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SATELLITE BASED ASSESSMENT OF SOIL MOISTURE AND ASSOCIATED FACTORS FOR VEGETATION COVER: A CASE STUDY OF PAKISTAN AND ADJOINING REGIONS

IMRAN AHMED KHAN[1], MUDASSAR HASSAN ARSALAN[2], LUBNA GHAZAL[1], MUHAMMAD FAHEEM SIDDIQUI[3], MOHAMMED RAZA MEHDI[4], IBRAHIM ZIA[5] AND IRAM US SALAM[6]

[1]*Department of Geography, University of Karachi, Karachi 75270, Pakistan*
[2]*Geoinformatics and Sustainable Development Research Lab, Institute of Space and Planetary Astrophysics, University of Karachi, Karachi 75270*
[3]*Department of Botany, University of Karachi, Karachi 75270, Pakistan*
[4]*Department of Urban & Infrastructure Engineering, NED University of Engineering, Karachi 75270, Pakistan*
[5]*National Institute of Oceanography, ST.47, Block 1, Clifton, Karachi 2E8 Pakistan*
[6]*Department of Botany, Federal Urdu University for Arts, Science & Technology, Karachi-75000, Pakistan*
[*]*Corresponding author's email: imranak32@hotmail.com*

Abstract

Soil Moisture is a vital requirement for plant growth and its measurement with laboratory instruments is still limited to micro-geographic levels only. However, Satellite remote sensing happens to be efficient for macro scale measurements at regional levels. Soil Moisture depends on factors such as rainfall, temperature, rate of surface run-off and evapotranspiration. To develop a deeper and clearer insight into the interrelationship of these dependent factors, the Remote Sensing (RS) technology is being effectively employed in this study for assessing the seasonal and their inter-annual variations. A Standard NASA GES DISC product of Global Land Data Assimilation System (GLDAS) based on the mathematical algorithms of satellite model data has been employed for this investigation. The data pertaining to Pakistan and adjoining areas was collected for soil moisture, soil temperature, rainfall, surface run-off and total evapotranspiration over the year from January to December 2014 and quarterly from April to June, July to September and October to December. Composite and Seasonal maps as well as time series graphs were used throughout the process. Results for all variables clearly indicate that in high altitude areas, almost every variable has relatively higher values. It was concluded that spatial variations in soil moisture are quite reliant upon land cover types and the amount of precipitation (rainfall).

Key words: Soil, Soil moisture, Soil temperature, Evapotranspiration, Surface run-off, Rainfall, Remote sensing of soil, Soil of Pakistan.

Introduction

Global hydrological cycle has several components and soil moisture is one of the important components of this system. It has an essential role of interaction between the land and atmosphere. The level of infiltration in the surface layer of soil relative to the soil field capability illustrates the soil moisture which is controlled by rainfall and potential evaporation. Soil moisture regulates the rate of infiltration and runoff production as it act as water storage between precipitations. It is also a main natural water resource for agriculture and natural vegetation. Near surface soil moisture controls the energy available at land surface and modifies it into the sensible and latent heat. Soil temperature and soil moisture has an association of energy interactions through the atmosphere and water-energy balances (Petropoulos, 2013; Gitelson *et al.,* 2015).

Water is said to be a precious resource for each and every sector of economy at global and regional scale.In countries with agro-based economy, management of land resources such as soil and water is indispensable (Ghazal & Kazmi, 2014)**.** Pakistan is an agricultural country but it is highly prone to natural disasters as it is amongst the high vulnerability indexes countries of the World (Kreft *et al.,* 2013).The majority of the people earn their basic earnings and fulfill their needs through agricultural Production of seasonal crops *i.e.* Kharif (monsoon crop) and Rabi(winter crop).

For vegetation and its normal growth soil moisture is one of the major controlling factors especially in the regions of semi-arid climates. There are two main types of soil moistures *i.e.* surface soil moisture and root zone soil moisture. Surface soil moisture is actually described as the existence of water quantity in the upper 10cm of soil, whereas the root zone soil moisture is the water that is available to plants, which is generally considered being present at the depth of 10 to 200 cm of soil (Scott *et al.*, 2003). However, soil profiles water content is adjusted with rainfall distribution, soil capillarity and drainage, surface run-off, rate of evapotranspiration, and irrigation etc. (Santos *et al.*, 2014).

Soil moisture is one of the main factor that affect plant's early development and liable for its strength (Magagi & Kerr, 2001; Wang *et al.*, 2007, Petropoulos *et al.*, 2015). However, the high spatial and temporal variability of soil moisture is mainly influenced by various factors such as the heterogeneity of soil texture, topography, vegetation type, and climate, thus in the natural environment, soil moisture is complicated to measure (Koster *et al.,* 2004; Kong *et al*., 2011). Additionally, soil moisture is a key factor in determining the annual growth of natural environments and human systems (Chen *et al.,* 2014). In plant and vegetation situations soil moisture information can be vital support in making decisions regarding plant variety choice, irrigation needs, and the timing of various farming and gardening activities (Andrew *et al.*, 2014).

Scientific progress and improvement in satellite remote sensing have offered a variety of methods to estimate surface soil water content as a key variable in numerous environmental studies (Kim & Hong, 2007; Petropoulos, 2013, Sadeghi *et al.*, 2015; Khan *et al.*, 2016). Optical methods are particularly valuable for remote sensing of soil moisture since reflected solar radiation is the strongest passive signal available to satellites and thus observations at optical wavelengths are capable of providing high spatial resolution data. Since remote sensors do not measure soil water content directly, mathematical algorithms and models that describes the connection between the measured signal and surface water content (Scott *et al.*, 2003; Bastiaanssen & Ali, 2003; Laiolo *et al.*, 2014, Petropoulos *et al.*, 2015). For the last 30 years, several international organizations have been engaged in performing research on monitoring soil moisture conditions and related factors across the world. Names of some significant remote sensing products/programs are listed Table 1.

The Global Land Data Assimilation System (GLDAS) is generating a series of land surface state (e.g., soil moisture and surface temperature) and flux (e.g. evaporation and sensible heat flux) products simulated by four land surface models: Mosaic, Noah, the Community Land Model (CLM), and the Variable Infiltration Capacity (VIC) (Table 2). These products can be accessed at the Hydrology Data and Information Services Center (HDISC), a component of the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC).

Materials and Methods

Study area: Pakistan is divided into six major topographical regions, namely Northern and North-Western Mountains, Western Mountains, The Balochistan Plateau, The Potwar Plateau and Salt Range, The Indus Plain and Desert areas. Almost 60% of Pakistan's total land area is classified as unusable for agriculture or forestry as it consists of deserts and mountainous areas. The soils of Pakistan are mostly arid and have high concentrations of calcium carbonate and a low content of organic matter. Each region has particular soil types that have different ability to percolate and store water. Fertile soils of Indus Basin is made up of deposit fine sediments of sand silt and clay and found along the current course of the Indus River. Following are the six major groups of soil. However, several subgroups also found (Fig. 1).

Table 1. Soil moisture research program or products.

