STUDY ON LONG -TERM SOIL MOISTURE CHARACTERISTICS OVER BANGLADESH AND ITS RELATIONS TO ATMOSPHERIC VARIABLES

A dissertation submitted to the Department of Physics, Bangladesh University of Engineering and Technology (BUET), Dhaka in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN PHYSICS

Submitted by

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DEPARTMENT OF PHYSICS

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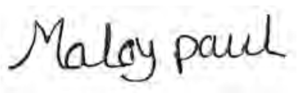
CANDIDATE'S DECLARATION

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

Signature of the Candidate



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CERTIFICATION OF THESIS

The thesis titled "STUDY ON LONG-TERM SOIL MOISTURE CHARACTERISTICS OVER BANGLADESH AND ITS RELATIONS TO ATMOSPHERIC VARIABLES", submitted by **Maloy Paul**, Roll No: 1014142503F Session: **October/2014**, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **Master of Science (M.Sc.) in Physics** on **23 July, 2016.**

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Dedicated
To
My Beloved Parents
And
All of My Friends

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The Author

ABSTRACT

Soil moisture is the water occupying pore spaces between soil particles, which plays an important role for hydrological cycle. The moisture for four different depths of soil in Bangladesh was analyzed using ERA-Interim reanalysis data from ECMWF (European Centre for Medium-Range Weather Forecasts). The dataset have approximately 80 km grid resolution and 60 vertical levels from the surface up to 0.1 hPa. The daily data was extracted and averaged for annually, monthly, and seasonally to analyze soil moisture in the soil layer-1 (0-7cm), soil layer-2 (7-28cm), soil layer-3 (28-100cm), and soil layer-4 (100-255cm) in Bangladesh for 36 years from 1979 to 2014. Soil moisture in each layer is gradually increasing in this region from 1979 to 2014 by 7.63%, 7.42%, 6.50% and 5%, respectively for soil layer-1 to layer-4. Soil moisture also increases vertically downward from the surface layer. The yearly average moisture differences between the successive layers are found to be 0.53%, 2.54% and 3.28%. The spatial variation shows that soil moisture is decreasing from the eastern toward western parts of Bangladesh up to the third layer where fourth layer maintains almost unique value in all over Bangladesh. The value of soil moisture provides an annual periodicity with maximum value of ~0.288 m^3m^{-3} in all four layers on July and minimum value of ~0.18 m^3m^{-3} in the first layer on March. May is found as a transition month where moisture in all the four layers are started to coincide with each other with the approximate value of 0.24 m^3m^{-3}. Differences in Soil moisture in the four layers is prominent in the dry season (November-May) with the values of 0.204, 0.207, 0.218 and 0.23 (m^3m^{-3}), respectively from the surface layer to the bottom layer. On the other hand, in the wet season (June-October), moisture reaches the saturated condition for all layers with a constant value of ~0.278 (m^3m^{-3}). Soil moisture contributes 56% of the total moisture in the wet season where 44% in the dry season in a year. North eastern side of Bangladesh holds 12.4% more moisture than the south western side in the surface layer.

Atmospheric variables of evaporation minus precipitation (E-P), surface relative humidity and temperature are correlated with soil moisture in the all layers. The surface layer i.e. the first layer moisture indicates the strong negative relation with (E-P) and strong positive relation with surface relative humidity having the correlation coefficients of -0.87 and 0.88, respectively. The relations between soil

moisture and atmospheric variables are decreasing from the surface layer to the bottom layer. The surface air temperature also proportionally affects the amount of soil moisture. The per degree changing of surface temperature change soil moisture amount significantly after two months later with an approximate value of 0.01 m^3m^{-3}.

CHAPTER 1

INTRODUCTION

1.1 Prelude

Bangladesh is mainly an agricultural based country where most of the people (about 80%) of the country are directly or indirectly involved in agricultural related activities to earn their livelihood. Previously, agriculture contributes 50% to the Gross Domestic Product (GDP) of Bangladesh, which has been reducing slowly because of industrialization [1]. Despite of reducing the contribution of the agriculture sector to GDP, still it is playing a vital role and is known as the most important sector of the economy of the country. Bangladesh naturally possesses a very fertile land (soil) with ample water supply in which diversified crops grow very easily. According to the World Bank, the total arable land in Bangladesh is 61.2% of the land area. Therefore, the land (soil) of Bangladesh is called valuable than gold [2-5].

Soil is the greatest resource of Bangladesh or any other agro-based country. The soil is defined as the top layer of the earth's crust [6], which mainly composed on five basic components i.e. mineral, water, organic matter, gases and micro-organisms. Among them, soil water is the major basic component in relation to plant growth and many other atmospheric factors [7, 8]. Soil contains 2-50% of water where 45-49% of minerals, 1-5% of organic matter, 2-50% of gases and 1% of micro-organisms. The quantitative water content occupying in terms of volume (volumetric) or mass (gravimetric) of the pore spaces between soil particles is defined as soil moisture [9, 10]. Surface soil moisture is measured by the water that is in the upper 10 cm of soil, whereas root zone soil moisture is the water that is available to plants, which is generally considered to be in the upper 200 cm of soil [11].

Chapter 1

The earth's land surface acts as a thin reservoir that stores and distributes water spatially and temporally. This reservoir is commonly referred to as soil moisture [12] and it plays a significant role in the land-atmosphere interactions. The state of soil moisture, as described by the level of saturation in the upper soil layer relative to the soil field capacity, is regulated by rainfall and potential evaporation. Both of these atmospheric forcing exerts significant control on the evolution of the soil moisture state and appear explicitly in the soil water balance equation [12]. The various processes in hydrology cycle (Fig. 1.1) i.e. infiltration, evapotranspiration (ET), interflow or rapid shallow ground water flow, surface runoff, groundwater recharge and discharge, and soil water storage and movement (both saturated and unsaturated) are controlled by or reflected as soil moisture [13, 14].

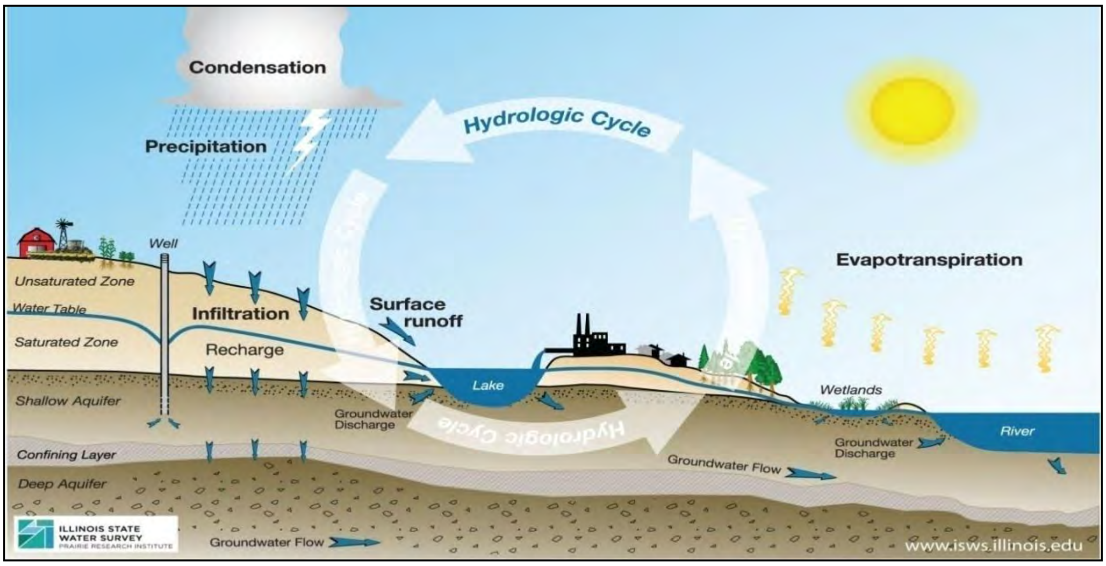

Fig. 1.1: Hydrologic cycle of the earth.

Soil moisture physically represents only the surface layer of soil, most of the time it is highly correlated with the total water in the soil profile and is an indicator of total water availability. Unfortunately, soil moisture is not a uniform variable in either a spatial or temporal sense. The extremely large spatial variability of soil moisture is the results of variable inputs like rain or snowmelt, land cover, highly variable soil properties and topography. The temporal patterns of soil moisture respond to the variable atmospheric forcings and their spatial distributions [12, 13]. These forcings determine the important thermodynamic properties of soil, such as heat conductivity, hydro conductivity, and the Bowen ratio. As a result, soil moisture interacts with soil temperature, air temperature and relative humidity in controlling the exchange of water and heat energy between the land surface and the atmosphere through evaporation and plant transpiration [10]. Therefore, soil moisture is a small but important component of both the hydrologic cycle and surface energy budget.

Soil moisture is important source of water for plants and crops in the rain fed agriculture like Bangladesh [15]. The availability of soil moisture is the key to plant growth and to the net production of crops [16]. Under irrigation conditions, the relationship between crop yield and water supply can be determined the requirement or deficit of crop water [17]. However, not all the available water capacity can be considered as equally available to plants. The upper 200 centimeters of soil is important for describing the water that is available to plants which is particularly affected by soil structural conditions [9, 16]. Soil moisture measurements in agricultural settings provide important information for the early warning of drought. When drought occurs, there is a deficit amount of moisture in the root zone, and consequently crop productivity diminishes. Therefore, continuous soil moisture measurements will lead to improve the information of crop yield which could help for forecasting purpose, and irrigation planning [9].

Soil moisture measurements are also important for predicting floods, except crop production and irrigation planning. The wetness of the soil before a rainstorm can indicate the potentiality for flooding to occur. If the soil is already oversaturated, at its maximum water-holding capacity, a rain event will not be absorbed adequately through the soil and flooding will likely occur [9].

In addition, soil moisture is recognized as an essential climate variable in 2010 by the Global Climate Observing System (GCOS). As soil moisture links together the water, energy and carbon exchanges between the land and the atmosphere, so observing soil moisture measurements allows for an assessment of the entire Earth system, and analyzing global changes which is extremely important for understanding future climate change impacts [9]. Variations in soil moisture may result in large changes in the latent and sensible heat fluxes, which affect the near-surface air temperature and humidity. Anomalous soil moisture conditions of sufficient magnitude, duration and spatial coherence, therefore, may have a significant effect on the weather and climate of a region. So it can play an important role in understanding and predicting climatic patterns [18, 19].

There are many studies around the world which indicates about the importance of the soil moisture and its effect on the atmospheric variables.

Deliberty et al. [19] have worked on interannual and seasonal variability of modelled soil moisture in Oklahoma, USA. He has shown in his work that the soil moisture conditions in both winter and spring in Oklahoma are about 70% of field capacity and decrease to below 30% during the summer. He also concluded with the decision that soil moisture variability changes the amount of energy that can be transferred by latent heat exchange, and thus substantially influences the near-surface atmosphere with considerable impact on land surface temperature, boundary-layer development, and air temperature and humidity.

Teuling [20] has showed the interaction between soil moisture and land surface-atmosphere. He has showed the nonlinear relation between soil moisture and evapotranpiration in combination with climate variability.

Western et al. [23] have studied on spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes at five different sites in Australia and three different sites in New Zealand. They found that there was a seasonal evolution in the spatial soil moisture variance that was related to changes in the spatial mean moisture content at all sites. At the Australian sites there was also a seasonal evolution in the correlation length related to changes in the spatial mean moisture, but not at the New Zealand sites. The seasonal evolution of the correlation length in the Australian catchments is likely to be associated with a seasonal change in the processes controlling the soil moisture pattern. The results demonstrate that the processes controlling spatial patterns can change between places and over time with catchment moisture status; however, when similar general conditions reoccur in a catchment, similar spatial patterns result.

Rahmani et al. [24] have studied on multiyear monitoring of soil moisture over Iran through satellite and reanalysis soil moisture products. Surface soil moisture (SSM) datasets at six subregions of Iran with different climate conditions were extracted from two satellite-based passive and (active + passive) microwave observations, and two reanalysis (ERA-Interim and ERA-Interim/Land) products in this research work. They found all SSM products were in good agreement with each other with correlation coefficients higher than 0.5. The better agreement was found in the Northeast and Southwest region with average correlation values equal to 0.88 and 0.91, respectively. Most SSM products have strong correlations with maximum, minimum and average temperature as well as with total monthly precipitation.

Chuanli et al. [25] have worked on simulation and variability of soil moisture in East Asia. From his study, he concludes with the decision that soil has become drier in most areas of East Asia in recent years except southern China and the Tibetan Plateau where soil gets wetter. He indicates with further analysis that such dry trend may have a close link to warming surface climate through enhanced evaporation.

Asharaf et al. [26] have studied on soil moisture–precipitation feedback processes in the Indian summer monsoon season. He showed that pre-monsoonal soil moisture has a significant influence on the monsoonal precipitation.

Sing et al. [27] have worked on spatial and temporal variability of soil moisture over India. He suggests that Variations of soil moisture over India qualitatively show close agreement with the monsoon and rainfall pattern, showing the highest soil moisture during June–July and the lowest soil moisture during April–May. Along the coastal regions of India moisture content is generally found to be higher as compared to other regions.

Shrivastava et al. [28] have analyzed soil moisture variations in remotely sensed and reanalysis datasets during weak monsoon conditions over central India and central Myanmar. They found from day-to-day variations of soil moisture in central India and central Myanmar during weak monsoon conditions indicate that, because of the rainfall deficiency. The observed European Space Agency (ESA) and the climate forecast system reanalysis (CFSR) soil moisture values are reduced up to $0.1 m^3 m^{-3}$ compared to climatological values of more than $0.35\ 1 m^3 m^{-3}$.

In Bangladesh, few studies on soil moisture have been done especially, regarding the affects of soil moisture on different kinds of crops.

Sen et al. [29] have studied different soil moisture regime on the yield and its effect on onion. They have concluded with the decision that soil moisture regime 1.00 IW/CPE (Irrigation Water/ Cumulative Pan Evaporation) ratio was found optimum for onion production in grey terrace soil of Gazipur.

Nahar et al. [30] explained the effects of water stress on moisture content distribution at different soil layers (pot) and on morphological characters of tomato plants. They revealed that 70% moisture of the field capacity (FC) was adequate to moisture supply for the investigated tomato plants and recommended this amount for higher fruit yield and better fruit size.

