Model. Earth Syst. Environ. (2015) 1:13
DOI 10.1007/s40808-015-0008-3

ORIGINAL ARTICLE

Multi-model cropping seasons projections over pakistan under representative concentration pathways

Maida Zahid[1] · **Waheed Iqbal**[2]

Received: 2 January 2015 / Accepted: 18 May 2015 / Published online: 7 July 2015

Abstract This study examines the changes in soil moisture derived from 24 global climate model (GCM) simulations of Coupled Model Intercomparison Project phase 5 (CMIP5) over the cropping seasons (Kharif and Rabi) of Pakistan from 2021 to 2050. The comparison of historical run with reanalysis global land data assimilation system for the period 1971–2000 have shown that the soil moisture conditions in Rabi season were well captured by most of the CMIP5 GCMs as compared to Kharif. The historical and projected temporal trends of soil moisture showed slightly decreasing trend in soil moisture during Kharif under representative concentration pathways (RCP) 8.5 while Rabi depicted a well-marked declining trend under both the RCPs (4.5 and 8.5) from 1951 to 2050. The decadal and mean near future projections for Kharif and Rabi had been analyzed from 2021 to 2050. Kharif showed soil moisture stress (−3 to −9 %) in the decade 2041–2050 whereas Rabi projected the decrease in soil moisture (−5 to −15 %) in all the three decades (2021–2030, 2031–2040 and 2041–2050) by RCP 4.5 which was then further amplified (−5 to −20 %) under RCP 8.5. The mean projections also showed the negligible decrease in soil moisture during Kharif and severe soil moisture stress over the southern parts of Pakistan specifically south western areas of Balochistan, Khyber Pakhtunkhwah, southern Punjab and southern Sindh. In order to support the soil moisture changes over Pakistan crop land the decadal and mean evaporation of water from the soil projections also showed decline (−4 to −12 %) in Kharif and extreme drop (−6 to −24 %) in water evaporation from soil under both the RCPs. In nut shell the study clearly indicates the intensification of soil moisture stress in near future during Rabi season in Pakistan.

Keywords Soil moisture · Kharif · Rabi · RCP 4.5 · RCP 8.5 · CMIP5

✉ Maida Zahid
maidazahid.pmd@gmail.com

1 Meteorological Institute, University of Hamburg, Hamburg, Germany

2 Department of Meteorology (MISU), Stockholm University, Stockholm, Sweden

Introduction

Soil moisture is an important component and main repository of water for the crops growth. It is highly susceptible to the variations in hydrological cycle. It is considered to be a vital indicator of drought and is used by the scientists to characterize the global and regional drought (Sheffield and Wood 2007). The monthly soil moisture variability signifies the regions which are more prone to drought events as compared to those where hardly drought occurs. China and South East Asia apparently experienced more frequent droughts from 1990 to 2005. The future projections indicate the increase in frequency and intensity of drought in some areas of China and South East Asia during 2020s (Wang et al. 2011). China is the prime producer of wheat and rice in the world and maize in Asia. The maize and wheat cultivation is mainly found in central and eastern China however rice production is common in south and north eastern China (Leff et al. 2004). The climate projections illustrate the dryness of soils in China. Wheat and Maize croplands are projected to experience one of the largest reductions in growing season mean soil moisture levels, relative to 1990–2005, of all the Asian countries (Challinor et al. 2010).

The Wheat and Maize are also produced in bulk in central and northern regions of India which is the second largest in the world. Climate model simulations projected the increase in drought risk for maize and wheat production. The northern and central India showed the lowest adaptive capacitates for Wheat and Maize production. The adverse impacts of climate on Wheat and Maize harvesting are expected to amplify in the 2020s (Simelton et al. 2012). Challinor 2011 stated that the high latitude countries crop yield may increase due to extensive growing season under the global warming scenario [high concentrations of carbon dioxide (CO_2)]. Conversely, the countries lying in the tropical belt are likely to have reduced crop yields. The global average spring yield is projected to decrease up to 25 % over the next 50 years. The South Asia and South Africa are the most vulnerable regions in the near future. The extreme weather events are already experiencing drop in the crop yield (Lobell et al. 2008). According to the Intergovernmental Panel on Climate Change (IPCC) forecasts the agriculture yield will decline approximately from 2.5 to 10 % by 2020 and 5 to 30 % by 2050 compared to 1990 (Parry et al. 2007). Moreover, the scarcity of water is also a biggest threat of climate change to agriculture sector in Asian region.

Wang 2005 studied the impact of greenhouse gases on soil moisture through 15 global climate models (CMIP3) participated in IPCC fourth assessment report. The models predicted summer dryness and winter wetness in the northern middle and high latitudes. The wetness in Eurasia and dryness in Siberia and mid latitude Northeast Asia has been observed. The decrease in soil moisture is evident in tropics and subtropics. North America, Central America, the Mediterranean, Australia, and the South Africa predicted drier soils in all seasons. The drying of soil in Amazon and the West Africa in June–July–August (JJA) season and in monsoon regions of Asia during December–January–February (DJF) season have been noticed by more than half of the models. Now Coupled Model Intercomparison Project phase 5 (CMIP5) experiments based on a set of new scenarios called representative concentration pathways (RCPs) are being used to evaluate the future climatic changes worldwide (Meinshausen et al. 2011; Taylor et al. 2012). The data of numerous variables simulated by the climate models under CMIP5 are available at (http://cmip-pcmdi.llnl.gov/cmip5/data_portal.html). CMIP5 experiments comprise of more comprehensive models with variety of applications. CMIP5 models are generally of higher resolution as compared to their CMIP3 counterparts (Stouffer et al. 2011; Meehl and Bony 2011).

Soil moisture is a dominant source of land surface interaction investigations (Dirmeyer 2011). Soil moisture contribution in climate variability influencing the atmosphere globally has been studied by various scientist (Koster et al. 2010, 2011; Findell et al. 2011; Santanello et al. 2011 and Guo et al. 2012) CMIP5 project has provided an opportunity to evaluate the past and present land atmosphere relations in a broader way. General circulation models (GCMs) are now main source of estimation of soil moisture drought by the end of 21st century. Orlowsky and Seneviratne 2013 predicted increase in frequency of drought in Mediterranean, Central America/Mexico, the Amazon, North-East Brazil and South Africa on the basis of soil moisture anomalies in CMIP5 simulations. Dirmeyer et al. 2013 stated that drying trend like decrease in soil moisture and evaporation from past-to-present and present-to-future periods over the globe have been captured by CMIP5 models which are quite similar to CMIP3 simulations. Aiguo Dai 2013 reported increase in the risks of global aridity both in observed and model simulated patterns. The study predicts frequent and intense soil moisture based droughts in the next 30–90 years over the lands of world as a result of decreased precipitation or increased evaporation.