S. No.	Program/ Data products	Web links
1.	The advanced scatterometer (ASCAT)	http://www.eumetsat.int/Home/Main/News/Features/708786
2.	The Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E)	http://nsidc.org/data/docs/daac/ae_land3_l3_soil_moisture.gd.html
3.	ESA's Soil Moisture Ocean Salinity (SMOS)	http://www.esa.int/esaMI/smos/
4.	International Soil Moisture Network (ISMN) (in situ data)	http://www.ipf.tuwien.ac.at/insitu/
5.	Global Land Data Assimilation System (GLDAS)	http://ldas.gsfc.nasa.gov/gldas/
6.	USGS (Africa)	http://earlywarning.usgs.gov/fews/africa/index.php
7.	Modern-Era Retrospective analysis for Research and Applications (MERRA)	http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=MERRA_MONTH_2D
8.	the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT)	http://www.eumetsat.int/website/home/index.html
9.	National Snow and Ice Data Center (NSIDC)	https://nsidc.org/data/amsr_validation/soil_moisture/index.html
10.	National Environmental Satellite, Data, and Information Service (NESDIS)	https://www.nesdis.noaa.gov/
	NOAA Environmental Visualization Laboratory	https://www.nnvl.noaa.gov/view/globaldata.html#SOIL
11.	NOAA Climate.gov	http://www.ospo.noaa.gov/Products/land/spp/sharedprocessing.html#SM
12.	ARCGIS GEOSS Water Services	http://www.arcgis.com/home/webmap/viewer.html?webmap=43a5de9f17a3441bb1cc72779cf810df
13.	Soil Moisture Active Passive Data (SMAP)	https://nsidc.org/data/smap/smap-data.html
14.	Soil Moisture Operational Products System (SMOPS)	http://www.ospo.noaa.gov/Products/land/smops/

Table 2. Global land data assimilation system (GLDAS) versions and its models.

GLDAS	GLDAS Version 1	1. CLM Model 2. Mosaic Model 3. NOAH Model 4. VIC Model	GLDAS-1 forcing data sources were switched several times, over the record from 1979 to present, which introduced unnatural trends and resulted in highly uncertain forcing fields in 1995-1997. More information about the GLDAS-1 forcing data is available at http://ldas.gsfc.nasa.gov/gldas/GLDASforcing.php.
	GLDAS Version 2	1. NOAH Model	GLDAS-2 has two components, GLDAS-2.0 and GLDAS-2.1. The main objective for GLDAS-2.0 is to create more climatologically consistent data sets, using the "Global Meteorological Forcing Dataset" from Princeton University, currently extending from 1948 - 2010. GLDAS-2.1 is analogous to GLDAS-1 product stream, with upgraded models forced by a combination of GDAS, disaggregated CMAP, and AGRMET radiation data sets.

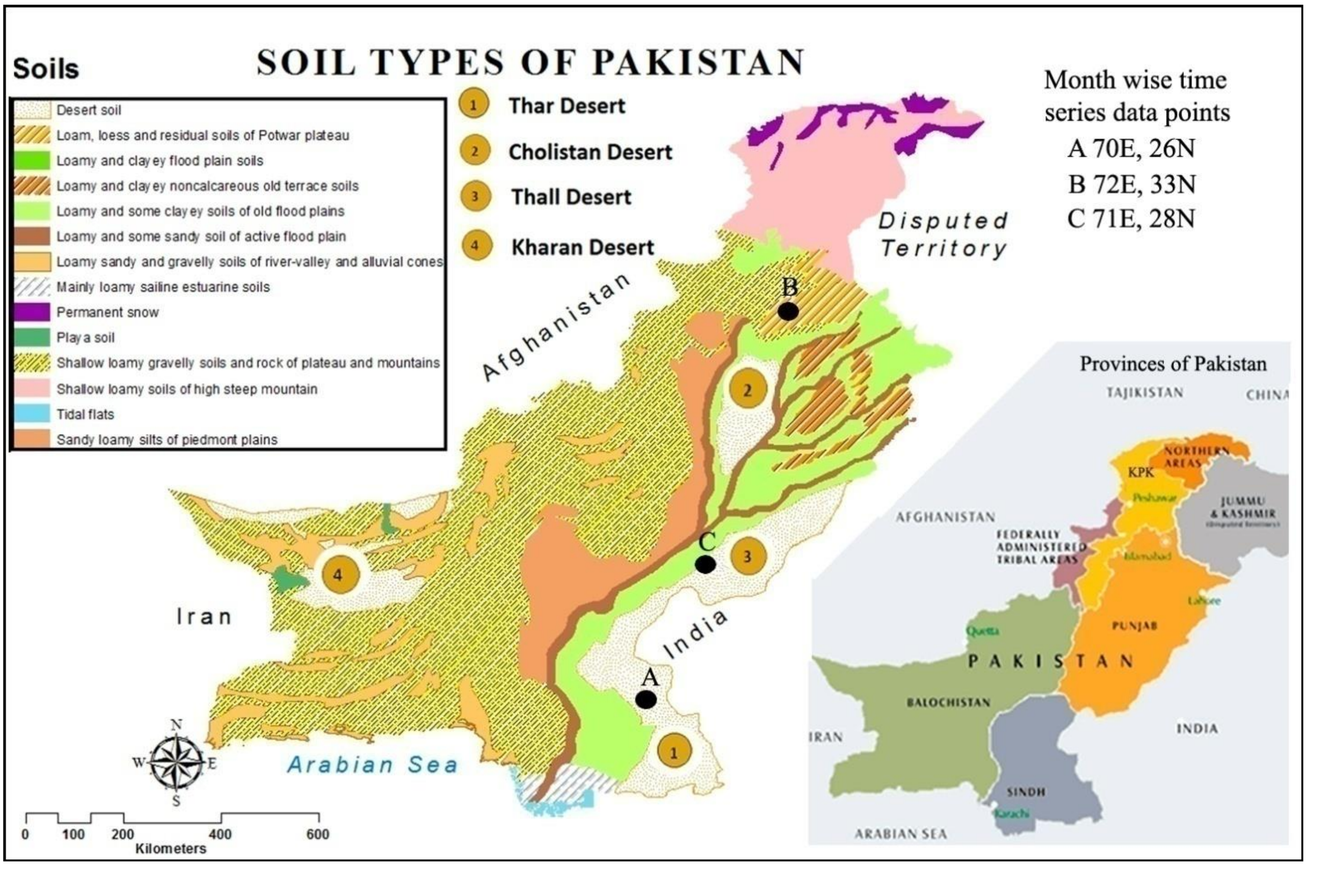

Fig. 1. Soil types in Pakistan.

- The soils which are found in the old flood plain and are best soils for agriculture is locally known as Bhangar Soil.
- Similarly, fresh alluvium of active flood plain found adjacent to rivers is often termed as Khaddar.
- Sandy desert soils are made by the deposition and sedimentation of sand, they are found in the arid and semi-arid areas of Pakistan.
- Sandy loamy silt is found at the foothills of piedmont plains.
- Shallow loamy soil is found in the rocky highlands of northern and western areas of Pakistan.
- Loamy and saline soils cover the current Indus River delta. Most of this soil is very clayey and was developed under seasonal flood waters.

