Relation Between the Rainfall and Soil Moisture During Different Phases of Indian Monsoon

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Abstract—Soil moisture is a key parameter in the prediction of southwest monsoon rainfall, hydrological modelling, and many other environmental studies. The studies on relationship between the soil moisture and rainfall in the Indian subcontinent are very limited; hence, the present study focuses the association between rainfall and soil moisture during different monsoon seasons. The soil moisture data used for this study are the ESA (European Space Agency) merged product derived from four passive and two active microwave sensors spanning over the period 1979–2013. The rainfall data used are India Meteorological Department gridded daily data. Both of these data sets are having a spatial resolution of 0.25° latitude–longitude grid. The study revealed that the soil moisture is higher during the southwest monsoon period similar to rainfall and during the pre-monsoon period, the soil moisture is lower. The annual cycle of both the soil moisture and rainfall has the similitude of monomodal variation with a peak during the month of August. The interannual variability of soil moisture and rainfall shows that they are linearly related with each other, even though they are not matched exactly for individual years. The study of extremes also exhibits the surplus amount of soil moisture during wet monsoon years and also the regions of surplus soil moisture are well coherent with the areas of high rainfall.

Key words: Soil moisture, rainfall, flood and drought years, interannual variability.

1. Introduction

The Indian summer monsoon from June to September, also known as the southwest monsoon season, is mainly governed by the huge land–sea thermal contrast. It consists of large organized convective cloud bands over the south Asian monsoon domain, which extend more than 100 days. The rainfall received in the subcontinent from these cloud bands diverted into evaporation, runoff, and infiltration. The infiltrated water is held in the soil as soil moisture. Therefore, there is a consistent relation of soil moisture with rainfall, even though the relation is non-linear (Douville et al. 2001). Atmospheric boundary layer plays a vital role in regulating weather and climate by exchanging large amount of surface water and energy with the overlying atmosphere (Zhang et al. 2004). In this context, the seasonal rainfall variability affects the variability in soil moisture, which influence the wetness/dryness of monsoon season (Douville 2002). In India, a country controlled predominantly by the agrarian economy and high population, even the small changes in rainfall impact the economic and social strategies. Both the internal dynamics and boundary forcing contribute to the internal atmospheric variability (Shukla 1985). Namias (1959, 1960) studied soil moisture as a boundary forcing to the atmospheric precipitation and they suggested that reduced soil moisture during the late winter or spring over central United States could induce a dry summer over the same region. Therefore, the study of soil moisture is imperative to understand the behavior of the Indian monsoon system. In the present study, we made an attempt to understand the basic characteristics of soil moisture and associated rainfall on climatological scale in addition to the interannual variabilities.

Studies on soil moisture and rainfall relation are very limited because of non-availability of soil moisture data on a spatial domain. A few studies were made using model data set; however, the comparison of model data with the observation was very difficult especially in the tropics; moreover, comparison of the model data set with certain in situ measurements showed huge bias (Robock et al. 1998). Gates (1992) compared soil moisture derived from the Atmospheric Model Inter Comparison Project (AMIP) with in situ observation and concluded that the model data are far away from the observations and this is due to

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the derivation of soil moisture from the water budget models (Mintz and Serafini 1992). Douville et al. (2001) studied the model derived soil moisture to relate Asian and African rainfall based on 2 year period. They concluded that surface wetness over northern India contributed to increased rainfall; however, the relation is inversed for all India average and they attributed this change to the chaotic nature of the Asian monsoon system. Namias (1989) found that the responsible factor for the 1988 US drought is the low soil moisture during spring time. Some research studies reported positive soil moisture rainfall feedback through evaporation (Pal and Eltahir 2001; Meehl 1994; Froidevaux et al. 2014). Kantharao and Rakesh (2017) reported that soil moisture during the spring season is positively feed the rainfall during the month of June over Indian region. However, some other studies found that soil moisture is not sensitive to rainfall (Sud and Smith 1985).

Negative feedback mechanism of soil moisture to rainfall was also demonstrated by Cook et al. (2006) based on their community atmospheric model. They argued that the increased soil moisture modulates the surface energy balance. Thus, it converts sensible heat to latent heat; consequently, it cools the surface and increases surface pressure. This increases the stability of the atmosphere and, therefore, leads to decreased precipitation (New et al. 2003). Shukla and Mintz (1982) also support this feedback mechanism by simulating increased rainfall amount in dry soil moisture condition. Whether the soil moisture affects the rainfall in positive or negative pathways, it is obvious that it displays an important role in determining the regional climate and surface hydrology (Yeh et al. 1984). However, the study over the Indian subcontinent is very limited. Barnett et al. (1989) reported that the negative feedback mechanism is driving the Indian summer monsoon season. Asharaf et al. (2012) using COSMO model found that the pre-monsoon soil moisture has dominant role in immediate southwest monsoon rainfall with positive feedback. They further established that the pre-monsoon soil moisture during dry episodes can delay the southwest monsoon onset by 11 days.

