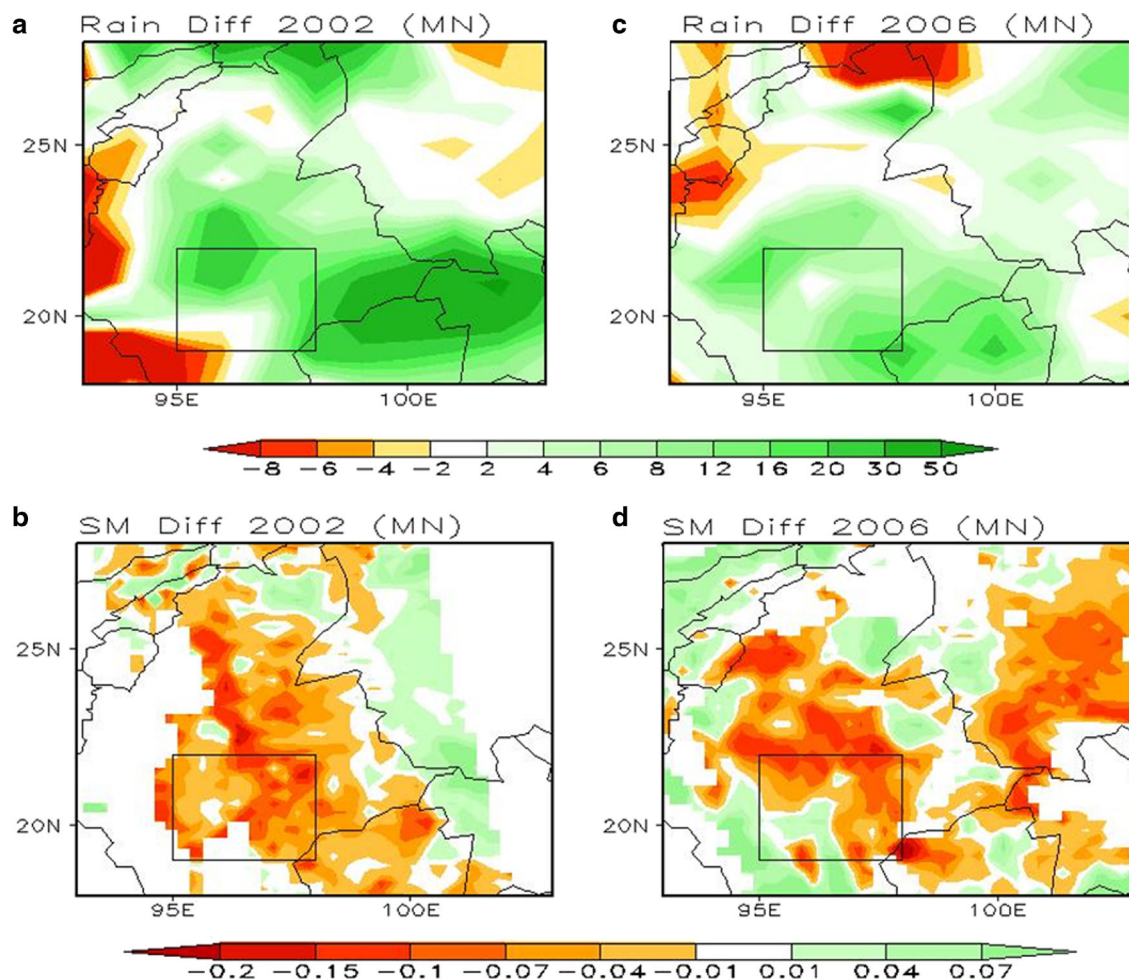

Fig. 10 Rainfall and soil moisture differences between an active rainfall day followed by weak monsoon phase for the selected region in Myanmar **a** rainfall in 2002; **b** soil moisture in 2002; **c** for rainfall in 2006; **d** soil moisture in 2006
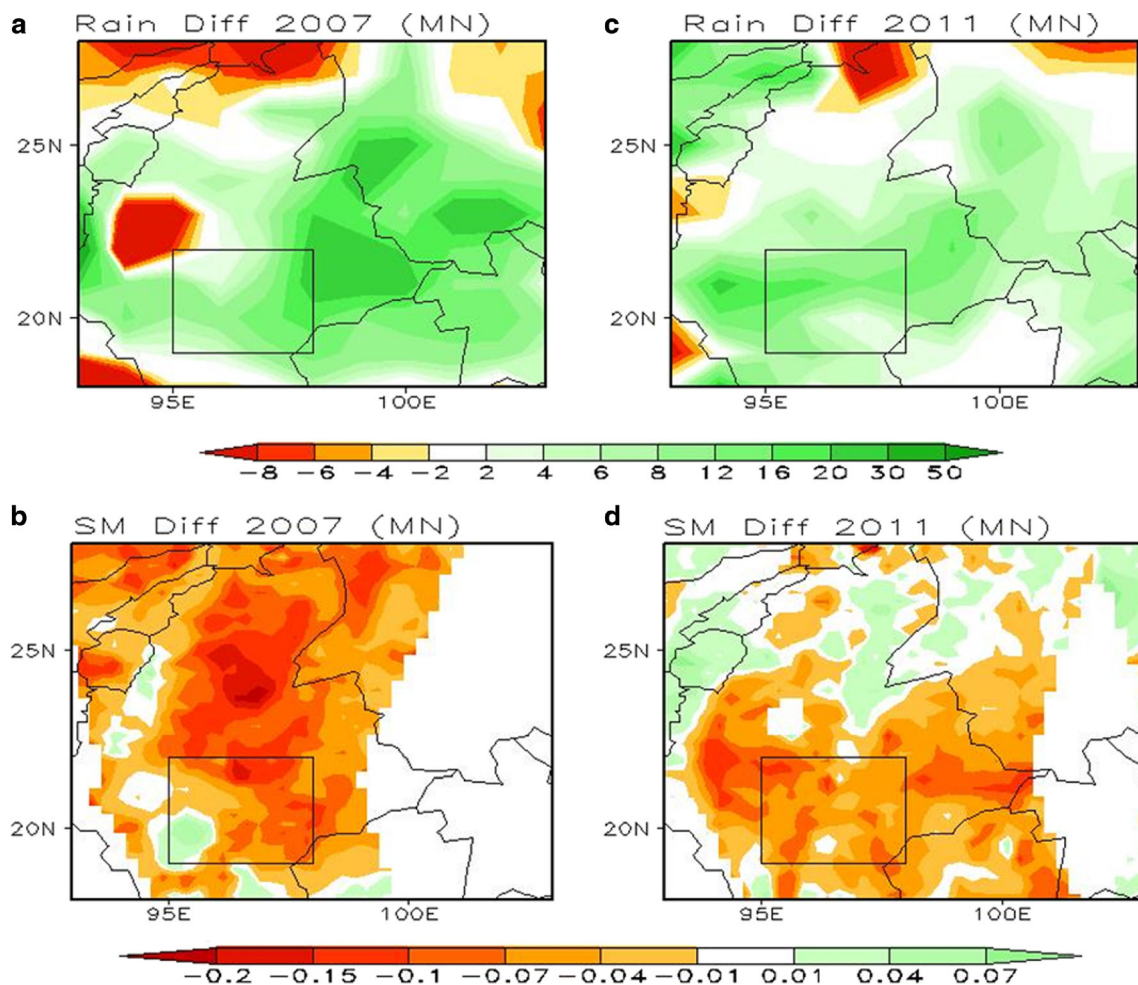
Fig. 11 Same as Fig. 10 but for **a** rainfall in 2007; **b** soil moisture in 2007; **c** for rainfall in 2011; **d** soil moisture in 2011

reduction took place in the central Myanmar region with high magnitude during the dry spells.

3.6 Time series of rainfall and soil moisture during weak monsoon phases

Daily evolution of soil moisture during dry spells (weak monsoon phases) over the study regions has been examined. Such an analysis provides indication regarding rate of soil moisture reduction in the regions when there is no rainfall for several days during the monsoon seasons. While data for all the years from 2002 to 2011 have been examined, results for only the years discussed in Sect. 3.5 are presented here. In order to examine daily evolution of soil moisture in reanalysis data, similar analysis has also been done using CFSR and ERA-I analysis. In addition, observed daily climatology of ESA soil moisture has also been used. Figure 12 and Fig. 13 show the daily evolution of soil moisture for the central Indian region, while Fig. 14 and Fig. 15 show the similar plots for central Myanmar. Observed rainfall area averaged for the region is also plotted in the same figures.