Pakistan is an agriculture-dependent country; most of its population earns their livelihood from cultivation. The vagaries of climate change have adverse effects on the crop production and a continuous threat for the farming community. Therefore, it is essential to generate near future projections of soil moisture changes over the agricultural lands of Pakistan in both the cropping seasons Rabi and Kharif. The study aims to (i) validate the CMIP5 based historical soil moisture (1971–2000) for Pakistan by comparing the GLDAS based climatology (ii) selection of models well simulating soil moisture conditions for Pakistan through Taylor's Diagram in both cropping seasons. (iii) assessed the historical and projected temporal trends from 1951 to 2050 under both RCP 4.5 and RCP 8.5. (iv) analyzed the decadal and mean projected soil moisture percentage changes for the period 2021–2050 during Rabi and Kharif over Pakistan. (v) investigated the decadal and mean projected percentage changes in water evaporation from soil for the period 2021–2050 over Pakistan.

Data and methodology

Reanalysis data

The monthly data of soil moisture (10 cm) has been obtained from data archive of global land data assimilation system (GLDAS) for the period 1971–2000 ftp://hydro1.sci.gsfc.nasa.gov/data/s4pa/GLDAS/GLDAS_NOAH10_M.020/. The resolution of GLDAS data is 1° × 1°. This observed data is used for the evaluation of GCMs data sets (Rodell et al. 2004). The GLDAS data show more fidelity when compared with Pakistan Meteorological Department data sets.

CMIP5 data

The Couple Model Intercomparison phase 5 (CMIP5) is a globally synchronized set of GCMs experiments which provides the present past and future climate simulations. The monthly data of 24 GCMs for the upper layer soil moisture [that compute the mass of water in all phases in the upper 0.1 m (10 cm) of soil] have been used in this study. CMIP5 historical run (r1i1p1) for the evaluation of GCMs over Pakistan from 1971 to 2000 and RCPs data for analyzing future scenarios (RCP 4.5 and RCP 8.5) have been obtained from http://cmip-pcmdi.llnl.gov/cmip5/. The name, modeling centers and resolutions of all the models are listed in the Table 1. Taylor et al. (2012) reports that about 1/3rd of the models have atmospheric resolution of approximately 1.5° latitude or less. This higher resolution will be helpful in examining regional hydro climate variables over the globe, although still coarser than would be desirable in regions of complex topography and coastlines. RCP 8.5 and RCP 4.5 represent the core concentration pathways used for the CMIP5 project (Taylor et al. 2012). These experiments represent high concentration and moderate mitigation pathways in which radiative forcing due to anthropogenic factors reaches 8.5 and 4.5 Wm^{-2} by 2100, respectively. Meinshausen et al. (2011) states that radiative forcing continues to grow beyond 2100 in RCP 8.5, whereas in RCP 4.5 stabilization at 4.5 Wm^{-2} occurs around 2050 and remains fixed. In terms of the time evolution and value of globally-averaged radiative forcing at 2100, these pathways most closely resemble the A1B and A2 scenarios for CMIP3 used in the IPCC Assessment Report 4 (IPCC 2007).

Methodology

The study domain is Pakistan which has latitude 23°N–38°N and longitude 61°E–78°E as shown in Fig. 1. Pakistan has two well-marked cropping seasons i.e. Kharif (May–September) and Rabi (Oct–April). The evaluation of CMIP5 GCMs has been done to check which model well simulates the soil moisture conditions in cropping seasons over Pakistan. The GCMs have wide range of resolutions from 0.5° to 3.75°. Therefore, all data was regrided at 2° × 2° so that comparison among models and observed data set can be easily made. The biases have been calculated using the historical run (1971–2000). The validation of CMIP5 models has been done through bias analysis to check the spatial variability in surface layer soil moisture during Kharif and Rabi in Pakistan. The selection of models for both the cropping seasons has been done through Taylor Diagram. The selected models have been enlisted in Table 2. The multi model ensemble mean of the available selected models was calculated for both Kharif and Rabi. Then historical and future projections of climate change have been analyzed on temporal scale. The temporal analysis have been done from 1951 to 2050 to analyze the long term trends of soil moisture over Pakistan during Rabi and Kharif. The spatial analysis have been done both on decadal basis (2021–2030, 2031–2040 and 2041–2050) and as well as for the mean period (2021–2050). Signal to noise ratio test has been applied on spatial analysis of both the seasons to check the uncertainty in these projections and indicating the signal of changing climate over Pakistan.

Results and discussion

Validation of CMIP5 models over Pakistan during Kharif and Rabi

The 24 CMIP5 model simulated baseline climatologies have been compared with GLDAS reanalysis data climatologies from 1971 to 2000 for both Kharif and Rabi seasons (Fig. 2). The spatial biases pattern of surface layer soil moisture is diverse in both the cropping seasons i.e. Kharif and Rabi. Most of the models either underestimate or overestimate the state of surface soil moisture over Pakistan. In Kharif the BCC-CSM1, CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, FGOALS-G2, GISS-E2-H, GISS-E2-R, HadCM3, HadGEM2-ES, HadGEM2-CC, IPSL-CM5A-LR, IPSL-CMA-MR, IPSL-CM5B-LR, INMCM4, MIROC4H, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, MRI-CGCM3, NorESM1-M and NorESM1-ME were underestimating the soil moisture conditions while FGOALS-S2 is the only model that was showing the lowest bias. On the contrary in Rabi season BCC-CSM1, CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, FGOALS-G2, GISS-E2-H, GISS-E2-R, IPSL-CM5A-LR, IPSL-CMA-MR, IPSL-CM5B-LR, MRICGCM3, NorESM1-M and NorESM1-ME were showing the highest biases.

However the HadCM3, HadGEM2-ES, HadGEM2-CC, INMCM4, MIROC4H, MIROC5, MIROC-ESM and MIROC-ESM-CHEM were overestimating in some parts of Pakistan and underestimating in other. The FGOALS-S2 showed the lowest bias in Rabi season as well. All the 24 models showed better results in Rabi season as compared to Kharif. One of the prime reasons for this is the monsoon precipitation during Kharif. Monsoon is a complex phenomenon and it is very difficult for all the models to simulate well during Monsoon.