By the advent of the remote sensing technology, remote sensing data sets of soil moisture are available in spatial and temporal scale. This data set is valuable in gaining more insight to the feedback mechanism of soil moisture on rainfall. In this study, we made an attempt to explore the climatological features of soil moisture and rainfall for different seasons in addition to the features of extreme events.

2. Data and Methodology

The present research uses remote sensing data from merged products of active and passive microwave sensors by combining the scatterometer and radiometer products (Liu et al. 2011, 2012; Wagner et al. 2012). The active, passive, and merged soil moisture data sets over the globe were downloaded from http://www.esa-soilmoisture-cci.org/node/145. The detailed product description can also be available from the website http://www.esa-soilmoisture-cci.org/node/139. The merged soil moisture product has a spatial resolution of $0.25° \times 0.25°$ latitude–longitude grid with a daily time step centered at 00:00 UTC. The microwave soil moisture products represent at a depth of about 2 cm of the soil (Owe and Van de Griend 1998). This merged daily product is available from 1st November 1978 to 31st December 2013, and it was developed under the project Water Cycle Multi-mission Observation Strategy and Climate Change Initiative of European Space Agency (Wagner et al. 2012; Mecklenburg et al. 2012). The merged soil moisture product was derived from six microwave sensors, both passive and active sensors. The passive sensors include SMMR, SSM/I, TMI, and AMSR-E, while active sensors are ERS AMI and ASCAT microwave sensors (Dorigo et al. 2014). The availability of the passive and active products was variable over the time. The soil moisture products are combined based on their vegetation density sensitivity; over the low vegetation areas, passive sensors are used, and for moderate areas, active sensors are used.

In addition to the soil moisture data, we used IMD (India Meteorological Department) gridded rainfall data available from 1901 to 2012 with a spatial resolution of $0.25°$ latitude–longitude grid. The gridded rainfall data are available for the entire Indian subcontinent (6.5°N–37.5°N and 66.5°E–101.5°E). Details of this data set can be found at Pai et al. (2014). The interpolation technique and station

details of the in situ observation of rainfall are explained in Rajeevan et al. (2006) and Rajeevan and Bhate (2009).

In a recent study, Dorigo et al. (2014) evaluated the merged soil moisture product based on the available in situ soil moisture data through international soil moisture network (Dorigo et al. 2011, 2013) and found that the absolute value of the merged soil product has significant correlation with in situ observation with a value of 0.46 and a value of 0.36 with anomalies. They also concluded that the merged product showed better results than the individual active/passive sensors. Dorigo et al. (2012) also studied the linear trends and compared with the reanalysis data set and found that they are in good agreement. The evaluation studies of Dorigo et al. (2014) found that the merged product of soil moisture is well comparable with the available in situ soil moisture data set over the Indian subcontinent.

3. Results and Discussion

3.1. Climatology of Rainfall and Soil Moisture

Rainfall climatology during the summer monsoon (June–September), post-monsoon (October–December), northeast monsoon (January and February), and pre-monsoon (March–May) seasons using IMD gridded rainfall data is shown in Fig. 1. During the summer monsoon season, high rainfall is mainly concentrated over Konkan coast (windward side of Western Ghats) and northeast regions including foot hills of Himalaya. The rainfall over these areas exceeds more than 16 mm day^{-1}. The high rainfall over the Konkan coast is attributed to the orographic precipitation (Grossman and Durran 1984) and high rainfall over the foot hills of Himalaya can be attributed to the monsoon trough extending from the head Bay to the Pakistan low (Barros and Lang 2003). The central Indian regions receive moderate rainfall, while northwest and southeast regions receive less rainfall during the summer monsoon season. The rainfall patterns during the pre-monsoon and post-monsoon seasons show similar spatial distribution with different magnitudes. During the post-monsoon season, the entire eastern coastal belt received high rainfall while comparing with pre-monsoon rainfall pattern. During the winter monsoon season, Indian subcontinent received minimum amount of rainfall; however, southeastern region including southern tip of India received almost normal rainfall. In general, rainfall received during the summer monsoon and post-monsoon seasons contributed much to the annual rainfall received over the Indian subcontinent.