From the figures, it is found that the soil moisture decreases gradually with time in case of no rainfall and it increases in some point because of light (1 or 2 mm) rainfall. Moreover, the observed soil moisture gradually decreases during no rainfall phases and the volumetric soil moisture content reaches up to 0.1 m^3/m^3 when the observed climatological soil moisture is about 0.25 to 0.35 m^3/m^3. The soil moisture in CFSR also decreases during these dry spell phases. However, the ERA-I soil moisture values move according to the observed climatology of soil moisture. It is found that during long phases of weak monsoon (with less or no rainfall), the CFSR soil moisture values are better than those from ERA-I. During normal years, the relationship between observed and reanalysis soil moisture does not show significant differences.

From the IAV of reanalysis datasets, it was found earlier that soil moisture over the Myanmar region does not vary much during JJAS. Both reanalyses show very high values and more than the climatology. During the less or no rainfall phases, daily variations of volumetric soil moisture content vary from 01 to 0.3. Whereas, both reanalysis datasets provide values ranging from 0.25 to 0.45. The impact of dry spell is
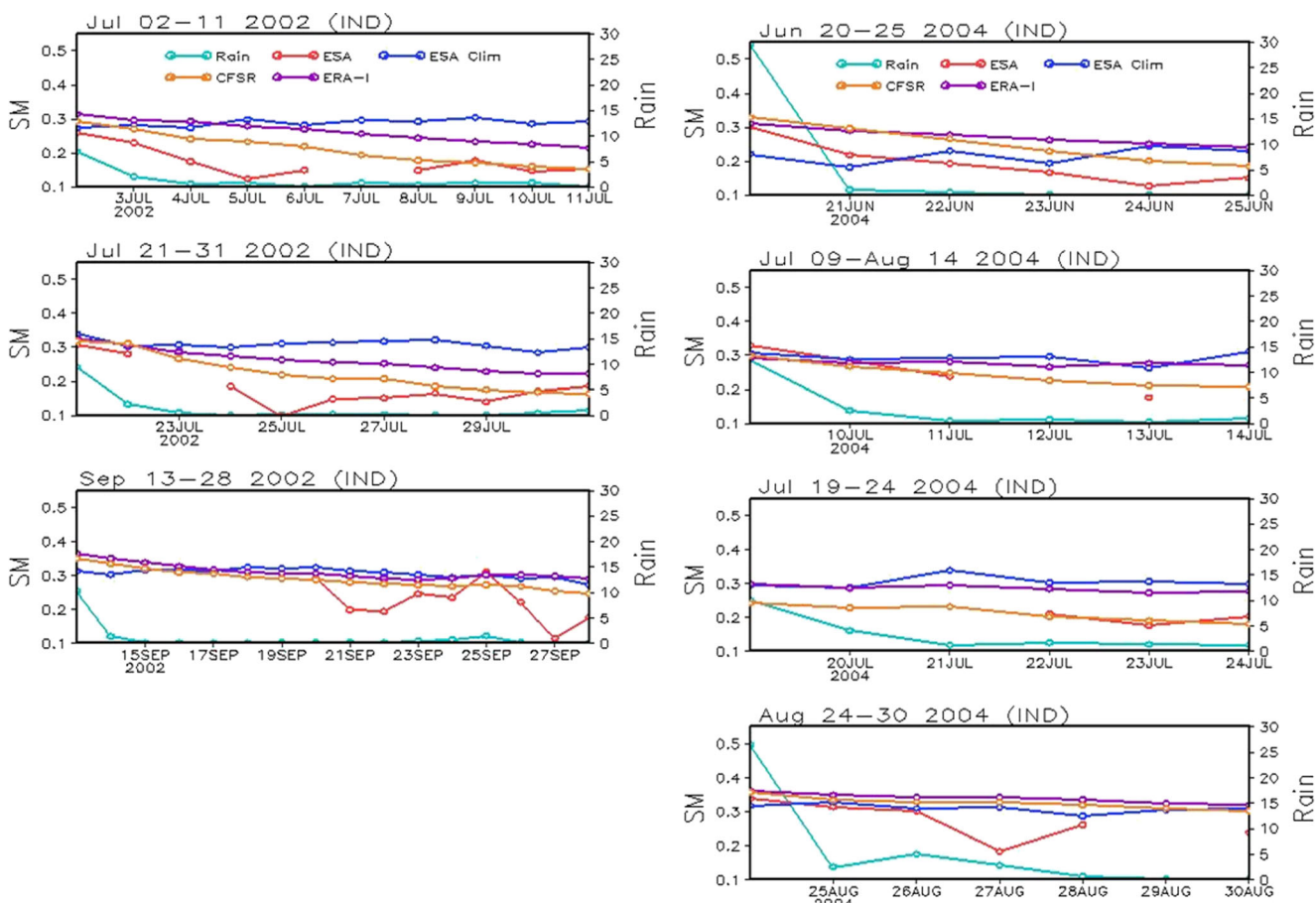
Fig. 12 Comparison between observed rainfall (mm/day), observed soil moisture, observed soil moisture climatology, ERA-I and CFSR soil moisture (m^3/m^3) over central India during dry spells in 2002 and 2004