Pakistan has a diverse range of soil and climate characteristics due to variations in topography. It differentiates from mild, moist winters and hot dry summers in the north to arid zones and semi-arid in the west and parts of the south. Mostly in summer monsoon, the part of northeastern mountainous and sub mountainous areas are received more than 1700 mm precipitation. Whereas the arid plains of southwest Balochistan is received only about 30 mm during the whole year. Additionally, thermal regimes indicate extreme diurnal, seasonal and annual variations. For instance, the temperature falls as low as -26°C in the north to as high as 52°C in the central arid plains. Additionally, in the semi-arid plains, temperature up to 42°C is commonly recorded at different meteorological stations in summer. The connection of evaporation and transpiration is vital with the distribution of soil moisture to predict the combined influence of land surfaces to weather and climate (Robock *et al*., 2000). Recently, the research across numerous fields, especially agriculture, hydrology and ecology is being focused on soil moisture and the progressions 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 with atmosphere (Jebellie *et al.*, 1996; Xiaomin *et al*., 2017).

With this background, it is very interesting to explore the relationship between the soil moisture conditions and climate of Pakistan. Therefore, the objectives of the study are to assess the regional scale spatio-temporal variability in soil moisture, its relationship with meteorological factors, and influence of soil type on soil moisture.

Spatial analysis and visualization and GLDAS data extraction: The GES-DISC Interactive Online Visualization and Analysis Infrastructure or **Giovanni** is a Web interface that allows users to perform interactive analysis online without downloading any model data (https://giovanni.gsfc.nasa.gov/giovanni/). Giovanni platform provides interactive, online, analysis tools for data users to facilitate their research. This tool is very useful and multipurpose for model and algorithm scientist, global and regional trends researchers, teachers, students, etc. GES-DISC Giovanni formulates gridded data available in a format that anyone can learn to use within minutes and put to work productively for research or applications. Soil moisture and its allied factor's estimation based on mathematical algorithms satellite model data that come out from the spectral signature of soil (Common Land Model (CLM) V2.0, 1 degree NOAH model).

The spatial coverage of study area was from 57.55° to 80.00° east longitude 17.94° to 43.14° north latitude for study area by using Java scripted spatial coverage tool from Giovanni. We used Lat-Long map, Time-averaged, Correlation map, Scatter plot, Time-averaged maps. We evaluated the data for over the period of year (12 months composite data) from January to December and periodical (quarterly composite data) *i.e*. from January to March, April to June, July to September and October to December in the year 2014.

Five key ecological attributes of plants were focused upon, these are; Soil moisture (layer 1 and 2), soil temperature (layer 1 and 2), rainfall, surface run-off and total evapotranspiration. Two type of assessment has been made one is over the year (Inter-annual variability) other is about temporal three moths evaluation It exhibits following characteristics for Multi-temporal assessments (Seasonal variability).

- Over the year and Multi-temporal (seasonal assessment) soil moistures (layer 1 and 2) pattern analysis
- Over the year and Multi-temporal (seasonal assessment)soil temperature (layer 1 and 2) pattern analysis
- Over the year and Multi-temporal (seasonal assessment) rainfall pattern analysis
- Over the year and Multi-temporal (seasonal assessment) surface run-off pattern analysis
- Over the year and Multi-temporal (seasonal assessment) total evaporation pattern analysis
- Assessment of relationships among variables i.e. rainfall, soil moisture, evapotranspiration and soil temperature data.

For each attribute, spatio-temporal data is used to assess its variability and we also assess relationships among variables (Correlation among variables).

Results and Discussion

Inter-annual variability: Fig. 2 shows the spatial distribution of study variables over the year in 2014; Soil moisture layer 1 and 2 (a and b), soil temperature, rainfall, surface run-off and total evapotranspiration (c-f). All variables clearly indicate that in high altitude areas almost each variable having comparative values, whether high or low, *i.e.* higher values in soil moisture layer 1 and layer 2, lower values in soil temperature, and higher rainfall, runoff and total evaporation rate. Regarding low altitude and plain areas value are gradually low.

Fig. 3a and 3b describe the spatial distribution of soil temperatures of layer 1 and layer 2 respectively. In northern mountainous areas are having low temperature that maintains snow in this region and high temperature in plain areas. Fig. 3c and 3d characterizes the temporal distribution of soil temperatures of layer 1 and layer 2 respectively. The soil temperature seems to have a typical, normal distribution from January to June trend rises whereas June to December exhibits declining trend. A particular correlation trend among soil moisture, rainfall and total evapotranspiration has been noticed. These three variables have two peak values in the months of March-April and during August-September, whereas the lowest values of these variables are seen in the month of June. In order to confirm this situation (having two peak values) time series data of three regions of the study area were later evaluated with half degree square *i.e.* (a) 69.5E to 70E, 26N to 26.5N, (b) 72E to 72.5E, 33N to 33.5N and (c) 70.5E to 71E, 28N to 28.5N(A,B and C location shows in Fig. 1). Resultant graphs can be seen in Fig. 4.

Seasonal variability: In Fig. 5a, 5b, 5c and 4d, spatial distribution of soil moisture of layer 1 soil that is found up to 10 cm depth is shown from January to March, April to June, July to September and October to December respectively. Soil moisture value ranges from 5 kg/m^2 to 50 kg/m^2 and it remains high in northern mountains and some part of the western region. The phenomena are quite clear in the period of January to March, as in these months western depression brings light shower rain in the western margin of Pakistan (Fig. 5a), whereas soils of Punjab and Sindh provinces are exhibited low content of moisture. Similarly October to December are very dry months in the study area so the lowest amount of soil moisture is computed during these months especially in the province of Sindh and Balochistan (Fig. 5d).

Fig. 6 depicts the spatial distribution of soil moisture that is ranging from 10 to 40 cm depth (Layer 2). Quarterly computed average values maps are obtained for three months composite from January to March, April to June, July to September and October to December as shown in Fig. 6a-6d. Generally quarterly computed soil moisture values throughout the study area were ranging between 70 to 80 kg/m^2 while, annual average soil moisture is ranging from 20 kg/m^2 to 150 kg/m^2. Likewise, layer1soil moisture, the layer2 soil moisture values are also higher in the northern parts as compared with the rest of the country. Similarly the plain areas are less moist where lowest average soil moisture is being noticed that is below 40 kg/ m^{2}due to the presence of arid landscape in the form of Thar, Cholistan, Thal and Kharan deserts (Fig. 6a-6d).

The spatial distribution of rainfall for three months composite is shown in Fig. 7, whereas surface run-off is given in Fig. 8. The distribution of rainfall shows that it occurs throughout the year, but unevenly distributed, as most of the rainfall occurs in the northern part of the country. Therefore, with rain fall largely surface run-off takes place in that area. Similarly, with a high rainfall, rate of total evapotranspiration is also high in the northern part of the country refer Fig. 9to observe the spatial distribution of total evapotranspiration from January to March, April to June, July to September and October to December as shown in Fig. 9a, 9b, 9c and 9d respectively.