The Models performance was further investigated through Taylors Diagram statistics during Kharif and Rabi from 1971 to 2000 as shown in Fig. 3. Chaturvedi et al. 2012 stated that the Taylor diagram is the most convenient method to compare the model's performances as it comprises of three parameters i.e. pattern correlation with reanalysis/observed, centered root mean square (RMS) and standard deviation in a single glimpse. The semi circles

Table 1 List of CMIP5 Models used in the study

Sr. No	Modeling center	Model	Resolution (Lon × Lat}
1	Beijing Climate Center, China Meteorological Administration, China	bcc-csml-1 model	2.8 × 2.8
2	Canadian Centre for Climate Modelling & Analysis, Canada	CanESM2	2.8 × 2.8
3	National Centre for Meteorological Research, France	CNRM-CM5	1.4 × 1.4
4	Canadian Centre for Climate Modelling & Analysis, Canada	CanCM4	2.8 × 2.8
5	National Center for Atmospheric Research, USA	CCSM4	1.25 × 0.94
6	Met Office Hadley Centre, UK	HadCM3	3.75 × 2.5
7	Met Office Hadley Centre, UK CC (Chemistry coupled)	HadGEM2-CC	1.875 × 1.25
8	Met Office Hadley Centre, UK	HadGEM2-ES	1.875 × 1.25
9	Institute for Numerical Mathematics, Russia	INM-CM4	2 × 1.5
10	Institut Pierre Simon Laplace, France	IPSL-CM5A-LR	3.75 × 1.8
11	Institut Pierre Simon Laplace, France	IPSL-CM5A-MR	2.5 × 1.25
12	Institut Pierre Simon Laplace, France	IPSL-CM5B-LR	3.75 × 1.894
13	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	LASG FGOALS-G2	2.8 × 1.6
14	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	LASG-FGOALS-S2	2.8 × 1.6
15	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence	CISRO-MK3-6.D	1.8 × 1.8
16	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC-ESM	2.8 × 2.8
17	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC-ESM-CHEM	2.8 × 2.8
18	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan	MIR0C4H	0.56 × 0.56
19	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan	MIROC5	1.4 × 1.4
20	Meteorological Research Institute, Japan	MRI-CGCM3	1.1 × 1.1
21	Norwegian Climate Center, Norway	NorESMl-M	2.5 × 1.9
22	Norwegian Climate Center, Norway	NorESMl-ME	2.5 × 1.9
23	NASAGoddard Institute for Space Studies	GISS-E2-H	2.5 × 2.5
24	NASAGoddard Institute for Space Studies	GISS-E2-R	2,5 × 2.5

centered at the reference point depicts the loci of constant RMS and the semi circles apparent at the origin represent the loci of constant standard deviation. Correlation is represented as cosine of the angle from the X-axis. Models with as much variance as observation/reanalysis, largest correlation and least RMS error are considered best performers on the Taylor diagram.

Figure 3a has shown that the most of the models deviate from the reanalysis. However, BCC-CSM-1, CanCM4, CanESM2, GISS-E-R, MIROC5, MIROC-ESM-CHEM, HadCM3, NorESM-M, NorESM-ME and CCSM4 were the models closer to the reanalysis (GLDAS) during Kharif. The CanCM4, CCSM4, HadCM3 were excluded due to non-availability of future datasets. Figure 3b illustrated the good performance of the models during Rabi season. The BCC-CSM-1, MIROC5, MIROC-ESM-CHEM, IPSL-CM5A-LR, IPSL-CMA-MR and IPSL-CM5B-LR were the models closest to the reanalysis with high correlation, least RMS and standard deviation. The multi model ensemble mean of the selected models for Rabi and Kharif were taken and further used to calculate the near future changes in soil moisture over Pakistan.

Historical and projected temporal trends over pakistan 1951–2050

The cropping season historical and projected temporal trends of surface soil moisture over Pakistan from 1951 to 2050 are

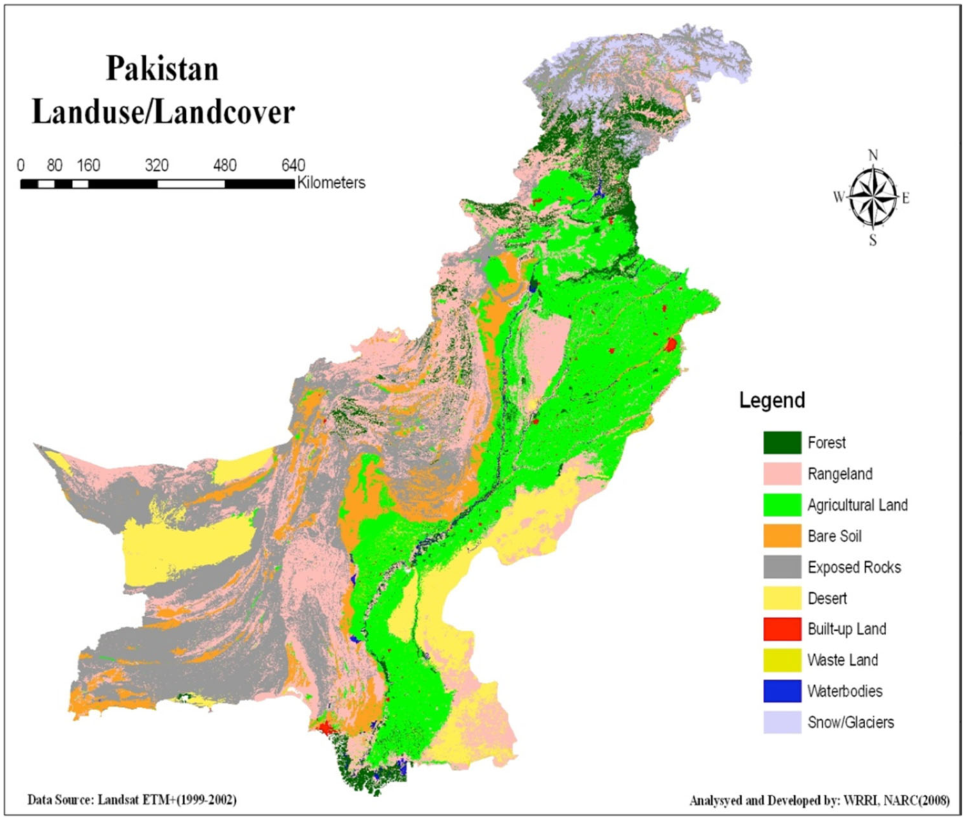

Fig. 1 The study domain (23°N–38°N—61°E–78°E)

Table 2 List of selected models for Kharif and Rabi Projections (2021–2050)

Sr. No	Kharif	Rabi
1.	MIROC5	MIROC5
2.	MIROC-ESM-CHEM	MIROC-ESM-CHEM
3.	BCC-CSM1-1	BCC-CSM1-1
4.	CanESM2	IPSL-CM5A-LR
5.	NorESMl-M	IPSL-CM5A-MR
6.	NorESMl-ME	IPSL-CM5B-LR
7.	CCSM4	CCSM4
8.	GISS-E2-R	

shown in Fig. 4. The multi model ensemble of Kharif and Rabi has been used to generate historical and future temporal trends. The increasing trend of surface soil moisture is evident in Kharif (Fig. 4a) from 1951 to 2020. Thereafter decrease and increase in surface soil moisture begins in cycles. RCP 4.5 showed almost similar pattern of soil moisture observed during historical period. The peak values of soil moisture were observed in between 2010 and 2020 and the slight drop in soil moisture condition was seen from 2041 to 2050 under RCP 8.5. The Kharif season was overall showing the slight variability in increase and decrease in surface soil moisture.

