Spatial Trends of AMSR-E Soil Moisture across Agro-Climatic Zones of Pakistan 2003-2010

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Abstract

This study has been conducted to assess the spatial trends of soil moisture across different agro-climatic zones of Pakistan in the recent decade. The analysis have been performed annually and in the cropping seasons i.e. Kharif and Rabi using available monthly soil moisture AMSR-E satellite data from 2003-2010. The monthly precipitation and temperature (mean, maximum and minimum) data has also been analyzed during the study period. The AMSR-E has strong correspondence with observed precipitation records across Pakistan. The annual analysis showed significant decreasing trends of soil moisture in agriculture fields (sub humid – arid) from 2003-2010. The Kharif season soil moisture variability is closely associated with the monsoon precipitation (Jul-Aug) in the rain fed areas of Pakistan. The Kharif cropping season analysis has shown the increasing trends of soil moisture in the years (2003, 2005, 2006 and 2010) when substantial amount of monsoon precipitation occurred in the rain fed (humid-semi arid) areas of Pakistan. However, noticeable decreasing trend of soil moisture has been observed during 2004 and 2009 when monsoon precipitation was suppressed during Kharif season. The Rabi season analysis initiate just after the Kharif season and availability of soil moisture is equally vital for the sowing period. The Rabi season analysis showed the increasing trends of soil moisture from 2003-2010 with the exception of 2004 and 2009 in which slight decrease in soil moisture has been found in the agriculture cropland (semi arid- arid). It has been noticed that success and failure of monsoon generally affects the amount of soil moisture both annually and seasonally. Therefore it is expected that the erratic precipitation patterns may enhance the soil moisture stress in agriculture lands of Pakistan leading to agriculture drought.

Key Words: Soil moisture, AMSR-E, precipitation, Kharif and Rabi

Introduction

Soil moisture is an important component of global hydrological cycle. It plays an essential role in the interaction between the land and atmosphere. The level of saturation in the surface layer of soil relative to the soil field capacity describes the soil moisture which is controlled by rainfall and potential evaporation. Soil moisture act as water storage between precipitation which regulates the rate of infiltration and run off production. Soil moisture is a main source of natural water resources for agriculture and natural vegetation. Near-surface soil moisture controls the energy available at land surface and converts it into the sensible and latent heat. The condition of soil temperature and soil moisture then links these exchanges with the atmosphere and water-energy balances. The linkage of evaporation and transpiration is necessary with the distribution of soil moisture to predict the combined influence of land surfaces to weather and climate (Robock et al., 2000).

Soil moisture determines the availability of water as well as the water holding capacity of the soil. Thus, it significantly controls the rates of exfiltration and evaporation. The surplus amount of soil moisture conditions enhances the net solar radiations and transfers the sensible and latent fluxes heat from the surface in to the boundary layer which in result produce precipitation. The role of soil moisture in rainfall dynamics using general circulation models (GCMs) have been discussed in various studies (Yeh et al., 1984; Oglesby and Erickson, 1989; Oglesby, 1991 and Pan et al., 1995). These studies show that the soil moisture changes during early summer, may influence the summer rainfall over the land significantly. The access in the quantity of soil moisture results in relatively more amount of rainfall which support the soil moisture-rainfall feedback (Eltahir, 1998).

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Recently the research across many disciplines (agriculture, hydrology and ecology etc) is focusing soil moisture and the processes interacted with it. Soil moisture affects the rate of nitrification (Boyer et al., 2006), hydrologic processes (D'Odorico et al., 2000) and interaction of plants to atmosphere (Rodriguez-Iturbe, 2000). Lawrence, 2007; Fernandez and Ceballos, 2003 calculated the variability of soil moisture using time-domain refectometry (TDR) neutron probes and gravimetric analysis.Teuling and Troch, 2005 developed a soil moisture variability dynamics model which describes the variations in soil and vegetation properties. The variability in soil moisture is absolutely handled by the temporal variability by atmospheric conditions and spatial variability in land-surface conditions (Lawrence and Hornberger, 2007).

The soil moisture is also considered to be one of the best drought indicators at global and regional scales. The soil moisture trends over the global terrestrial areas, excluding Greenland and Antarctica from 1950-2000 have been analyzed by Sheffield and Woods, in 2007. Globally the soil moisture trends showed positive (wetting) trends due to the forced precipitation particularly in North America over the Western Hemisphere, Australia, Europe and Western Asia but negative trends (drying) occur in Africa and parts of Eastern Asia. However, Regional deviation is quite evident; the West Africa is facing significant drying driven by decreasing precipitation. On the contrary no significant variation in soil moisture has been experienced in Europe and South East and Southern Asia from 1950-2000 (Sheffield and Woods, 2007).