Ferdousi [31] studied the effect of soil moisture on growth, yield and biochemical attributes of lentil genotypes. They found that the interaction between genotypes and soil moisture levels was significant for most of the characters.

The studies that have been done in Bangladesh have only emphasized the impacts of soil moisture particularly on crops and vegetables in Bangladesh. But to our knowledge, long-term variation of soil moisture over Bangladesh and its seasonal characteristics has not been yet studied. In addition, to improve climate model over Bangladesh, relations to soil moisture and the atmospheric variables like surface temperature, precipitation, evaporation and relative humidity are needed to be studied.

1.2 Objectives of the Research

The objectives of the present research work are:

1. To calculate long-term soil moisture variability over Bangladesh for different soil layers.

2. To find out the characteristics of monthly averaged soil moisture in different layers

3. To find out the characteristics of seasonal variability of soil moisture in different layers.

4. To analyze the relations between soil moisture and the atmospheric variables of temperature, precipitation, evaporation and relative humidity at surface.

As soil moisture is one of the key atmospheric variables so it is important to know the characteristics of the soil moisture over Bangladesh. This study will help for making decision in irrigation, seasonal crop production and flood management of Bangladesh. It can also help in better weather forecasting by improving the surface layer physics.

CHAPTER 2

LITERATURE REVIEW

2.1 Previous Work

The past studies on soil moisture around the world including Bangladesh are described in this section.

Jin et al. [10] have studied on the relations between soil moisture, soil temperatures (T_{soil}) and surface temperatures (T_{skin}) using Atmospheric Radiation Measurement (ARM) observations and offline Community Land Model (CLM4) simulations at Lamont, Oklahoma. It showed that soil moisture obtained from CLM4 has stronger correlation between T_{soil} and T_{skin} (r = 0.96) than that by ARM observations (r =0.64), while the predicted night time T_{skin} is 0.5–2 °C higher than the observations.

Eltahir [13] has showed a soil moisture–rainfall feedback mechanism. This observation highlights the similarity between the roles of vegetation cover and soil moisture content in land-atmosphere interactions. Basically, each of the two variables dictates the magnitudes of surface albedo and Bowen ratio, and for this reason both of them influence hydrological, radiative, and turbulent processes at the land-atmosphere boundary in the similar ways.

Deliberty et al. [19] have worked on interannual and seasonal variability of modelled soil moisture in Oklahoma, USA. He has shown in his work that the soil moisture conditions in both winter and spring in Oklahoma are about 70% of field capacity and decrease to below 30% during the summer. He also concluded with the decision that soil moisture variability changes the amount of energy that can be transferred by latent heat exchange, and thus substantially influences the near-surface atmosphere with considerable impact on land surface temperature, boundary-layer development, and air temperature and humidity.

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Hunt [21] has showed the relationship of soil moisture and biophysical variables in wet and dry seasons at a rainfed and irrigated field in eastern Nebraska, USA. He explained a drought case which not only showed the importance of irrigation during a prolonged dry spell, it also showed the utility of using short-term drought indices for identifying the water stress of a rainfed field.

Jacobson [22] has showed the effects of soil moisture on temperatures, winds, and pollutant concentrations in Los angeles, USA. The findings of this study may apply in simulations at different times and locations, since soil moisture is affected by spatial and temporal distributions of radiative fields, evaporative fluxes, and ground temperatures.

Western et al. [23] have studied on spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes at five different sites in Australia and three different sites in New Zealand. They found that there was a seasonal evolution in the spatial soil moisture variance that was related to changes in the spatial mean moisture content at all sites. At the Australian sites there was also a seasonal evolution in the correlation length related to changes in the spatial mean moisture, but not at the New Zealand sites. The seasonal evolution of the correlation length in the Australian catchments is likely to be associated with a seasonal change in the processes controlling the soil moisture pattern. The results demonstrate that the processes controlling spatial patterns can change between places and over time with catchment moisture status; however, when similar general conditions reoccur in a catchment, similar spatial patterns result.

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Ferdousi [31] studied the effect of soil moisture on growth, yield and biochemical attributes of lentil genotypes. They found that the interaction between genotypes and soil moisture levels was significant for most of the characters.

Rao et al. [32] have studied on soil moisture mapping over India (Gurdaspur in north, Bankura in east, Jaisalmer and Jodhpur in the west and Pune (near Mumbai) in the middle part of India) using aqua AMSR-E (Advanced Microwave Scanning Radiometer – Earth Observing System) derived soil moisture product during the period 200-2005. It has been observed that AMSR-E derived soil moisture in arid region (desert area) over estimates by 4%. About 2% underestimation of soil moisture was obtained at another test site with agriculture practices. By comparing estimated soil moisture and rainfall data, we found that estimated soil moisture varies well with rainfall for uniform bare fields. The heavy rainfall events in several parts of India that lead to flooding were clearly seen through soil moisture maps of 4 years.

Parinussa et al. [33] have analyzed on intercomparison of remotely sensed soil moisture products at various spatial scales over the Iberian Peninsula. Soil moisture (SM) data retrieved from active microwave (AM), passive microwave (PM) and thermal infrared (TIR) observations, each having unique spatial and temporal coverages. All three remotely sensed SM products showed good agreement to the ground observations. The comparison showed that these ground observations and satellite data are consistent, based on the correlation coefficient (r) and root mean square error (RMSE).

2.2 Overview of the Study

2.2.1 Geographical Description of Bangladesh

Bangladesh is a country in southern Asia (Fig. 2.1). It is located in the delta of the Padma (Ganges) and Jamuna (Brahmaputra) rivers in the northeastern part of the Indian subcontinent. The country is bordered by India in west, north and east and it

Fig. 2.1: Geographical map of Bangladesh.

has a small border with Myanmar (Burma) in south east. Bangladesh has a geographical coordinate of $20^0$7´N-26°7´N & 88°E-92°8´E. Bangladesh has an total area of 147,610 square kilometres and extends 820 kilometres north to south and 600 kilometres east to west. Bangladesh is bordered on the west, north, and east by a

4,095 kilometres land frontier with India and, in the southeast, by a short land and water frontier (193 kilometres) with Burma (Myanmar). On the south is a highly irregular deltaic coastline of about 580 kilometres, fissured by many rivers and streams flowing into the Bay of Bengal. The territorial waters of Bangladesh extend 22 kilometers, and the exclusive economic zone of the country is 370 kilometers.

It is divided into six divisions and sixty districts. It has a population of about 160 million. In point of the size of the population, it is the eleventh largest state in the world. The physical features of Bangladesh are mainly a plain land criss-crossed by a network of rivers and canals. In the eastern and south-eastern regions there are only a few hilly tracts. Places like Paharpur, Mahasthangar and Mainamati and numerous historical monuments and relics give evidence to our glorious past, rich culture and high civilization.

Bangladesh is a reverine country within mighty drainage systems (Gangas, Brahmaputra and Maghna) along with its innumerable tributaries which orginates in the Himalayas Mountains is largely responsible for the hydro-meteorological cycles of the whole Indian subcontinent including Bangladesh.

Roughly 80% of the landmass is made up of fertile alluvial lowland called the Bangladesh Plain. The plain is part of the larger Plain of Bengal, which is sometimes called the Lower Gangetic Plain. Although altitudes up to 105 metres above sea level occur in the northern part of the plain, most elevations are less than 10 metres above sea level; elevations decrease in the coastal south, where the terrain is generally at sea level. With such low elevations and numerous rivers, water—and concomitant flooding—is a predominant physical feature. About 10,000 square kilometres of the total area of Bangladesh is covered with water, and larger areas are routinely flooded during the monsoon season.

Bangladesh often called a land of natural calamities. Flood, cyclone, storm and heavy downpour and drought often visit the country. People here work and live fighting against recurring natural calamities. Bangladesh lies in the tropical region and its land is low. Almost every year cyclone or storm hits the land in summer or in the late autumn.

Agriculture is the largest employment sector in Bangladesh. As of 2016, it employs 47% of the total labor force and comprises 16% of the country's GDP. The performance of this sector has an overwhelming impact on major macroeconomic objectives like employment generation, poverty alleviation, human resources development and food security. A plurality of Bangladeshis earns their living from agriculture. Crop production in Bangladesh has achieved milestone because of its' fertile soil and normally ample water supply. Therefore, the land (soil) of Bangladesh is called valuable than gold.

2.2.2 Seasons of Bangladesh

For detail analyzing of the characteristics of the moisture in the twelve months of a year is divided into two seasons in this study i.e. dry season and wet season.

2.2.2.1 Dry Season

Dry season extends November to May. During dry season the weather remains cool, dry and sunny. Occasionally a small amount of rainfall (50 mm) occurs but is highly variable and uncertain and is usually very useful for agriculture. Temperature and evaporation rates are in the lowest value during November to March but in April and May temperature and evaporation rates are increasing all over Bangladesh. Devastating cyclone storms called nor westerns blow in almost all areas of Bangladesh in April and May.

2.2.2.2 Wet Season

Wet season extends from June to October. Maximum rainfall occurs during this season in Bangladesh. Around 80% of the total annual rainfall is received during this period. Humidity is usually high and sky remains overcast with clouds sometimes for days together. Because of heavy rainfall floods in Bangladesh occur this season. There is also rainfall variability within this season.

2.2.3 Hydrologic Cycle

Water is the basic element of the nature. It covers 70% of the earth's surface. It provides life, eases out heat, drains harmful substance and mediates many day to day works. Water needs to be replenished, purified and circulated again and again so that it can perform its functions. Nature does this job through a process called the water cycle. The scientific discipline in the field of physical geography that deals with the water cycle is called hydrology. It is concerned with the origin, distribution, and properties of water on the globe. Consequently, the water cycle is also called the hydrologic cycle in many scientific textbooks and educational materials. Hydrologists are interested in obtaining measurable information and knowledge about the water cycle. Also important is the measurement of the amount of water involved in the transitional stages that occur as the water moves from one process within the cycle to other processes. Hydrology, therefore, is a broad science that utilizes information from a wide range of other sciences and integrates them to quantify the movement of water.

The global water cycle can be described with nine major physical processes which form a continuum of water movement. Complex pathways include the passage of water from the gaseous envelope around the planet called the atmosphere, through the bodies of water on the surface of earth such as the oceans, glaciers and lakes, and at the same time (or more slowly) passing through the soil and rock layers underground. Later, the water is returned to the atmosphere. A fundamental characteristic of the hydrologic cycle is that it has no beginning and it has no end. It can be studied by starting at any of the following processes: evaporation, condensation, precipitation, interception, infiltration, percolation, transpiration, runoff, and storage (Fig. 2.2).

The information presented below is a greatly simplified description of the major contributing physical processes.

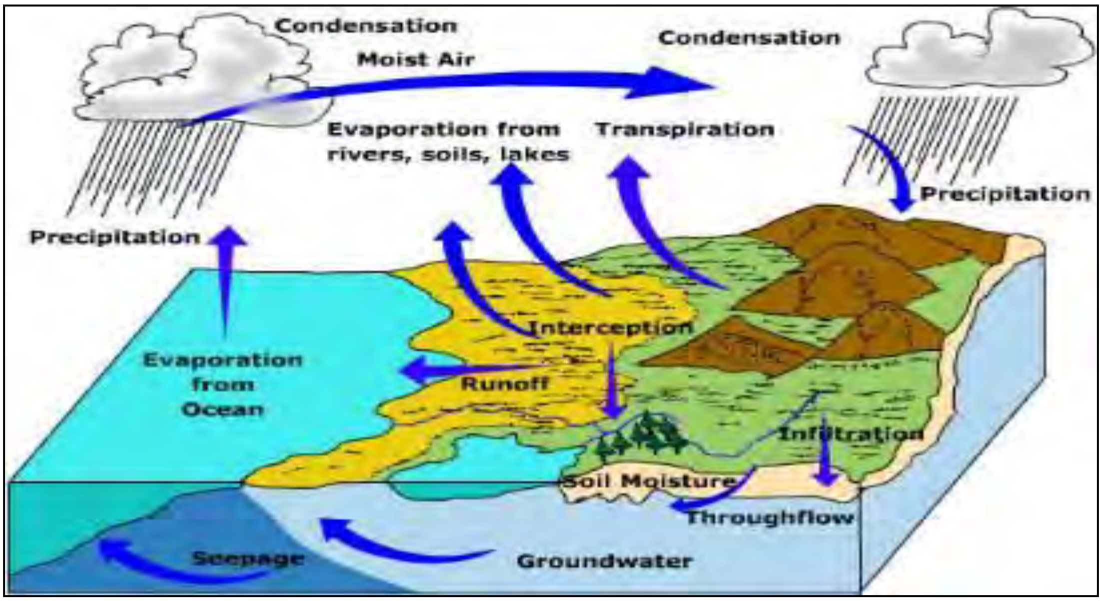

Fig. 2.2: Hydrologic cycle.

2.2.3.1 Evaporation

Evaporation occurs when the physical state of water is changed from a liquid state to a gaseous state. A considerable amount of heat, about 600 calories of energy for each gram of water, is exchanged during the change of state. Typically, solar radiation and other factors such as air temperature, vapor pressure, wind, and atmospheric pressure affect the amount of natural evaporation that takes place in any geographic area. Evaporation can occur on raindrops, and on free water surfaces such as seas and lakes. It can even occur from water settled on vegetation, soil, rocks and snow. There is also evaporation caused by human activities. Heated buildings experience evaporation of water settled on its surfaces. Evaporated moisture is lifted into the atmosphere from the ocean, land surfaces, and water bodies as water vapor. Some vapor always exists in the atmosphere.

In Bangladesh, maximum evaporation occurs in May and minimum in January. Throughout the country, there is little variation of evaporation. Mean annual evaporation is around 1000-1200 mm. Total annual evaporation is smaller than total annual precipitation (rainfall) everywhere in the country but evaporation exceeds rainfall during dry season. Excess rainfall over evaporation during monsoon season ranges from about 600 mm in the centre west to more than 2500 mm in the northeast of Bangladesh.