Correlation: A strong positive association has been estimated among soil moisture layer 1 with soil moisture layer 2, rainfall, surface runoff and total evapotranspiration *i.e.* 0.6, 0.4. 0.3 and 0.5 respectively (Table 3), whereas, soil moisture layer 1 has negative association with soil temperature with both layer 1and layer 2 soil temperatures *i.e.* 0.5which proves that high rainfall regions will have sufficient soil moisture and low soil temperature on contrary low rainfall regions depict high soil temperature and less soil moisture.

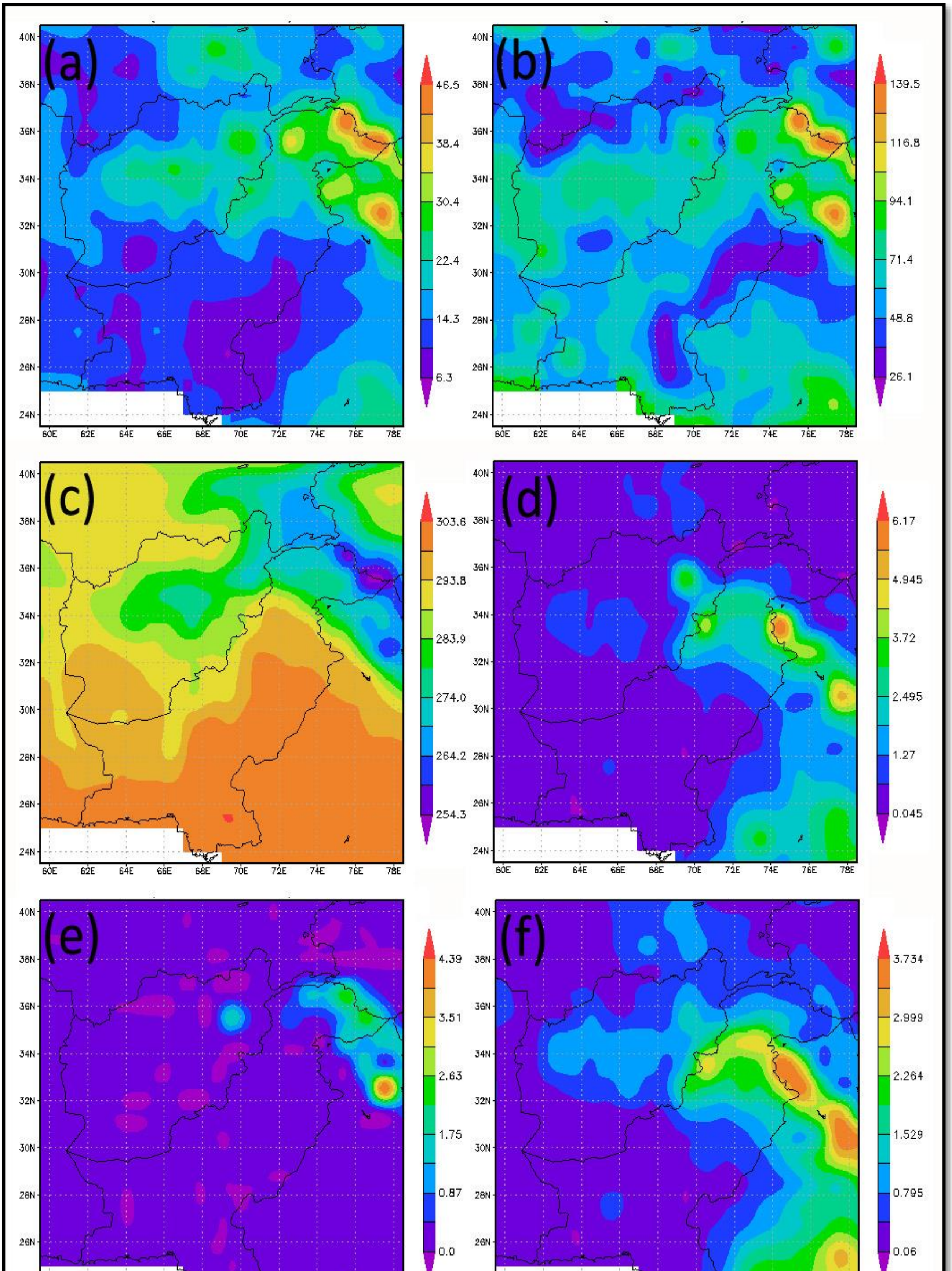

Fig. 2. Spatial distribution of study variables composite over the year in 2014 (a) Layer 1 soil moisture (0 to 10 cm), (b) Layer 2 soil moisture (10 to 40 cm), (c) Soil temperature, (d) Rainfall, (e) Surface run-off, (f) Total evapotranspiration.