The IPCC 15 global climate models project the consistent summer dryness and winter wetness in merely fraction of the northern middle and high latitudes. More than half models predict constant wetness in central Eurasia and dryness in Siberia and mid-latitude Northeast Asia. In tropics and subtropics the decrease in soil moisture is a dominant. The drier soil is predicted in all the seasons over the southwest North America, Central America, the Mediterranean, Australia, and the South Africa. This decrease in soil moisture is also predicted over Amazon and western Africa in JJA and during DJF in the Asian monsoon region (Wang, 2005).

Satellites are also well capturing the soil moisture changes in the surface layer of the soil. These include Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E), Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager and Soil Moisture and Ocean Salinity (SMOS) mission. The AMSR-E microwave signals can penetrate into the clouds and has direct relation with the soil moisture through soil dielectric and it is less sensitive to the surface roughness and vegetation. The National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) launched the project Advanced Microwave Scanning Radiometer–Earth Observing System (AMSR-E). AMSR-E was the first satellite which includes soil moisture as a standard product. The validation of AMSR-E soil moisture has been done using in situ soil moisture data (Jackson, 2010). Draper et al., 2008 evaluated the AMSR-E derived soil moisture over Australia.

Pakistan has very large population, agriculture based economy and high vulnerability index to natural disasters. Majority of the people earn their bread and butter through agriculture yield annually and seasonally (Kharif and Rabi). The excess and deficit of soil moisture adversely affect the crop yield as it is a key component of biogeochemical cycles, irrigation schedule management and in generating floods and drought. Despite of its importance the in situ measurement of soil moisture is very difficult and requires resources both human and financial. The in situ data of soil moisture is not available for Pakistan therefore AMSR-E satellite data has been considered as the best alternative to evaluate the trends of soil moisture in Pakistan. The present study investigates the spatial trends of soil moisture on annual basis and in cropping seasons i.e. Rabi and Kharif across the climatic zones of Pakistan over the period 2003-2010. The available AMSR-E soil moisture data has been used. The intent of the study is to mostly emphasis on the soil moisture variability in the agriculture lands and factors influencing it. The result of study will reveals the changes in surface layer soil moisture annually and in cropping seasons across different climatic zones of Pakistan.

Data and Methodology:

The monthly satellite data of AMSR-E for the ground surface soil moisture has been obtained from the link https://gcom-w1.jaxa.jp for the period 2003-2010. AMSR (Advanced Microwave Scanning Radiometer) is multi-frequency, dual-polarized microwave radiometer that detects microwave emissions from the Earth's surface and atmosphere. Various geophysical parameters, particularly those related to water (H2O), can be estimated from AMSR data. In addition to the proven parameters such as water vapor, precipitation, and sea surface wind speed, novel geophysical parameters, including sea surface temperature and soil moisture, are expected to be retrieved by using new frequency channels. The largest ever microwave radiometer antenna enables AMSR to perform continuous global observation with high spatial resolution (Koike et al., 2004). The real time monthly data of precipitation, maximum temperature, minimum temperature and mean temperature has also obtained from data archives of Pakistan Meteorological Department for the duration 2003-2010. The percentage change soil moisture anomalies have been calculated by subtracting and dividing the actual values of soil moisture with the 2003-2010 mean appropriate values and then multiplying it by 100. The study domain covers all the climatic zones of Pakistan ranging from hyper arid to humid one. The land use map and crop growth classes of Pakistan is shown in Figure 1.The spatial annual and cropping seasons (Rabi and Kharif) analyses have been done to investigate the variability and trends of soil moisture across climatic zones of Pakistan from 2003-2010. The data for the study domain has been extracted via GrADS (Grid analysis and Display System) and then mapping has been done using ArcGIS 9.3. The statistical significance has been calculated at 95% confidence level by applying the Mann Kendall test in R –Software.