Figure 4b showed increasing trend of surface soil moisture during Rabi from 1951 to 2010. Thereafter marked decreasing trend of soil moisture can be viewed from 2010 to 2050. On comparison with historical period it is apparent that both the RCP's (4.5 and 8.5) were showing soil moisture stress over Pakistan during Rabi season in near future 2021–2050. The extreme decrease events were apparent in each decade i.e. 2021–2030, 2031–2040 and 2041–2050 under RCP 8.5. However, the soil moisture deficit shown by RCP 4.5 was gradual from 2021 to 2050. The decrease in soil moisture during Rabi most probably indicates the elevation in temperatures and less wet spells in the near future. In short the soil moisture stress is more dominant in Rabi season than Kharif.

Decadal and mean projections (2021–2050) during Kharif over Pakistan

The Multi model ensemble based decadal soil moisture projections during Kharif over the period 2021–2050 are shown in Fig. 5. The RCP 4.5 has shown sufficient soil moisture (3–12 %) over the croplands of Pakistan during the first two decades (2021–2030 and 2031–2040) of the study. However some parts of Gilgit Baltistan, southern Punjab and adjoining Balochistan have shown patches of minor soil moisture stress (−3

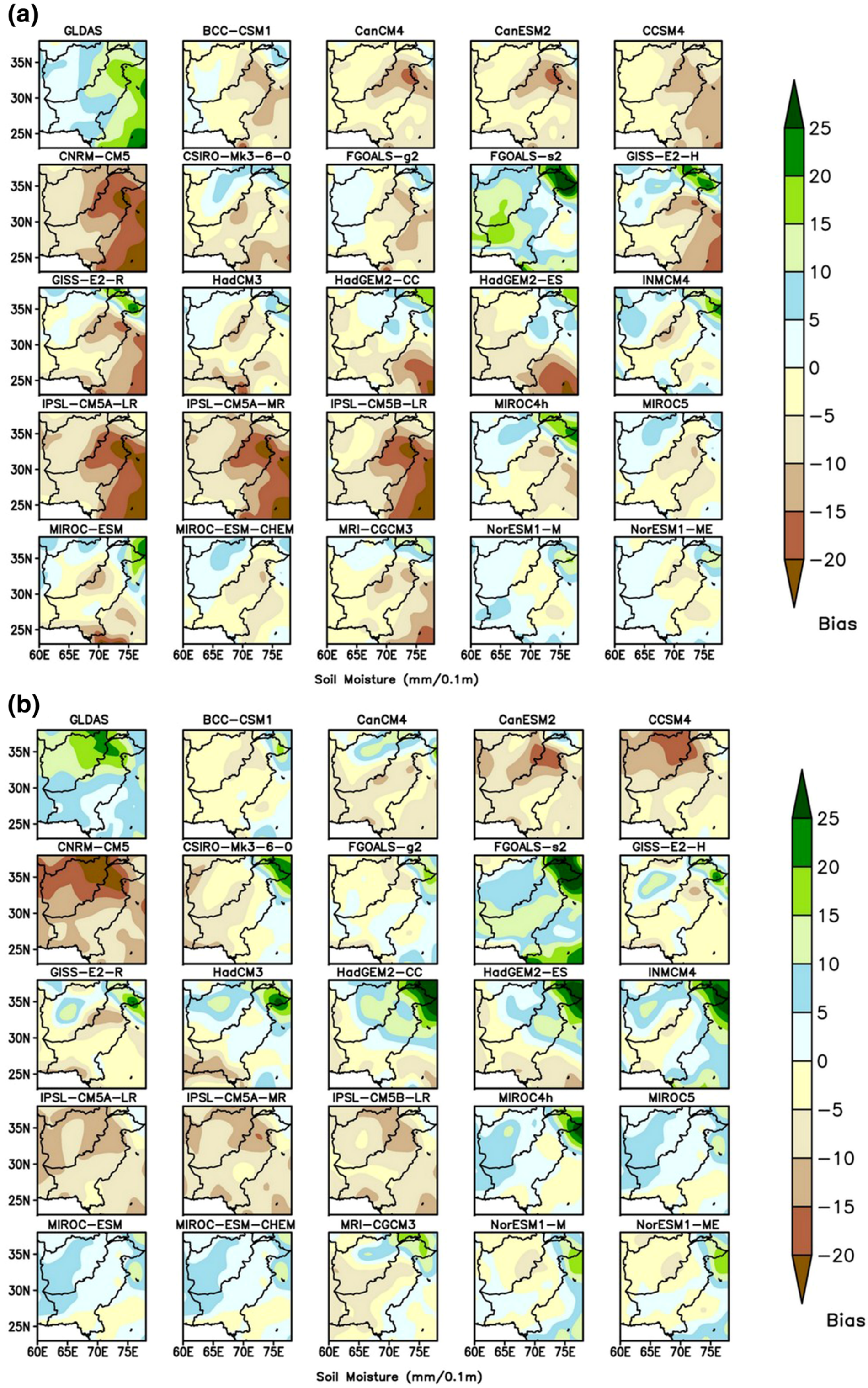

Fig. 2 Annual mean of surface layer soil moisture of reanalysis dataset (GLDAS) and different GCMs from 1971 to 2000 **a** Kharif **b** Rabi

to −6 %) during 2021–2030.The third decade (2041–2050) projected the discernible changes in surface soil moisture and experience the well-marked soil moisture stress (−3 to −9 %) over most of the cultivated land of Pakistan except some parts of Punjab and Khyber Pakhtunkhwah.