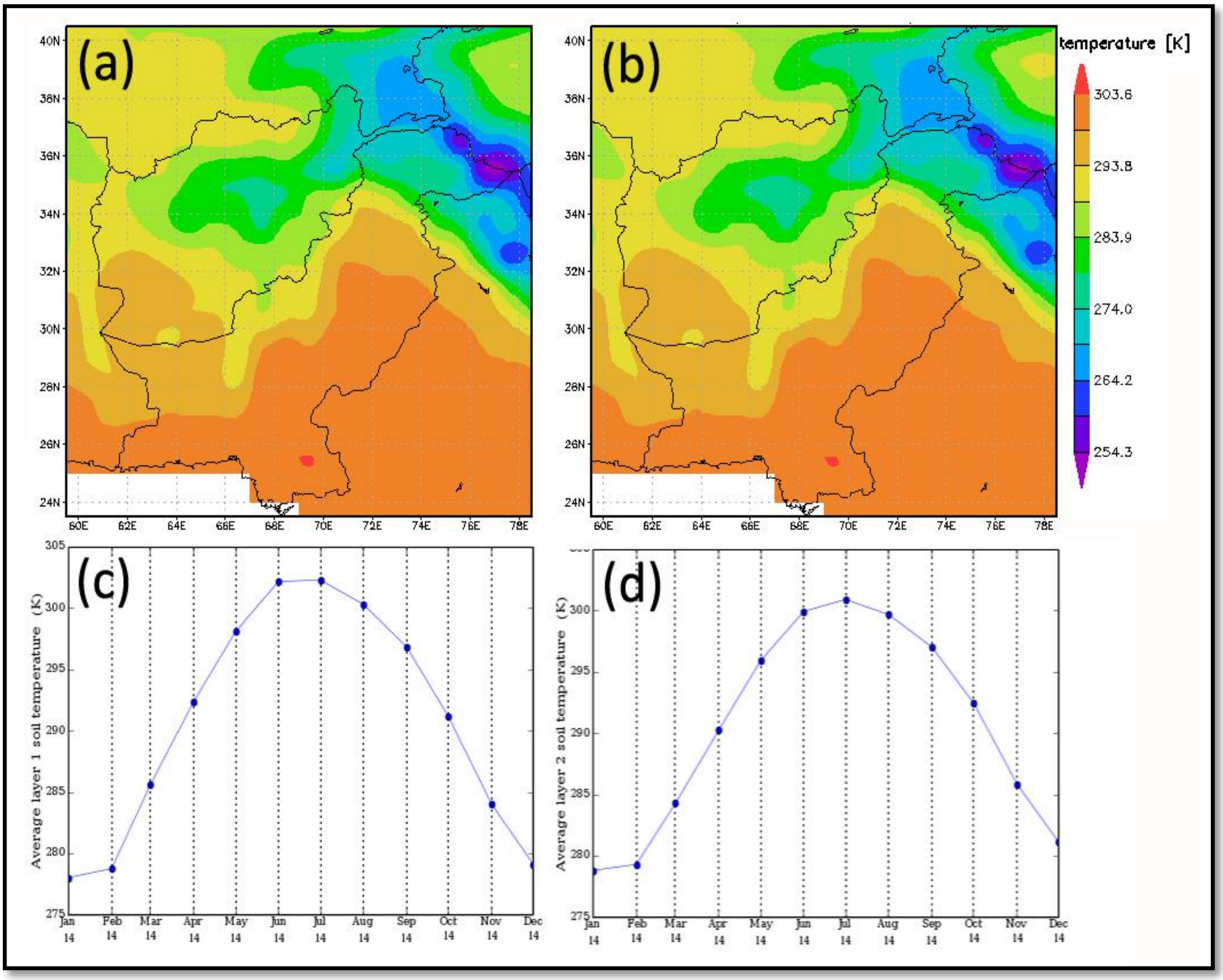

Fig. 3. Spatial distribution of soil temperatures composite over the year 2014 (a) Layer 1, (b) Layer 2 and Temporal distribution of soil temperatures (c) Layer 1, (d) Layer 2.

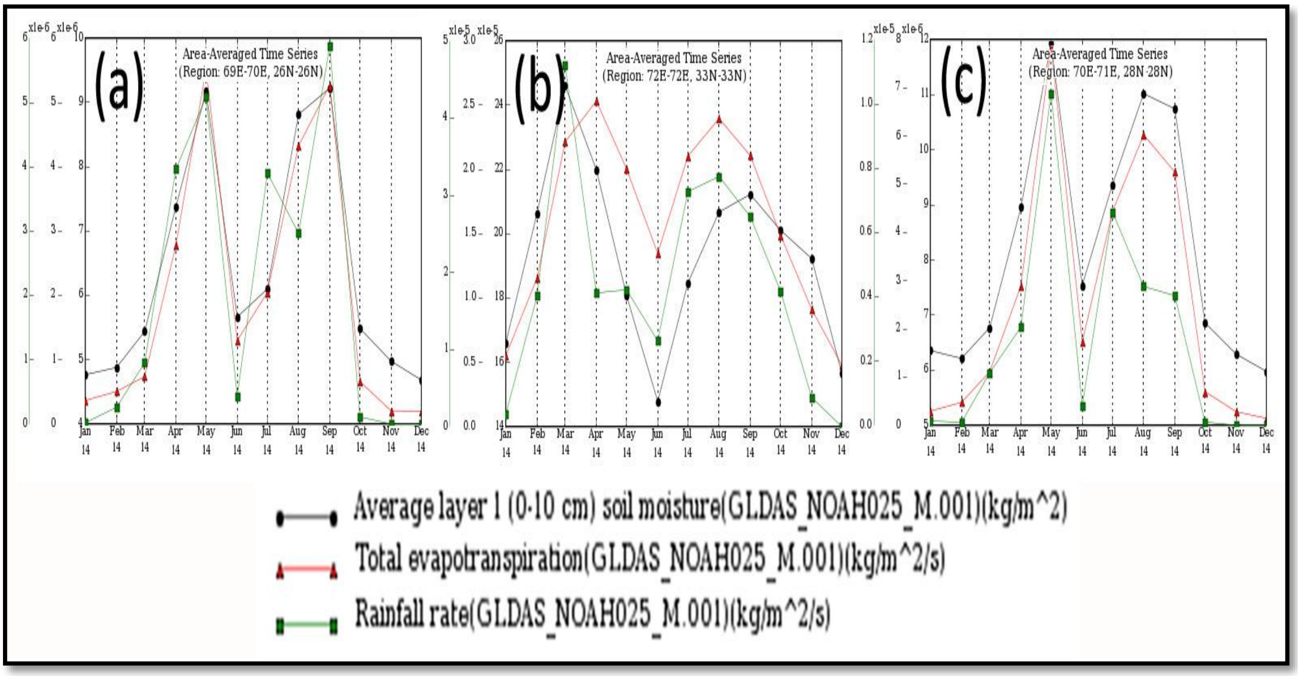

Fig. 4. Month wise time series data during 2014 of soil moisture, total evaporation and rainfall data at various places with half degree square: (a) 69.5E to 70E, 26N-26.5N (b) 72E to 72.5E, 33N-33.5(c) 70.5E to 71E, 28.5N-28N.