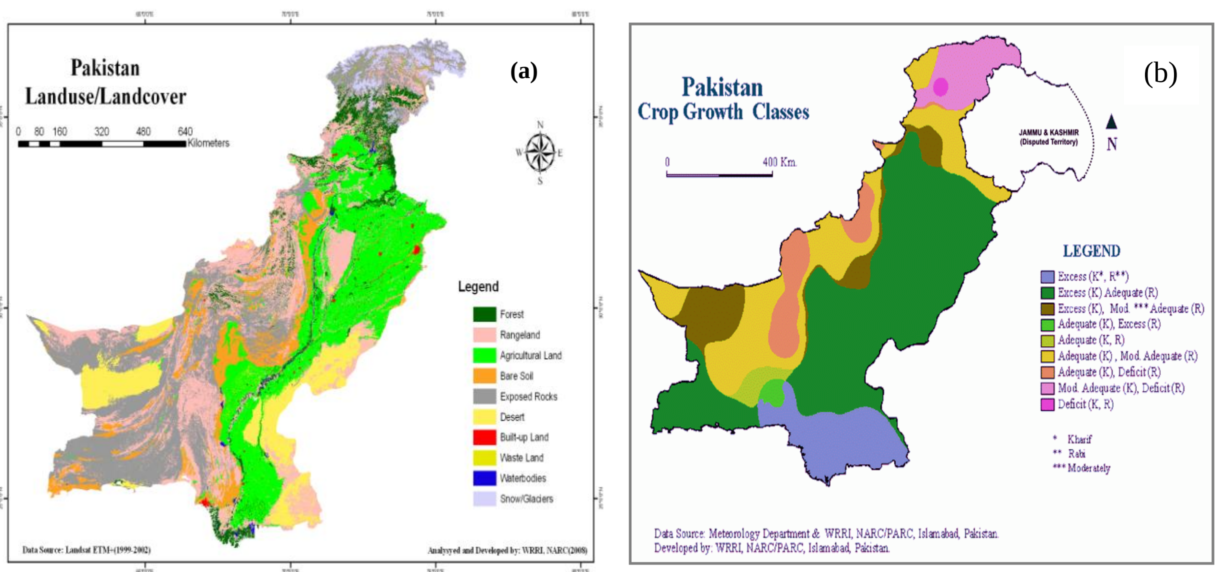

Figure 1: (a) Pakistan Landuse/Landcover **(b)** Pakistan Crop Growth

Climatic Zones of Pakistan:

Pakistan experiences various types of climates that range from arid to humid. The total area lies under arid zone is about 3/4th and humid climate covers a very small patch. The water scarcity is the major limiting factor in the arid and the semi-arid zones and is highly responsible for good or bad crop-production while erratic and excessive rains are the principal constraint in the sub-humid and the humid zones. The areas located between 33°N and 35°N latitude, are considered to be the best for food-crop production due to rain fed conditions. Above and below these latitudes, the agricultural production is possible only when supplementary irrigation is made available. The agricultural plains of Pakistan are located at altitudes ranging from a few meters above mean sea-level in the south to more than 3,000 meters in the north (Figure 1).The climatic zones of Pakistan on annual basis, during rabi and Kharif are shown in the Figure 2 (Chaudhry and Rasul, 2004).

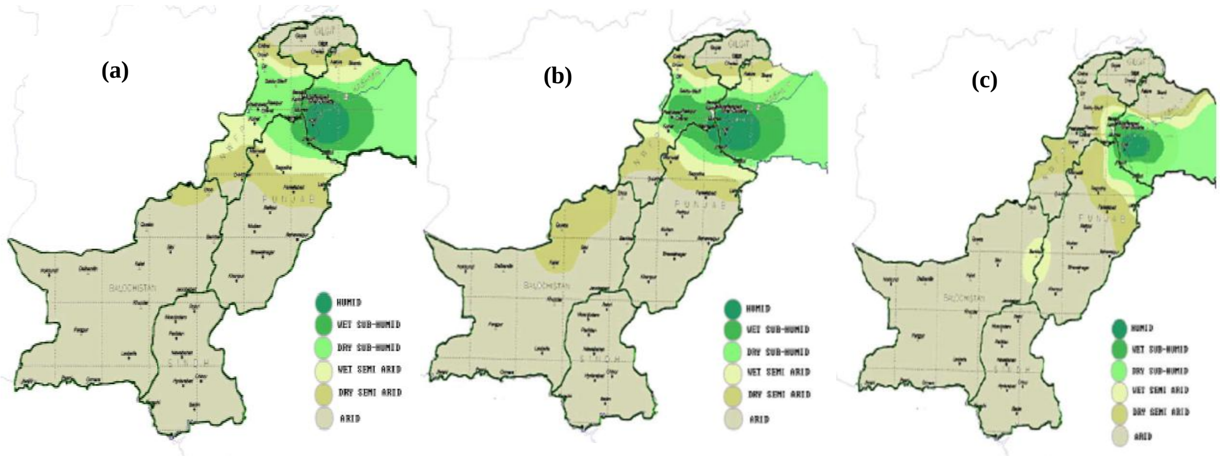

Figure 2: Climatic Zones of Pakistan **(a)** on Annual basis **(b)** during Rabi and **(c)** during Kharif