not seen in these reanalysis products. In drought as well as non-drought years, the reanalysis soil moisture is overestimated over central Myanmar. The overestimation of reanalysis datasets shows that very week relationship between observed soil moisture and the reanalysis datasets over the central Myanmar region.

4 Conclusions

Variations of soil moisture during crop growth period are very important for sustenance of the crop and subsequent crop yield. Indian monsoon shows considerable variability in intraseasonal timescales with active and weak monsoon
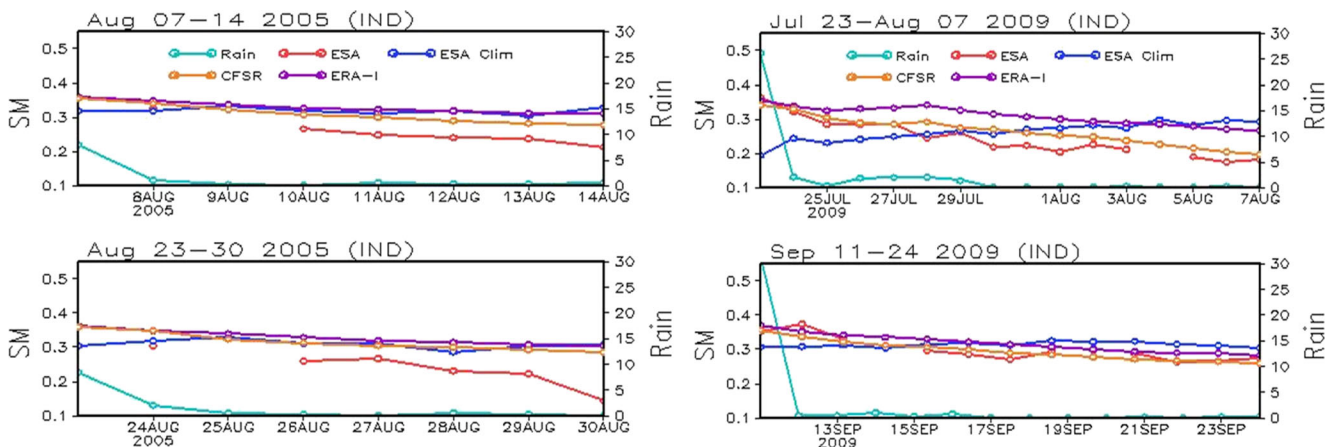

