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Impact of Soil Moisture Initialization in the Simulation of Indian Summer Monsoon using RegCM4

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Abstract: Soil moisture is one of the key components of the land surface processes and a potential source of atmospheric predictability that has received less attention in the regional scale studies. In this study, an attempt was made to investigate the impact of soil moisture on Indian Summer Monsoon simulation using a regional model. We conducted seasonal simulations using Regional Climate Model (RegCM4) for two different years viz., 2002 (deficit) and 2011 (normal). The model was forced to initialize with the high--resolution satellite--derived soil moisture data obtained from the Climate Change Initiative (CCI) of the European Space Agency (ESA) by replacing the default static soil moisture. Simulated results were validated against high-resolution surface temperature and rainfall analysis datasets from India Meteorology Department (IMD) data.). Careful examination revealed that there was significant advancement in the RegCM4 simulation while initialized with the soil moisture from ESA-CCI despite of having regional biases. Whilst inIn general, the model exhibited slightly higher soil moisture than observation, RegCM4 with ESA setup showed lower soil moisture than that of with default one. Model skill was relatively better in capturing surface temperature distribution when initialized with high--resolution soil moisture. Rainfall biases over India as well asand homogeneous regions were significantly improved with the use of ESA-CCI soil moisture. Several statistical measures such as temporal correlation, standard deviation and, equitable threat score (ETS)), etc. were also employed for the assessment. ETS values were found better in 2011 and higher in the simulation with the ESA setup. However, RegCM4 still couldn't able to enhance its skill in simulating temporal variation of rainfall adequately. Although initializationinitializing with the soil moisture from the satellite performed relatively better in normal monsoon year (2011) but had limitationlimitations in simulating different epochs of monsoon in an extreme year (2002). Thus, the study concluded that the simulation of the Indian Summer Monsoon was improved by using RegCM4 initialized with high--resolution satellite soil moisture although having limitationlimitations in predicting temporal variability. OverallThe study suggests that soil moisture initialization has critical impact on the accurate prediction of atmospheric circulation process and convective rainfall activity.

Keywords: Indian Summer MonsoonConvective rainfall, land surface model, soil moisture initializationmixed convection scheme, regional climate model, satellite-derived soil moisture.

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1. Introduction

The strong impact of land surface processes is well recognized in modulating the weather and climate system in subseasonal to seasonal and even longer time scale. Land surface acts as an interface between the biosphere and the overlying atmosphere. It interacts with the atmosphere through the exchange of mass, momentum, energy and hence is considered as the lower boundary of the atmosphere at approximately 30% of the earth's surface [1]. It is also well understood that the earth's surface is the reservoir of our main energy resources ~~that comes~~ from the solar radiation. Both short and long wave form of the solar radiation is absorbed by the land surface and reemitted. When releasing the energy through the planetary boundary layer, the earth's surface works like a separator ~~and~~. It redistributes the net incoming radiative energy into various fluxes such as sensible, latent and other ground fluxes. Hence, the energy required ~~for the development~~to develop and ~~sustenance of~~sustain any weather system~~, particularly~~ over landmass, is supplied from the underlying land surface [2-–5]. Therefore, the land-atmosphere interaction plays a vital role in modulating the weather and climate systems ~~both in~~on a regional and global scale [6-–10]. Due to its immense impact, the functions of the land surface have been explored extensively in observation as well as modeling studies across the globe [9–14].

Land surface-atmosphere interaction may be ~~regarded as~~ a positive and/or negative feedback mechanism between the atmosphere and different land surface characteristics such as soil moisture, soil temperature, soil types, vegetation cover, snow cover etc. Each of them is not of similar importance for a weather system over a region. In particular, soil moisture is an important component of the global water budget and hydrology cycle [1, 8, 15]. The function of the soil moisture may be described in two ways. Primarily, rate of evaporation from the land surface is determined by the soil moisture quantity which controls the moisture supply to the atmosphere. Secondly, as mentioned earlier, it mainly partitions the net absorbed solar radiation into fluxes. It is mentioned by Dutta et al. [16] that soil moisture and snow cover are the two leading land surface variables ~~those~~that have a potential impact on the variation of weather system if the effect of sea surface temperature is excluded.

Climate downscaling using a Regional Climate Model (RCM) is well accepted and widely used ~~since past several decades~~ for the simulation of various weather and climate systems~~.~~ for the past several decades. It is demonstrated in numerous earlier ~~literatures~~works of literature [17–22] that the RCMs show better competence in simulating climatic features due to better representation of the sub-grid scale physical process and topography ~~compared to~~than the Global Circulation Model. Land surface processes mostly occur at a subgrid-‐scale but ~~plays very~~play an important role in controlling the weather systems [6–7, 23]. Through evaporation, the exchange of heat and moisture fluxes from the land surface to the atmosphere ~~particularly~~ helps ~~to~~ form convection and precipitation. Proper representation of soil moisture is therefore extremely crucial for the numerical weather forecast as well as climate simulations on seasonal, annual and decadal scale using fully coupled RCMs. In each state-of-the-art RCM, physical parameterization of the land surface is taken care of through different Land Surface Model (LSM henceforth). Soil moisture initialization technique is different in different LSMs. However, ~~provision of~~providing an accurate state of the soil parameters has a serious impact on ~~the evaluation of~~evaluating the weather and climate ~~models~~modes which are associated with the retrospective research-‐based on the terrestrial hydrology cycle. Therefore, better simulation of atmospheric processes can be achieved through initializing the climate models with realistic observational/reanalysis soil moisture datasets.

Several ~~researches~~kinds of research have already been carried out to emphasize the impact of land surface model initialization with realistic soil moisture datasets [6–7, 24–32]. Fennessy and Shukla [24] studied the importance of initial soil wetness in seasonal prediction with dynamical models ~~and~~. They concluded that the effect of initial soil wetness is local and greatest in the near-‐surface fields, viz. evaporation, surface temperature and precipitation. Douville and Chauvin [25] used a land surface scheme that was forced with meteorological observation and analysis using relaxation technique and inferred that the relaxation ~~has positive impact on~~positively impacts both model climatology and variability at an interannual scale. Kanamitsu et al. [27] showed that the predictive skill of the initial soil moisture is higher in arid/semi-arid regions and ~~have~~has a sound impact on surface temperature simulation. Douville [28] investigated the effect of soil moisture on climate variability and potential predictability and highlighted ~~about~~ its strong contribution to ~~the~~ climate variability.

Moufouma-Okia and Rowell [2] investigated the sensitivity of soil moisture initialization on West African Monsoon by using a RCM and revealed that specification of initial soil moisture is little sensitive to the West African Monsoon rainfall. Douville [3] highlighted the significant impact of soil moisture on regional climate and suggested further comprehensive and systematic investigation ~~of it~~. Bisselink et al. [4] performed a similar study by initializing a RCM with satellite derived soil moisture and showed ~~that the~~more impact ~~is more~~ during dry years. Suarez et al. [7] performed numerical experiment for three synoptic events using two different mesoscale models with varying soil moisture. They illustrated that the rainfall is ~~increased (decreased~~increases (decreases) with ~~the use of~~ enhanced (reduced) soil moisture respectively. These studies ~~clearly~~ indicate that the soil moisture ~~has significant effect on~~significantly affects the weather and climate simulation, but varies from region to region. However, no studies have yet been discussed in this context over the Indian region.

Among the various RCMs available, the regional climate modeling system which is commonly abbreviated as RegCM of International Center for Theoretical Physics (ICTP, Italy) becomes remarkably popular due to its successful application towards numerous scientific studies [15, 17~~-~~–22, 30, 35~~-~~–37] and many studies have tested its performance over Indian regions [17~~-~~–22, 37]. In the context of soil moisture, RegCM is also used over various regions [30~~-~~–31, 38]. Hu et al. [38] argued that the treatment of soil moisture should pay more attention while performing an experiment on ~~the~~ soil moisture data assimilation ~~of soil moisture~~ using RegCM over China. Patarcic and Brankovic [30] investigated the skill of surface temperature seasonal forecast over Europe using RegCM by initializing it with three different types of soil moisture condition during summer and winter time. Their study showed that the systematic error was reduced and deterministic skill was improved during summer using realistic soil moisture. Liu et al. [31] evaluated the impact of soil moisture using RegCM simulation ~~and~~. They showed that initialization with wet (dry) soil moisture anomalies increased (reduced) the subsequent precipitation amount and reduced (increased) surface temperature. Due to sparse observation networks, the availability of accurate soil moisture data (observation and/or reanalysis) in the past was very rare. ~~Now-a-days~~Nowadays different organizations offer accessibility of satellite- derived as well as reanalysis soil moisture datasets. Climate Change Initiative (CCI) of the European Space Agency (ESA) is one such piece of data ~~that was~~ publicly released in 2015. This dataset has been successfully applied in some ~~of the~~ observational [39] and modeling studies [40] over the other regions across the globe. However, it is not extensively explored over Indian regions. Although ~~there are~~ few observational studies over India are available in the literature [8, 10, 11], it is not comprehensively used in the modeling studies. This study mainly deals with the soil moisture initialization over India to understand their role on the seasonal simulation (May-September) of the Indian Summer Monsoon (ISM) ~~by~~ using RegCM. To our knowledge, our attempt to investigate the impact of soil moisture on ISM using a regional model is the first time over India. The rest ~~part~~ of the paper is structured as the following: brief model information, experimental design ~~and~~, descriptions of the various datasets and validation strategy are discussed ~~dif-~~

ferent subsection ofin section 2. Results and discussion isare described in section 3 followed by Summary and concluding remarksdiscussion, conclusion, limitation and future scope in section 4, 5, 6 respectively.

2. Materials and Methods

2.1. Model description

In the present study, RegCM version 4.4.5 (RegCM4 henceforth) is employed. It is a compressible, hydrostatic, terrain-following, finite difference, limited area model havingwith a similar dynamical core to that of its previous version (RegCM3 [41]). The model offers a variety of parameterization schemes to represent different physical processes. Cumulus convection is represented using five major schemes such as Kuo [42], Grell [43], MIT [44], Tiedke [45] and Kain-Fritsch [46]. Due to variation in performance, RegCM4 shows flexibility of using different schemes separately over land and ocean, referred to as "mixed" schemeschemes. Land surface processes are represented using two LSMs namely, the BATS scheme [47] as well as CLM (version 3.5 [48]; version 4.5 [49]). Radiative transfer package from the global model CCM3 [50], planetary boundary layer from Holtslag [51] as well as University of Washington [52] are also available in RegCM4. DetailedA detailed description of other available physics schemes viz., ocean fluxes parameterization schemes, interactive aerosol schemes and interactive lake models are described in Giorgi et al. [15].