Climatology of Pakistan from 2003-2010

The climatology of Pakistan has been investigated by drawing trends of monthly precipitation, mean temperature, maximum temperature and minimum temperature during the study period to link the soil moisture variability with them. The monthly precipitation of Pakistan from 2003-2010 have been

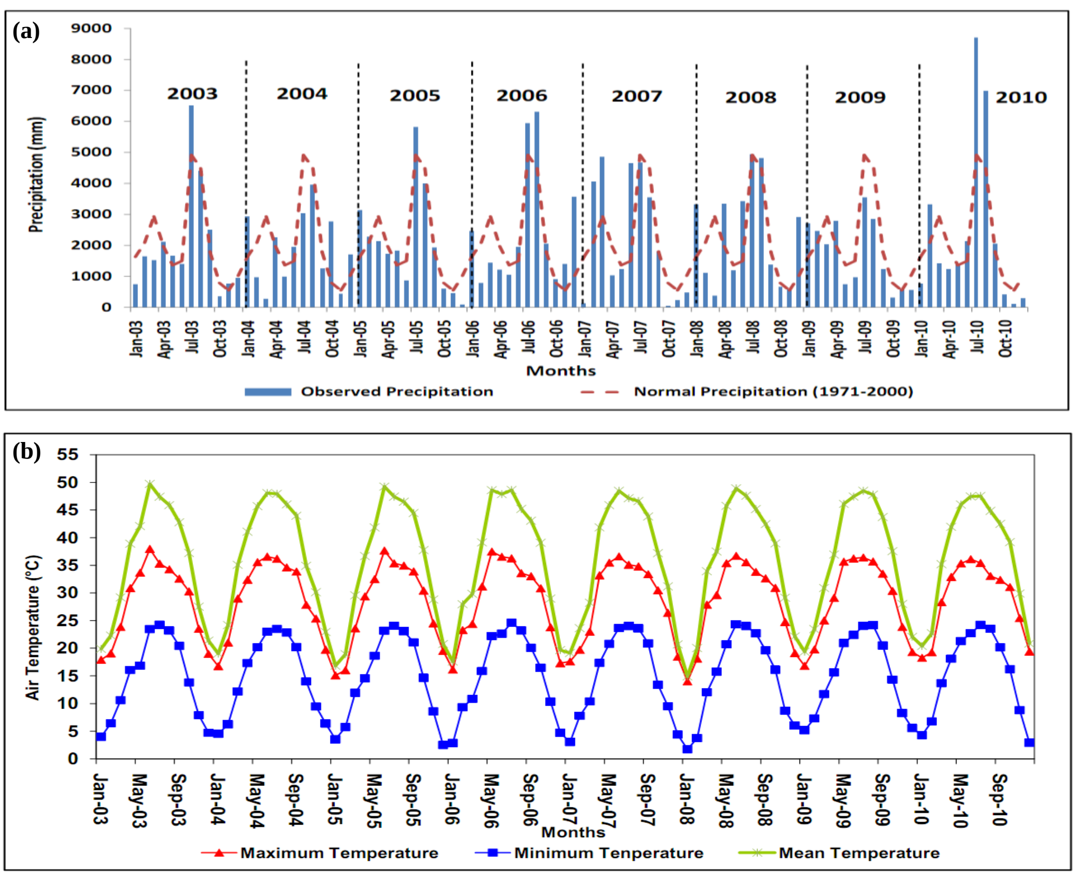

Figure 3: Climatology of Pakistan from 2003-2010 **(a)** Monthly precipitation
(b) Maximum, minimum and mean temperature

illustrated in Figure 3a. The normal precipitation trend from 1971-2000 have also been drawn to see the above and below normal rainfall years. The substantial amount of precipitation has been experienced in 2003, 2005, 2006 and 2010 and scanty amount of precipitation has been analyzed in 2004 and 2009. The normal amount of precipitation has been seen in 2007 and 2008. The maximum amount of precipitation received during each year is the month of July and August due to the onset of monsoon in Pakistan. The monsoon is the major source of water in Pakistan and thousands of people livelihood and the agriculture yield depend upon it. The above normal winter (DJFM) precipitation has been viewed in 2007.