The climatology of merged soil moisture derived from ESA satellite active and passive products (Fig. 2) showed similar spatial pattern of seasonal climatology of rainfall. The climatology of soil moisture is very important especially in the model input as the model derived soil moisture is entirely dependent on the model (Robock et al. 1998). Therefore, understanding the soil moisture in the spatial and temporal scales is required. During the summer monsoon season, the maximum soil moisture is found in the western coastal regions and central parts of the Indian subcontinent. Over these regions, the soil moisture is more than 0.4 m^3 m^{-3} (soil moisture is given as volumetric unit). The northwest regions show minimum amount of soil moisture (< 0.1 m^3 m^{-3}). During the post-monsoon season, soil moisture maximum is in the southeast and northeast regions and it is coherent with the areas of increased rainfall, except in north/northwest India. In the winter monsoon, central India, southeast, and northeast regions showed high amount of soil moisture (~ 0.2 m^3 m^{-3}). During the pre-monsoon season, soil moisture is comparatively less throughout the Indian subcontinent and the value is less than 0.2 m^3 m^{-3}, except in some northeastern regions. The soil moisture is more prominent during the southwest monsoon season and less during the pre-monsoon season showing similar seasonal pattern of the rainfall.

3.2. Annual Cycle of Rainfall and Soil Moisture

The annual cycle of rainfall is well known (Shea and Sontakke 1995); however, the annual cycle of soil moisture is not studied in depth due to the lack of sufficient spatial data set. For understanding the annual cycle of rainfall and soil moisture, we prepared an area weighted average of both the
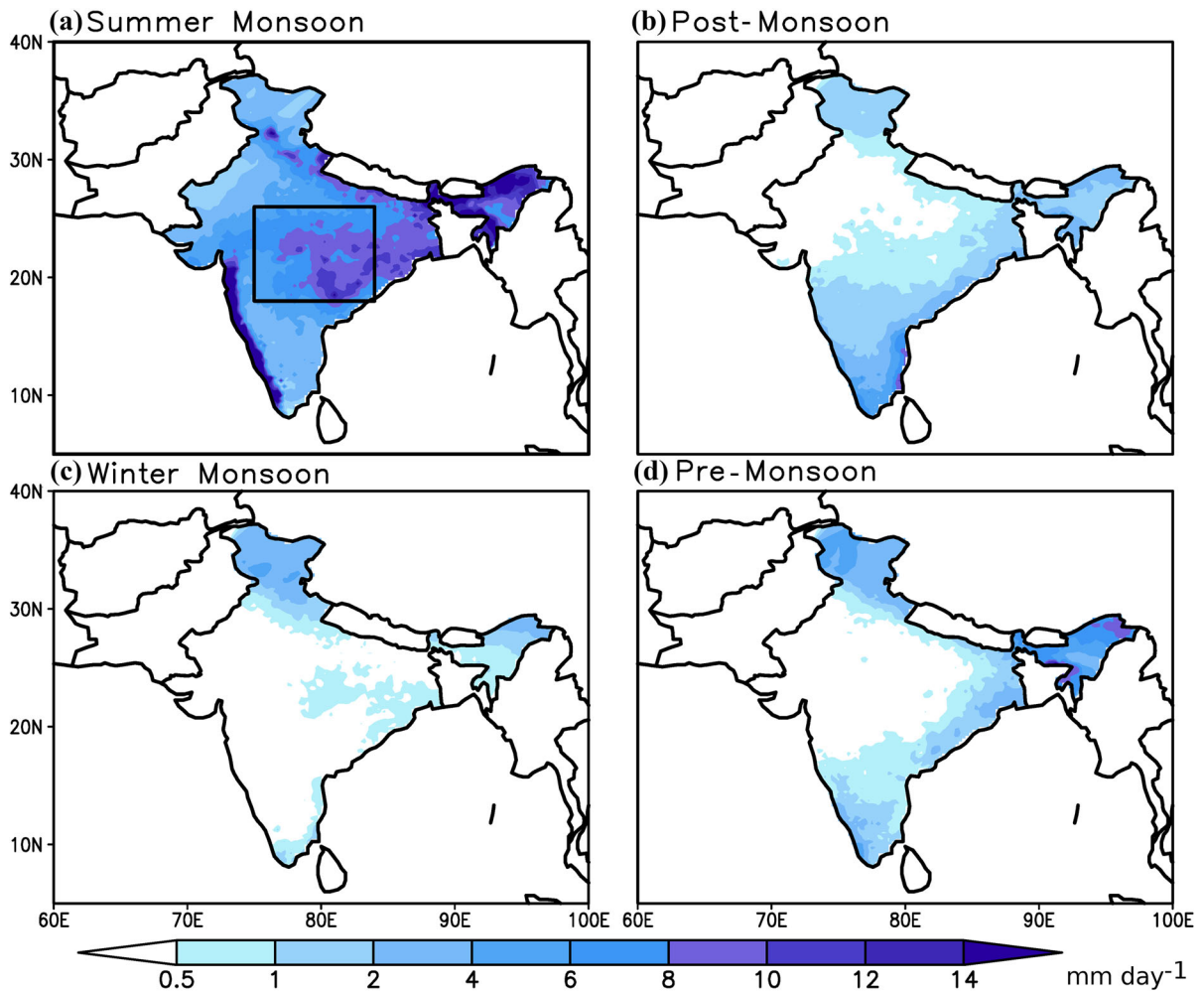
Figure 1
Climatology of Indian rainfall (mm day^{-1}) for **a** summer monsoon (JJAS), **b** post-monsoon (OND), **c** winter monsoon (JF) and (d) pre-monsoon (MAM) seasons. The marked region is considered as central India (75°−84°E; 18°−26°N) for further studies of annual cycle, interannual variability and lead—lag analysis