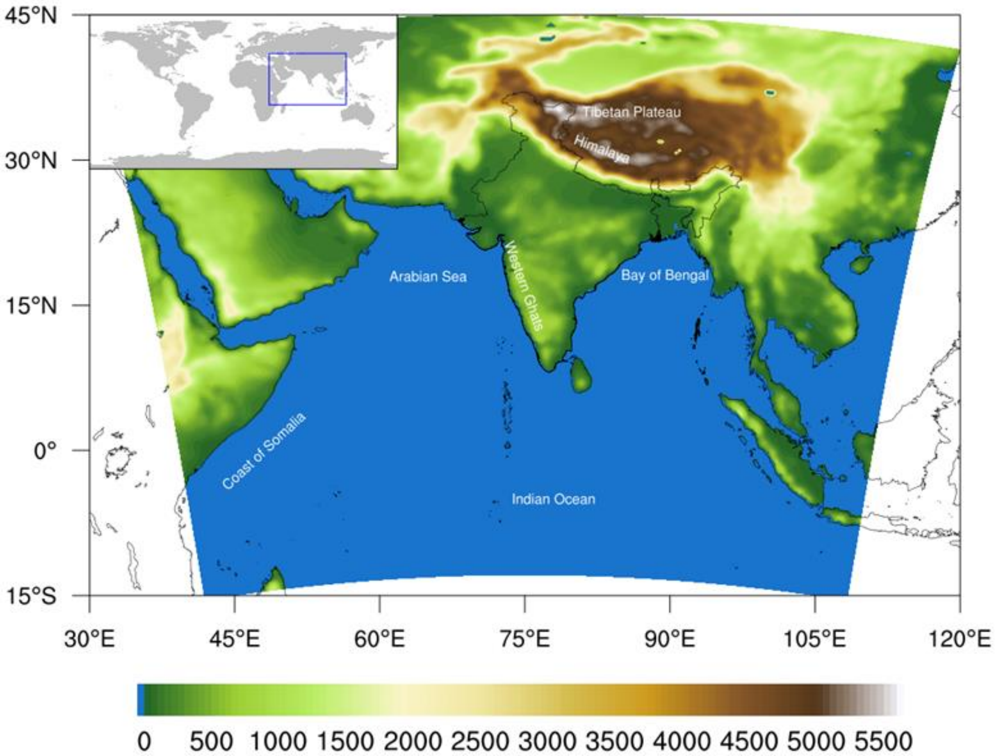


Figure 1:. Map of the simulation domain used in the study. The domain encompasses 30°E––120°E, 15°S––45°N overin Lambert Conformal map projection. Different color shades specify the topographical height above sea level (in meters).

In this study, we focused on the soil moisture initialization in the seasonal simulation of ISM using RegCM4. Two LSMs differ with their formulation in various aspects. One of the major disparities is in the description of the soil moisture column. BATS is composed of three soil moisture layers with varying depth from 10 cm to 3 m [35]. On the other hand, the CLM soil column consists of 10 unevenly distributed soil layers at 1.8 cm, 2.8 cm, 4.6 cm, 7.5 cm, 12.4 cm, 20.4 cm, 33.6 cm, 55.4 cm, 91.3 cm and 113.7 cm depth, for a total depth of 3.4m [53]. In the earlier version of RegCM, soil moisture was initialized using static soil water content relative to saturation as a function of land cover type [54]. Patarcic and Brankovic [30] suggested that this technique is ~~rather~~ a crude way of defining the initial soil moisture which includes neither seasonal nor interannual variation~~ and due~~. Due to that, the model took a higher spin-up time to get stable, particularly for deeper soil layers. Considering this, RegCM4 offers the option to be initialized using climatological soil moisture both in CLM and BATS [29, 55] along with the default static soil moisture. After getting initialized from the soil moisture climatology, RegCM4 evolves independently with its own internal water balance equation [30], which would reduce sudden shock to the model at the initial time step and consequently decreases the spin-~~-~~up time at the deeper soil layer of the model [29, 53].

2.2. Experimental design

Seasonal simulation (1 May, 00UTC~~—~~–30 September, 18UTC) of ISM is conducted using RegCM4 for two different years viz., 2002 and 2011 encompassing the geographical area encompassing 30°E~~-~~–120°E, 15°S~~-~~–45°N (Figure 1) at 30 km horizontal resolution. ~~Based on the criteria of~~According to the India Meteorological Department (IMD), India didn't face any excess monsoon year during last few decades subsequent to 1988. ~~India~~However, the country witnessed a severe drought in 2002 with 81% ISM rainfall of its long period average [56]. On the other hand, 2011 was a normal year with 102% ISM rainfall of its long period average. Model configuration setup is provided in Table 1 ~~(as mentioned in Maity~~ [57~~]).~~]. Simulation during May is considered as spin-~~-~~up and excluded from the subsequent analysis.

Table 1~~:~~. Overview of the model considered for this study~~ (Maity [57]).~~.

Contents	Description
Model domain	South Asia (30°E - 120°E ; 15°S - 45°N)
Resolution	Horizontal: 30 km, Vertical: 23 terrain following σ levels
~~Map projection~~Land surface	~~Lambert Conformal~~CLM4.5 [49]
Cumulus convection ~~scheme~~	Grell [43] over ocean and MIT [44] over land~~.~~
Cumulus closure ~~scheme~~	Arakawa and Schubert [58]~~–~~
Explicit moisture ~~scheme~~	SUBEX [~~60~~59]
Ocean flux	Zeng [60]

By default, RegCM4 gets initialized from the static soil moisture data through the BATS lookup table. In this study, the model is forced to get started with high-resolution satellite-derived soil moisture data [61–62] from the Climate Change Initiative (CCI) of the European Space Agency (ESA) [referred as ESA-CCI (http://www.esa-soilmoisture-cci.org)]. Detailed information of this dataset is given in the following subsection.

2.3. Data

The model was forced with six-hourly ERA-Interim reanalysis (EIN75 [63] hereafter) data at 0.75°× 0.75° resolution. Topography and land use were obtained from United States Geological Survey and Global Land Cover Characterization [64] global data at 10 minutes resolution. The sea surface temperature from optimum interpolation weekly mean sea surface temperature [65] was fed to the model at 1° × 1° resolution from National Oceanic and Atmospheric Administration. Additional datasets including land cover, soil texture, soil colour, leaf area index, plant functional type, emission factors, snow data etc. required for CLM4.5 [49] were obtained from the RegCM data portal (http://clima-dods.ictp.it/Data/RegCM_Data/CLM45/). Simulated surface temperature and rainfall were validated against high~~-resolution surface temperature (1°x1°; [66]) and rainfall (0.25°x0.25°; [67]) analysis data from IMD~~-resolution surface temperature and rainfall analysis data from IMD. The temperature data was constructed by IMD based on 395 station observatories data at 1°x1° spatial resolution [66] covering the land region of India (6.5°N–38.5°N, 66.5°E–100°E). Similarly, the rainfall data was prepared by IMD by considering the daily rainfall measurements from 6955 rain gauge stations at 0.25°x0.25° spatial grid [67]. These datasets are the finest observation data from IMD so far which uses highest number of station observations and are successfully utilized in various observation/modeling studies.

RegCM4 was initialized here with ESA-CCI soil moisture datasets (version 02.2). This dataset is a multi-decadal satellite-derived soil moisture product with high spatial resolution at 0.25°x0.25°. The primary data is accumulated through various spaceborne microwave scatterometers such as ERS-1/2 (SCAT) and METOP-A (ASCAT) as well as microwave radiometers viz., SMMR, SSM/I, TMI, AMSR-E, WindSat, AMSR2. The detailed information about the different satellite sensors and their specification ~~are~~is mentioned in Dorigo et al. [61–62]. ESA provides three types of soil moisture products viz., active only, passive only and combined datasets based on these gathered data. Active only data is made by merging all the data from the scatterometers while the passive only product is generated by merging all the data from radiometers. Afterwards these two products are further rescaled to the common platform of Global Land Data Assimilation System version-1 and merged ~~for the preparation of~~to prepare the combined soil moisture data [68]. Complete procedural technique and further details about this data preparation may be obtained from the literature cited above and the references therein. The datasets are available in the volumetric unit (~~m^3m^{-3}~~ m^3m^{-3}) at daily scale during 1979–2014. ~~Soil~~The soil depth of the data varies in the range of 0.5 cm–2 cm. For this study, we used the ESA-CCI combined soil moisture data only. The ESA-CCI dataset are the calibrated data prepared with in-situ observation from International Soil Moisture Network (ISMN; [62]). At present, ISMN data consists of 6100 soil moisture datasets from 1400 measurement stations operated by 40 different networks [62]. ISMN holds data globally having 10 station data in India. Validation is carried out for 28 data networks all over the globe. Detailed validation strategy including precise information about the measurement stations is mentioned in Dorigo et al. [62].

~~**3. Results**~~

2.4. Validation strategy

Model performance was assessed in terms of the spatiotemporal distribution of surface temperature, soil moisture and rainfall considering all India (AI henceforth) as well as its five homogeneous regions viz., North west India, West central India, Central and north east India, South peninsular India and North east India (NWI, WCI, CNEI, SPI, NEI henceforth) [69]. The simulation forced with a default lookup table (ESA-CCI) soil moisture will be referred to as default (ESA) hereafter. The validation includes some of the basic inferential statistics such as mean, standard deviation (SD) and correlation. ~~Furthermore~~In order to further estimate the model skill in predicting the rainfall, Equitable Threat Score (ETS) ~~[70] were calculated for different rainfall categories and~~was computed. ETS is a skill measure generally used for dichotomous (yes/no) forecasting events [70, 71]. Mathematically, ETS is defined as follows:~~in the assessment.~~

$$ETS = \frac{H - H_{rand}}{H + M + F - H_{rand}}$$

Where

$$H_{rand} = \frac{(H + M)(H + F)}{T}$$

H, M, F stands for no. of hits, misses and false alarms while T and H_{rand} refer to the total events and hits due to random chances respectively. These values are calculated based on a 2x2 contingency table. ETS measures the fraction of perfectly forecast points, corrected using hits due to random chance. It varies in the range of $-\frac{1}{3}$ to 1 with $ETS \le 0$ indicating no skill and $ETS = 1$ indicating perfect skill.