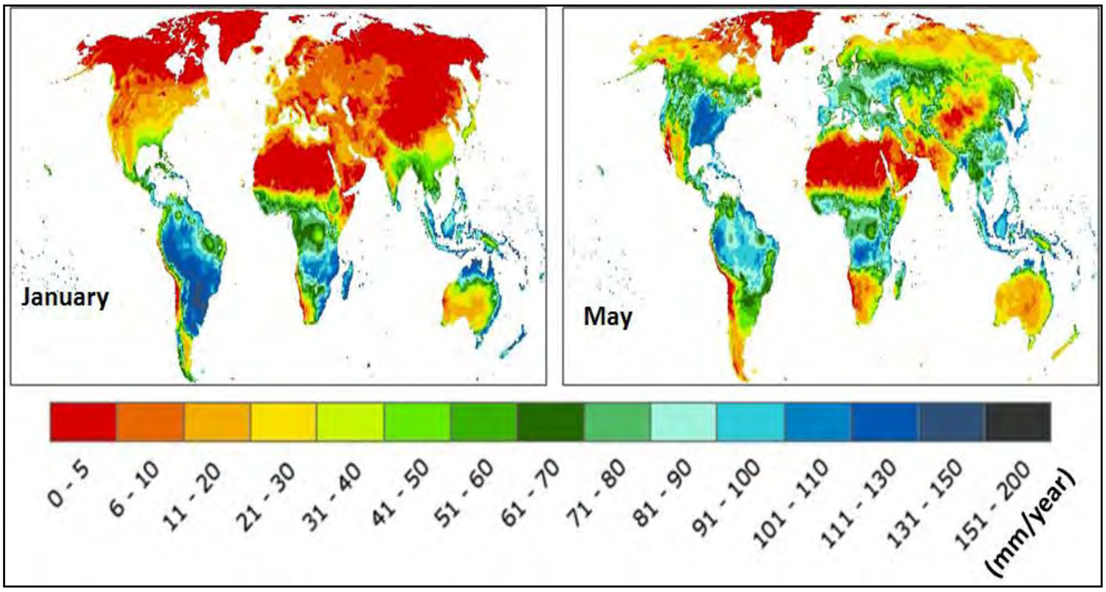

Fig. 2.3: Average global evaporation in a year for the Month of January and May since 1985-1999.

2.2.3.2 Condensation

Condensation is the process by which water vapor changes its physical state from a vapor, most commonly, to a liquid. Water vapor condenses onto small airborne particles to form dew, fog, or clouds. The most active particles (known as condensation nuclei) that form clouds are sea salts, atmospheric ions caused by lightning, and combustion products containing sulfurous and nitrous acids. Condensation is brought about by cooling of the air or by increasing the amount of vapor in the air to its saturation point. When water vapor condenses back into a liquid state, the same large amount of heat (600 calories of energy per gram) that was needed to make it a vapor is released to the environment.

2.2.3.3 Precipitation

Precipitation is the process that occurs when any and all forms of water particles fall from the atmosphere and reach the ground. There are two sub-processes that cause clouds to release precipitation, the coalescence process and the ice-crystal process. As water drops reach a critical size, the drop is exposed to gravity and frictional drag. A falling drop leaves a turbulent wake behind which allows smaller drops to fall faster and to be overtaken to join and combine with the lead drop. The other sub-process that can occur is the ice-crystal formation process. It occurs when ice develops in cold clouds or in cloud formations high in the atmosphere where freezing temperatures occur. When nearby water droplets approach the crystals some droplets evaporate and condense on the crystals. The crystals grow to a critical size and drop as snow or ice pellets. Sometimes, as the pellets fall through lower elevation air, they melt and change into raindrops. Precipitated water may fall into a water body or it may fall onto land. It is then dispersed several ways. The water can adhere to objects on or near the planet surface or it can be carried over and through the land into stream channels, or it may penetrate into the soil, or it may be intercepted by plants. When precipitation (rainfall) is small and infrequent, a high percentage of precipitation is returned to the atmosphere by evaporation.

The variability of rainfall and its magnitude in time and location in Bangladesh is vitally important for agricultural. The distribution of rainfall in Bangladesh varies widely throughout the year. Around 80 percent of the total rainfall occurs in a period of six months from May to October. Distribution of rainfall in Bangladesh also varies from place to place. The northeastern part receives the highest annual rainfall reaching a maximum of 5700 mm at Lallkhal in Sylhet district. Near Cox's Bazar, another high rainfall concentrate belt occurs with a maximum of around 3500 mm. There is gradual decrease of rainfall towards west reaching as low as 1500 mm at Chapi Nawbganj. According to one estimate, the mean annual rainfall over the entire country is about 2300 mm. The period from November-April is commonly dry. During dry season (November-April), around 50 mm of rainfall is received almost everywhere in Bangladesh. But this rainfall is highly variable and uncertain. In some years, drought may be so severe in April and May that rainfed agriculture is severely affected and signs of desertification become apparent. The central west is the most drought-prone area in Bangladesh where rainfall is the lowest. The seasonal distribution of rainfall indicates that in Bangladesh moisture is deficient in one season (November-March) and excessive in another season (June-October).

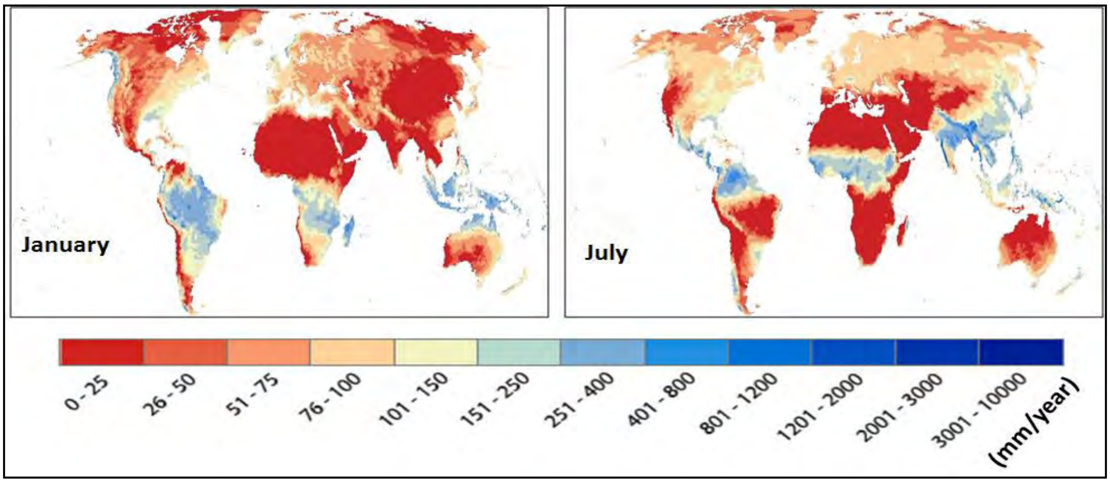

Fig. 2.4: Average global precipitation in a year for the Month of January and July since 1985-1999.

2.2.3.4 Interception

Interception is the process of interrupting the movement of water in the chain of transportation events leading to streams. The interception can take place by vegetal cover or depression storage in puddles and in land formations such as rills and furrows. When rain first begins, the water striking leaves and other organic materials spreads over the surfaces in a thin layer or it collects at points or edges. When the maximum surface storage capability on the surface of the material is exceeded, the material stores additional water in growing drops along its edges. Eventually the weight of the drops exceeds the surface tension and water falls to the ground. Wind and the impact of rain drops can also release the water from the organic material. The water layer on organic surfaces and the drops of water along the edges are also freely exposed to evaporation. Additionally, interception of water on the ground surface during freezing and sub-freezing conditions can be substantial. The interception of falling snow and ice on vegetation also occurs. The highest level of interception occurs when it snows on conifer forests and hardwood forests that have not yet lost their leaves.

2.2.3.5 Infiltration

Infiltration is the physical process involving movement of water through the boundary area where the atmosphere interfaces with the soil. The surface phenomenon is governed by soil surface conditions. Water transfer is related to the porosity of the soil and the permeability of the soil profile. Typically, the infiltration rate depends on the puddling of the water at the soil surface by the impact of raindrops, the texture and structure of the soil, the initial soil moisture content, the decreasing water concentration as the water moves deeper into the soil filling of the pores in the soil matrices, changes in the soil composition, and to the swelling of the wetted soils that in turn close cracks in the soil.

2.2.3.6 Percolation

Percolation is the movement of water though the soil, and it's layers, by gravity and capillary forces. The prime moving force of groundwater is gravity. Water that is in the zone of aeration where air exists is called vadose water. Water that is in the zone of saturation is called groundwater. For all practical purposes, all groundwater originates as surface water. Once underground, the water is moved by gravity. The boundary that separates the vadose and the saturation zones is called the water table. Usually the direction of water movement is changed from downward and a horizontal component to the movement is added that is based on the geologic boundary conditions.

2.2.3.7 Transpiration

Transpiration is the biological process that occurs mostly in the day. Water inside of plants is transferred from the plant to the atmosphere as water vapor through numerous individual leave openings. Plants transpire to move nutrients to the upper portion of the plants and to cool the leaves exposed to the sun. Leaves undergoing rapid transpiration can be significantly cooler than the surrounding air. Transpiration is greatly affected by the species of plants that are in the soil and it is strongly affected by the amount of light to which the plants are exposed. Water can be transpired freely by plants until a water deficit develops in the plant and it water-releasing cells (stomata) begin to close. Transpiration then continues at a must slower rate. Only a small portion of the water that plants absorb are retained in the plants. Vegetation generally retards evaporation from the soil. Vegetation that is shading the soil reduces the wind velocity. Also, releasing water vapor to the atmosphere reduces the amount of direct evaporation from the soil.

2.2.3.8 Runoff

Runoff is flow from a drainage basin or watershed that appears in surface streams. It generally consists of the flow that is unaffected by artificial diversions, storages or other works that society might have on or in a stream channel. The flow is made up partly of precipitation that falls directly on the stream, surface runoff that flows over the land surface and through channels, subsurface runoff that infiltrates the surface soils and moves laterally towards the stream, and groundwater runoff from deep percolation through the soil horizons. Part of the subsurface flow enters the stream quickly, while the remaining portion may take a longer period before joining the water in the stream. When each of the component flows enters the stream, they form the total runoff. The total runoff in the stream channels is called stream flow and it is generally regarded as direct runoff or base flow.

2.2.3.9 Storage

There are three basic locations of water storage that occur in the planetary water cycle. Water is stored in the atmosphere; water is stored on the surface of the earth, and water stored in the ground. Water stored in the atmosphere can be moved relatively quickly from one part of the planet to another part of the planet. The type of storage that occurs on the land surface and under the ground largely depend on the geologic features related to the types of soil and the types of rocks present at the storage locations. Storage occurs as surface storage in oceans, lakes, reservoirs, and glaciers; underground storage occurs in the soil, in aquifers, and in the crevices of rock formations. The movement of water through the eight other major physical processes of the water cycle can be erratic. On average, water the atmosphere is renewed every 16 days. Soil moisture is replaced about every year. Globally, waters in wetlands are replaced about every 5 years while the residence time of lake water is about 17 years. In areas of low development by society, groundwater renewal can exceed 1,400 years. The uneven distribution and movement of water over time, and the spatial distribution of water in both geographic and geologic areas, can cause extreme phenomena such as floods and droughts to occur.

2.2.4 Soil Moisture

Among three types of storage system in the storage section of hydrologic cycle, water stored in the ground is generally known as soil moisture i.e. the quantitative water content occupying in terms of volume (volumetric) or mass (gravimetric) of the pore spaces between soil particles is defined as soil moisture. Surface soil moisture is measured by the water that is in the upper 10 cm of soil, whereas root zone soil moisture is the water that is available to plants, which is generally considered to be in the upper 200 cm of soil.

The mean annual soil moisture, which ranges around 0.23-0.24 m^3 m^{-3} as global land average on the ERA-Interim period [39]. Figure 2.5 shows the average spatial distribution of soil moisture in January over the period of 1979-2010.

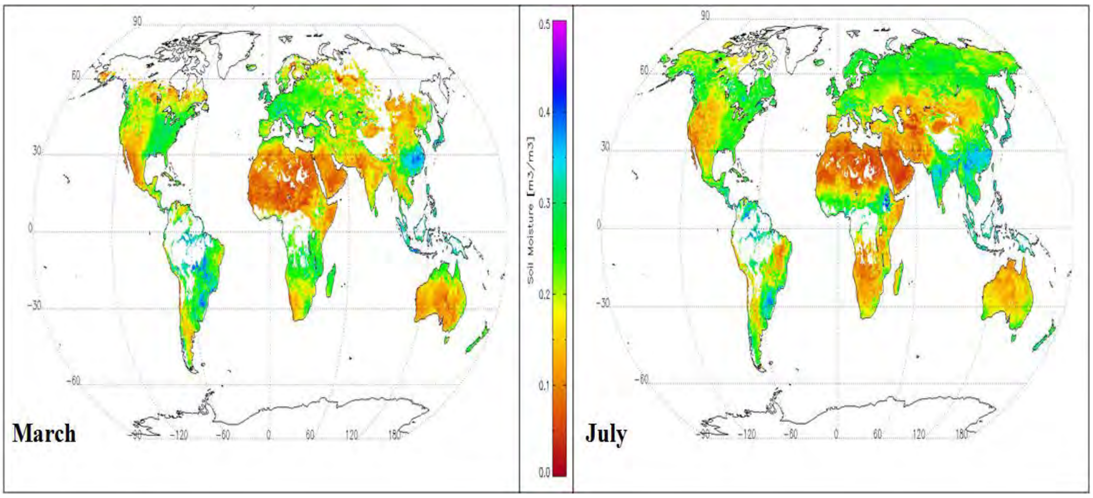

Fig. 2.5: Average surface Soil moisture (m^3m^{-3}) of the globe for the month of March and July over the period 1979 to 2010.

2.2.4.1 Measurement of Soil Moisture

There are two ways to measure the soil moisture:

Soil moisture tension

Soil moisture tension tells how easy it is to extract water from soil. When a soil is saturated, there is plenty of water in the pore spaces and plenty of water coating the soil particles. All this moisture makes it very easy for plant roots to get water and the soil moisture tension is low.

Soil Moisture Tension is a measure of suction, and the correct way to refer to it is minus or negative X kPa. However, it is quite common for the minus to be dropped. It can be a little counter intuitive when thinking of wet soil vs dry soil with soil moisture tension as smaller numbers that are closer to zero don't mean less water. In fact these low numbers indicate more water, wetter soils.

Soil moisture content

Soil moisture content tells how much water is in the soil usually as a percentage representing what percentage of total 'volume/mass' of soil is moisture.