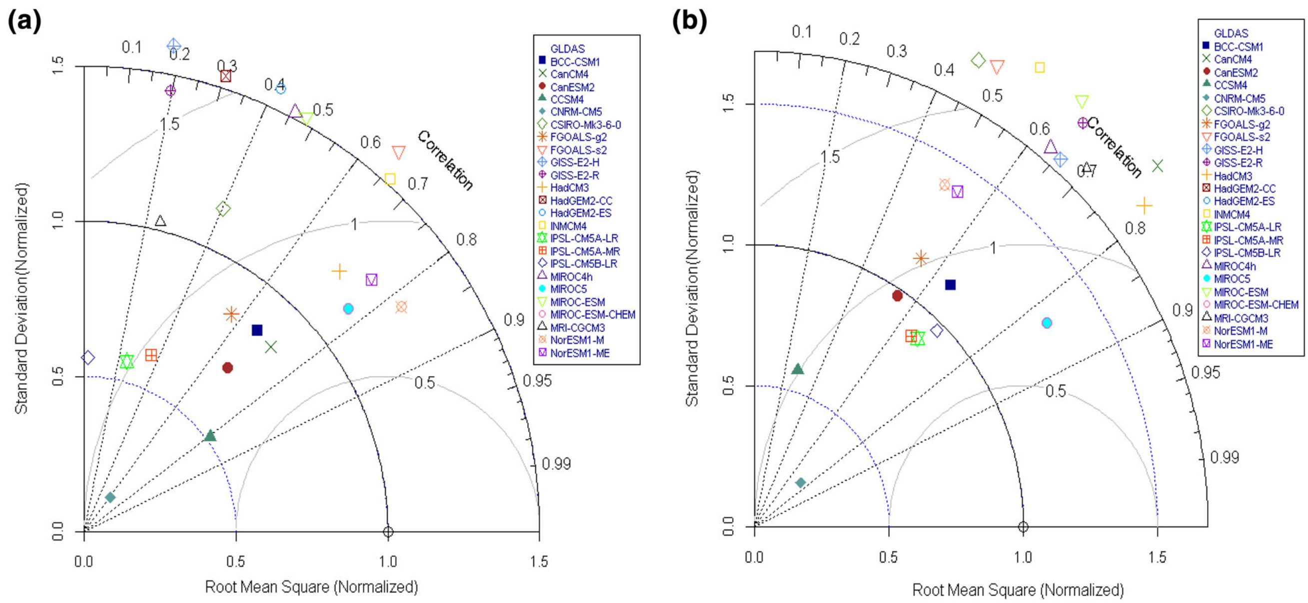

Fig. 3 Taylor diagrams of surface layer soil moisture comparing reanalysis (GLDAS) with 24 CMIP5 GCMs over Pakistan from 1971 to 2000 **a** Kharif **b** Rabi

The state of soil moisture projected by RCP 4.5 (moderate scenario) totally changes under (extreme scenario) RCP 8.5. The decrease in soil moisture is prominent in all the three decades (2021–2030, 2031–2040 and 2041–2050). The RCP 8.5 projected small patches of soil moisture deficit (−3 to −6 %) in the first decade (2021–2030) extended towards north covering the agriculture lands. The second decade (2031–2040) projected the extreme decrease (−3 to −12 %) in soil moisture particularly over the southern parts of Pakistan. The shortfall of soil moisture to such an extent will adversely affect the crop yields during the second decade. The third decade (2041–2050) also portrayed the extension of soil moisture deficit (−3 to −9 %) over most of the croplands during Kharif in Pakistan.

This dryness of croplands can be associated with the high rate of evapotranspiration under the global warming scenario (Wang 2005). The cotton and rice are the two major cash crops of the country during Kharif and their failure will not only influence the economy but all the stakeholders. The Kharif season over the mean period i.e. 2021–2050 have also shown increase (1–3 %) in soil moisture over most of the regions of Pakistan except few parts of Gilgit Baltistan, southern Punjab and Balochistan where there are apparent patches of slight decrease (−1 to −3 %) under RCP 4.5. While the extent of small patches of soil moisture stress extended towards the north of Pakistan and the soil moisture deficit enhances over the croplands of Punjab under RCP 8.5.

The projections of evaporation from soil has also been calculated on decadal and mean basis from 2021 to 2050 under RCPs (4.5 and 8.5) to further support the evidence of decrease in soil moisture over different areas of Pakistan. Figure 6 shows that the evaporation from soil is directly related to the soil moisture changes. The areas which have shown decrease in soil moisture were also showing decrease in evaporation from soil; while areas with adequate soil moisture portrayed an increase in evaporation from soil. The decadal analysis depicted that although the decline in evaporation from soil is evident in the first (2021–2030) and the three decade (2041–2050) over the southern half of Pakistan with the exception of an increase in evaporation from soil in the second decade (2031–2040). The mean period (2021–2050) the rate of evaporation from soil reduces (−4 to −12 %) over the northern Punjab and Sindh province nearly the areas where mean soil moisture decrease is visible in Fig. 5. The RCP 8.5 projected that the decline in evaporation from soil amplified as compared to RCP 4.5.The second decade (2031–2040) experienced the most alarming decrease (−4 to −20 %) in evaporation from soil indicating the dryness of lands. The mean duration (2021–2050) illustrated that the rate of evaporation from soil decrease enhances from southern Sindh to northern Punjab signifying the loss of soil moisture in these regions under RCP 8.5.

Decadal and mean projections (2021–2050) during Rabi over Pakistan

Figure 7 shows the multi model ensemble based decadal soil moisture projections during Rabi over the period 2021–2050. The RCP 4.5 has shown decline in state of