3. Results

3.1. Surface Temperature

The analysis was started with the discussion about the model simulated surface temperature and its validation with the IMD observation. Results from 2002 (2011) are given in Figure 2 (Figure 3). ~~First~~The first two columns represent bias with default and ESA configuration with their difference in the last column. First four rows (a–c, d–f, g–i, j–l) correspond to June, July, August and September while the last row (m–o) stands for seasonal (June-July-August-September; JJAS hereafter) mean. It ~~clearly~~ indicates that RegCM4 showed consistent cold bias over peninsular India, irrespective of the years and attain maxima in July, 2002 (Figure 2) and June, 2011~~.~~ (Figure 3). Contrastingly from the JJAS mean, it was noticed that the model exhibited cold (warm) bias during 2002 (2011) over north India. In the monthly distribution, RegCM4 experienced warm bias in August, September during 2002 while in July, August, and September during 2011.

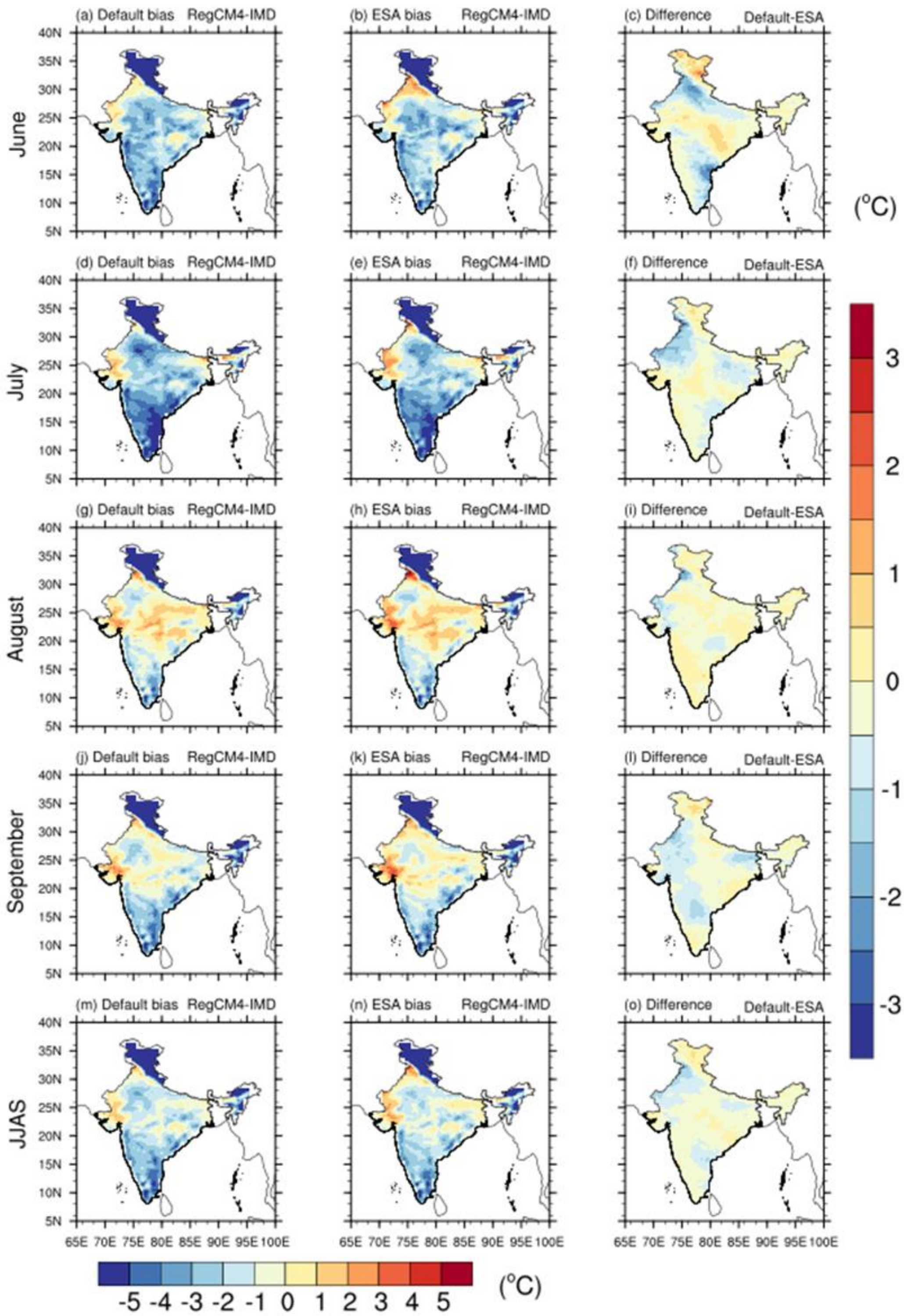
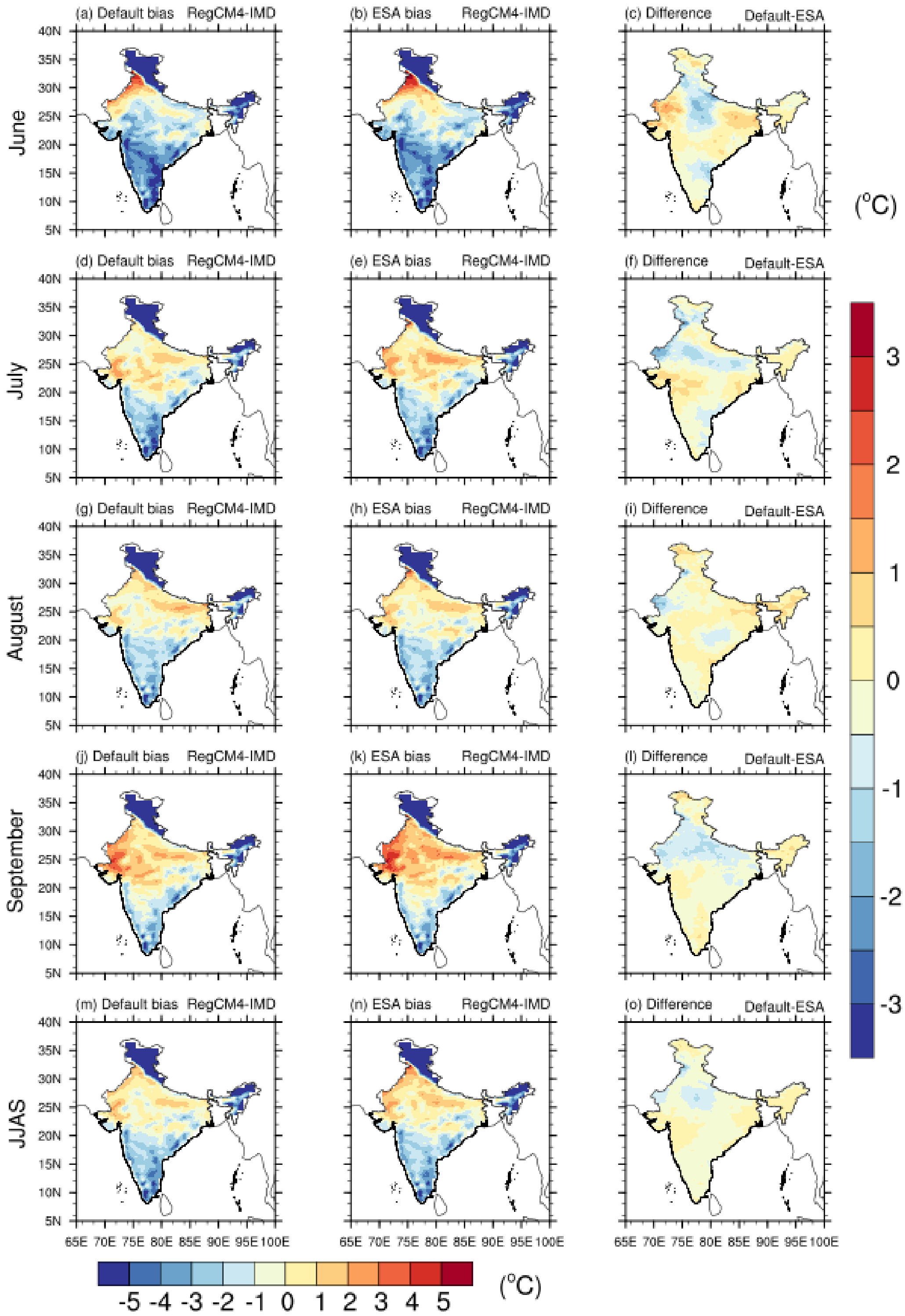


Figure 2. Surface temperature bias (°C) at monthly and seasonal scales during 2002 from both the model configuration. IMD analysis is considered as ground truth. Rows correspond to June, July, August, September and JJAS mean respectively. The column represents default and ESA setup alongwith their difference in third column.

~~*IMD analysis is considered as ground truth. Rows correspond to June, July, August, September and JJAS mean respectively.* Column represents default and ESA setup alongwith their difference in third column.~~



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300 **Figure 3.** Same as Figure 2 but for 2011.

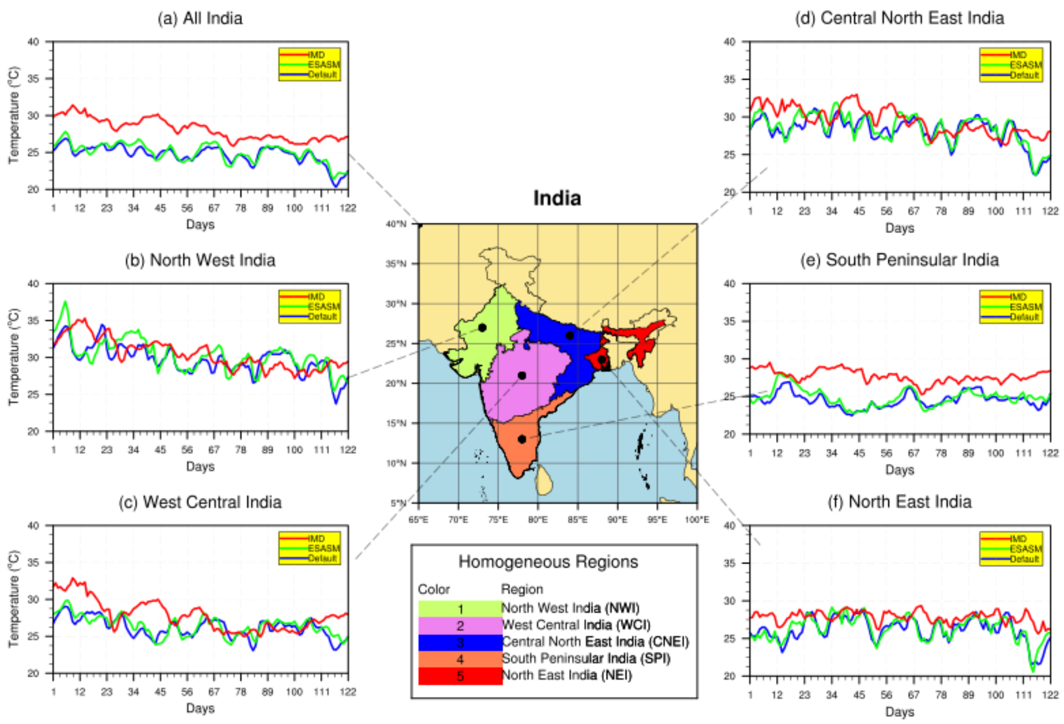

Figure 4. Daily variation of surface temperature (°C) over India and five homogeneous regions [69] from the two different setups and IMD analysis during 2002.