Volumetric/Gravimetric Soil Moisture Content refers to the volume/mass of water in a given volume/mass of the soil. This type of Soil moisture Content is measured in m^3m^{-3} / gm gm^{-1}. Alternately, the Volumetric/Gravimetric soil moisture content can be referred to as a % of volume/mass.

2.2.4.2 Importance of Soil Moisture Measurement

Although soil moisture is a small component of the hydrologic cycle, it influences hydrological and agricultural processes, runoff generation, drought development and many other processes. It also impacts on the climate system through atmospheric feedbacks. It plays a major role in understanding and predicting climatic patterns. Soil moisture is a source of water for evapotranspiration over the continents, and is involved in both the water and the energy cycles. Soil moisture was recognized as an Essential Climate Variable (ECV) in 2010.

Soil moisture measurements in agricultural settings provide important information for drought early warning. The upper 200 centimeters of soils is classified as the “root zone soil moisture” and is important for describing the water that is available to plants. When drought occurs, there is a deficit amount of moisture in the root zone, and consequently crop productivity diminishes. Having continuous soil moisture measurements will lead to improved crop yield forecasting, and irrigation planning. Soil moisture measurements also are important for predicting floods. By assessing how wet the soil is before a rainstorm, we can predict the potential for flooding to occur. If the soil is already oversaturated, at its maximum water-holding capacity, a rain event will not be absorbed adequately through the soil and flooding will likely occur.

Currently, weather prediction relies more heavily on observing the moisture levels in the atmosphere, instead of observing the moisture levels of soils; yet this is mostly due to the lack of soil moisture data available. Having soil moisture measurements may provide for a more accurate weather forecast. For example, soil moisture measurements could provide meteorologists with information on the amount of water available to evaporate from the land surface, which is directly related to weather and climate forecasting. Soil moisture links together the water, energy, and carbon exchanges between the land and the atmosphere. Observing soil moisture measurements allows for an assessment of the entire Earth system, and analyzing global changes is extremely important for understanding future climate change impacts.

2.2.5 Atmospheric Parameters

Atmospheric parameters such as precipitation, evaporation, surface temperature, relative humidity were used in the study. Evaporation and precipitation were discussed in the section 2.2.2.1 and 2.2.2.3 respectively. In this section surface temperature and relative humidity will be discussed.

2.2.5.1 Surface Temperature

Near surface air temperature is a measurement of the average kinetic energy of the air near the surface of the earth. The temperature of the air near the surface of the Earth is measured at meteorological observatories/weather stations with a standardized well-ventilated white-painted instrument shelter known as Stevention Screen. The thermometers should be positioned 1.25–2 m above the ground. Details of this setup are defined by the World Meteorological Organization (WMO). The measurement unit of surface temperature is Kelvin (k) or Celsius (^{0}C). Relation between Kelvin with Celsius is

$$0\ °C = 273.15\ K$$

In Bangladesh, on the basis of the distribution of temperature over the year, there can be two distinct season: the cool and the warm. Mean annual temperature ranges from 24.7 to 25.6^{0}C. Temperature regimes can, therefore, be classed as hyperthermic. The mean winter (Dec-Feb) and mean summer (Apr-Jul) temperatures are 19.5^{0}C and 28.6^{0}C respectively. The average temperature in July varies between 27^{0}C and 29^{0}C in the different parts of the country. The summer maxima range from 32 to 35^{0}C in the month of April. The minimum temperature of 8^{0}C is reached in January at Srimangal and Dinajpur.

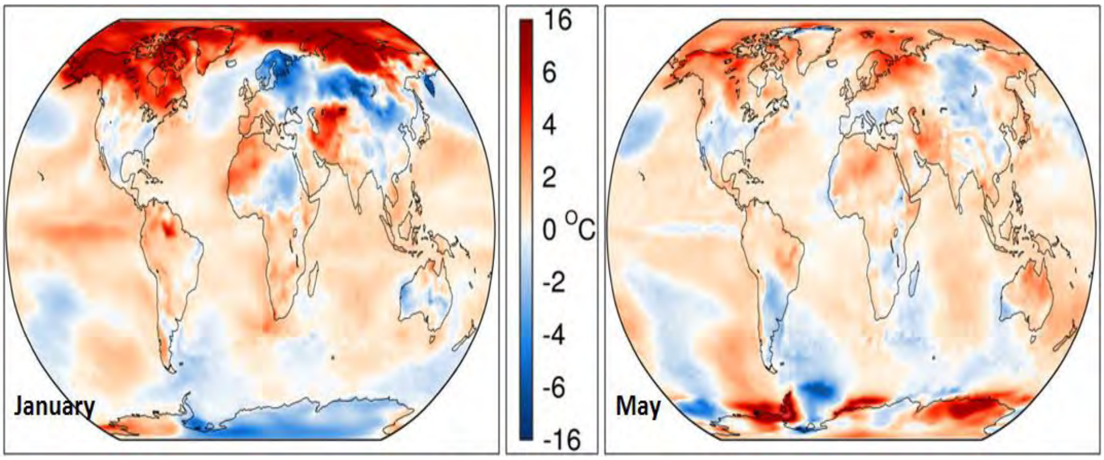

Fig. 2.6: Surface air temperature (^{0}C) anomaly for January and May, 2016.

2.2.5.2 Relative Humidity

Relative humidity is the amount of moisture in the air compared to what the air can hold at that time i.e. it indicates how moist the air is. Relative humidity may be defined as the ratio of the water vapor density (mass per unit volume) to the saturation water vapor density, usually expressed in percent:

$$\textbf{Relative Humidity (RH)} = \frac{\text{(Actual Vapor Density)}}{\text{(Saturation Vapor Density)}} \times 100\%$$

Relative humidity is also approximately the ratio of the actual to the saturation vapor pressure.

$$RH = \frac{\text{(Actual Vapor Pressure)}}{\text{(Saturation Vapor Pressure)}} \times 100\%$$

Actual vapor pressure is a measurement of the amount of water vapor in a volume of air and increases as the amount of water vapor increases. Air that attains its saturation vapor pressure has established equilibrium with a flat surface of water. That means, an equal number of water molecules are evaporating from the surface of the water into the air as are condensing from the air back into the water.

In Bangladesh, the annual average relative humidity is approximately 79%. Relative humidity gets its maximum value with a little variation (83-85%) in wet season and minimum value of (68%) in dry season. But in dry season, relative humidity varies a lot compare to wet season [35-38].

CHAPTER 3

DATA AND METHODOLOGY

3.1 Data Source

In this study, ERA-Interim global atmospheric reanalysis data was collected from European Centre for Medium-Range Weather Forecasts (ECMWF). The spatial resolution of the dataset is approximately 80 km on 60 vertical levels from the surface up to 0.1 hPa.

The details description of ERA-Interim data is given below:

ECMWF provides the ERA-Interim data which is a reanalysis of the global atmosphere covering the data-rich period since 1979 (originally, ERA-Interim ran from 1989, but the 10 year extension for 1979-1988 was produced in 2011), and continuing in real time. As ERA-Interim continues forward in time, updates of the archive will take place on a monthly basis. The ERA-Interim project was initiated in 2006 to provide a bridge between ECMWF's previous reanalysis, ERA-40 (1957-2002), and the next-generation extended reanalysis envisaged at ECMWF. The main objectives of the project were to improve on certain key aspects of ERA-40, such as the representation of the hydrological cycle, the quality of the stratospheric circulation, and the handling of biases and changes in the observing system. Gridded data products include a large variety of 3-hourly surface parameters, describing weather as well as ocean-wave and land-surface conditions, and 6-hourly upper-air parameters covering the troposphere and stratosphere. Vertical integrals of atmospheric fluxes, monthly averages for many of the parameters, and other derived fields have also been produced. The atmospheric model is coupled to an ocean-wave model resolving 30 wave frequencies and 24 wave directions at the nodes of its reduced 1.0^0x1.0^0 latitude/longitude grid.

The ERA-Interim atmospheric model and reanalysis system uses cycle 31r2 of ECMWF's Integrated Forecast System (IFS), which was introduced operationally in September 2006, configured for the following spatial resolution:

- 60 levels in the vertical, with the top level at 0.1 hPa.
- Spectral resolution of the outer loop is T255 (~79 km), and two successive inner loops at resolutions T95 (~210 km) and T159 (~125 km) are used for the minimization.
- a reduced Gaussian grid with approximately uniform 79 km spacing for surface and other grid-point fields.

The ERA-Interim data assimilation and forecast suite produces:

- Four analyses per day, at 00, 06, 12 and 18 UTC.
- Two 10-day forecasts per day, initialized from analyses at 00 and 12 UTC.

The analysis produced at 00 UTC on a given day involves observations taken between 15 UTC on the previous day and 03 UTC on the present day; the analysis at 12 UTC involves observations between 03 UTC and 15 UTC.

The ERA-Interim reanalysis is produced with a sequential data assimilation scheme, advancing forward in time using 12-hourly analysis cycles. In each cycle, available observations are combined with prior information from a forecast model to estimate the evolving state of the global atmosphere and its underlying surface. This involves computing a variational analysis of the basic upper-air atmospheric fields (temperature, wind, humidity, ozone, surface pressure), followed by separate analyses of nearsurface parameters (2m temperature and 2m humidity), soil moisture and soil temperature, snow, and ocean waves. The analyses are then used to initialise a short-range model forecast, which provides the prior state estimates needed for the next analysis cycle. In-situ soil moisture observations are valuable to evaluate modelled soil moisture. In the recent years huge efforts were made to collect observations representing contrasting biomes and climate conditions. The International Soil Moisture

Network (ISMN), http://www.ipf.tuwien.ac.at/insitu. is a new data hosting centre where globally available ground-based soil moisture measurements are collected, harmonized and made available to users. This includes a collection of more than 500 stations (with data from 2007 to March 2012) gathered and quality controlled at ECMWF. Albergel et al. [40-42] have used these data to validate various soil moisture estimates produced at ECMWF, including from ERA-Interim as well as from offline land simulations.

ERA-Interim data in either GRIB or NetCDF format can be downloaded from the ECMWF Data Server at http://data.ecmwf.int/data. Global fields are available at full resolution, both vertically (on model levels) and horizontally.

3.2 Data Used

ERA-Interim reanalysis provides fields of Volumetric Soil Moisture (VSM) data for soil layer-1 (0-7cm), soil layer-2 (7-28cm), soil layer-3 (28-100cm) and soil layer-4 (100-255cm) which were used for analyzing soil moisture. For analyzing the relationship between soil moisture and the atmospheric variables of precipitation, evaporation, 2-m air temperature, relative humidity were also used for the same areas using same data site. The daily average data from 6-hourly dataset was used for analyzing soil moisture and its relation to atmospheric variables for 36 years from 1979 to 2014.

3.3 Study Area

For analyzing soil moisture and the atmospheric variables, Bangladesh region (20.7°N-26.7°N & 88°E-92.8°E) is considered for study area shown in Fig. 3.1.

Islam et al. [43] found that the atmospheric moistures are varied between the eastern and western side of Bangladesh. Therefore, in this study, two representative domains (D1 and D2) of these two parts of Bangladesh are considered for analyzing and comparing the differences of soil moisture characteristics. D1 represents the north eastern (NE) (24°N-25.5°N & 90.6°E-92.6°E) side domain and D2 indicates the south western (SW) (22.5°N-24°N & 88°E-90°E) side of Bangladesh shown in Fig. 3.2.

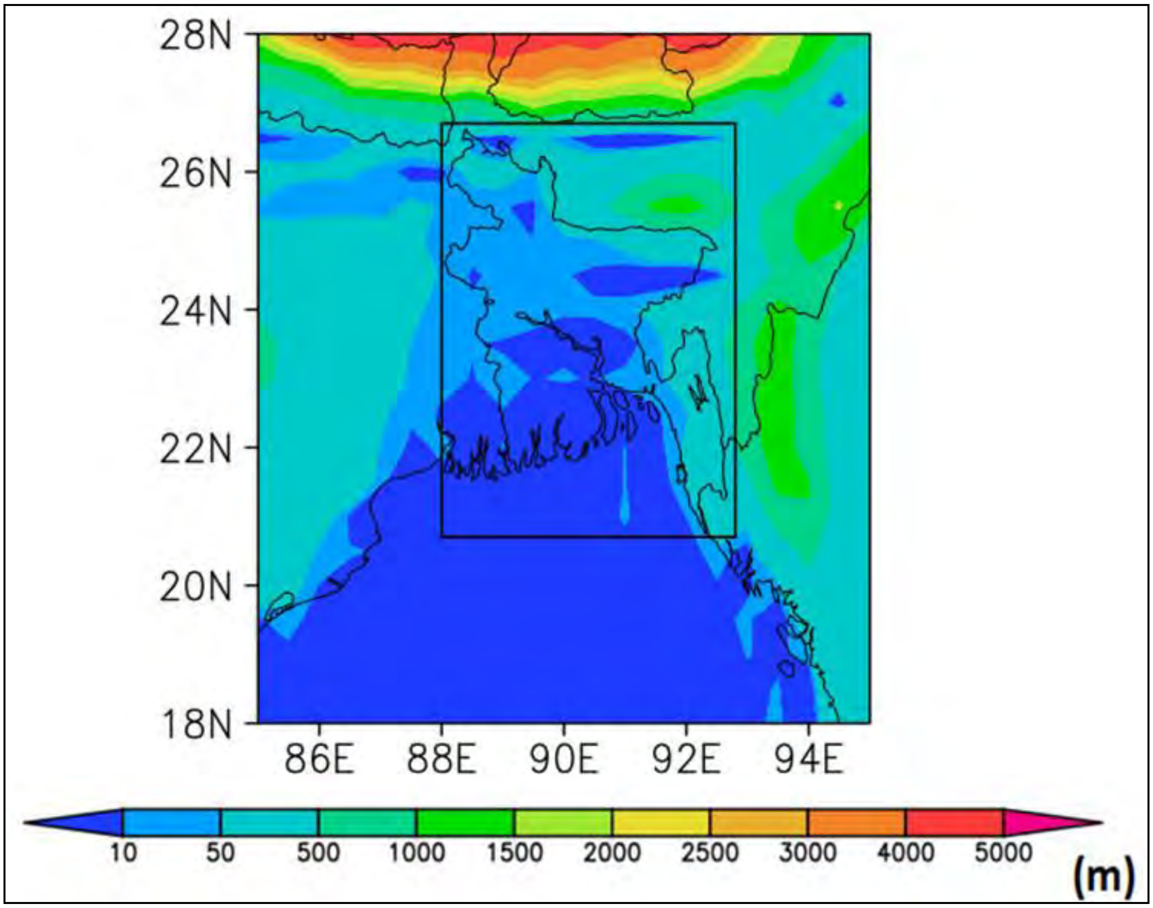

Fig. 3.1: Topography of Bangladesh. The box indicates the study area for Bangladesh.