The monthly mean, maximum and minimum temperatures have been plotted in graph is shown in Figure 3b. The cyclic trends of temperature (mean, maximum and minimum) are almost same it decreases from October to March and increases from April to September. The peak mean, maximum and minimum temperature has been observed during June, July and August each year. The rise in temperature not only cause early maturity of plants but also responsible for the wilting of plants in water scarcity areas adversely affecting the crop yield. The global warming has raised the temperature around the globe threatening the irrigation and agricultural practices in developing countries. The year 2010 has been declared as the hottest year on the globe by world meteorological organization (WMO). The climate has become unpredictable, elevated temperatures are making the hydrological cycle vigorous not only by changing the precipitation patterns but also varying the surface layer soil moisture trends which is a vital element of hydrological cycle. This change in temperature and precipitation patterns is quite lethal for agriculture lands of Pakistan.

Results & Discussion

Annual Spatial Trends of Soil Moisture 2003-2010

The annual spatial trends of AMSR-E ground surface soil moisture show variation in each year across the climatic zones over the time domain i.e. 2003-2010 (Figure 4). The soil moisture anomalies show

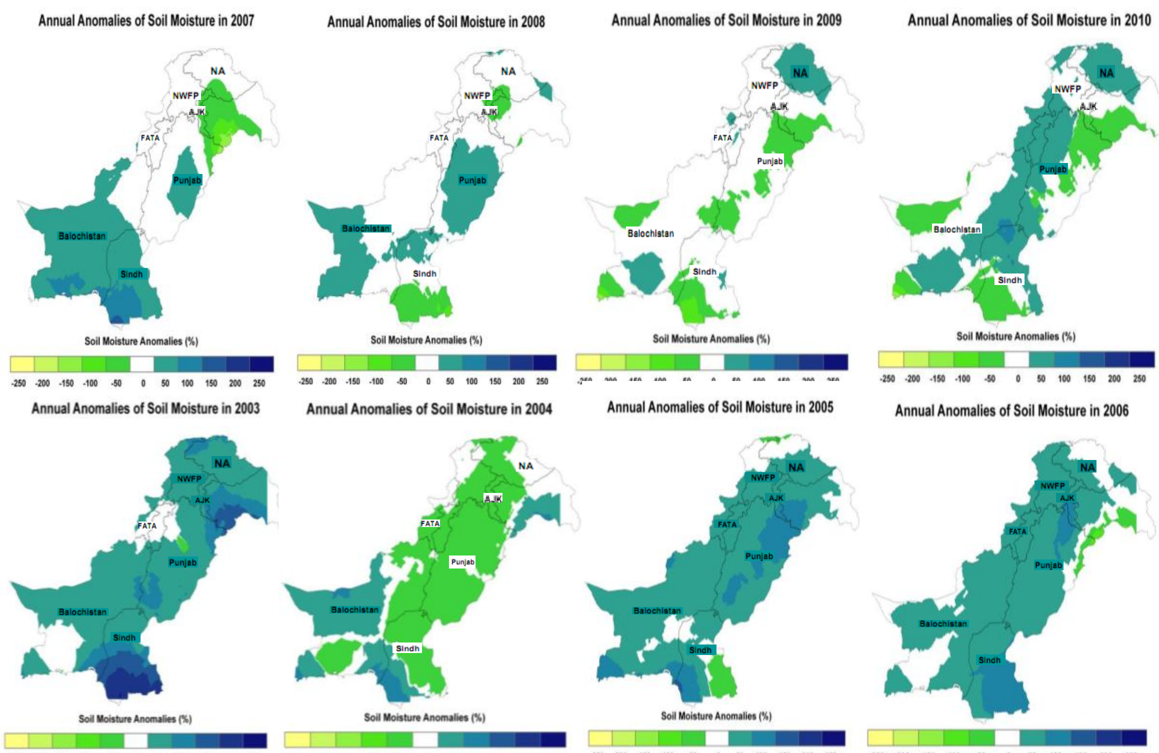

Figure 4: Annual trends of soil moisture in Pakistan from 2003-2010

increasing trends in all the climatic zones during 2003, 2005 and 2006 whereas extreme drop in soil moisture has been observed in 2004 and 2009. The southern half of the country which comes under arid zone has shown increase in soil moisture while decrease in humid zone during 2007 and 2008. The excess in soil moisture anomalies have been observed in the areas of Khyber Pakhtunkhwah (sub humid to semi arid climate), western Punjab (arid climate), eastern Balochistan (arid climate) and Northern Sindh (arid climate) while deficit in soil moisture over the monsoon belt (Potohar region), southern Sindh (arid climate) and western Balochistan (arid climate) have been experienced during 2010. Figure 3a depicts the amount of monthly rainfall in each year, and it has been noticed that the years with above normal rainfall are 2003,2005,2006 and 2010 while below normal rainfall are 2004 and 2009. The years of normal precipitation are 2007 and 2008. It has also been noted that there is a strong positive correlation between precipitation and soil moisture as most of the areas of Pakistan show increase in soil moisture during the years when it experience excessive or above normal rainfall. However the years (2007 and 2008) when the precipitation remains close to normal only enhance the amount of soil moisture in the southern half of the country particularly in arid zones. While extreme fall in amount of soil moisture have been observed during the suppressed rainfall years 2004 and 2009. The positive correlation has also been found between mean, maximum and minimum temperatures and soil moisture. The increase in temperature increases the rate of evaporation from soil resulting in soil moisture deficiency. The temperature remains above normal in 2004 and 2009 causing the extreme fall in surface layer soil moisture. The surface layer soil moisture is the most important indicator of irrigation scheduling, pest management, biomass production, floods and drought forecasting. So it is an essential element whose abundance or deficiency adversely affects the cultivation. The overall annual spatial trends of soil moisture depict the decreasing trend in the agriculture land which is statistically significant.