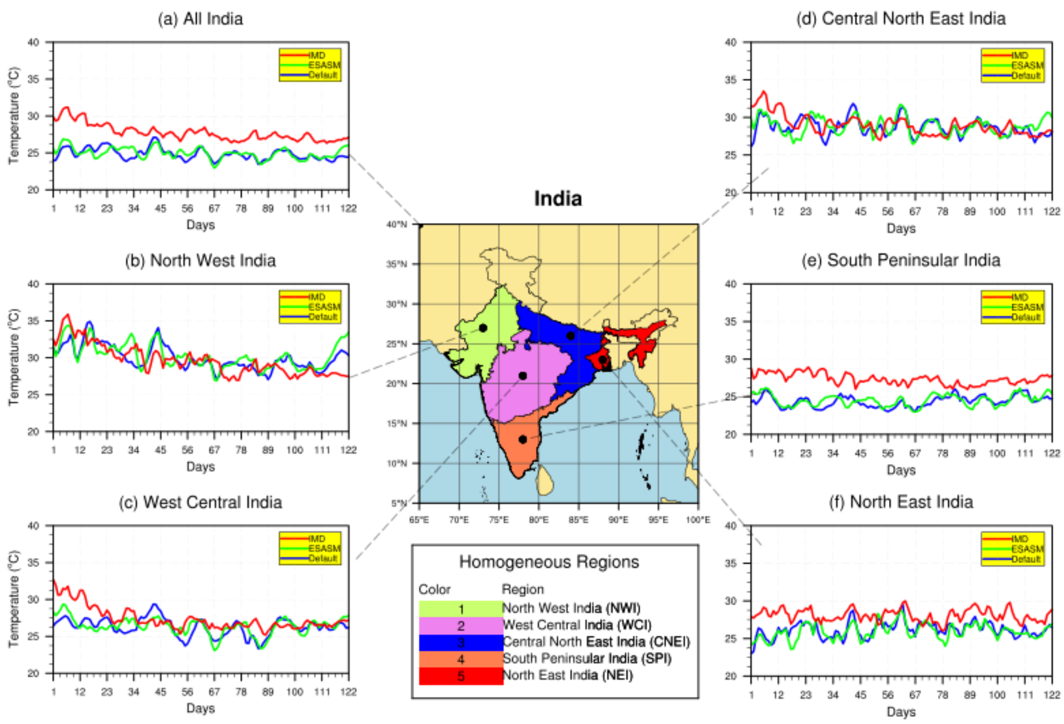

Figure 5. Same as Figure 4 but for 2011.

The simulated surface temperature was noticed to be more close to IMD data while initialized with ESA soil moisture. It ~~clearly~~ indicates that the model was sensible to the soil moisture initialization process and outperformed after getting initialized with real-~~-~~time soil moisture data by reducing existing cold bias in the default soil moisture combination. Eventhough, the present model bias (cold/warm) might be associated with the simulation of rainfall by the model. We have discussed ~~about~~ it in the later subsections, particularly the model inefficiency in predicting various epochs of rainfall (during initial months of ISM) which might have possible consequences in obtaining different surface temperature biases.

A discussion~~*Discussion*~~ was further extended by analyzing the daily variation of surface temperature. Time series of surface temperature during 2002 and 2011 over AI and its five homogeneous regions are described in ~~Fig.~~Figure 4 and 5 respectively. Irrespective of the regions, temporal variation of surface temperature was slightly better estimated by the model while initialized with the ESA soil moisture except for some evident exceptions. As observed earlier, the model showed consistent cold bias throughout the season in both the years over SPI, NEI as well as AI level. Underestimation was higher over SPI and AI compared to NEI. However, the temporal variation was not well simulated by the model. Model's skill was further investigated through the different temporal statistics. Temporal correlation and standard deviation over AI and five homogeneous regions during 2002 and 2011 are illustrated in Table 2. Except for SPI, the model showed a significant correlation with ~~both~~ the configuration (default and ESA) in both ~~the~~ years. Eventhough ~~there existed~~ minor ~~variation~~variations at the regional scale existed, RegCM4 exhibited slightly better skill at the AI level with ESA configuration. Interestingly, the correlation was consistently highest over NWI in both the configuration and the years, which indicated the daily variation of surface temperature was relatively better simulated over there. ~~It was~~The table also noticed ~~from the table~~ that the spread of surface temperature in ESA simulation was slightly higher in both the years. Overall, it concluded that soil moisture initialization in RegCM4 ~~apparently have~~has a significant impact in simulating surface temperature and subsequently ~~spatio-temporal~~spatiotemporal distribution of surface temperature in individual month ~~as well as~~and season are better predicted by the model while initialized with realistic soil moisture from ESA-CCI albeit having few lacunae.

Table 2~~:~~. Temporal statistics of surface temperature (°C) from default, ESA configuration and IMD data over all India and five homogeneous regions [69] during 2002 and 2011. *: significant at 95% and †: not significant at 95%.

	2002					2011				
	Correlation		Standard deviation			Correlation		Standard deviation		
	Default	ESASM	Default	ESASM	IMD	Default	ESASM	Default	ESASM	IMD
NWI	0.52*	0.48*	1.95	2.20	2.03	0.59*	0.54*	1.66	1.72	2.05
WCI	0.34*	0.39*	1.33	1.34	2.09	0.31*	0.50*	1.20	1.16	1.56
CNEI	0.42*	0.43*	1.84	1.94	1.81	0.32*	0.28*	1.33	1.17	1.33
SPI	-0.13†	0.03†	0.98	1.15	0.83	-0.10†	0.04†	0.75	0.78	0.74
NEI	0.46*	0.41*	1.62	1.58	0.78	0.38*	0.39*	1.06	1.06	0.83
INDIA	0.46*	0.49*	1.24	1.28	1.43	0.44*	0.47*	0.77	0.77	1.11

3.2. Soil Moisture

The model simulated seasonally averaged soil moisture from the two combinations (default and ESA) were compared for ~~the years~~ 2002 and 2011 and validated with that from ESA-CCI (Figure 6 and 7). It is worth ~~to mention~~mentioning that RegCM4 provides soil moisture output in two layers viz., upper/surface layer (with depth 10 cm) and root zone layer (with depth 100 cm). In this study, only upper layer soil moisture from ~~both~~ the simulation and observation were considered for the model validation although they differ marginally in depth. While analyzing JJAS mean, it was observed that RegCM4 simulated the soil moisture reasonably well using both the setup. ~~Soil~~In both simulation and observation, soil moisture was found to vary in the range of 0.1~~—~~–0.4 m^3m^{-3} over major parts of the Indian landmass ~~in both simulation and observation.~~. However, soil moisture was seen to be higher than that of ESA-CCI data in both ~~the~~ combinations. For example, soil moisture over central India and the adjoining region was largely distributed in the range of 0.3~~–~~–0.4 m^3m^{-3} in the model simulation, while ~~that in~~ ESA-CCI was found within 0.2~~–~~–0.3 m^3m^{-3}. Similarly, over western India and neighboring area, the magnitude of simulated soil moisture was found in the range of 0.1~~–~~–0.3 m^3m^{-3} but the same varied within 0.1~~–~~–0.2 m^3m^{-3} or even less in ESA-CCI. This disagreement was significantly noticed in 2002 (deficit year) compared to 2011 (normal year). As described earlier, the top soil layer in the model was deeper than that of ESA-CCI~~, therefore~~. Therefore, higher soil moisture in the model simulation may be attributed ~~by~~to this disparity in soil depth. Interestingly, soil moisture from the ESA setup was found more realistic in terms of spatial distribution. Soil moisture with default setup was considerably higher than ~~that of~~ using ESA data in both ~~the~~ years and it was very prominent over the central India and adjoining ~~region~~regions. Hence, it can be concluded that RegCM4 was sensible to the soil moisture initialization technique. Moreover, while initialized with ESA-CCI data, the model improved the soil moisture distribution by reducing the non-realistic bias from the default setup.