3.4 Study Method

In this work, four soil moisture layers are considered as moisture study. The layers are soil layer-1 (0-7cm), soil layer-2 (7-28cm), soil layer-3 (28-100cm) and soil layer-4 (100-255cm) which is shown in Fig. 3.3. The VSM data in different layers are extracted and averaged (annually, monthly, and seasonally) for the study area to analyze the spatial and temporal characteristics of soil moisture of Bangladesh. As western and eastern parts of Bangladesh are different in terms of atmospheric moisture (Islam et al.) [43]. So, soil moisture characteristics of these sides are also examined and compare with the variability.

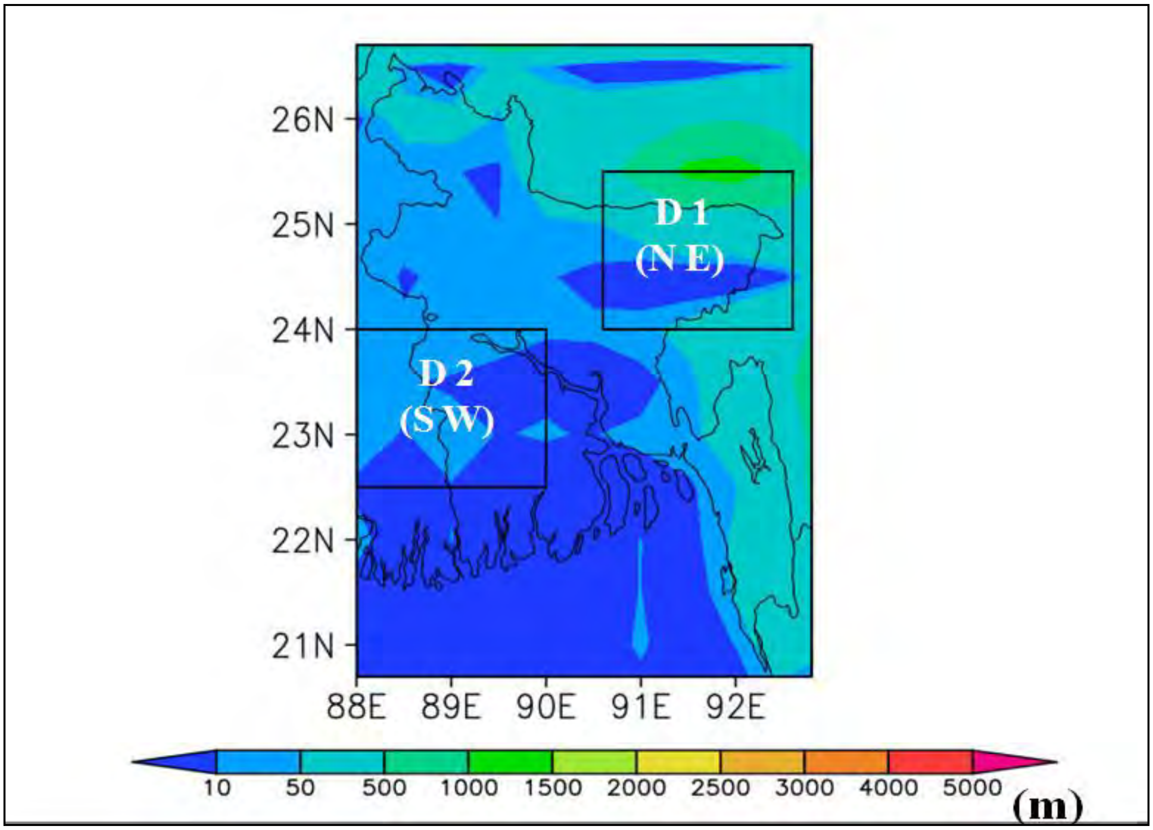

Fig. 3.2: Topography of Bangladesh. The boxes indicate two domains representing the north eastern (D1) and south western (D2) sides of Bangladesh.

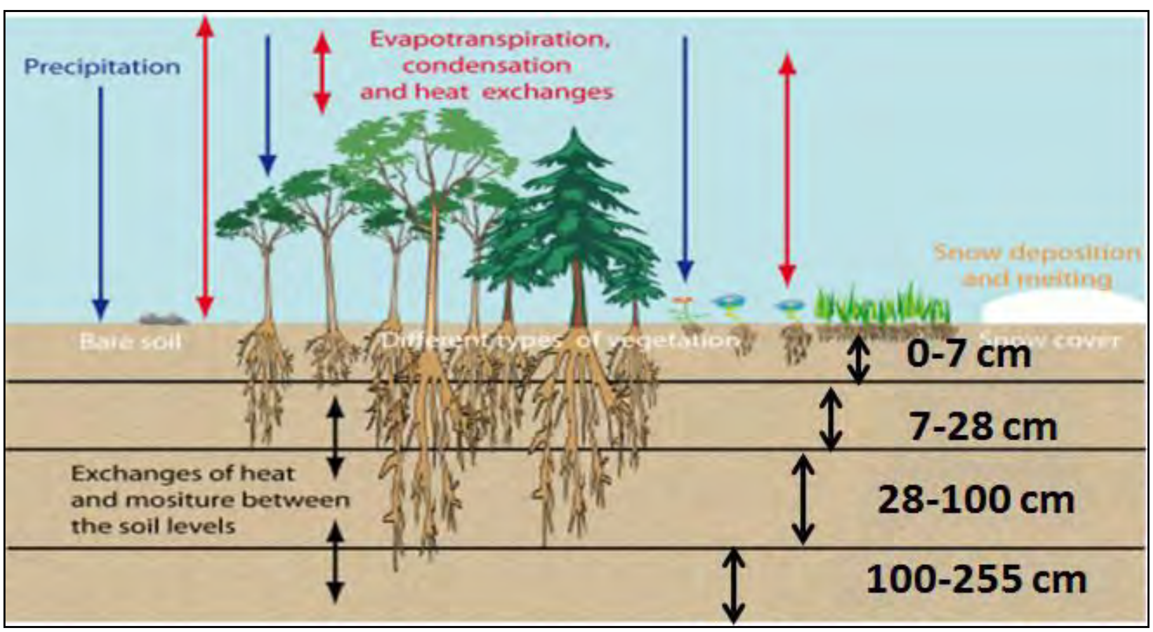

Fig. 3.3: Different soil moisture layers (SML) with different atmospheric variables.

In addition, to know the moisture effects on the atmospheric variables, the surface temperature, precipitation, evaporation, relative humidity are extracted from the same area. The average (annual, month, and seasonal) values of the parameters for 36-years are compared to find out the relation with soil moisture. Grid Analysis and Display System Software (GrADS) was used for graphical display and calculation of the parameters.

The details description of Grid Analysis and Display System Software (GrADS) is given below:

3.4.1 Grid Analysis and Display System Software (GrADS)

The Grid Analysis and Display System (GrADS) is an interactive desktop tool that is used for easy access, manipulation, and visualization of earth science data. GrADS has two data models for handling gridded and station data. GrADS supports many data file formats, including binary (stream or sequential), GRIB, NetCDF, HDF, and BUFR (for station data). GrADS has been implemented worldwide on a variety of commonly used operating systems and are freely distributed over the Internet. GrADS has a programmable interface (scripting language) that allows for sophisticated analysis and display applications. GrADS uses a 5-Dimensional data environment: the four conventional dimensions (longitude, latitude, vertical level, and time) plus an optional 5th dimension for grids that is generally implemented but designed to be used for ensembles. Data sets are placed within the 5-D space by use of a data descriptor file. GrADS handles grids that are regular, non-linearly spaced, gaussian, or of variable resolution. Data from different data sets may be graphically overlaid, with correct spatial and time registration. Operations are executed interactively by entering FORTRAN-like expressions at the command line. Data may be displayed using a variety of graphical techniques: line and bar graphs, scatter plots, smoothed contours, shaded contours, streamlines, wind vectors, grid boxes, shaded grid boxes, and station model plots. Graphics may be output in PostScript or image formats. GrADS was used for graphical display and calculation of the parameters.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Variations of Soil Moisture in Bangladesh

4.1.1 Annual Variation of Soil Moisture

Spatial distributions of soil moisture averaged for the period from 1979-2014 is shown in Fig. 4.1 for the four layers i.e. SML1, SML2, SML3 and SML4 from surface to bottom respectively. The Figure shows that the moisture varies from 0.27 (m^3m^{-3}) to 0.33 (m^3m^{-3}) which is increased from the upper layer to the bottom. However, the western side of Bangladesh is dryer (<0.3 m^3m^{-3}) than the eastern side up to the third layer from the surface. This characteristic is similar with Islam et al. [43]. However, he showed that moist environment in the eastern part of Bangladesh dry environment in the western part of Bangladesh from humidity anomalies. The fourth soil layer maintains almost unique value all over Bangladesh.

Fig. 4.2 shows the comparison of 36-year average values of soil moisture for different layers. The figure indicates that the average value of the soil moisture of the upper layer is 0.235 (m^3m^{-3}) and 0.251 (m^3m^{-3}) for the lower layer. The first two layers almost overlap with each other which mean that they contain almost the same quantity of soil moisture 0.235 (m^3m^{-3}), whereas, the value 0.243 (m^3m^{-3}) in the third layer and the value 0.251 (m^3m^{-3}) in the fourth layer show distinct difference in soil moisture. In terms of percentage, the average values for the first two layers are found 24.4% and 24.5%, respectively of the total soil moisture of the 0-255 cm layer, where the third and fourth layers have the soil moisture amount of 25.1% and 26%, of the total, respectively.

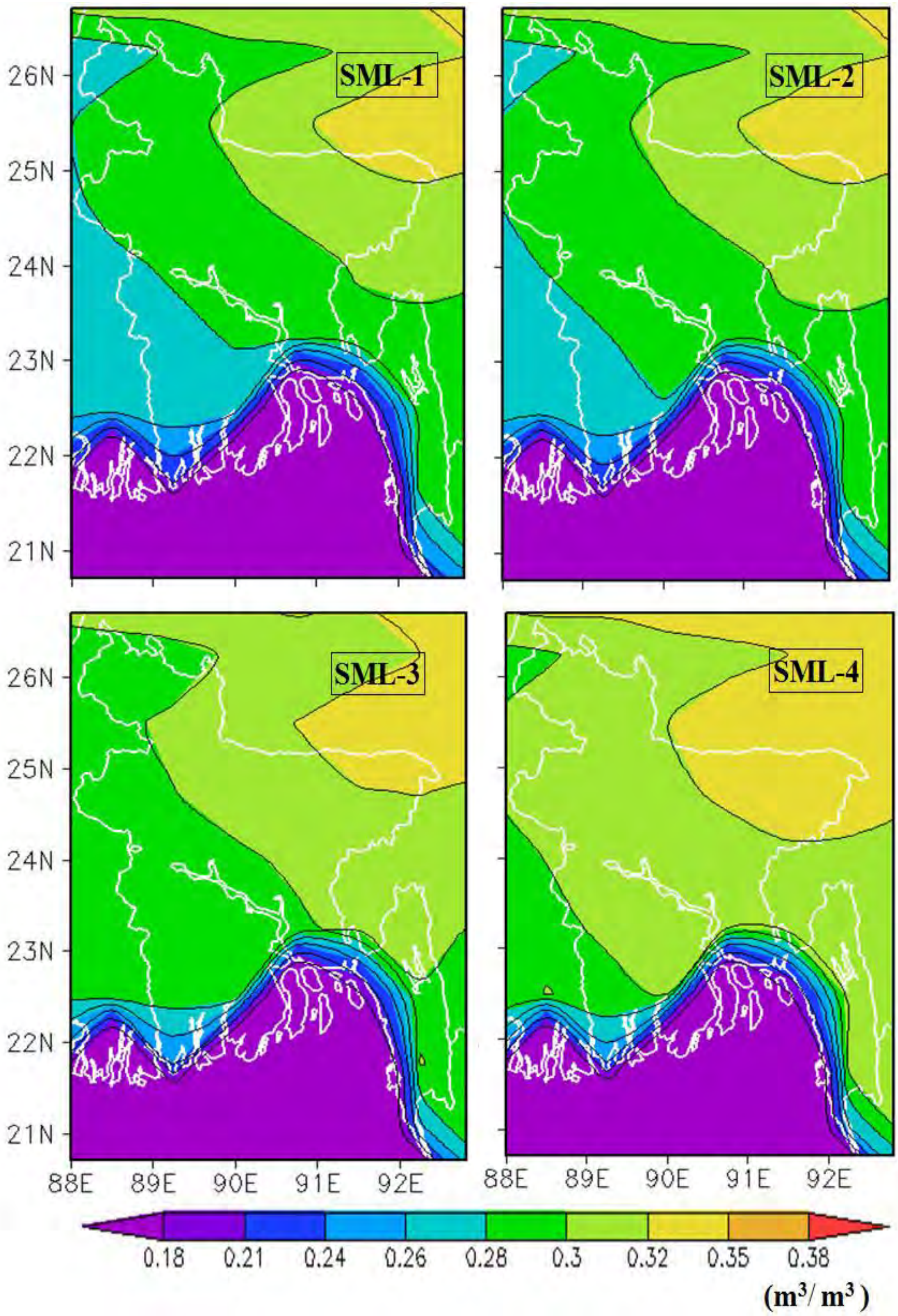

Fig. 4.1: Distribution of averaged soil moisture (m^3m^{-3}) for different layers over Bangladesh during the period of 1979-2014.