Spatial Trends of Soil Moisture for Kharif (May-Sept) 2003-2010

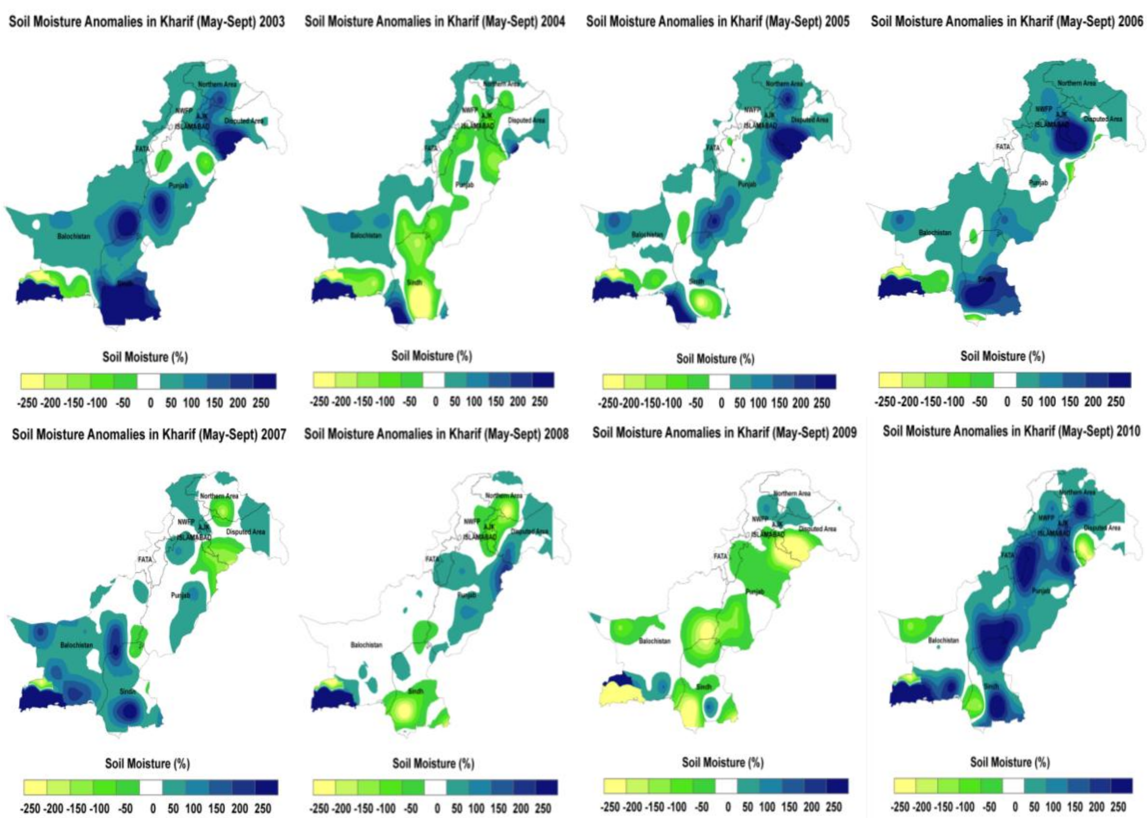

Figure 5: Trends of soil moisture during Kharif (May-September) in Pakistan from 2003-2010

The Kharif season starts with the driest month i.e. May and June every year. Cotton, rice and sugarcane are the important field crops. The July to September is the period when monsoon prevails in Pakistan and due to rainfall the soil moisture stress reduces slightly in land. The agriculture fields for Kharif crops usually vary from humid climate in rain fed areas to arid climate in the southern half of the country. The hottest months in Pakistan are from May to August which is the Kharif crop growing season. The monsoon currents plays an important role in Kharif season as it brings with them moisture thus reducing the rate of evaporation due to high level of humidity in the atmosphere. The soil moisture stress remains moderate in rain fed areas which are usually humid and situated in the northern half of the country. The soil moisture stress increases in the southern half of the country where the scanty amount of rainfall occur and the high temperatures enhances the rate of evapotranspiration during Kharif season.