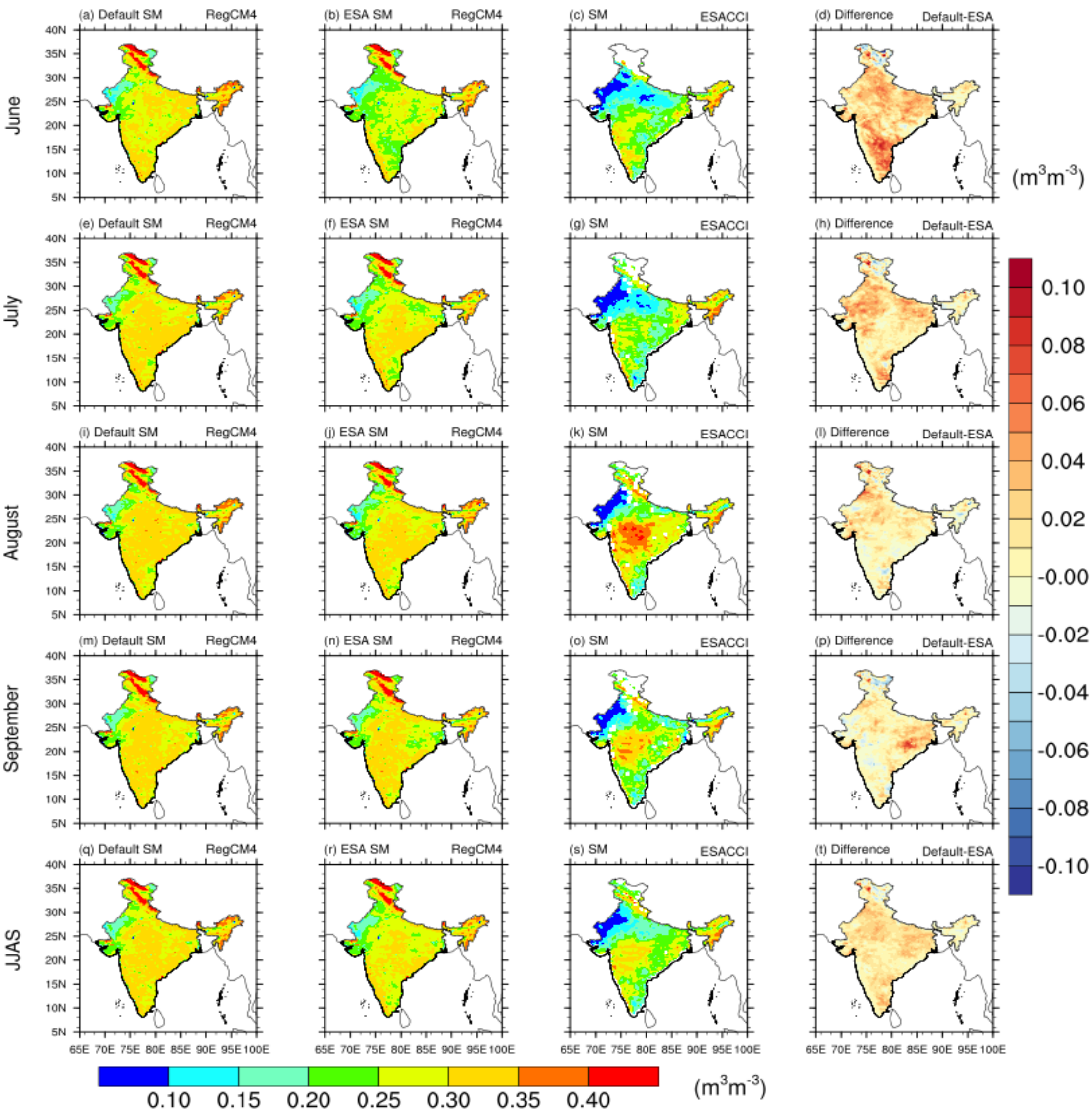

Figure 6~~:~~. Simulated soil moisture (m^3m^{-3}) at monthly and seasonal scale during 2002 from the two model setup (default and ESA), corresponding ESA-CCI data and the difference from the two model setup (arranged in a column). Rows represent June, July, August, September and JJAS mean respectively.

The analysis was further extended by analyzing monthly soil moisture (June, July, August and September). As observed seasonally, simulated soil moisture was distinctly higher than that of ESA-CCI data ~~in~~on a monthly scale as well. It was noticed that ESA-CCI soil moisture was lower in ~~the month of~~ June and it gradually improved in the month of July, August and September. ~~Highest~~The highest amount of soil moisture was noticed during August in both the years. Comparing both the simulation, RegCM4 with default setup overestimated the soil moisture in each of the months~~ and consequently~~. Consequently, soil moisture from ESA configuration was more realistic and hence closed to ESA-CCI. These differences were strongly visible from their difference indicated in the last column of ~~the figures~~Figure 6 and 7 which was noticed highest in June and lowest in August. Hence, based on the above analysis it is concluded that RegCM4 was extremely ~~sensible~~sensitive to the soil moisture initialization~~ and therefore~~. Therefore, RegCM4 using ESA setup showed reasonable enhancement on soil moisture simulation.

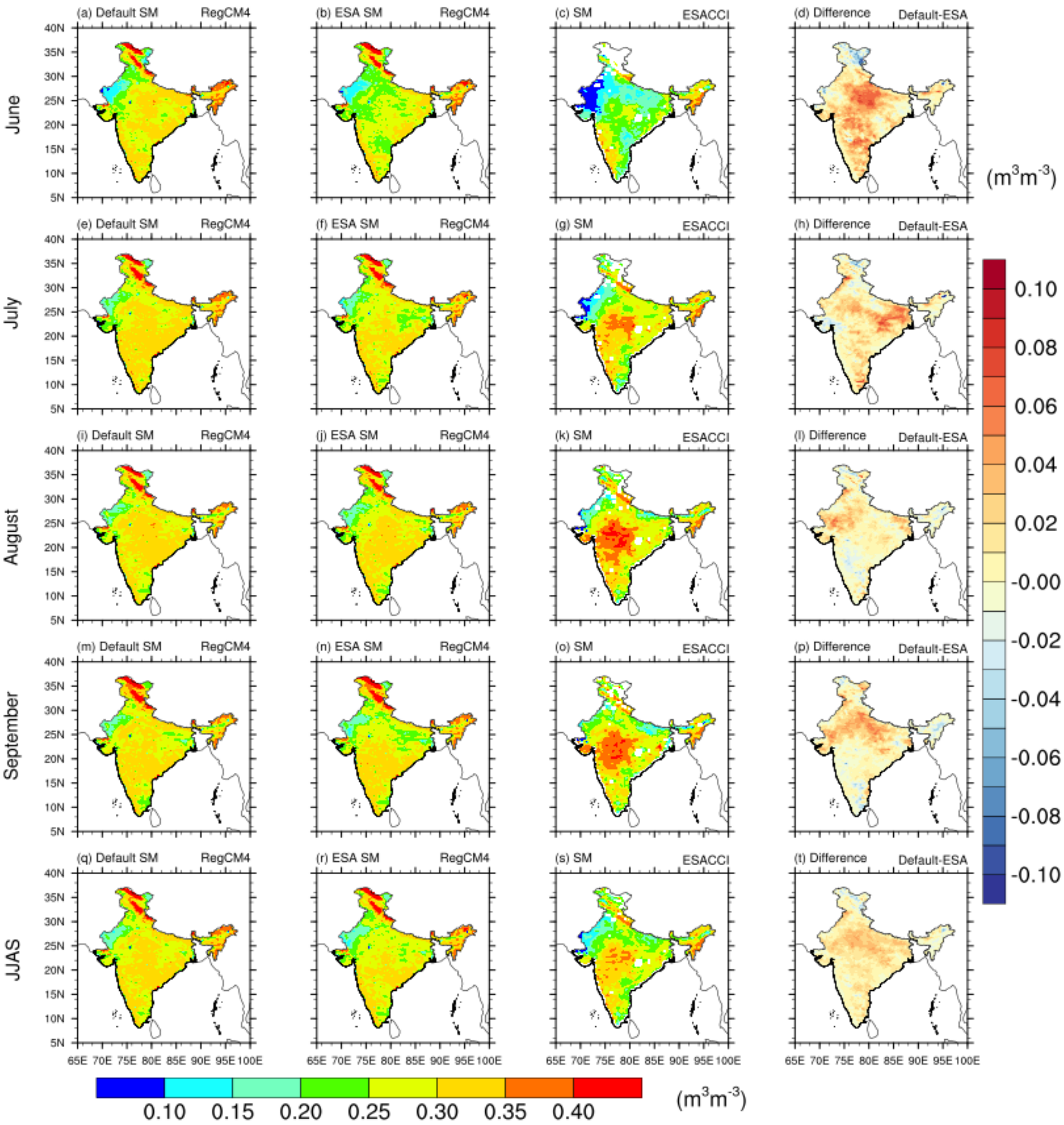

Figure 7~~:~~. Same as ~~figure~~Figure 6 but for 2011.

3.3. Rainfall

In order to investigate the impact of soil moisture initialization on rainfall, model simulated rainfall was analyzed in different ~~spatio-temporal~~spatiotemporal scale. Daily, monthly and seasonal rainfalls from the model simulation were compared with ~~those of from~~ IMD over AI and five homogeneous regions (mentioned earlier). The monthly and seasonal rainfall ($mmday^{-1}$) distribution from the two model combinations during 2002 and 2011 is illustrated in ~~Fig.~~Figure 8 and 9 respectively in terms of bias and individual difference. From the JJAS mean (last row of the figures), the model depicted wet bias over western and peninsular India and dry bias over NEI including Gangetic West Bengal and west coast. Wet bias was higher in 2002 (deficit) while the dry bias was stronger in 2011 (normal). Central India predominantly experienced wet bias in 2002 and dry bias in 2011. These disparities in biases might be related to the model's skill in accurately predicting intraseasonal variation of rainfall (discussed later).

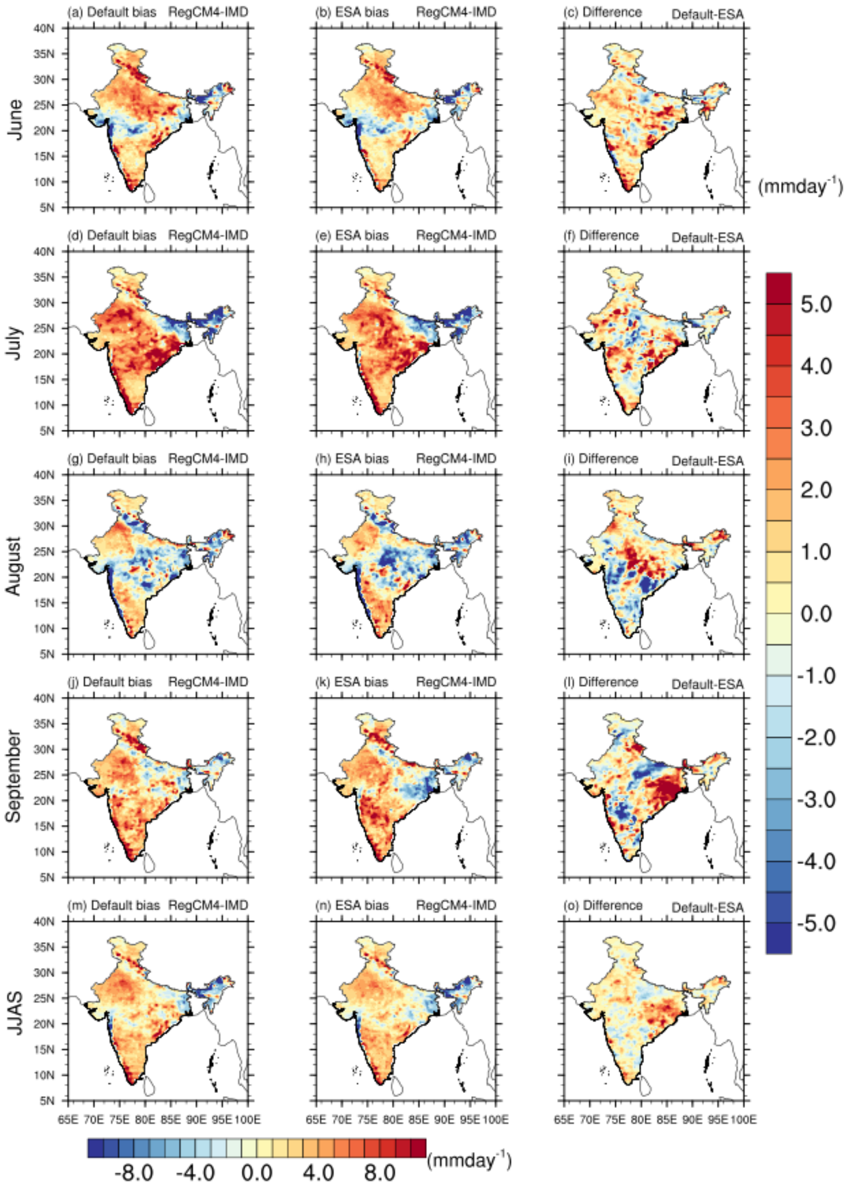

Figure 8~~:~~. Same as ~~Fig.~~Figure 2 but for rainfall ~~().~~($mmday^{-1}$).