Fig. 13 Same as Fig 12 but for central India during dry spells in 2005 and 2009
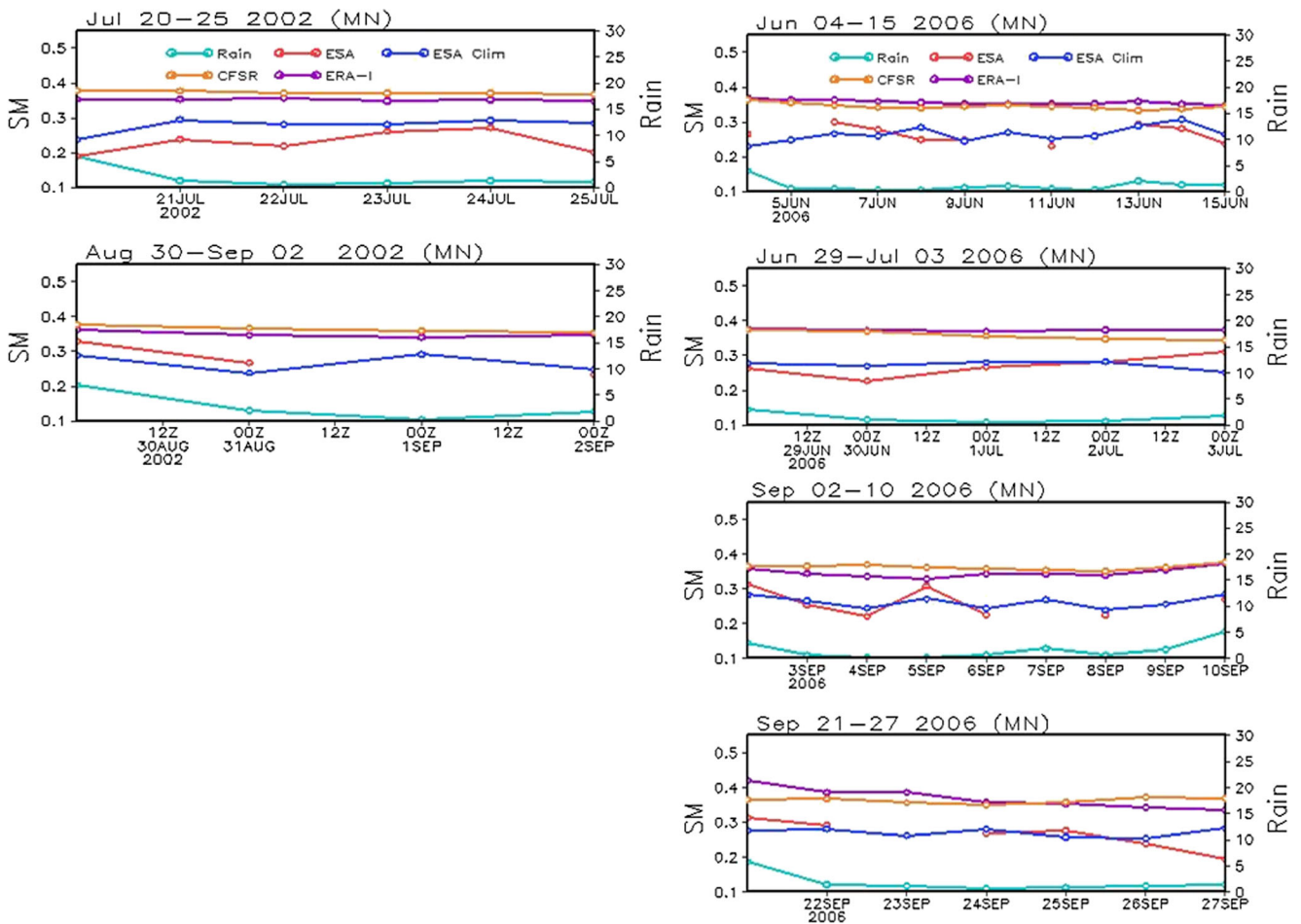
Fig. 14 Same as Fig 12 but for central Myanmar during dry spells in 2002 and 2006
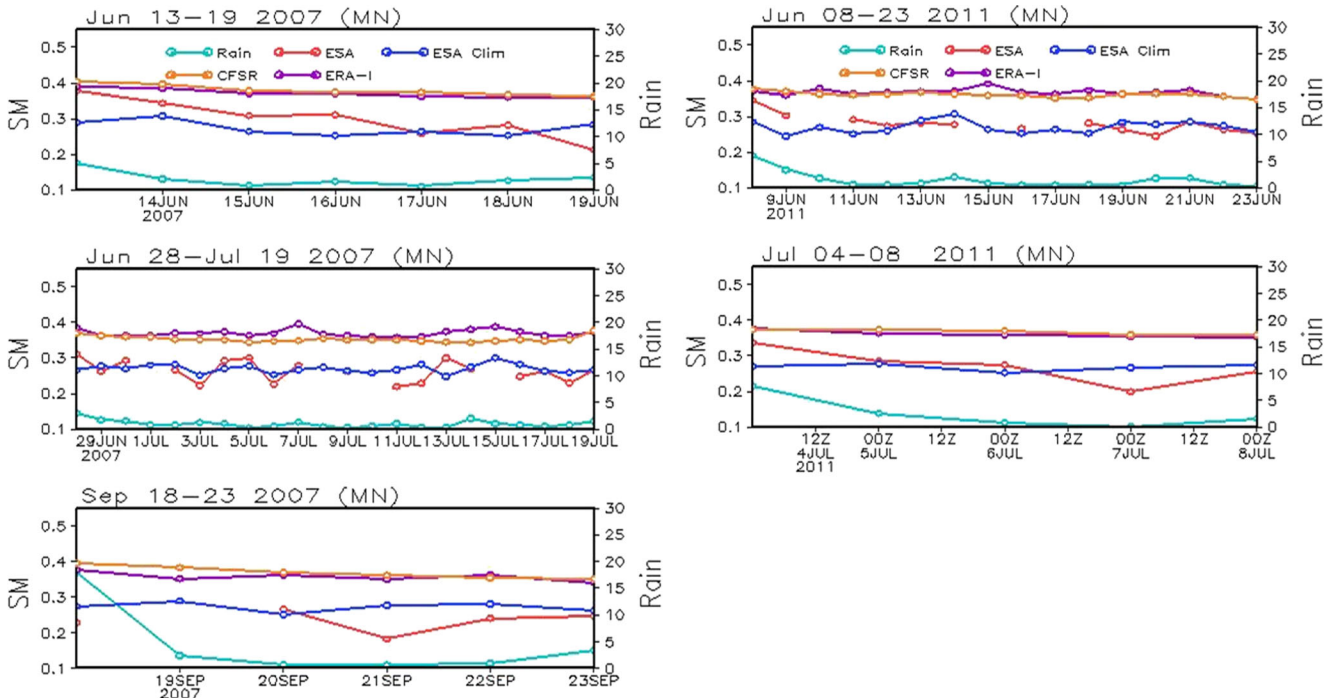