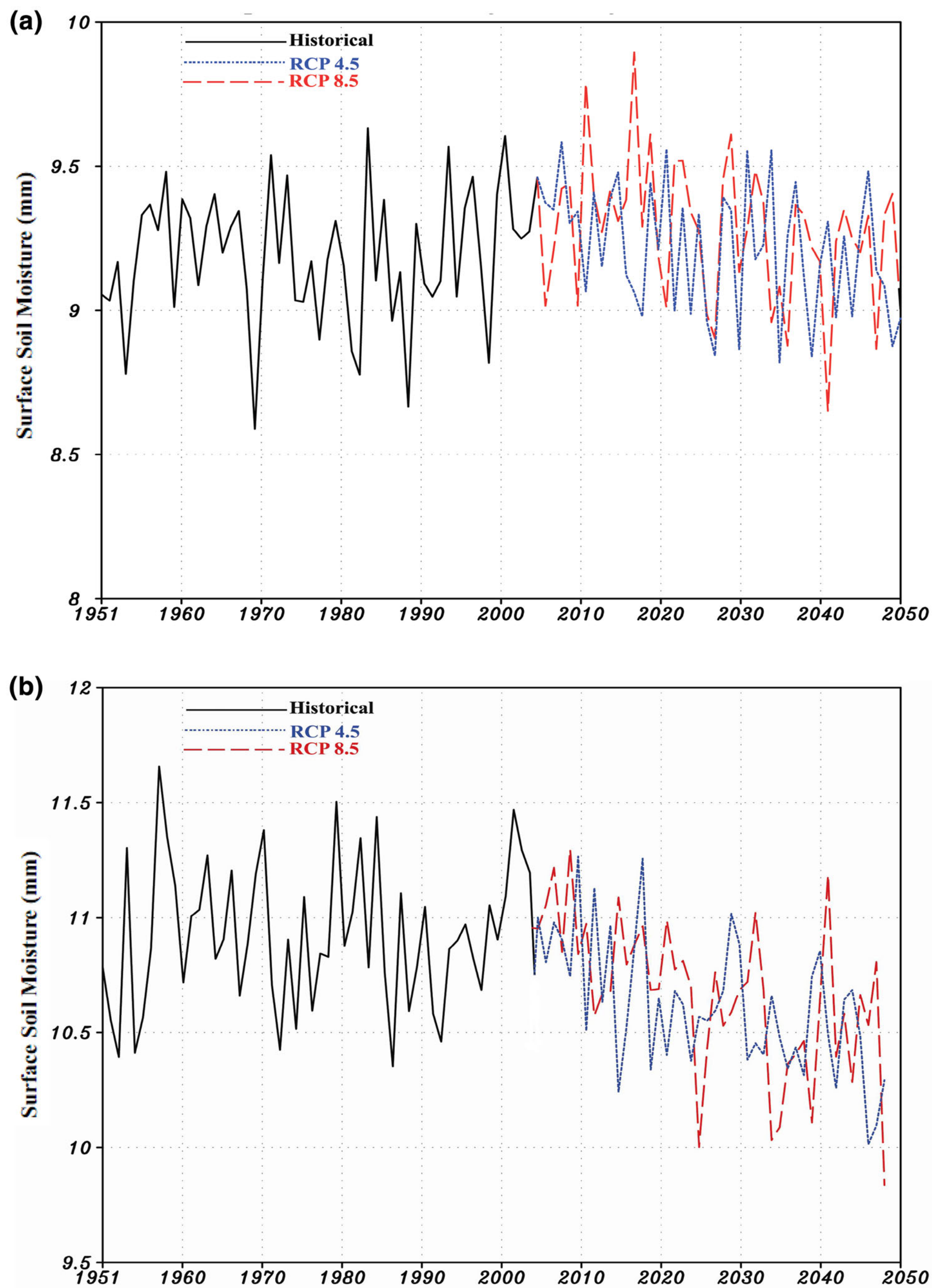

Fig. 4 Historical and projected multi model ensemble temporal trends of surface soil moisture over Pakistan from 1951 to 2050 during **a** Kharif **b** Rabi

surface soil moisture in all the three decades (2021–2030, 2031–2040 and 2041–2050) over Pakistan. The first decade (2021–2030) experienced the decrease (−5 to −20 %) in soil moisture which further intensified in the second (2031–2040) and third (2041–2050) decade over the entire agriculture lands of Pakistan during Rabi under RCP 4.5. The second (2031–2040) and third decade (2041–2050) projected the severe soil moisture deficit particularly over the south-western half of Pakistan under RCP 4.5. The mean period 2021–2050 illustrated that the entire croplands of Pakistan will be under soil moisture stress (−5 to −15 %) under RCP 4.5 during Rabi. The southern half; specifically south western parts of the country will be more vulnerable to agriculture drought in near future.

The RCP 8.5 projected sever decrease in soil moisture during Rabi over the entire Pakistan from 2021 to 2050 as compared to RCP 4.5. The first decade (2021–2030) showed −5 to −15 % decrease in soil moisture over Pakistan. However the severity of soil moisture stress increases towards north in the decade 2031-2040. The decrease in soil moisture (−5 to −20 %) was more apparent. Over the south western parts of Pakistan. The second decade was appeared to be most vulnerable to soil moisture stress among all the decades. The third decade

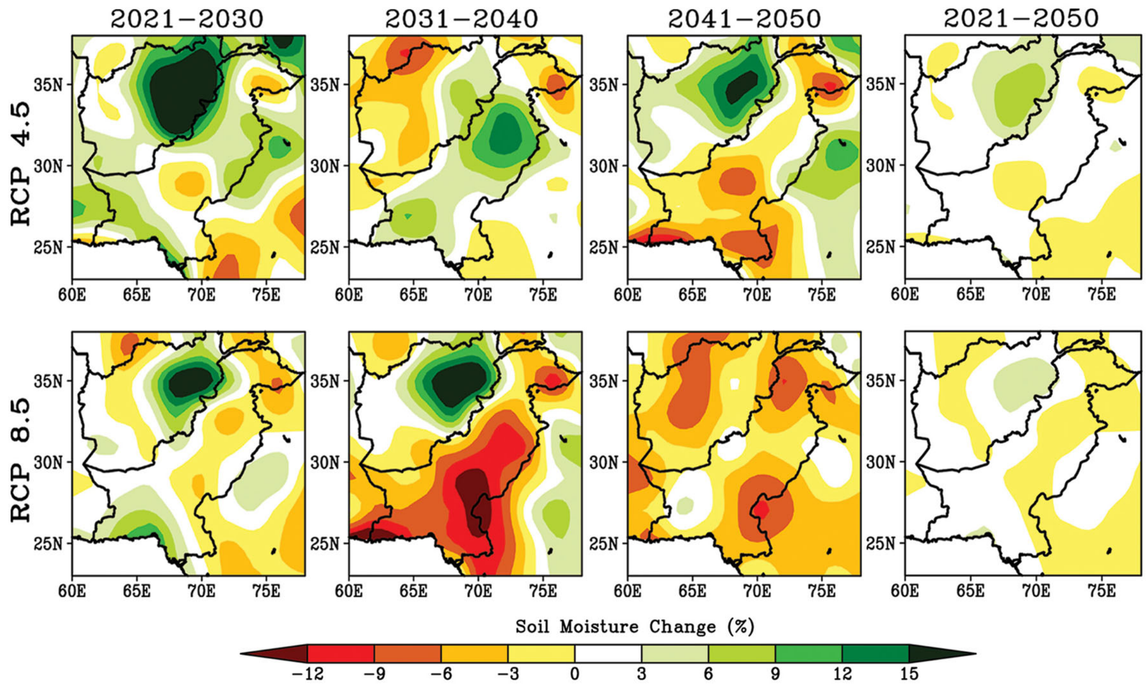

Fig. 5 Multi Model ensemble decadal (2021–2030, 2031–2040 and 2041–2050) and mean (2021–2050) soil moisture projections during Kharif over Pakistan

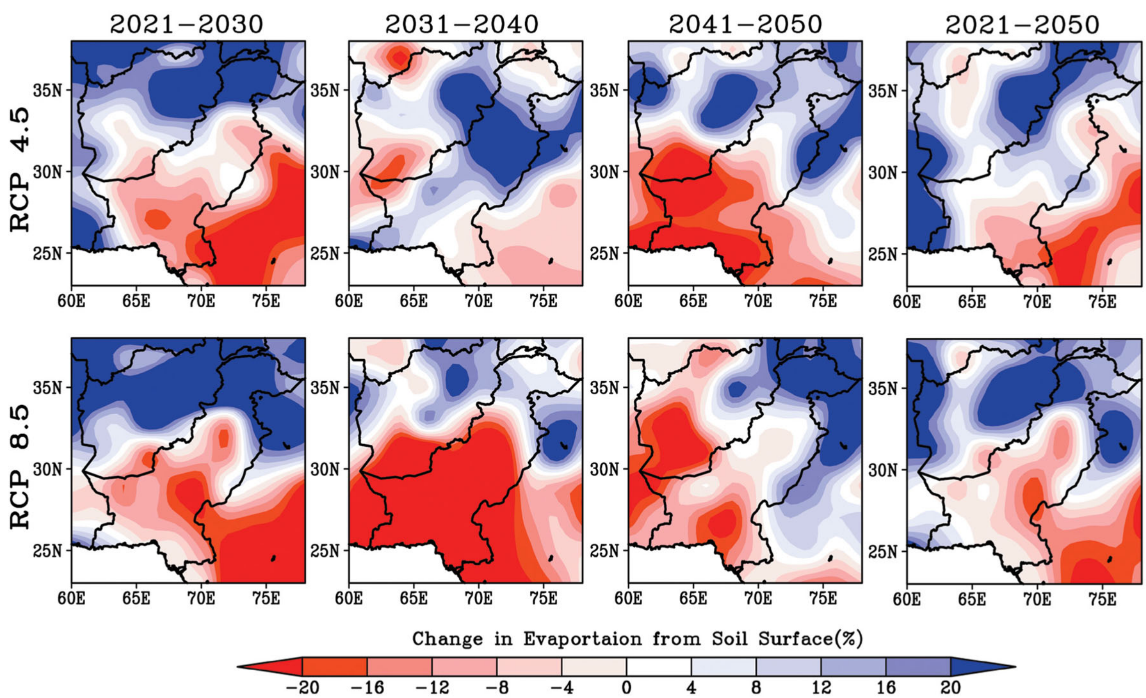

Fig. 6 Multi Model ensemble decadal (2021–2030, 2031–2040 & 2041–2050) and mean (2021–2050) evaporation from soil projections under RCP 4.5 and RCP 8.5 during Kharif over Pakistan