The spatial trends of soil moisture for the Kharif (May-Sept) season have been drawn to investigate the variability of soil moisture in cropping season from 2003-2010. Figure 5 clearly shows a noticeable statistically significant decrease in soil moisture have during 2004 and 2009 when the monsoon precipitation remained suppressed due to ENSO event. The rise in temperature can also be associated with this as incase of precipitation failure the heating of land increase the rate of evapotranspiration resulting in soil moisture stress. The adequate soil moisture is very important before sowing of crops and if the rain showers delays or dry spells prolong, it causes the late planting of crops which may affect the yield and delay the sowing of next crop. The analysis shows the increase in soil moisture in agriculture lands of Pakistan during the Kharif season in 2003, 2005 and 2006. The monsoon precipitation remained above normal during these years as shown in Figure 3a but in 2010 although flooding situation occurred in the country during the month of July and August but still decrease in soil moisture has been experienced in some rain fed areas. This is due to the change in monsoon track, all the monsoon precipitation shift westward and took place in Khyber h areas and flooded the whole country. The slight stress in soil moisture has also been noticed during 2007 in the rain fed zones of upper Punjab. In 2008 no noticeable stress in soil moisture has been seen except in lower Sindh and Azad Jammu and Kashmir areas during the Kharif season. It has been examined that the increasing and decreasing trends of soil moisture during the Kharif season varies generally with the fluctuation of monsoon rainfall. Therefore monsoon failure and success is the best indicator for the absence and presence of soil moisture in the field.

Spatial Trends of Soil Moisture for Rabi (Oct-Apr) 2003-2010

The Rabi season commences with the Kharif harvest i.e. starting from October and ends in April every year. Wheat is the major food-crop of Rabi season and an essential element of food required by the population in Pakistan. The driest month in Rabi season is October and November. The winter rains i.e. from December to March are solely responsible to provide the soil moisture during Rabi season. The wheat crop production has been done in the almost entire Punjab (sub humid-arid), some parts of western Sindh (arid areas) and eastern Balochistan (arid zones) along the plains of Indus River. The lack of availability of soil moisture during the post monsoon period is the biggest constraints for the good yields of Rabi crops. The soil moisture is highly significant for stabilized and better production of winter rain fed crops. The October to November is a transition period in which the chances of rainfall after sowing are very low. Therefore, the soil moisture at sowing stage mostly determines the productivity of Rabi crops with good weather conditions prevailing subsequently.

The spatial trends of soil moisture for Rabi season from 2003-2010 depicts the increase in soil moisture in almost all the regions of Pakistan during the study period except the years 2004 and 2009. The decrease in soil moisture has been observed in Punjab and upper Sindh during 2004 and 2009 (Figure 6) The most probable reason is the monsoon failure which affected the Rabi crops yield along with Kharif crops yield. These two years were the driest of all from 2003 to 2010. The statistical significance test has been applied to all the Rabi season spatial trends as well to analyze the level of significance of trends and it has been found that the variability of soil moisture is statistically significant at 95% confidence level.