Fig. 15 Same as Fig. 12 but for central Myanmar during dry spells in 2007 and 2011

conditions. In a dry spell, the soil moisture gradually reduces affecting the crop growth. In situ observations of soil moisture are few or not available in central India and central Myanmar. In the absence of such data, researchers use data derived from remote sensing satellites or use global reanalysis data. However, an intercomparison of soil moisture during dry spell within monsoon seasons has not been done. The main objective of the present study is to carry out such an analysis.

Observed rainfall and observed ESA-derived soil moisture as well as two reanalysis datasets ERA-I and CFSR for 10-year period from 2002 to 2011 have been studied for India and Myanmar. The climatology, interannual variability (IAV), correlation, and intercomparison at daily scale have been carried out. ESA soil moisture indicates that soil moisture increases over India from west to east and from north to south. ERA-I soil moisture is overestimated, while CFSR soil moisture more or less agrees with observation (except for underestimation in east and central India). Over Myanmar, soil moisture values from reanalysis are very high and ERA-I soil moisture does not show much variability from year to year. It is found that the ESA volumetric soil moisture is very well correlated with IMD/NCMRWF gridded rainfall. The correlation between rainfall and observed soil moisture is very high and significant. The CFSR soil moisture is reduced over central India during drought years as the observed soil moisture. The ERA-I does not show results similar to observed ESA soil moisture during drought and non-drought years. ERA-I underestimates IAV in soil moisture over India and neighboring countries, whereas CFSR overestimates it. The underestimation of IAV of soil moisture by ERA-I is larger over the Myanmar region. CFSR shows higher IAV of soil moisture over central India, northern India, and associated Himalayan region as compared to observations. Therefore, soil moisture from CFSR is closer to the ESA observed soil moisture than to ERA-I.

Day to day variations of soil moisture in central parts of India and central parts of Myanmar have been examined during weak monsoon conditions. The weak rainfall phases in the study areas have been identified from observed IMD/NCMRWF datasets for each year. It is found that during dry spells, because of the rainfall deficiency, soil moisture values also decreased up to 0.1 m^3/m^3 compared to climatological values of more than 0.3 m^3/m^3. The soil moisture in CFSR also decreases during these dry spell phases. However, the ERA-I soil moisture values move according to the observed climatology of soil moisture. It is found that during long phases of weak monsoon (with less or no rainfall), the CFSR soil moisture values are better than those from ERA-I.

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