parameters on monthly basis for the period of 1979–2012 over the central Indian region (75°E–84°E and 18°N–26°N), marked by a box in Fig. 1. The annual cycle of both the parameters along with their standard deviation is given in Fig. 3. The upper panel of the figure shows the annual cycle of rainfall over the region and lower panel is for soil moisture in volumetric unit. From January to March, the rainfall is almost steady, and, thereafter, it increases. From May onwards, the rainfall shows sharp increase over the central India and reaches a maximum during the month of August ($\sim$ 10 mm day^{-1} with a standard

deviation of 1.7 mm day^{-1}). Even though the rainfall shows maximum during the month of August, the standard deviation maximum is seen during the month of September (> 2.0) indicating high degree of uncertainty and it may be due to the withdrawal of the summer monsoon that vary from year to year. From August onwards, the rainfall is decreasing sharply till the month October and thereafter the rate of decrease is gradual. The soil moisture parameter is also high during the month of August with a value of 0.32 m^3 m^{-3} with a standard deviation of 0.02 m^3 m^{-3}. From the month of August onwards,
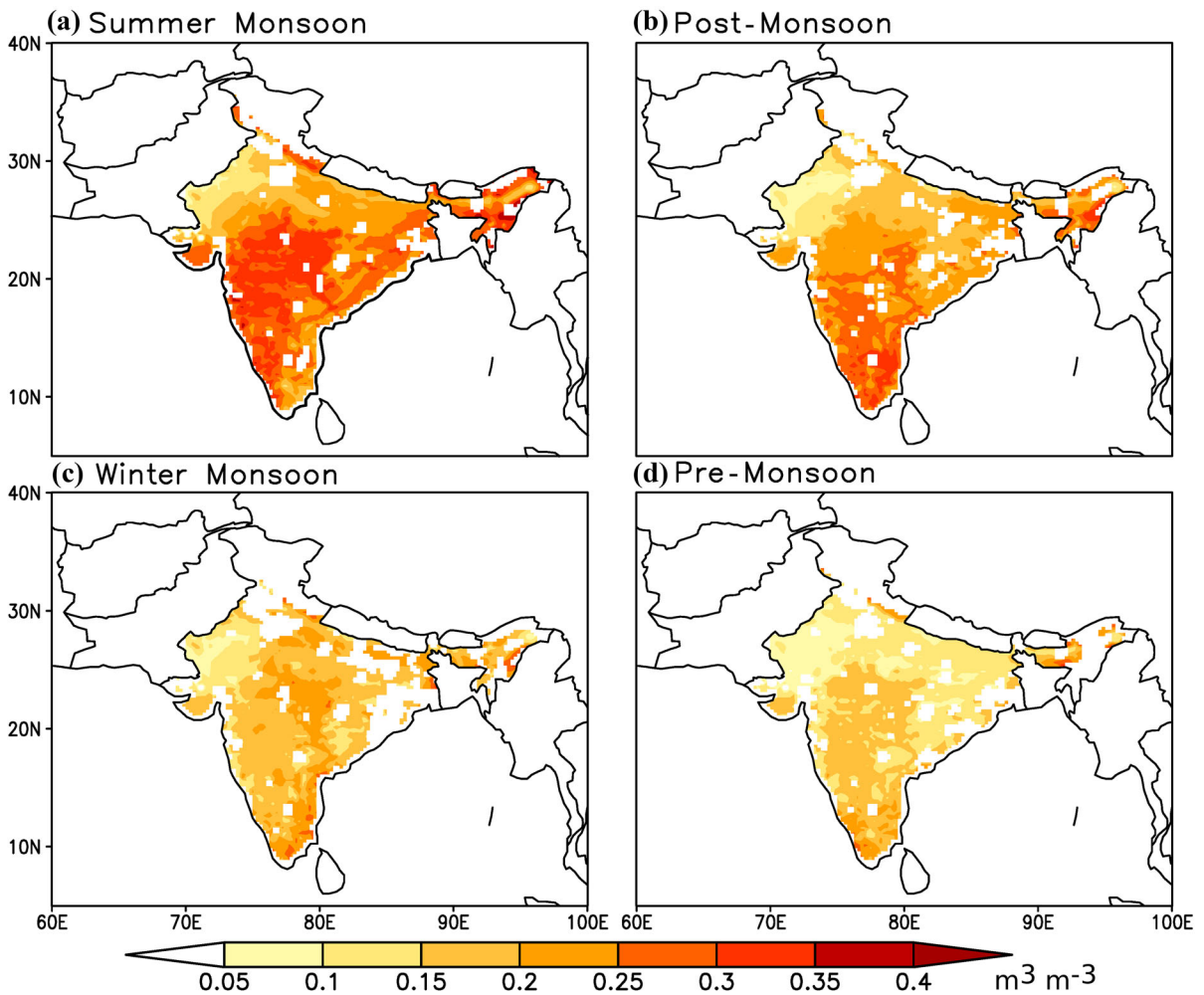
Figure 2
Climatology (1979-2013) of soil moisture ($m^3 m^{-3}$) from merged ESA product for **a** summer monsoon, **b** post-monsoon, **c** winter monsoon and **d** pre-monsoon seasons