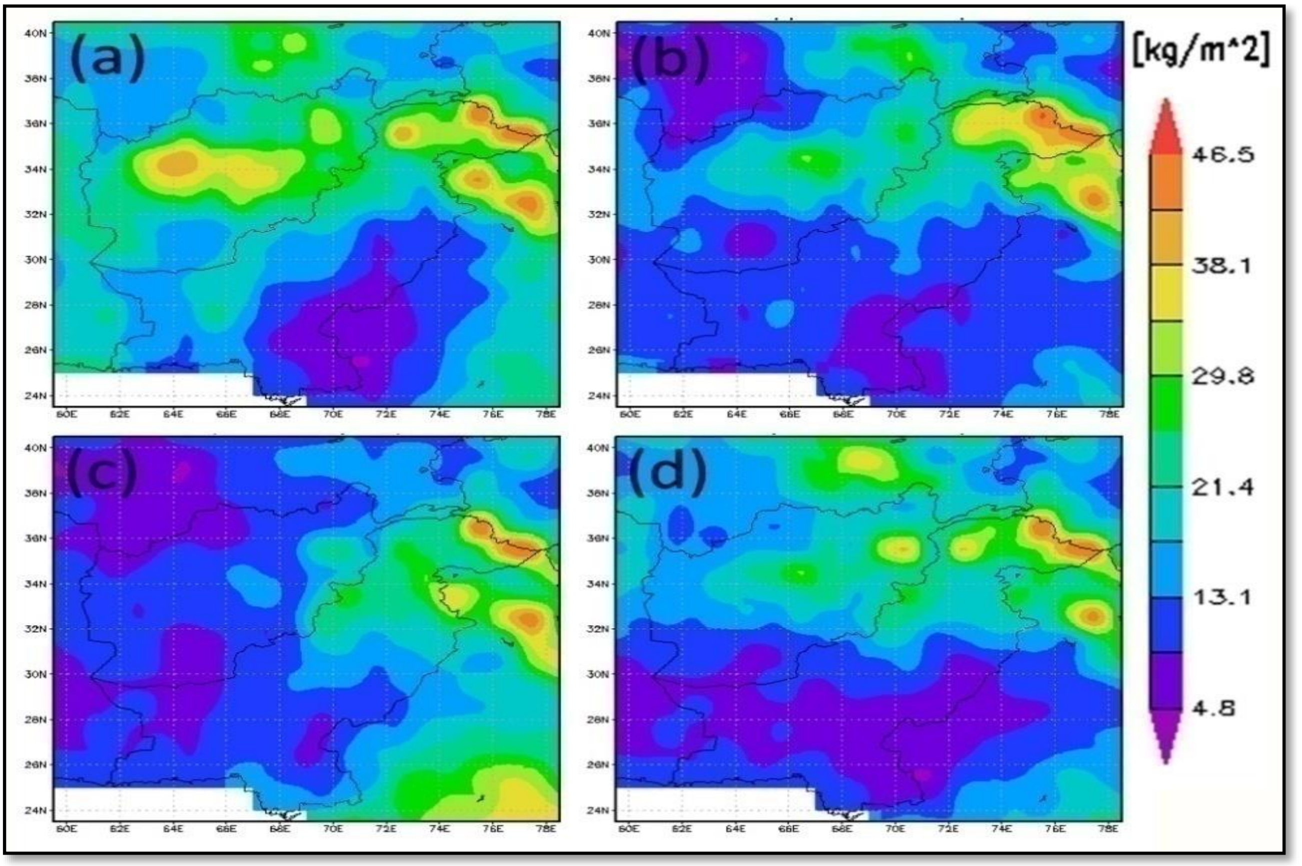

Fig. 5. Layer1 soil moisture three months composite (0 to 10 cm): (a) January to March (b) April to June (c) July to September (d) October to December.

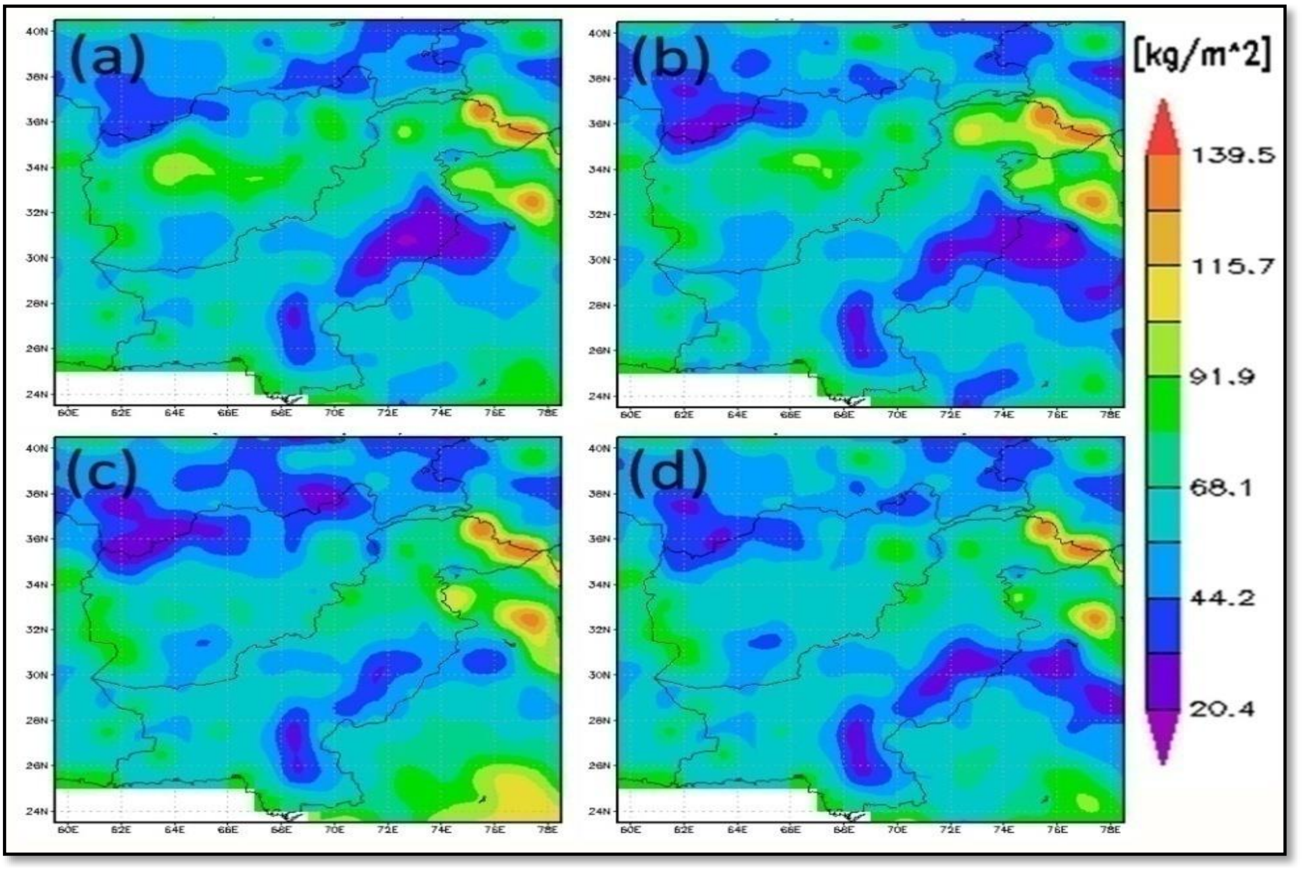

Fig. 6. Layer 2 soil moisture three months composite (10 to 40 cm): (a) January to March (b) April to June (c) July to September (d) October to December.