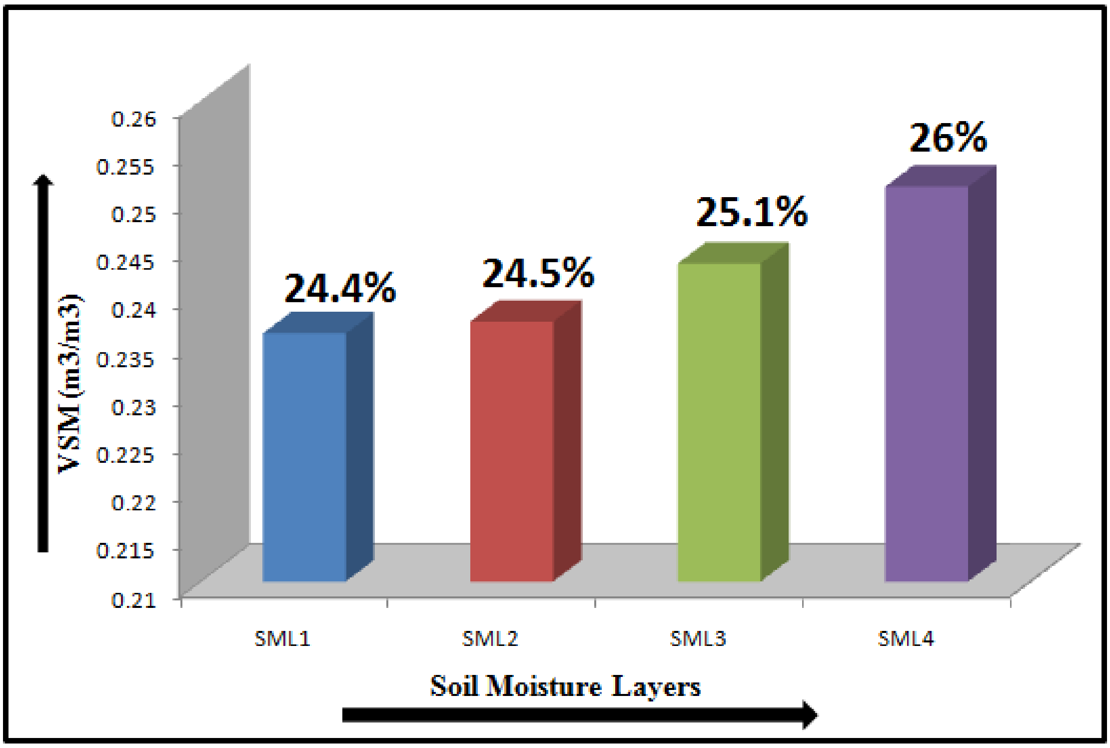

Fig. 4.2: Average value of soil moisture (m^3m^{-3}) in the four layers for 36 years.

The moisture differences between two successive layers from upper to bottom are found 0.53%, 2.54%, and 3.28%, respectively (Table-1). Therefore, moisture is increasing to 6.35% from the surface layer to the bottom layer. The moisture is found to increase since 1979 to 2014 by 7.6%, 7.4%, 6.5%, and 5% (Table-1) for the top layer to the bottom layer respectively. The percentage of increased soil moisture is found decreasing from the surface layer to the bottom layer.

Fig. 4.3 shows the annual temporal distributions of soil moisture for the four layers during the study period. Soil moisture for the four layers showed increasing trend. The maximum (minimum) values of soil moisture for the four layers (surface to bottom) are found 0.246 (0.219), 0.247 (0.221), 0.251 (0.229) and 0.258 (0.238), respectively in the 1990 (1979). Climatologically, it is clear that soil moisture is increasing day by day as increasing rate of soil moisture for the four layers (surface to bottom) are found 0.0023, 0.0022, 0.0019 and 0.0015, respectively. Increasing rate of moisture is found positive but not linear one. However, higher increasing (0.0023 m^3m^{-3}/year) rate in the surface layer indicates the climate change effects.

The 5-year running mean of soil moisture for the four layers is shown in Fig. 4.4. It also indicates that soil moisture in each of the four layers is increasing within the 36-year from 1979-2014. Increasing trend of each of the four layers show a unique pattern.

Table-1: Soil moisture characteristics from 1979-2014.

Soil layers	Total increase in soil moisture (%)	Difference in moisture between layers (%)
SML1	7.6	
SML2	7.4	0.53
SML3	6.5	2.54
SML4	5	3.28

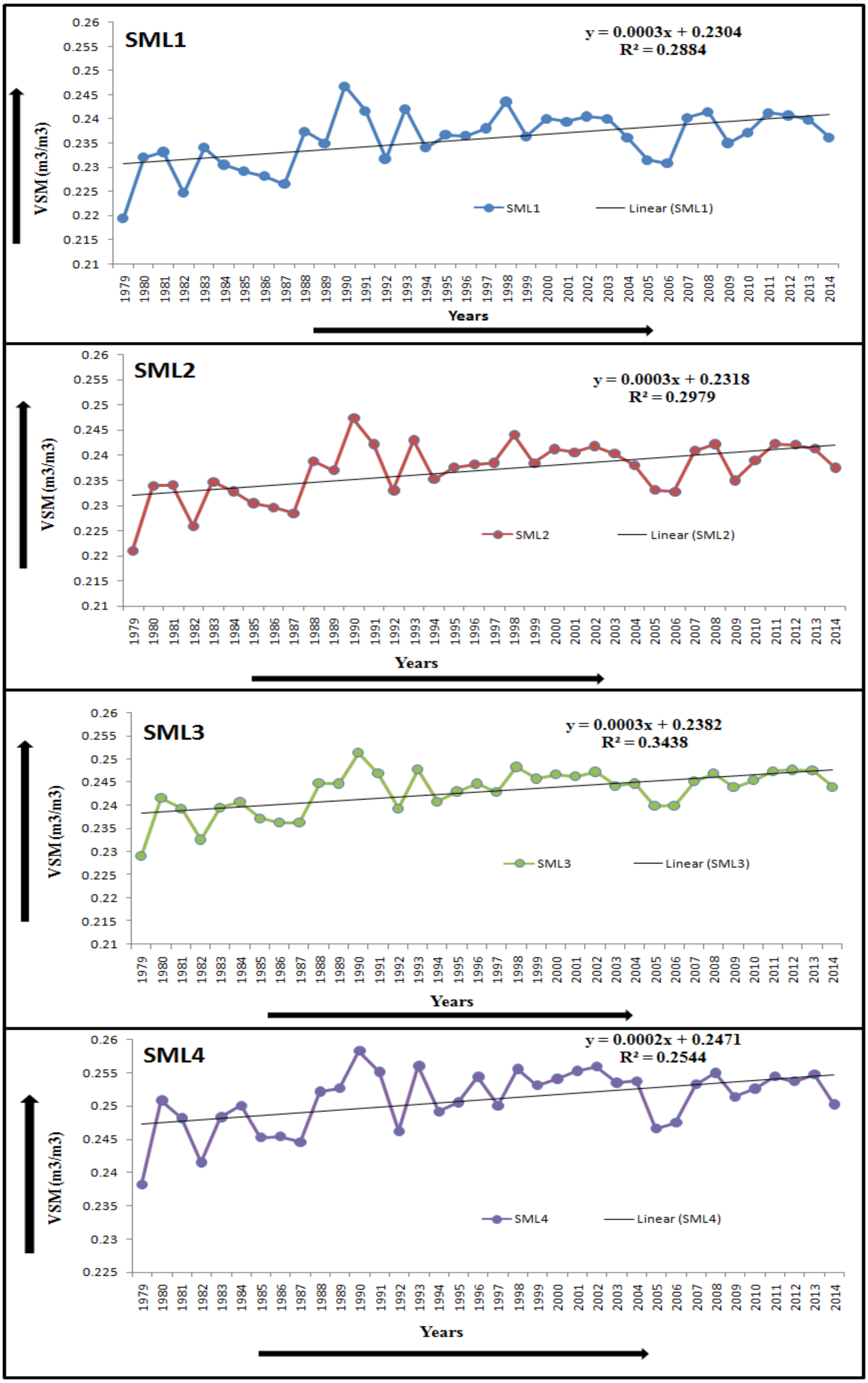

Fig. 4.3: Annual variation of soil moisture (m^3m^{-3}) for the period of 1979-2014.

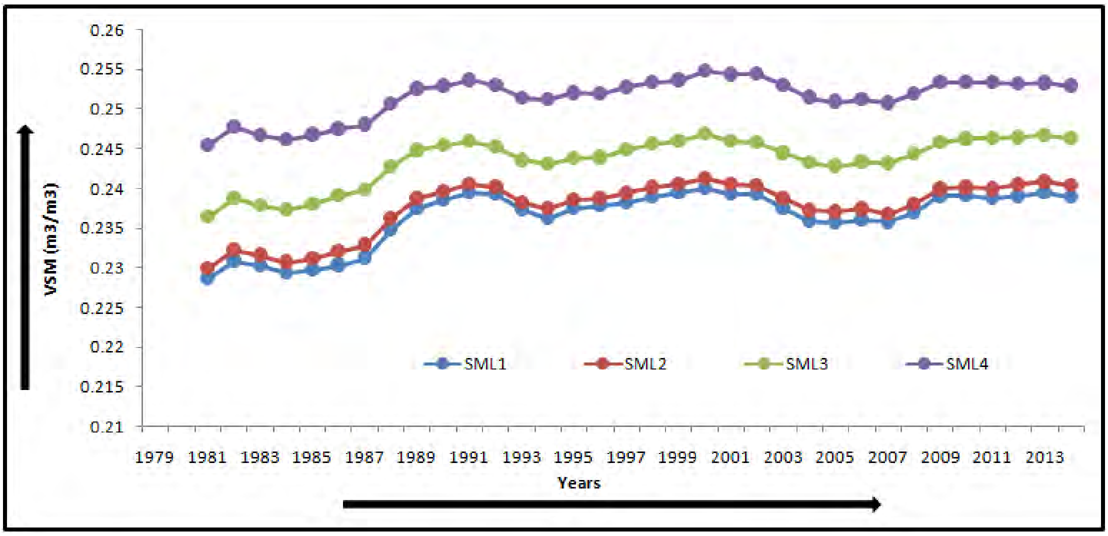

Fig. 4.4: 5-year running means of soil moisture (m^3m^{-3}) in different layers during 1979-2014.

4.1.2 Monthly Variation of Soil Moisture

Spatial distributions of monthly averaged soil moisture for each month from January to December during 1979-2014 are shown in Fig. 4.5 to Fig. 4.16 for the four layers (i.e. SML1, SML2, SML3 and SML4). In January, soil moisture of the first layer shows more than (>0.24 m^3m^{-3}) in the north eastern side of Bangladesh, which is gradually decreasing toward south western with the value less than (<0.24 m^3m^{-3}). The second and third layer show the same trend with different value but fourth layer has almost uniform value for whole Bangladesh. In general, horizontal distribution is found non uniform except the fourth layer.

Soil moisture is increasing from the surface layer to the bottom layer. In February and March, soil moisture in the four different layers shows same characteristics as previous. However, from January to March soil moisture is decreasing from the south western side to north eastern side of Bangladesh for each of the four layers. In April, soil holds moisture in the first layer with the value of more than (>0.26 m^3m^{-3}) in the north eastern whereas, soil holds less than (<0.26 m^3m^{-3}) moisture in the south western part of Bangladesh. Soil moisture is increasing from the top layer to the bottom layer. In May, soil moisture showed same phenomena like in April. But in June, soil moisture is decreasing from the surface layer to the bottom layer. From April to June, soil moisture is increasing from the north eastern part to south western part for each of the four layers. From July to October, vertical and horizontal distribution pattern of soil moisture in the different four layers are almost unique (>0.32 m^3m^{-3}). From November to December, soil moisture in all four layers starts to decrease and behaves like what it did in the month of January.

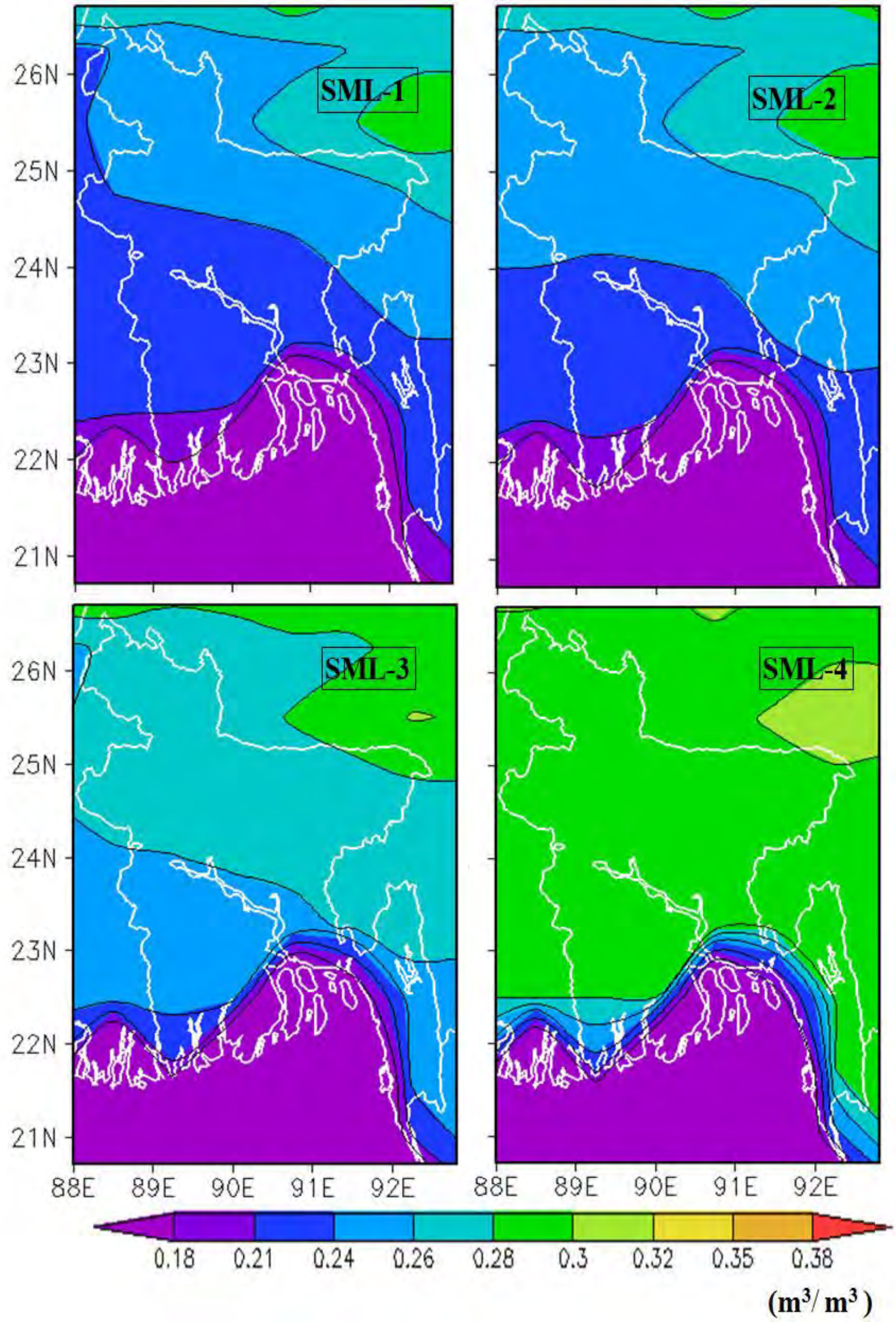

Fig. 4.5: Distribution of averaged soil moisture (m^3m^{-3}) for different layers over Bangladesh in January during the period of 1979-2014.