the soil moisture is continuously decreasing till next May. Annual cycle of soil moisture shows good resemblance with the annual cycle of rainfall and they show a very high correlation coefficient of 0.85 with a confident level of more than 99% based on Student's t test.

Latitudinal variation of rainfall and soil moisture over the longitude belt 75°E–80°E (to cover Indian region from extreme north to extreme south) is given in Fig. 4. Average rainfall over the longitudes 75°E–80°E in the entire latitudes starts to increases from May and intensifies further till July and August, and then, it recedes from middle of September (Fig. 4a).

Most of the rainfall occurred prior to May between 30°N and 40°N latitudes and during October–November between 10°N and 15°N. It seems that the soil moisture (Fig. 4b) followed the rainfall pattern. However, when examined precisely, the soil moisture shows a lag of one month with the rainfall. For example, at 23°N, while maximum rainfall occurs during July, the soil moisture occurs in August. This is also true at other locations, for, e.g., 30°N. This can be attributed to rainfall is feeding soil moisture or the rainfall on the earth surface infiltrate soil beneath which holds the water to reflect in the soil moisture. This result can also be seen in the
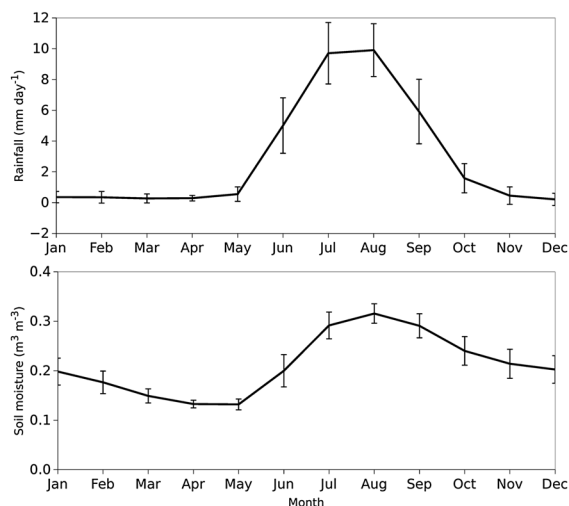
Figure 3
Averaged annual cycle of **a** rainfall (mm day^{-1}, upper panel) and **b** soil moisture (m^3 m^{-3}, lower panel) over central Indian region. The bars indicate the standard deviations for individual months

monthly lead—lag correlation analysis over central Indian region (Fig. 5).