(2041–2050) showed the deficit in soil moisture as well. Most of the regions showed −5 to −20 % decline in soil moisture except the few parts of north eastern and south eastern where increase was approximately 5 %. The extreme stress in soil moisture is evident under both the RCPs (4.5 and 8.5). However, mean period i.e. 2021–2050 projected soil moisture stress (−5 to −15 %) over the southern parts of Pakistan specifically south western areas

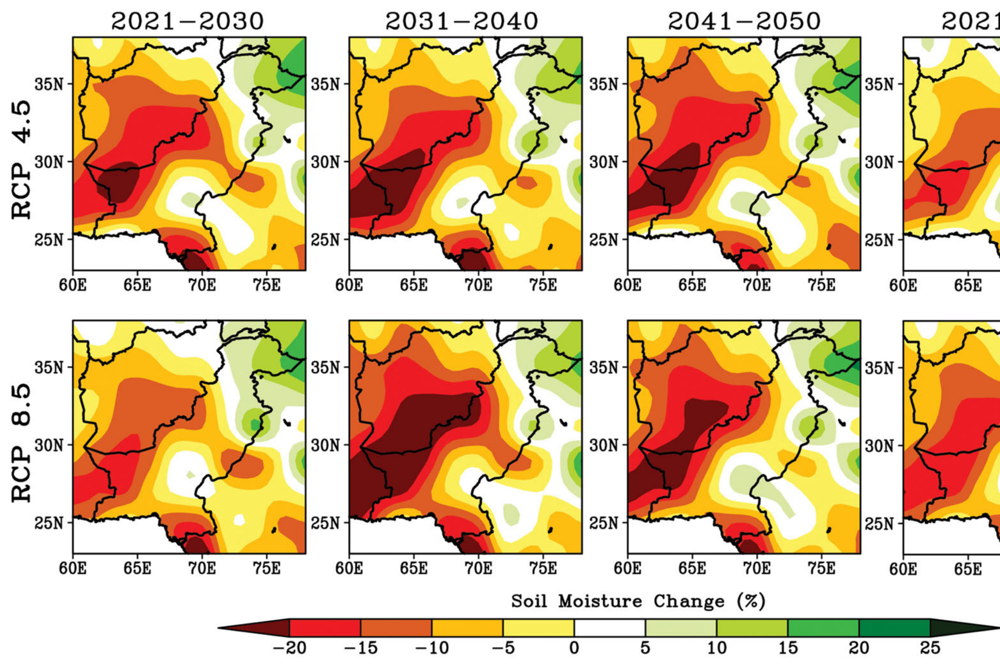

Fig. 7 Multi Model ensemble decadal (2021–2030, 2031–2040 & 2041–2050) and mean (2021–2050) soil moisture projections during Rabi over Pakistan

of Balochistan, Khyber Pakhtunkhwah, southern Punjab and southern Sindh. The locality of soil moisture stress shown under RCP 4.5 inflated under RCP 8.5.

Figure 8 projected the decadal and mean percentage changes in evaporation from soil during Rabi over Pakistan from 2021 to 2050. The decadal analysis portrayed that the southern and central parts of Pakistan have shown decrease in evaporation from soil under RCP 4.5 almost in the similar zone where the land is arid and soil moisture stress have been calculated as shown in Fig. 7. All the decades have shown decrease in evaporation from soil (−6 to −30 %) with the exception of increase in evaporation from soil (6 to 30 %) over extreme parts of north and south. The reduced evaporation from soil is indicating the deficiency in soil moisture in those areas. The RCP 4.5 mean period (2021–2050) depicted the reduction (−6 to −24 %) in evaporation from soil over the central parts of Pakistan. On the contrary RCP 8.5 has shown extreme decrease (−12 to −30 %) in evaporation from soil over the central and southern parts of the country in all the three decades of the study. However, the mean (2021–2050) projected that the extent of drop (−6 to −24 %) in evaporation from soil expanded from southern towards the northern Pakistan.

Conclusion

Limitations and uncertainties in models and future scenarios are the two major aspects of climate change projections. Global scale projections have comparatively more credibility than regional scale projections. But unless the high-resolution multi-model regional climate change projections are not available for Pakistan the results of this study are quite beneficial for the near future (2021–2050) agriculture planning during Kharif and Rabi in Pakistan. The critical findings of the study are (1) the majority of the 24 CMIP5 models can generally well capture the soil moisture conditions during Rabi as compared to Kharif in Pakistan for the historical period (1971–2000). The models in Rabi season have shown less deviation from the reanalysis (GLDAS) in the Taylor's diagram. On the contrary in Kharif season the models have shown vast deviation from the reanalysis. (2) The historical and projected temporal trends of soil moisture over Pakistan from 1951 to 2050 depicted that there is a slight decrease in soil moisture during Kharif only under RCP 8.5 from 2041 to 2050 as compared to past trend. However marked decline in the trends of Rabi can be observed from 2010 to 2050 under both the RCP's (4.5 and 8.5). (3) The multi model ensemble based decadal soil moisture projections (2021–2050) during Kharif showed that soil moisture stress will be maximum (−3 to −9 %) from 2041 to 2050 whereas the mean projections have shown almost negligible changes in soil moisture over croplands of Pakistan under both the RCPs. On the other hand in Rabi the stress in soil moisture (−5 to −15 %) projected by RCP 4.5 is evident in all the three decades (2021–2030, 2031–2040 and 2041–2050) which further intensified (−5 to −20 %) and engrossed the croplands of Pakistan under RCP 8.5 scenario. Even the mean (2021-2050) projected soil moisture stress (−5 to −15 %) is very high over the