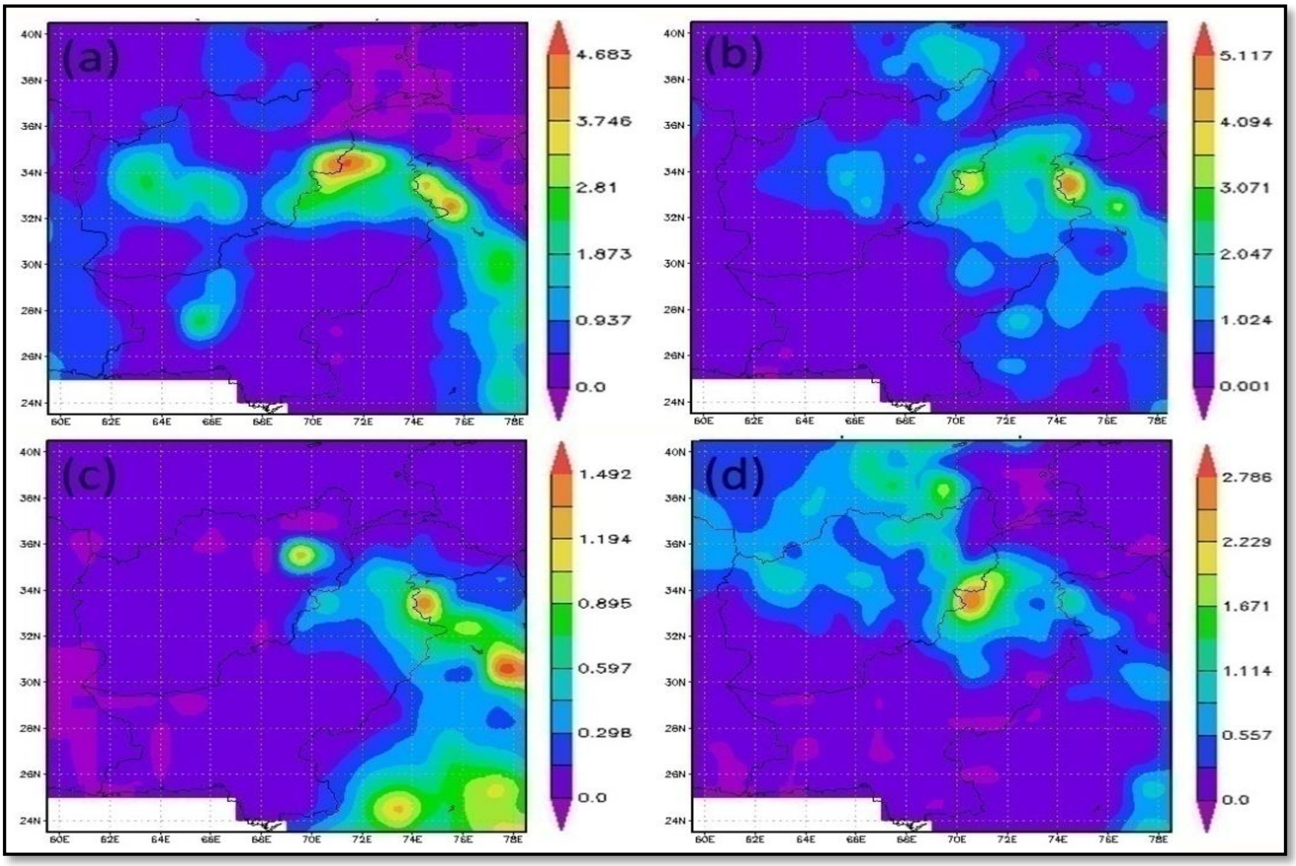

Fig. 7. Spatial distribution of Rainfall three months composite: (a) January to March (b) April to June (c) July to September (d) October to December.

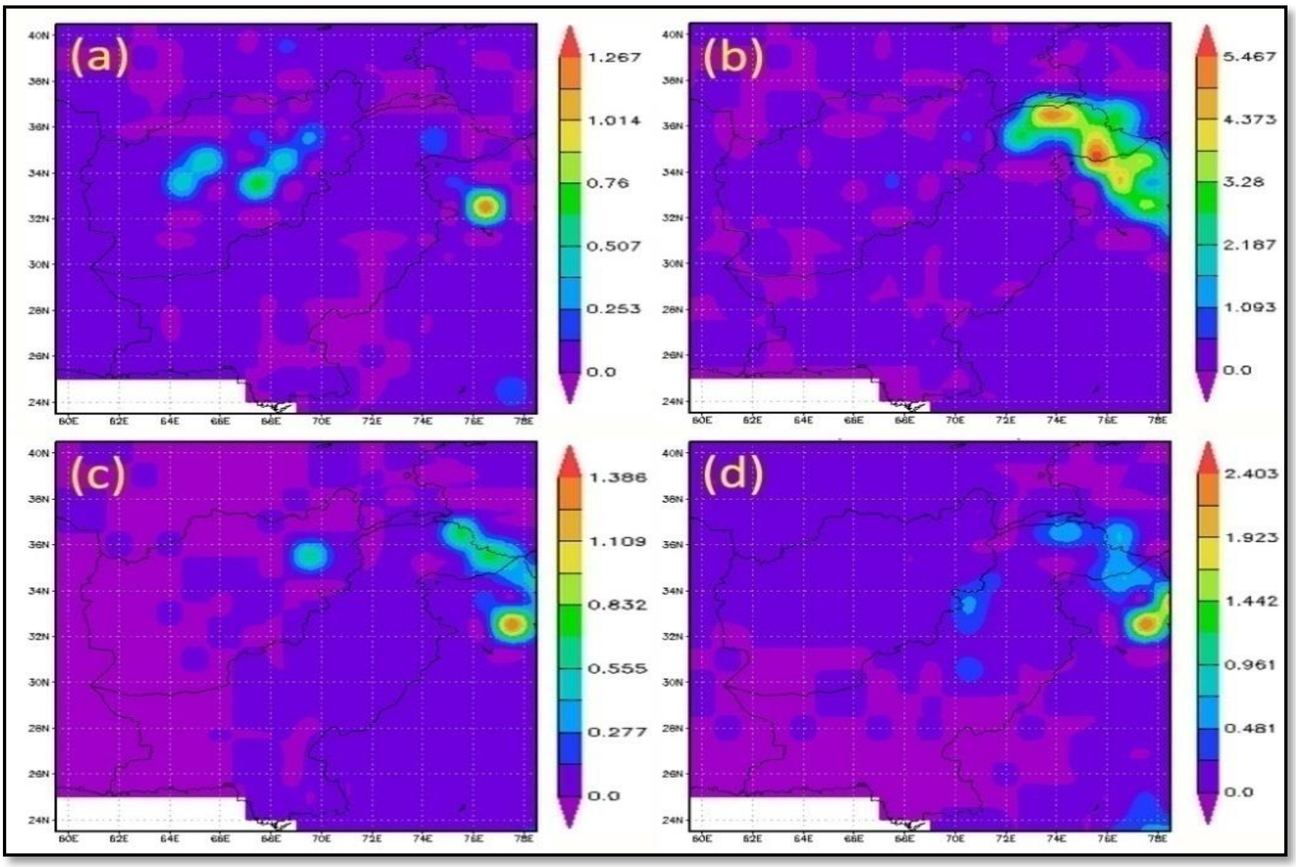

Fig. 8. Spatial distribution of surface run-off three months composite: (a) January to March (b) April to June (c) July to September (d) October to December.