3.3. Interannual Variability and Extreme Events

The year-to-year variation of rainfall and soil moisture normalized against unity in the central Indian region (marked in Fig. 1) is given in Fig. 6. It is clear that both the parameters show year-to-year variability and in most of the years they followed consistent variation. However, the values are not matching either in maximum or in minimum. Both the parameters are correlated with a correlation value of 0.58 and it is statistically significant at 99% confidence level. The rainfall shows maximum over the region during the year 1990 and maximum for soil moisture in 1998. Therefore, the variation in magnitude of rainfall and soil moisture did not match coherently with each other and thus, it can conclude that the soil moisture is also influenced by some other parameters (such as topography, soil type, ecosystem, circulation parameters, etc.) other than the rainfall.

In order to examine the extreme events, we have studied the spatial characteristics of rainfall and soil moisture during the southwest monsoon period associated with drought and flood years. For this, we have considered wet years (1988 and 1994) and dry years

(1979, 1982, 1986, 1987, 2002, 2004, and 2009) based on their percentage of departure of southwest monsoon rainfall from their climatology. Figure 7 shows the composite of rainfall and soil moisture during flood and drought years with their difference. The left panels of the figure show the rainfall pattern and the right panels show the spatial pattern of the soil moisture. During the flood years, rainfall is higher in the central, western coastal and northeast regions. However, the spatial pattern of soil moisture reveals that the pattern is not coherent with the rainfall pattern during both the flood and drought years. The soil moisture pattern shows a slight westward shift in its peak values especially over central Indian region. However, the difference between flood and drought years shows that both the rainfall and soil moisture exhibit almost similar pattern in spatial distribution (Fig. 7e, f). An increase in soil moisture is observed over the areas of high precipitation especially over the western coastal region, Gujarat and southern parts of Rajasthan, and foothills of Himalayas. The rainfall and soil moisture is void over the southeast regions, because the soil moisture is mainly regulated by the rainfall.