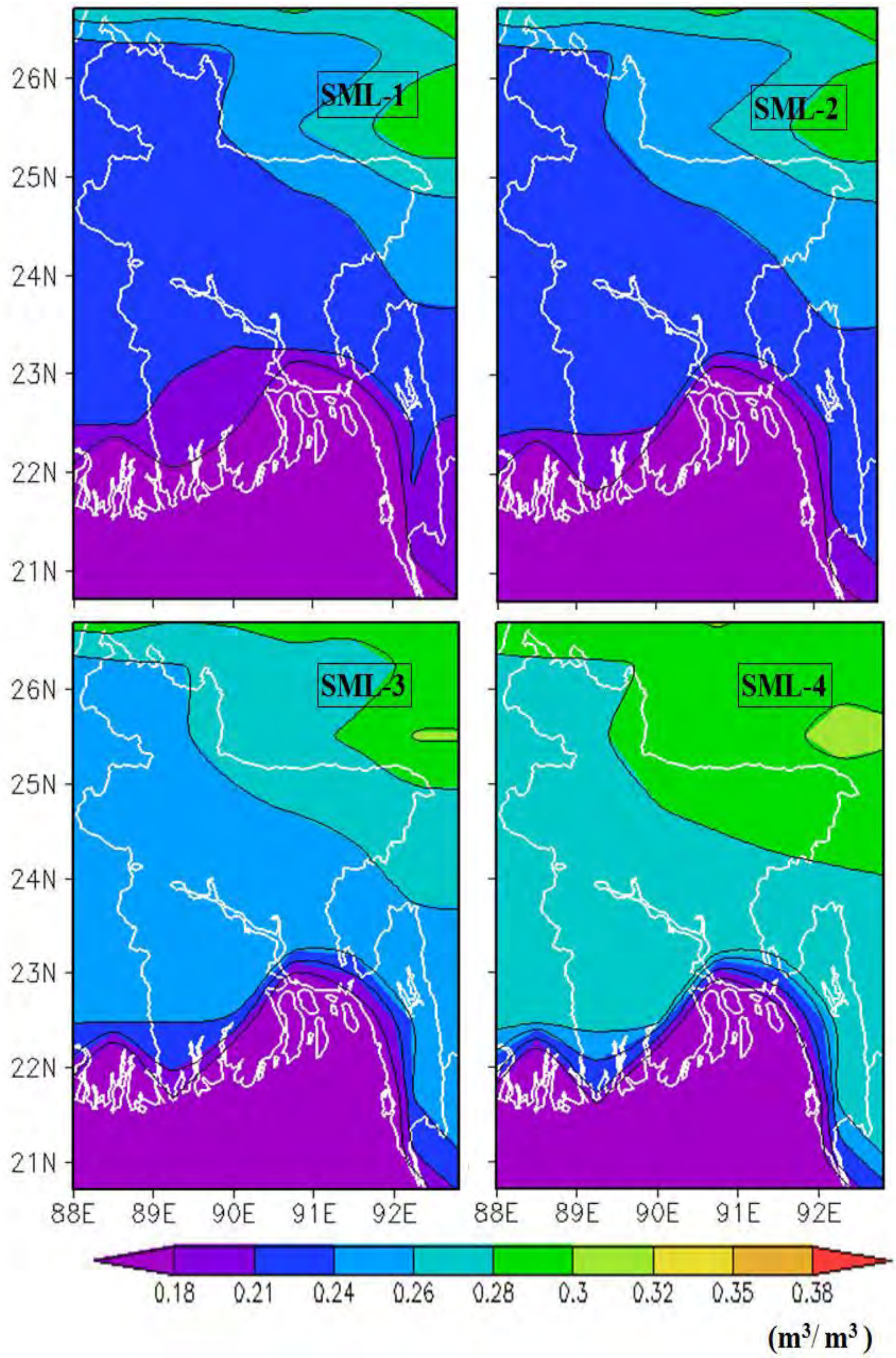

Fig. 4.6: Distribution of averaged soil moisture (m^3m^{-3}) for different layers over Bangladesh in February during the period of 1979-2014.

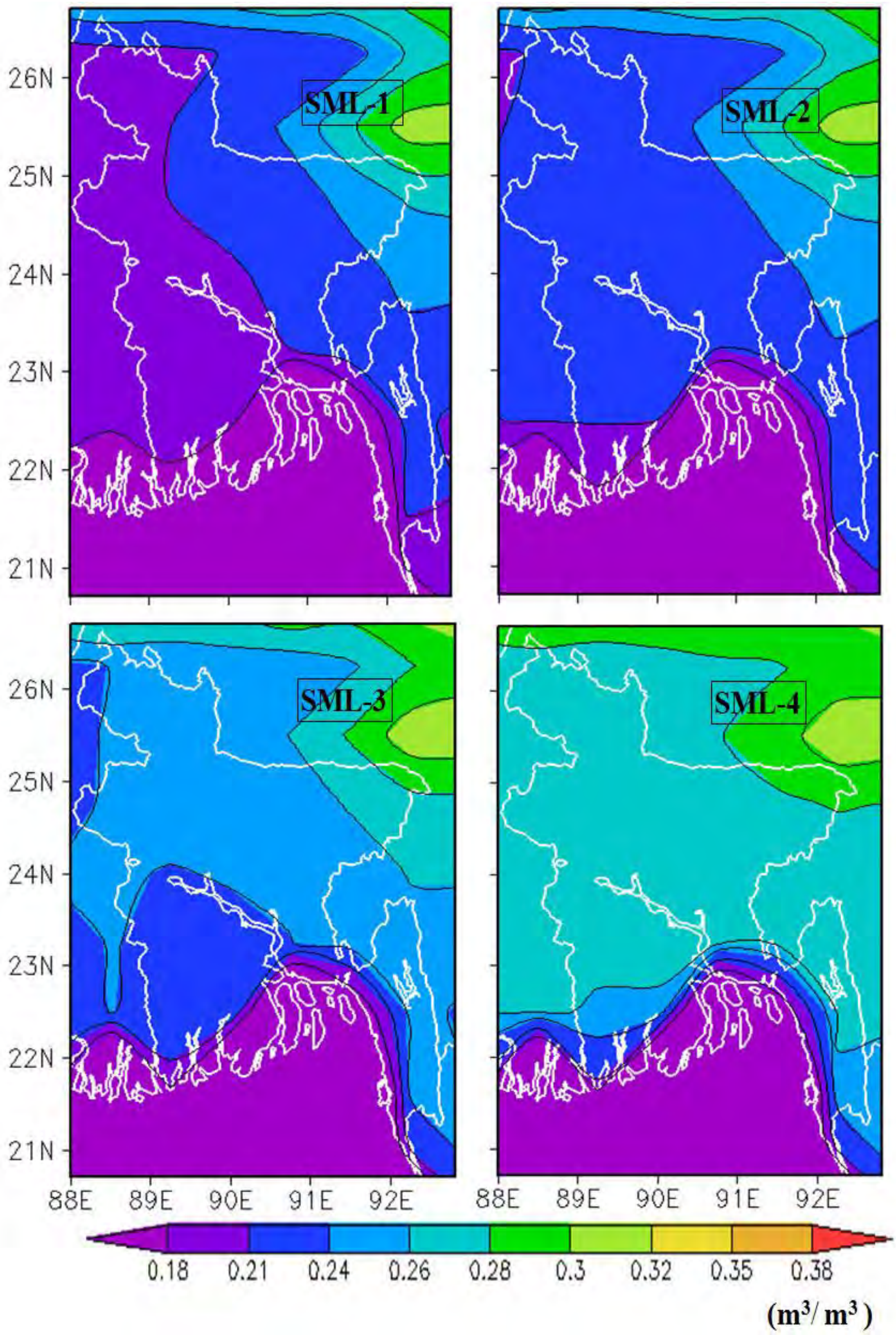

Fig. 4.7: Distribution of averaged soil moisture (m^3m^{-3}) for different layers over Bangladesh in March during the period of 1979-2014.

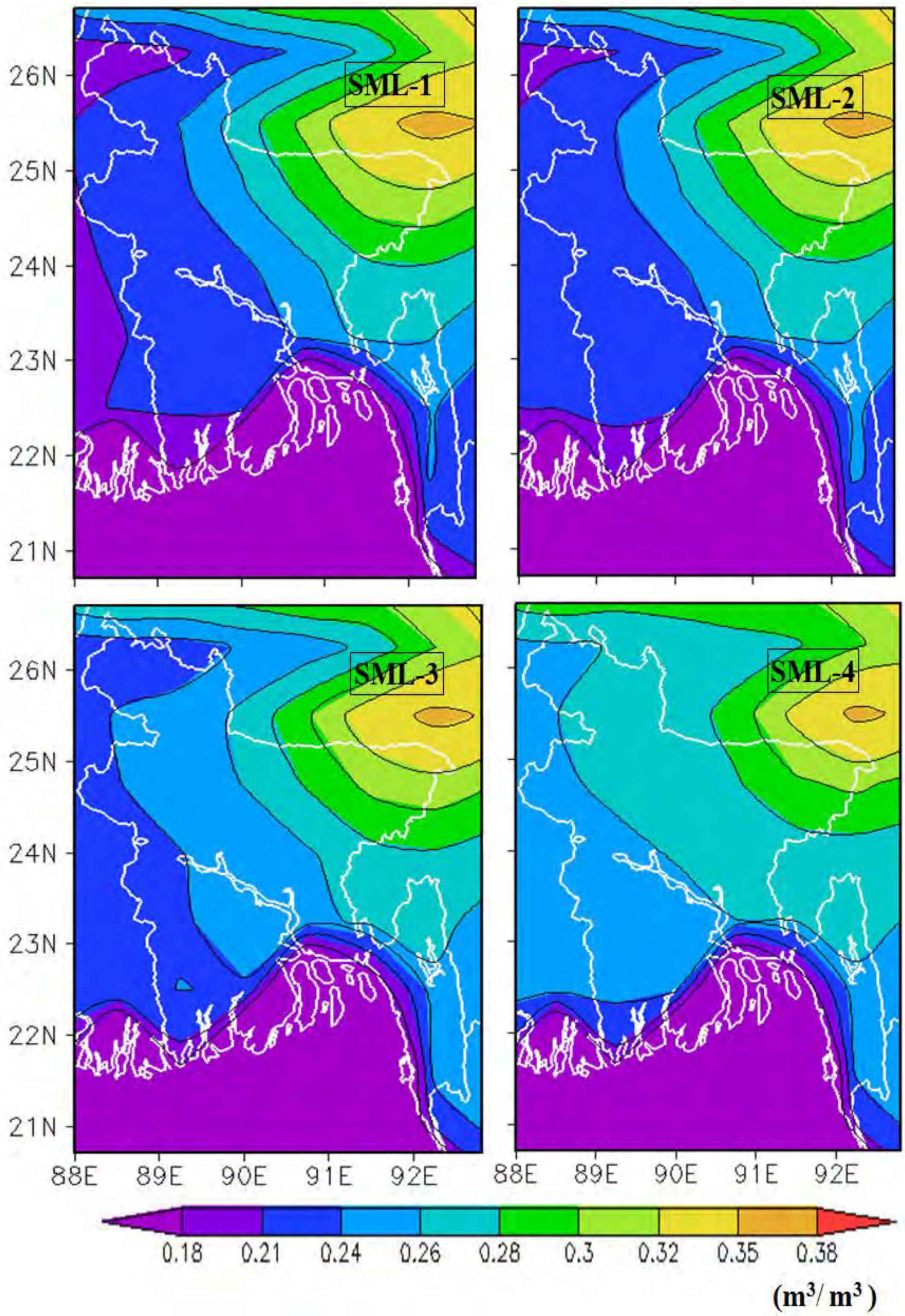

Fig. 4.8: Distribution of averaged soil moisture (m^3m^{-3}) for different layers over Bangladesh in April during the period of 1979-2014.