~~Model~~The model simulated monthly rainfall (June, July, August and September) during 2002, 2011 were also analyzed (Figure 8 and Figure 9) as a part of the validation. During June, July and September of 2002, the model showed wet bias over the major part of the Indian landmass except for NEI and Gangetic West Bengal where dry bias was noticed. Both the biases were found highest in July. ~~In a similar way~~Similarly, dry bias regions remained similarly visible in 2011 while the coverage of wet bias regions were reduced with lower magnitude which, indicating an improvement in model skill. Nevertheless, it is important to mention that RegCM4 with ESA setup reduced the rainfall bias.

Table 3:. Temporal rainfall statistics of rainfall ($mmday^{-1}$) from default, ESA configuration and IMD data over all India and five homogeneous regions [69] during 2002 and 2011. *: significant at 95%; †: not significant at 95%.

	2002					2011				
	Correlation		Standard deviation			Correlation		Standard deviation		
	Default	ESASM	Default	ESASM	IMD	Default	ESASM	Default	ESASM	IMD
NWI	-0.14†	-0.14†	2.62	2.48	3.37	0.27*	0.38*	2.80	2.80	5.56
WCI	-0.14†	-0.12†	2.98	2.81	5.89	0.16†	0.22*	2.63	2.66	4.81
CNEI	-0.06†	-0.03†	3.77	3.29	5.62	0.41*	0.19*	2.83	3.29	5.29
SPI	-0.07†	-0.03†	3.52	3.77	2.24	0.02†	0.03†	3.39	3.69	5.11
NEI	0.40*	0.34*	4.67	4.12	6.41	0.11†	0.17†	3.74	3.43	5.49
INDIA	-0.04†	0.03†	1.77	1.70	2.86	0.51*	0.47*	1.43	1.64	2.99

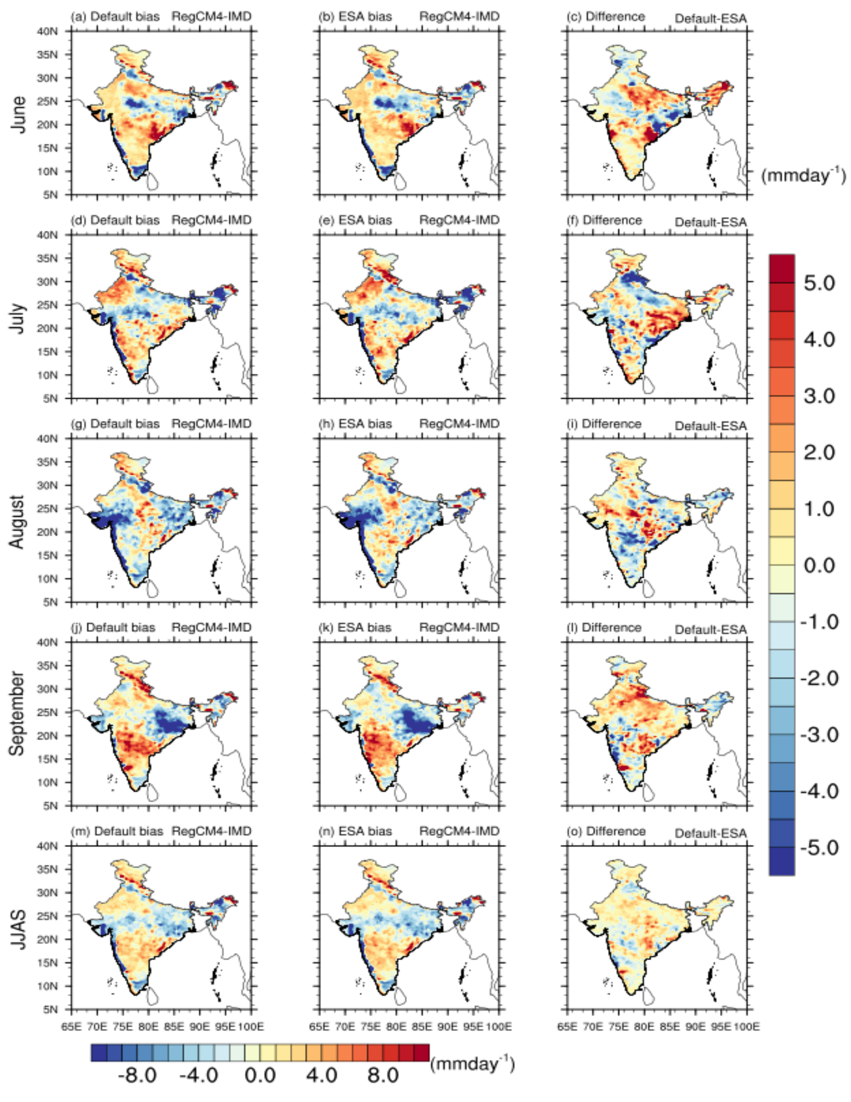

Figure 9:. Same as Fig.Figure 8 but for 2011.

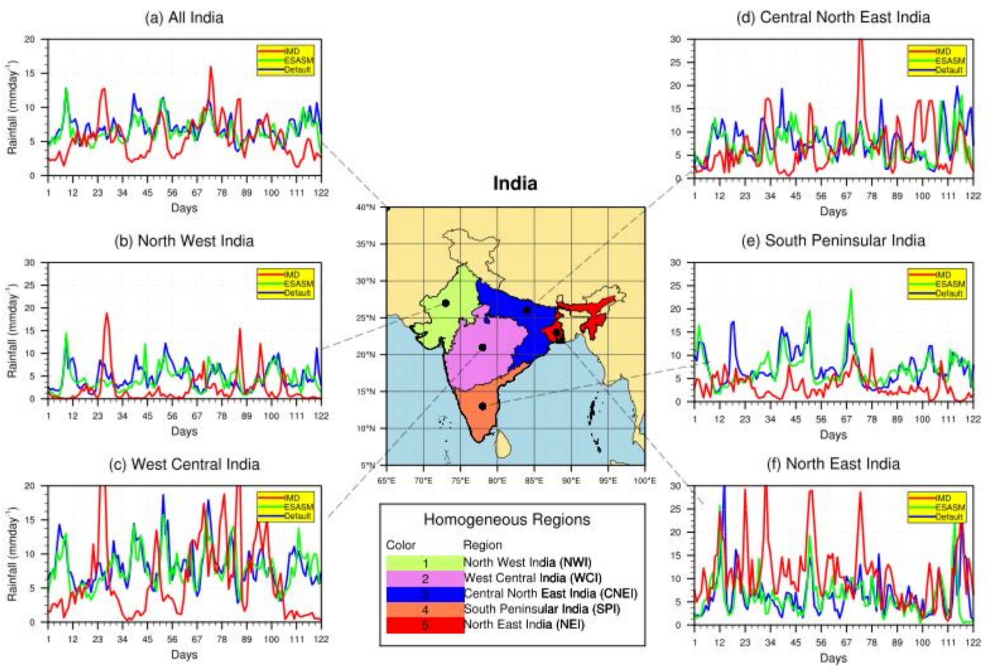

Figure 10~~:~~. Same as ~~Fig.~~Figure 4 but for rainfall ($mmday^{-1}$).

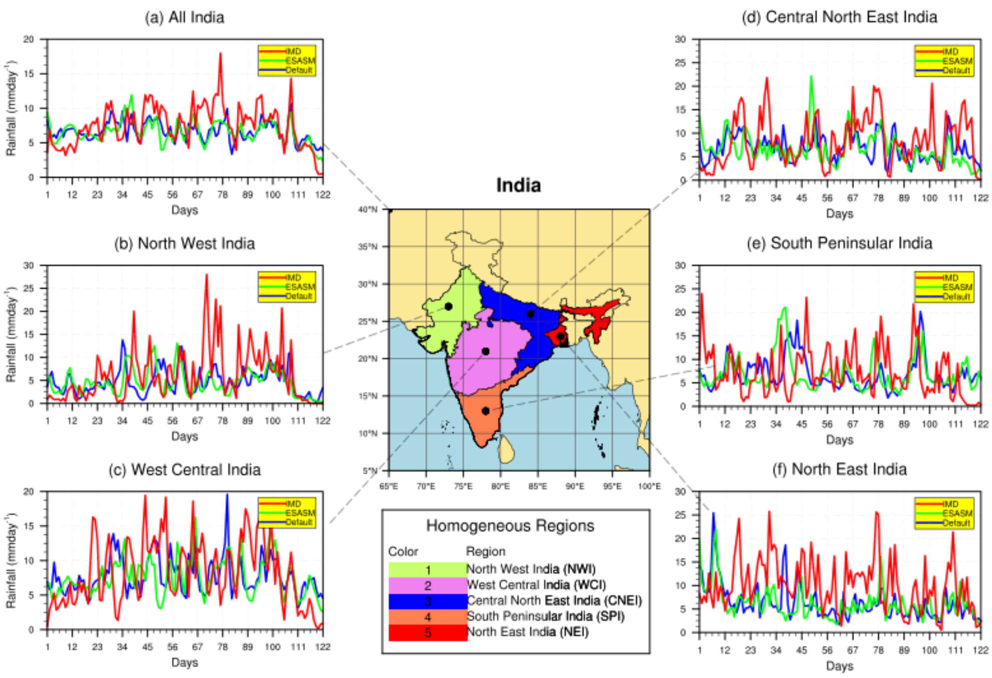

Figure 11~~:~~. Same as ~~Fig.~~Figure 10 but for 2011.

Day to day variation of rainfall is an important aspect of ISM which controls the overall performance of the model throughout the season. Hence, daily rainfall variations from the model simulation in both the years were examined over the whole of India and the other five regions against IMD observation (Figure 10 and Figure 11). The rainfall was significantly overestimated (underestimated) over major Indian land throughout the season in 2002 (2011) by the model except for few extreme epochs. Moreover, the variation within the season was also not reasonably well simulated by the model. During 2002, it was observed that rainfalls were not initiated ~~in~~on the same dates over all the homogeneous domains rather maintained a few days interval.