4. Summary and Conclusions

This paper explored the relation of rainfall with soil moisture from merged data sets of active and passive sensors produced by the European Space Agency (ESA) in terms of its climatology, annual cycle, interannual variability, and latitudinal propagation in climatological scale. The climatology of rainfall and soil moisture depicts that they are differently distributed in spatial domain. Sathyanadh et al. (2016) also found different distributions of soil moisture over central, western, and northern Indian regions. However, the rainfall and soil moisture are high during southwest monsoon season followed by post-monsoon season. The annual cycle of both the rainfall and soil moisture follows the same path with unimodal variation. The latitudinal variation also shows the same result; however, the soil moisture show its peak almost 1 month after it received the rainfall over the region and the lead–lag analysis also confirms the result and this is in agreement with the
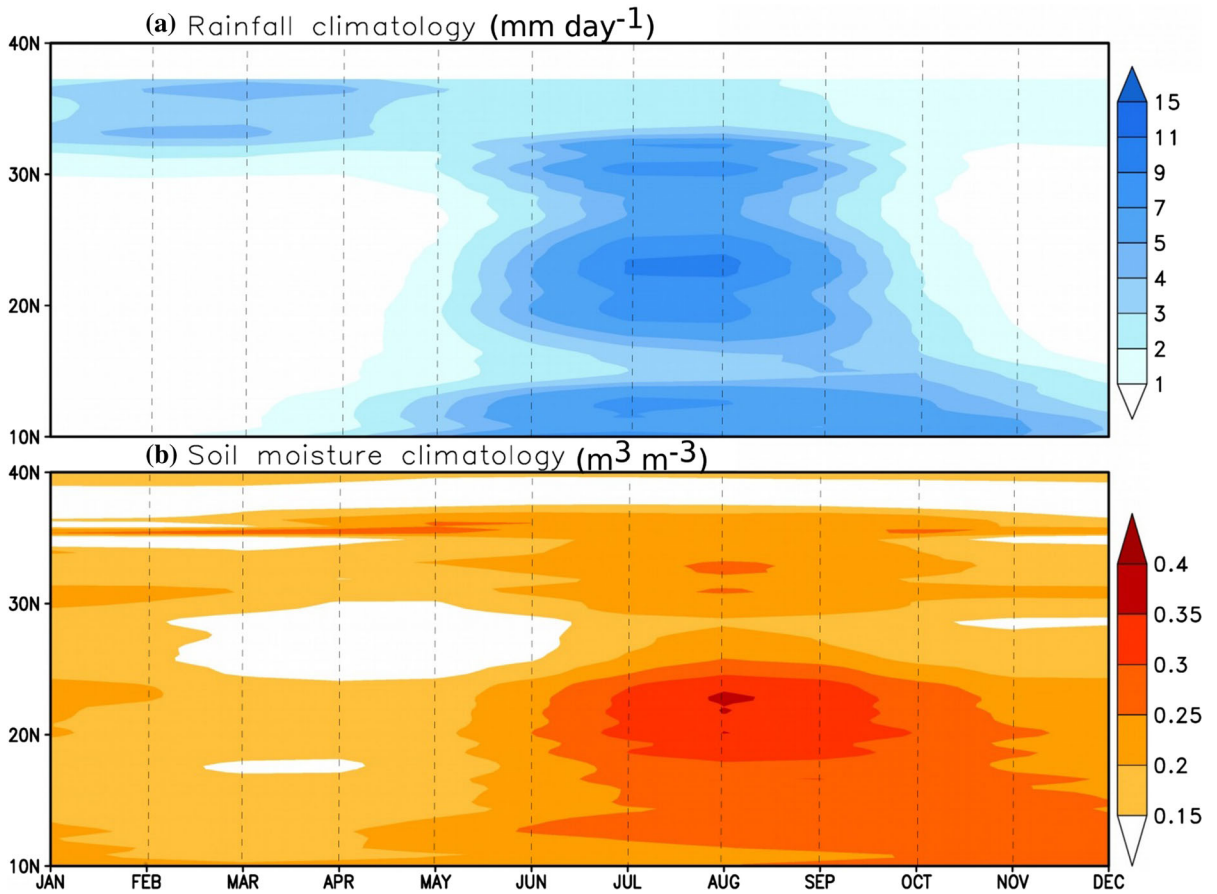
Figure 4
Latitudinal variation of **a** rainfall (mm day^{-1}, upper panel) and **b** soil moisture (m^3 m^{-3}, lower panel) over the longitude belt 75°E to 80°E. The bars indicate the standard deviations for individual months
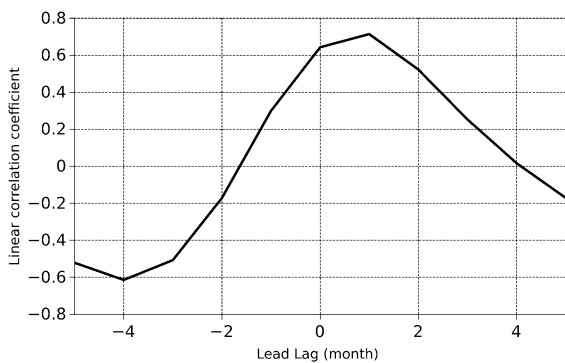

Figure 5
Lead–lag linear correlation of monthly rainfall with the monthly soil moisture in the central Indian regions. In the X-axis, the negative (positive) values refer that soil moisture lead (lags) rainfall
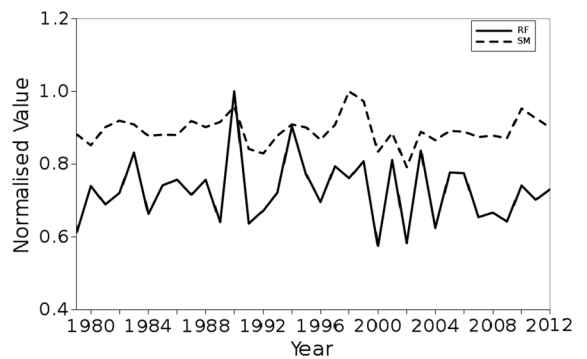