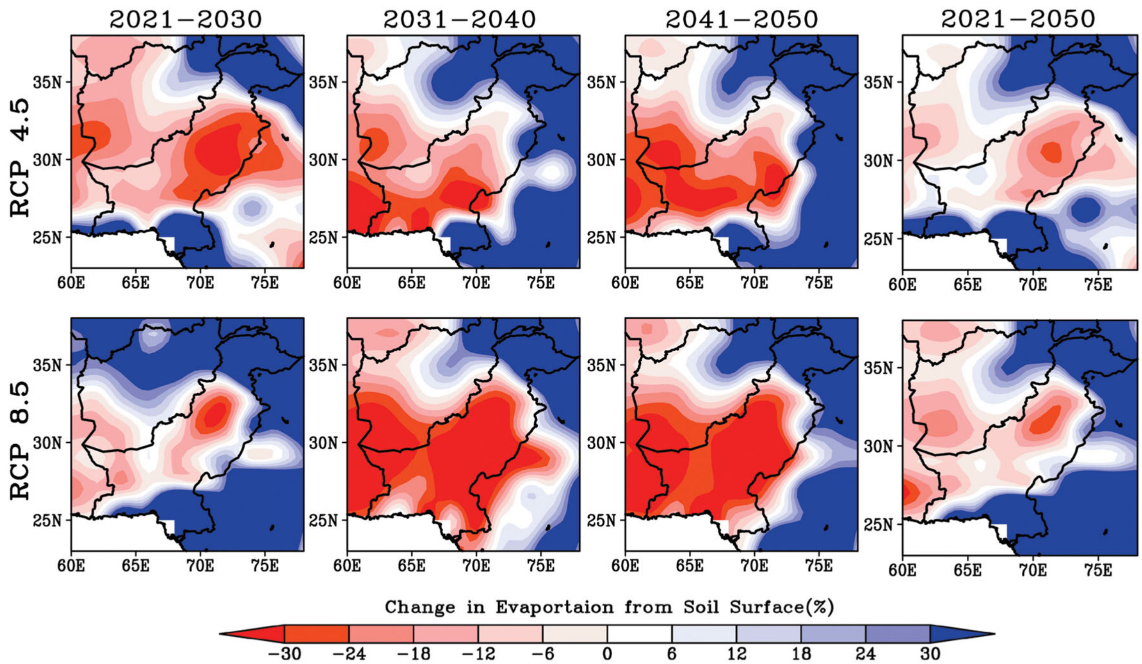

Fig. 8 Multi Model ensemble decadal (2021–2030, 2031–2040 & 2041–2050) and mean (2021–2050) evaporation from soil projections under RCP 4.5 and RCP 8.5 during Rabi over Pakistan

southern parts of Pakistan specifically south western areas of Balochistan, Khyber Pakhtunkhwah, southern Punjab and southern Sindh. (4) The decadal and mean evaporation of water from the soil from 2021 to 2050 projected by RCPs (4.5 and 8.5) further supported the evidence of soil moisture decrease in croplands of Pakistan. The Kharif has shown slight decrease (−4 to −12 %) in evaporation of water from the soil while Rabi has shown severe drop (−6 to −24 %) in water evaporation from soil.

References

Challinor A (2011) Agriculture: forecasting food. Nat Clim Chang 1:103–104

Challinor AJ, Simelton ES, Fraser ED, Hemming D, Collins M (2010) Increased crop failure due to climate change: assessing adaptation options using models and socio-economic data for wheat in China. Env Res Lett 5(3):034012

Chaturvedi RK, Joshi J, Jayaraman M, Bala G, Ravindranath NH (2012) Multi-model climate change projections for India under representative concentration pathways. Curr Sci 103(7):1–12

Dai A (2013) Increasing drought under global warming in observations and models. Nat Clim Chang 3:52–58

Dirmeyer PA (2011) A history of the Global Soil Wetness Project (GSWP). J Hydrometeor 12:729–749

Dirmeyer PA, Jin Y, Singh B, Yan X (2013) Trends in Land-Atmosphere Interactions from CMIP5 Simulations. Am Meteorol Soc 14:829–849

Findell K, Gentine P, Lintner BR, Kerr C (2011) Probability of afternoon precipitation in eastern United States and Mexico enhanced by high evaporation. Nat Geosci 4:434–439

Guo Z, Dirmeyer PA, DelSole T, Koster RD (2012) Rebound in atmospheric predictability and the role of the land surface. J Clim 25:4744–4749

Koster RD et al (2010) The contribution of land surface initialization to subseasonal forecast skill: first results from the GLACE-2 project. Geophys Res Lett 37:L02402. doi:10.1029/2009GL041677

Koster RD et al (2011) The second phase of the Global Land Atmosphere Coupling Experiment: soil moisture contributions to subseasonal forecast skill. J Hydrometeorol 12:805–822

Leff B, Ramankutty N, Foley JA (2004) Geographic distribution of major crops across the world. Global Biogeochem Cycles 18:GB1009. doi:10.1029/2003GB002108

Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL (2008) Prioritizing climate change adaptation needs for food security in 2030. Science 319:607–610

Meehl GA, Bony S (2011) Introduction to CMIP5. CLIVAR Exchang 16:2–5

Meinshausen M, Smith SJ, Calvin K, Daniel JS, Kainuma MLT, Lamarque J-F, Matsumoto K, Montzka SA, Raper SCB, Riahi K, Thomson A, Velders GJM, van Vuuren DPP (2011) The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change 109:213–241. doi:10.1007/s10584-011-0156-z

Orlowsky B, Seneviratne SI (2013) Elusive drought: uncertainty in observed trends and short- and long-term CMIP5 projections. Hydrol Earth Syst Sci 17:1765–1781

Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (2007) Climate Change 2007: Impacts, Adaptaton and Vulnerability. Cambridge University Press, Cambridge

Rodell M, Houser PR, Jambor U, Gottschalck J, Mitchell K, Meng CJ, Arsenault K, Cosgrove B, Radakovich J, Bosilovich M, Entin JK, Walker JP, Lohmann D, Toll D (2004) The Global Land Data Assimilation System. Bull Amer Meteor Soc 85(3):381–394

Santanello JA, Peters-Lidard Christa D, Kumar SV (2011) Diagnosing the sensitivity of local land-atmosphere coupling via the soil moisture-boundary layer interaction. J Hydrometeorol 12:766–786

Sheffield J, Wood EF (2007) Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Clim Dyn 13(1):79–105. doi:10.1007/s00382-007-0340-z

Simelton E, Fraser EDG, Termansen M, Benton TG, Gosling SN, South A, Arnell NW, Challinor AJ, Dougill AJ, Forster PM (2012) The socioeconomics of food crop production and climate change vulnerability: a global scale quantitative analysis of how grain crops are sensitive to drought. Food Sec 4:163–179

Stouffer RJ, Taylor KE, Meehl GA (2011) CMIP5 long-term experiment design. CLIVAR Exch 16:5–7

Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. Bull Amer Meteor Soc 93(4):485–498

Wang G (2005) Agricultural drought in a future climate: results from 15 global climate models participating in the IPCC 4th assessment. Clim Dyn 25:739–753

Wang A, Lettenmaier DP, Sheffield J (2011) Soil moisture drought in China, 1950-2006. J Clim 24(13):3257–3271. doi:10.1176/2011JCLI3733