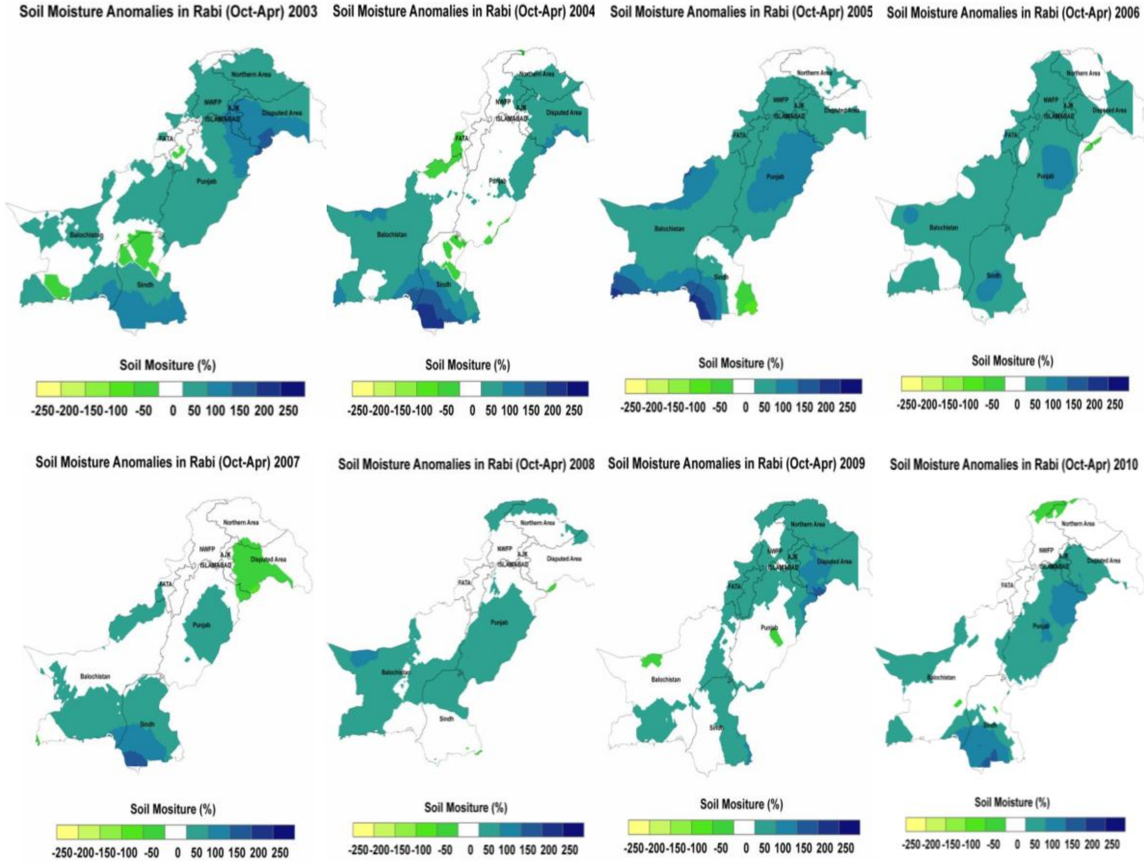

Figure 6: Trends of soil moisture during Rabi (October-November) in Pakistan from 2003-2010

It has been noticed that the soil moisture trends are more diverse for Kharif season as compared to Rabi season most probably due to temperature and precipitation fluctuations during the study. The Kharif season is more susceptible to drought and floods events than Rabi season. The stress in soil moisture during Kharif is apparent in years when the monsoon precipitation fails leading to the intense heating of arid agriculture lands. Rabi season has not shown any major soil moisture deficit in the domain of crop fields. Thus we may infer from the results that the Kharif crops yield is quite vulnerable and at stake due to the climate change. Therefore more planning and strategies is imperative to deal with the soil moisture changes during Kharif season. The farmers must be introduced to the improve varieties of drought and temperature tolerant crops and the strong irrigation management is required to cope up with the forthcoming challenges in agricultural sector.

Conclusion

The annual spatial analysis of ground surface soil moisture have shown decreasing trend in 2004 and 2009 and increasing trend in 2003, 2005, 2006 and 2010 across the climatic zones during the study period. The positive correspondence has been observed between precipitation and variability of soil moisture from 2003 to 2010. The increase in soil moisture has been observed during the years with significant precipitation (2003, 2005, 2006 & 2010) while drop in soil moisture has been experienced in suppress precipitation years (2004 and 2009). There are two cropping seasons in Pakistan i.e. Kharif (May-September) and Rabi (October –April). The sufficient soil moisture availability before the sowing season is very important for both the cropping seasons. The Kharif season analysis has also shown the high variability in soil moisture in different regions of Pakistan. The stress in soil moisture has been observed in the rain fed zones during 2010, 2008, 2007 and extreme decrease has been seen in 2004 and 2009. The sufficient soil moisture has been experienced in 2003, 2005 and 2006.The availability of soil moisture strongly relates the monsoon precipitation (Jul-Aug) during Kharif season. Therefore decreasing trends of soil moisture have been observed from 2003-2010 during Kharif in Pakistan. The increasing trends of soil moisture have been shown in most of the regions of Pakistan during the Rabi season from 2003-2010. However, the slight decrease in soil moisture in Punjab and upper Sindh occurred in 2004 and 2009 during Rabi season. The study concludes that the 2004 and 2009 were the crucial years for Pakistan agriculture lands when soil moisture stress increases not only annually but seasonally (Kharif and Rabi) as well. Most of the agriculture land southwards of Pakistan comes under the arid climate and thus it is anticipated that under the scenario of global warming and climate change the stress in soil moisture during the cropping season may enhance and leads to the agriculture drought.

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