~~First~~The first rainfall peak was noticed over SPI followed by WCI, NWI, CNEI and NEI. While compared with the same from IMD over the corresponding regions, it was noticed to be pretty earlier by few days in the model simulation. This indicated that the model showed early onset over each of the regions compared to the IMD data. ~~In a similar way~~Similarly, RegCM4 exhibited delayed withdrawals from each of the regions during the end of the season. In contrast to 2002, moderately better performance was perceived during 2011. Even though the model showed a large amplitude of over and underestimation during the peak rainfall months of July and August, it followed the daily rainfall pattern of IMD.

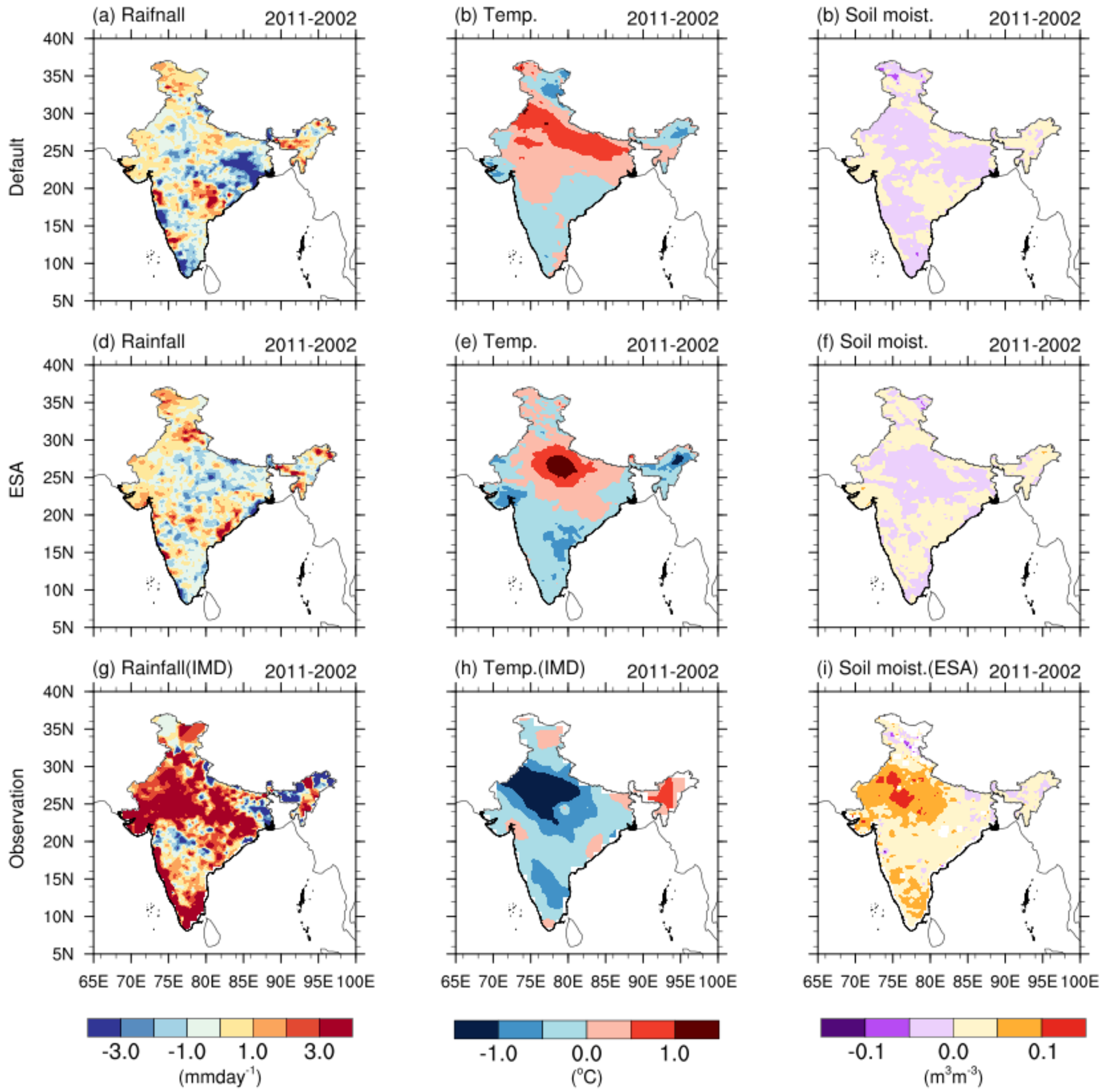

Figure 12~~:~~. JJAS mean difference (2011-2002) of rainfall ($mmday^{-1}$), surface temperature (°C) and soil moisture (m^3m^{-3}) arranged columns. Rows represent results from simulation with default and ESA setup alongwith observation in the third row.

Interestingly, the onset and withdrawal of this year (2011) were also reasonably well simulated by the model. It implies that the model exhibited better skill during normal monsoon year (2011) as compared to extreme year (2002). Temporal statistics (correlation and standard deviation) for the two years are provided in Table 3. It showed a 95% significant correlation during 2011 in both the simulation over major parts of India and therefore, simulation using ESA soil moisture was slightly better in comparison to other. Contrarily, correlations were insignificant and negative over entire India in 2002 which indicated deviation in model skill. However, the standard deviation was significantly less than ~~that of~~ IMD, which inferred limited model performance about the accurate prediction of magnitude.

To investigate the model skill during extreme monsoon years, differences of seasonal average (2011 - 2002) of the three parameters (rainfall, surface temperature and soil moisture) were analyzed (Figure 12). It was noticed that soil moisture and rainfall were relatively higher during 2011 while the surface temperature was lower in 2011 (last row of ~~the figure~~Figure 12). Simulated results are depicted in the 1st and 2nd row using default and ESA setup. It was noticed that the spatial patterns in both the model combinations were not prominent while comparing with observation. Moreover, simulated surface temperature over north India was slightly higher in 2011 ~~which contradicted with~~contradicting the same from the observation. Even though RegCM4 with ESA setup improved the simulation by reducing bias, further enhancement is needed. There was hardly any difference between the two years in soil moisture using both the combinations.

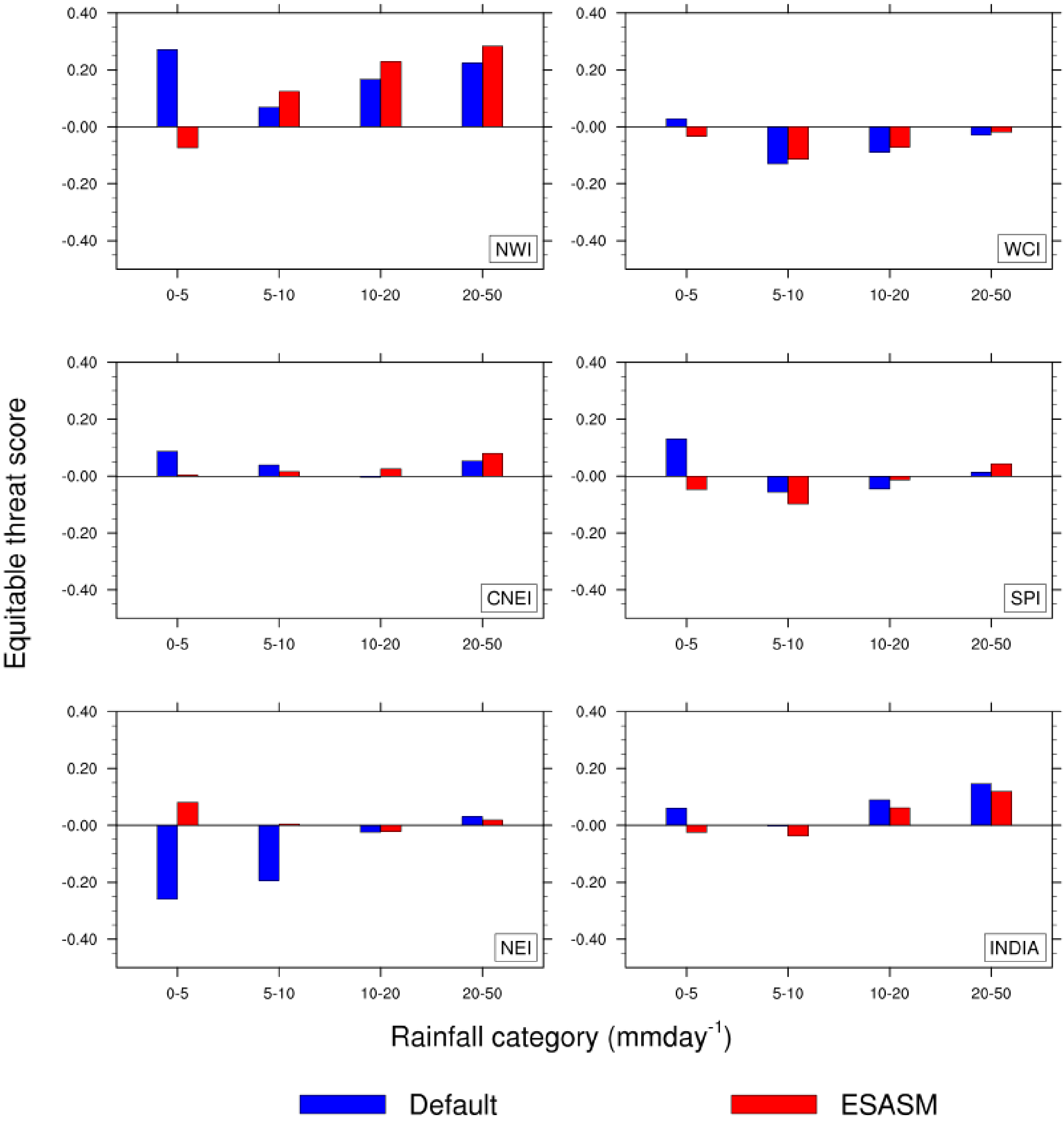

Figure 13. Equitable threat score for different rainfall categories (0 – 5, 5 – 10, 10 – 20 and 20 – 50 $mmday^{-1}$) during 2002 over all India and five homogeneous regions [69].

Surprisingly, the model showed mixed performance in simulating rainfall during two years and therefore the results were not convincing. Hence, based on the above analysis, it is concluded that the contrasting monsoon features were not well captured by the model in comparison to the observations.