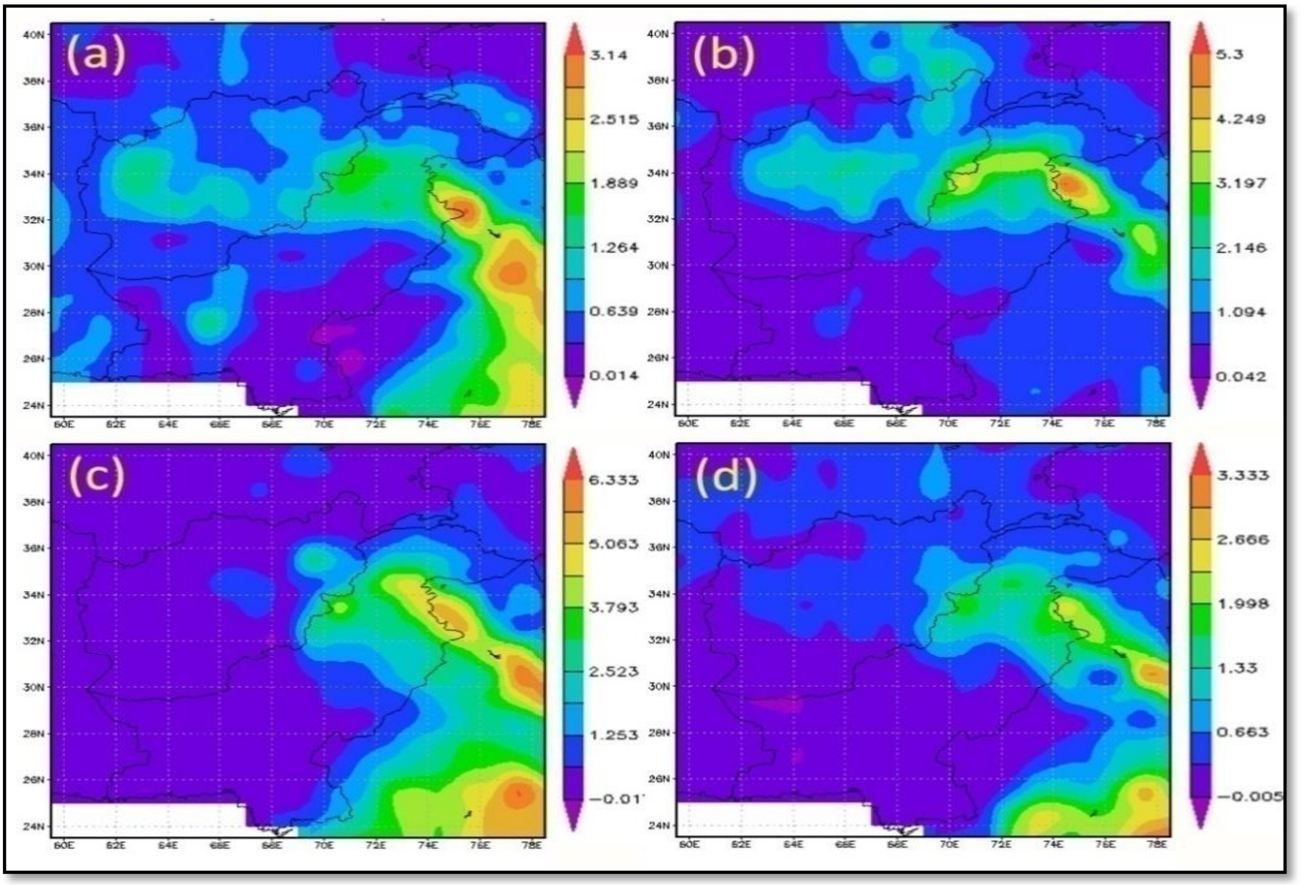

Fig. 9. Spatial distribution of total evapotranspiration three months composite: (a) January to March (b) April to June (c) July to September (d) October to December.

Table 3. Correlation among variables.

	Layer 1 Soil moisture	Layer 2 Soil moisture	Layer 1 Soil temperature	Layer 2 Soil temperature	Rainfall	Surface run-off	Total evapotrans-piration
Layer 1 Soil moisture	1	0.6	-0.5	-0.5	0.4	0.3	0.5
Layer 2 Soil moisture	0.6	1	-0.2	-0.2	0.3	0.2?	0.3
Layer 1 Soil temperature	-0.5	-0.2	1	0.9	0.1	-0.1	0.09
Layer 2 Soil temperature	-0.5	-0.2	0.9	1	0.1	-0.2	0.08
Rainfall	0.4	0.3	0.1	0.1	1	0.2	0.7
Surface run-off	0.3	0.3	-0.1	-0.2	0.2	1	0.1
Total evapotranspiration	0.5	0.3	0.09	0.08	0.7	0.1	1

Discussions

Soil moisture instability harmfully affects the crop yields, as it is an important component of biogeochemical cycles, irrigation schedule management and in generating floods and drought. In spite of the importance of soil moisture the ground measurement is very complicated. In this study, an evaluation of the current methodologies for soil-moisture estimation was performed based on their common soil cover conditions. Overall results show that soil moisture mainly depend upon rainfall occurrence, soil type has no significant affect in this data set, however it is obvious if in the case of same amount of rainfall occur in all region, soil type can affect to soak up, percolate and store water content.

Variation in rainfall occurrence and rate of evaporation along regional scale as diverse climate prevails all over Pakistan like in northern part by mild, moist winter and hot, dry summer, semi-arid and arid zones in the west and south parts of country. The northeastern mountainous and sub mountainous areas receive more than 1700 mm precipitation mostly in summer monsoon during the month of July to September. Winter rainfall (December to March) is mainly received from western areas incoming from Iran and Afghanistan. The arid plain of southwest Balochistan receives only about 30 mm during the whole year. Thermal regimes indicate extreme diurnal, seasonal and annual variations. Temperature varies as low as -26°C in the north to high as 52°C in the central arid plains. Temperature raise to 42°C was recorded at various stations (Meehl, 1994, Dudhia, 1989, Akhter & Arshad, 2006, Farooqi *et al.*, 2005).

Nearly about more than 60% area of Pakistan is dry and receives usual rainfall is less than 250 mm annually, whereas semi-arid area is almost 20% that receives average rainfall is less than 250-400 mm annually. In these zones temperature rises abruptly during summer and drops sharply in the winter giving rise to great variations in diurnal temperature (Middleton *et al.*, 1986; Sardar *et al*., 2014). Therefore, the arid and semi-arid parts of the country are characterized by small precipitation, extreme temperatures and low humidity in the atmosphere (Suleman *et al.*, 1995). Frequent water scarcities which slow down plant growth may be seen in many areas, since vegetation cover is greatly associated with the fluctuations in precipitation (Farooqi *et al.*, 2005). North and northwestern mountainous areas of country are the major contributors of the water resources in term of rain. South Asian countries face variation in agricultural production due to the soil moisture stresses and events of drought (Douville *et al.*, 2001). The rise in temperature in the past few decades along with the variability in precipitation and runoff patterns may result into deficit in agricultural lands influencing the crop growth that is why soil moisture assessment is very vital in this region.

As per estimates Pakistan is the home of over 182 million population and nearly about 70% of them are affiliated with directly and indirectly to agriculture sector (Hanif *et al.*, 2010). Spatio-temporal variation in soil moisture can have a significant effect on the socioeconomic conditions of the country. Rapid growth in population and significant degradation in natural resources are responsible for rise in poverty level and uncertainty in food production. South Asian countries collectively have become the most vulnerable part of the world, suffering from the impacts of climate change. Temporal shift in soil moisture pattern may have either positive or negative impact on cropping pattern. Appropriate management plans can overcome the possible occurrences of negative effects.

Strength and Limitation: The main purpose of this study was to provide information about generously available remote sensing data of soil moisture and associated variables to botanist, ecologist and geographers as many scientists in this part of the world still lacking. We used very limited data set larger data in this study could be enhanced for better results better. However, this shows soil moisture and allied factors dynamics in this very highly populated dense region where agriculture is much significant.

Conclusion

South Asian countries are having higher populations and for sustainable development and nourish a huge population monitoring soil moisture is crucial. GLDAS Noah model data is a valuable and easily accessible tool for soil moisture measurement at regional scale. This study tells us that disparity of spatial soil moisture pattern is more sensitive to change in temperature and rainfall occurrence differences. Spatial variability of soil moisture is significantly influenced by meteorological factors and each of the meteorological factors has a certain period of consequence. Change in soil moisture pattern may have either constructive or unhelpful effects on cropping pattern. We have to prepare ourselves for management in order to control the occurrence of harmful consequences.

Acknowledgements

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