Figure 6
Year-to-year variability of rainfall and soil moisture over central Indian region, both are normalized against their unity. The solid line and dashed lines represent rainfall and soil moisture, respectively
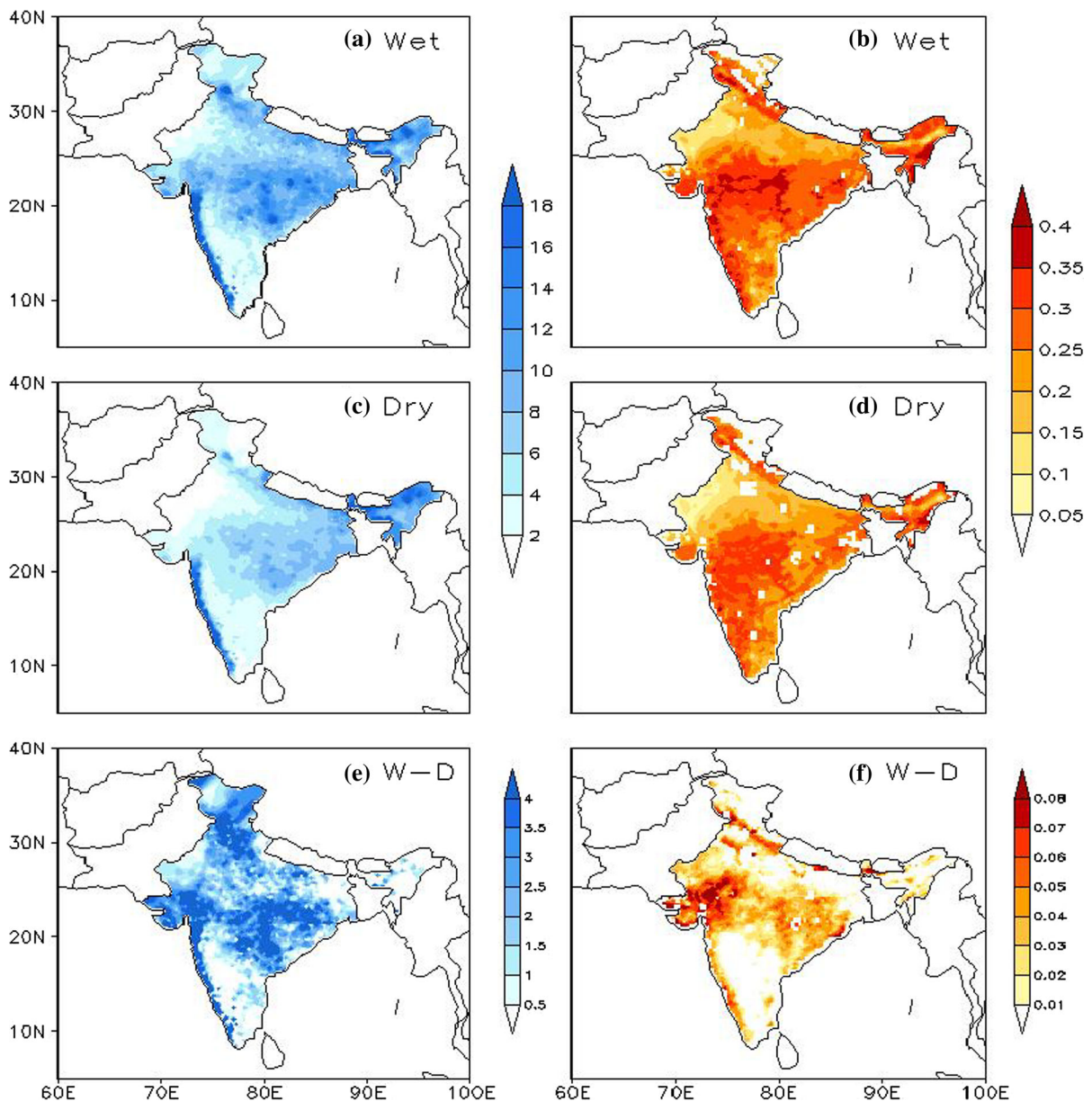
Figure 7

Composite analysis of (**a**, **c**) rainfall (mm day^{-1}) and (**b**, **d**) soil moisture (m^3 m^{-3}) during (**a**, **b**) wet years (1988 and 1994) and (**c**, **d**) dry years (1979, 1982, 1986, 1987, 2002, 2004 and 2009) during the southwest monsoon season. The last panels of the figure show the difference between the wet and dry years of (**e**) rainfall and (**f**) soil moisture

finding of Douville (2002) and Meehl (1994). The information of lead–lag on soil moisture in monthly scale is required for farmers to sustenance of the crop and succeeding crop yields (Shrivastava et al. 2017). The interannual variability of soil moisture concurrently follows rainfall variability and, therefore, it can

be concluded that the soil moisture is more governed by the rainfall of the same year, even though it does not match with the extreme events. During the extreme years of rainfall, we found that soil holds more water during flood years and less water during

drought years. The excess soil moisture is observed in the regions where the rainfall is high.

Acknowledgements

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