3.4. Quantitative evaluation: equitable threat score

In order to further estimate the model skill in predicting the rainfall, ETS was computed. ETS is a skill measure generally used for dichotomous (yes/no) forecasting events [71]. Mathematically, ETS is defined as follows: Where

of hits, misses and false alarms while T and H_{rand} refers to the total events and hits due to random chances respectively. *These values are calculated based on a 2x2 contingency table. ETS measures the fraction of perfectly forecast points, corrected using hits due to random chance.* It varies in the range of $-\frac{1}{3}$ to 1 with $ETS \leq 0$ indicating no skill and $ETS = 1$ indicating perfect skill. In our study, ETS is computed over AI and five homogeneous regions (described earlier) for different rainfall category (0 – 5, 5 – 10, 10 – 20 and 20 – 50 $mmday^{-1}$) during 2002 and 2011 and are illustrated in Fig. 13 and Fig. 14 respectively.

The Higher ETS in 2011 (Figure 14) indicates that the precipitation events at all India level were better estimated by the model in 2011 compared to 2002 (Figure 13 & 14). Magnitude of ETS was relatively higher in ESA simulation for all rainfall categories in 2011 indicating improvement in rainfall simulation using ESA soil moisture.

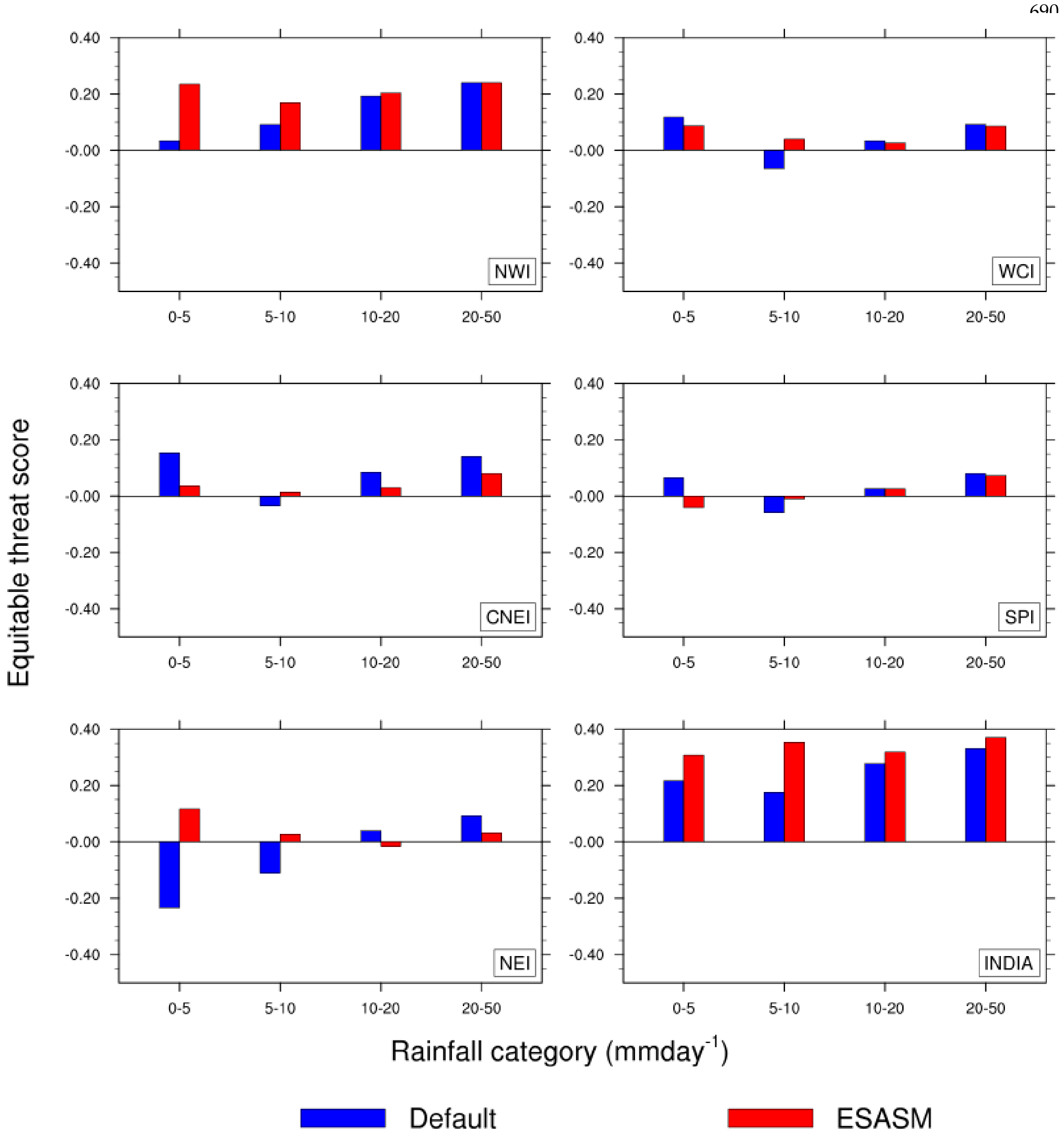

Figure 14. Same as figure 13 but for 2011.

Although, RegCM4 with default setup showed similar skill in higher rainfall category (10 – 20 and 20 – 50 $mmday^{-1}$), its efficiency deviated in low (0 – 5 $mmday^{-1}$) or moderate (5 – 10 $mmday^{-1}$) rainfall cases. At regional scale, highest ETS was noticed over NWI followed by CNEI, WCI, SPI and NEI. In 2011, the model with default configuration showed higher ETS in the low category rainfall over CNEI, WCI and SPI. Moderate rainfall was better estimated using the ESA setup. As observed earlier, ETS values were similar for both the setup in high rainfall cases indicating superior efficiency of the model in predicting high rainfall compared to other categories. During 2002, higher ETS was noticed in higher rainfall cases over NWI followed by AI but failed to estimate other categories. The model was unable to show any skill for other regions. It is noteworthy to mention that RegCM4 consistently showed better skill over NWI in estimating moderate/high rainfall events irrespective of the years. Performance of RegCM4 in 2011 (normal year) was better compared to 2002 (deficit year) and consequently exhibited superior skill in predicting all categories of rainfall while initialized with ESA soil moisture.~~-~~

4. Discussion

~~: Same as figure 13 but for 2011.~~

~~4. Summary and concluding remarks~~

In this study, the impact of soil moisture initialization technique in the model RegCM4 was investigated ~~through the incorporation of~~by incorporating high-~~-~~resolution satellite-~~-~~derived soil moisture data from ESA-CCI. In order to evaluate this aspect, seasonal simulations were conducted during two specific years viz., 2002 (deficit monsoon year) and 2011 (normal monsoon year) with default ~~soil moisture~~as well as modified soil moisture. A comprehensive evaluation was carried out based on the three essential parameters viz., surface temperature, soil moisture and rainfall~~ through the investigation of these~~. These parameters were investigated with their distribution and accuracy at different temporal and spatial ~~scale~~scales.

~~From the~~The surface temperature distribution~~, it was~~ clearly noticed that model skill was relatively better while ~~initialized~~initializing with the soil moisture from the ESA. The magnitude and distribution of the temperature were better predicted by the model ~~in this setup~~ although having warm and cold biases over various regions of the country. In comparison to the default configuration, RegCM4 reduced the surface temperature biases significantly in the ESA setup. Statistical values such as correlation and standard deviation is consistently better using ESA soil moisture. Simulated soil moisture was higher in RegCM4 than ~~that of~~ ESA-CCI, but when initialized using ESA soil moisture, it lowered the magnitude of soil moisture and portrayed better performance. Rainfall validation demonstrated that model showed superior skill while initialized with ESA soil moisture ~~both in~~on a seasonal and monthly scale. However, the model couldn't ~~able to predict~~ accurately predict the temporal variation at daily rainfall. Studies on soil moisture initialization with RegCM over other regions across the globe also highlighted similar skills. Over European region, Patarcic and Brancovic [30] investigated the skill of RegCM3 and found reduction (enhancement) in systematic errors (deterministic skill) of RegCM3 while initialized with high-resolution soil moisture. Over Asia, Liu et al. [31] mentioned that RegCM4 with higher initial soil moisture reduced the surface temperature and consequently increased the rainfall although the impact was more in mid-latitude compared to the tropics. This study also highlighted that temperature (rainfall) response was stronger (weaker) over India. Hu et al. [38] indicated that description of soil moisture with RegCM2 affected the model bias over China. Similar studies with other models (e.g., Weather Research and Forecasting Model) also showed that the skill scores and frequency bias of rainfall and root mean square of temperature were improved while used soil moisture from global forecast system [72].

Although, RegCM4 with ESA setup appeared to ameliorate the performance, ~~still~~ improvement is still necessary. Careful examination proclaimed that the model performance ~~was~~ deteriorated, particularly during the extreme monsoon year (2002) although it showed acceptable accuracy during normal monsoon year (2011). Major association of the poor skill during 2002 was the inefficiency to pick up various epochs of ISM precisely and thereby showed early onset and delayed withdrawal. However, it was also recognized that simulated rainfall was surprisingly low during the peak monsoon months viz., July and August during 2011 (normal). In addition, rainfall was extremely high in June and

July during 2002 (deficit). This indicated that RegCM4 couldn't be able to capture the contrasting features of ISM accurately. ~~Thus, this~~In brief, the soil moisture initialization can significantly improve the model skill in simulating weather/climate features and hence should be paid more attention. Our overall analysis infers significant improvement in the model skill in simulating surface temperature and rainfall distribution while using high-resolution ESA soil moisture albeit lacunae noticed in temporal variation. ETS of rainfall was higher with ESA setup.

5. Conclusion

This study provided a primary assessment of the realistic soil moisture initialization through seasonal simulation of ISM using ~~regional model and imparts potential improvement. Although systematic investigation with added number of extreme years may deliver the results in further meaningful means, this work presented the preliminary ideas for those future studies.~~the regional model. In summary, we found RegCM4 was sensitive to the soil moisture initialization and consequently imparts potential improvement in simulating surface temperature and rainfall while initialized with high-resolution, satellite-derived soil moisture data. Although, the model showed reasonable skill in normal year, it still came across difficulties in simulating different epochs of monsoon in extreme year in particular. Further investigation is therefore required to enhance the model skill.

6. Limitation and future studies

The investigations presented here are the preliminary ideas for similar modeling studies in future. Thus, systematic investigation with the added number of extreme years may reproduce more robust results. In addition, it is also important to test the model skill using soil moisture data from different sources.

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Data Availability Statement: The ERA Interim reanalysis, sea-surface temperature, soil characteristics, soil moisture and other geophysical data used in this study are obtained from the http://clima-dods.ictp.it/regcm4/. Rainfall and temperature analysis data used for validation are freely available from India Meteorological Department.

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Conflicts of Interest: The authors declare no conflict of interest.

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