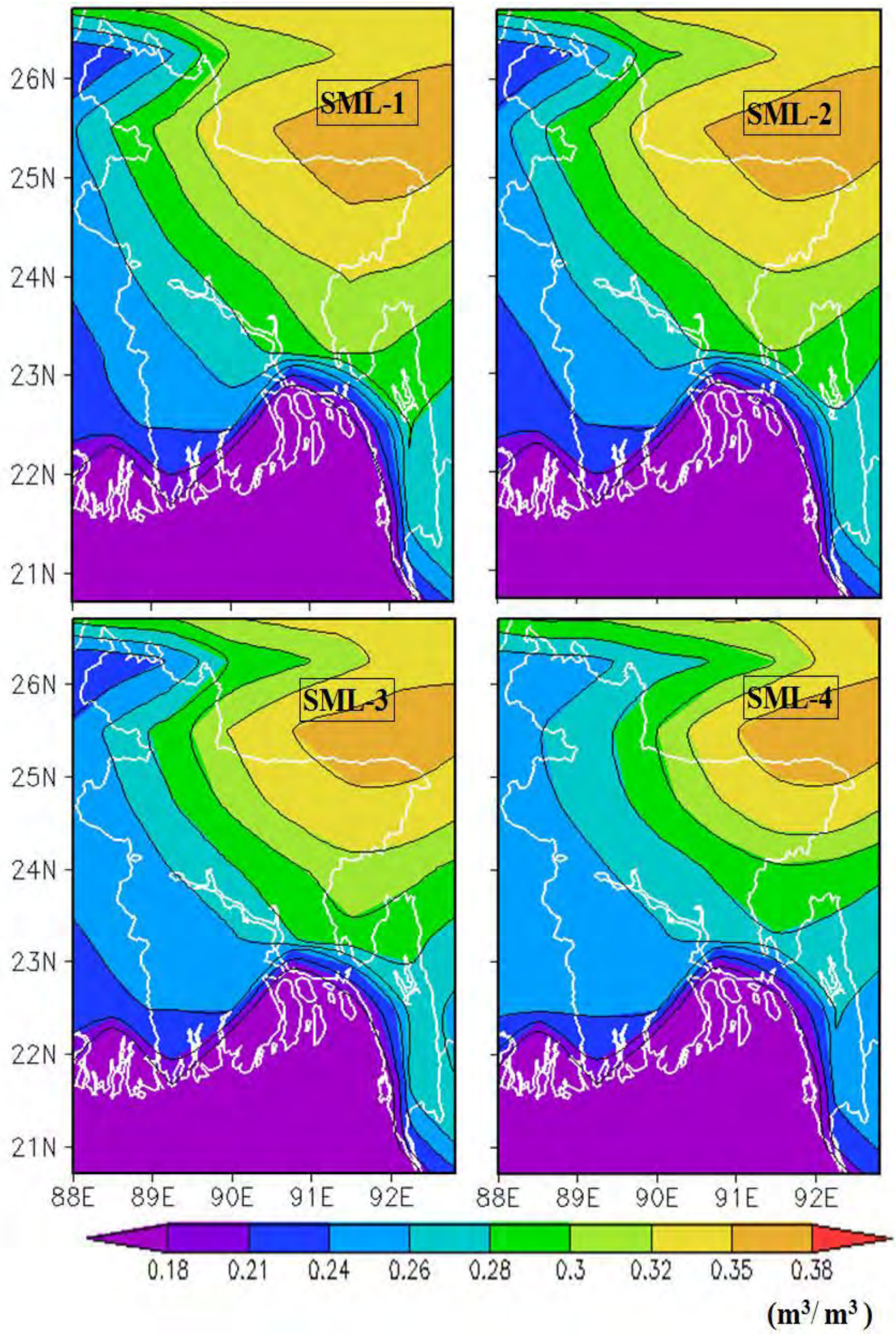

Fig. 4.9: Distribution of averaged soil moisture (m^3m^{-3}) for different layers over Bangladesh in May during the period of 1979-2014.

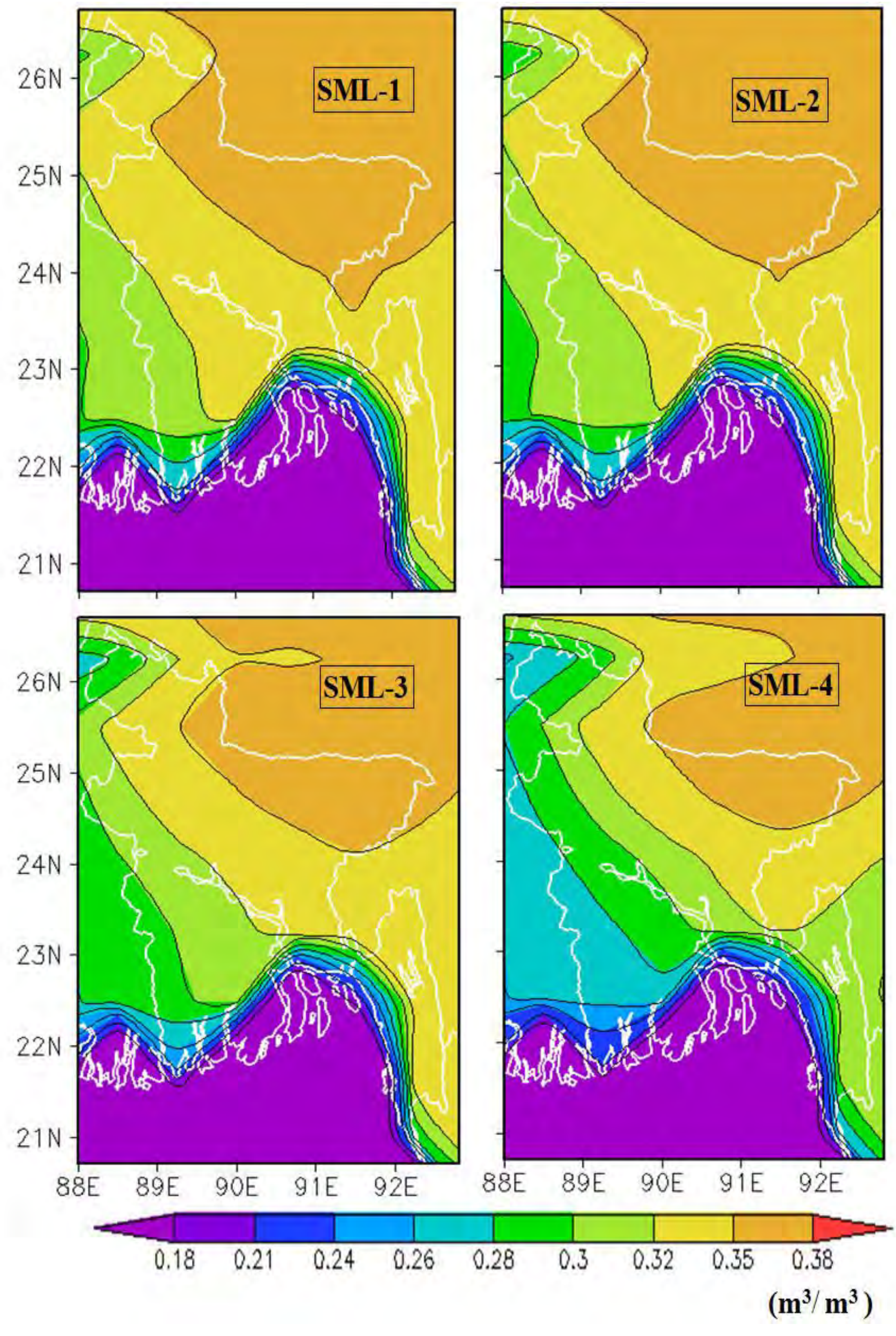

Fig. 4.10: Distribution of averaged soil moisture (m^3m^{-3}) for different layers over Bangladesh in June during the period of 1979-2014.

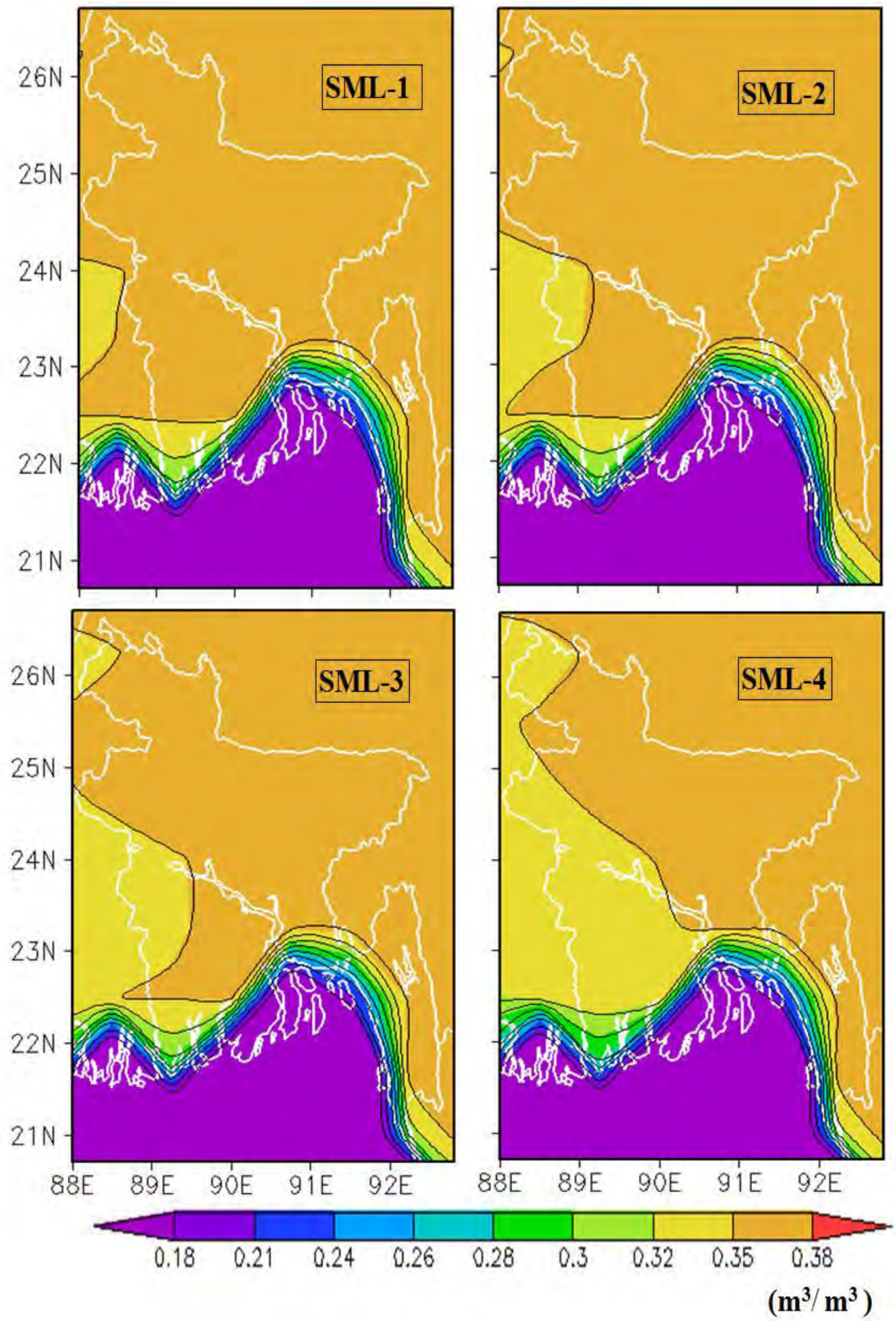

Fig. 4.11: Distribution of averaged soil moisture (m^3m^{-3}) for different layers over Bangladesh in July during the period of 1979-2014.

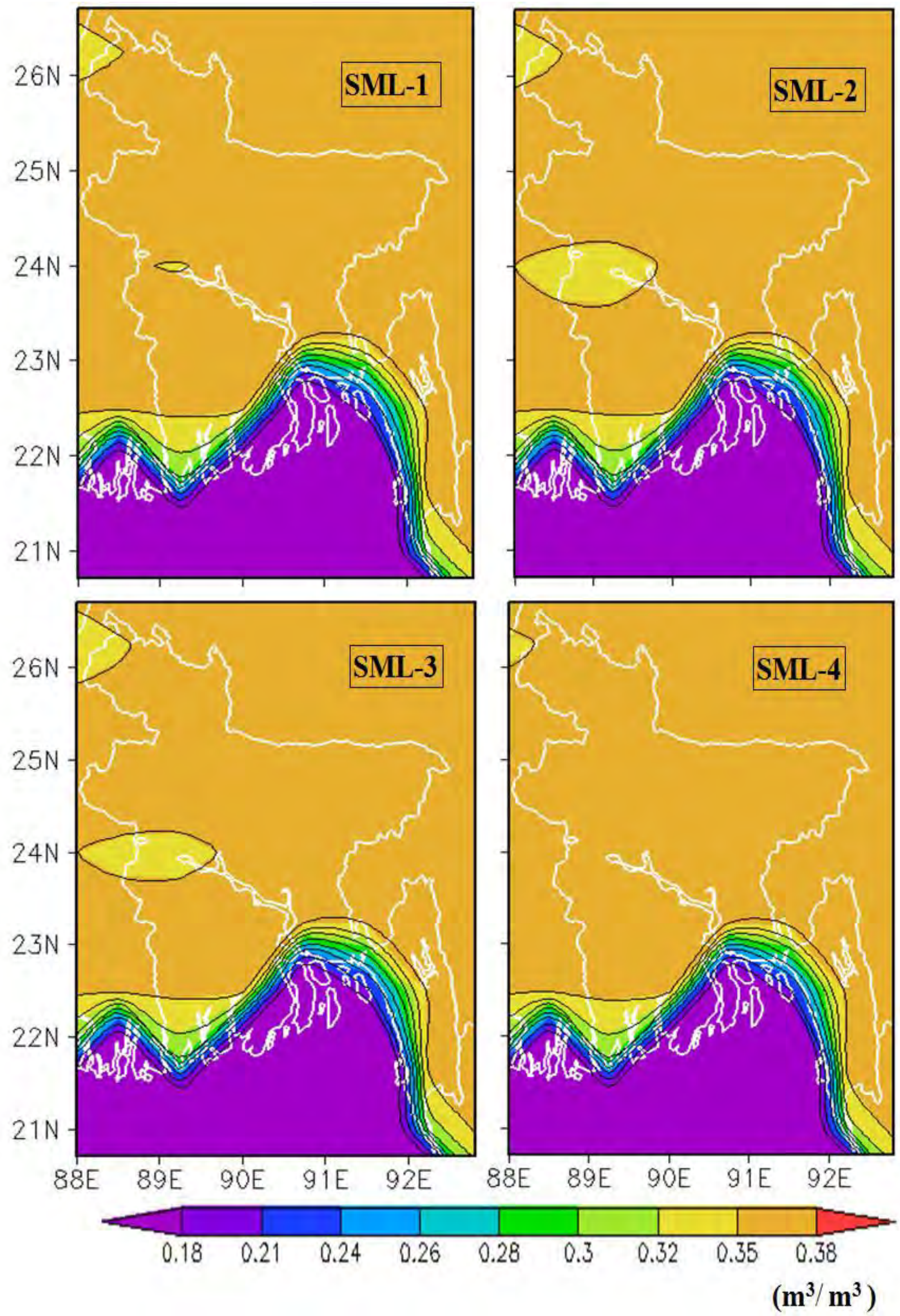

Fig. 4.12: Distribution of averaged soil moisture (m^3m^{-3}) for different layers over Bangladesh in August during the period of 1979-2014.

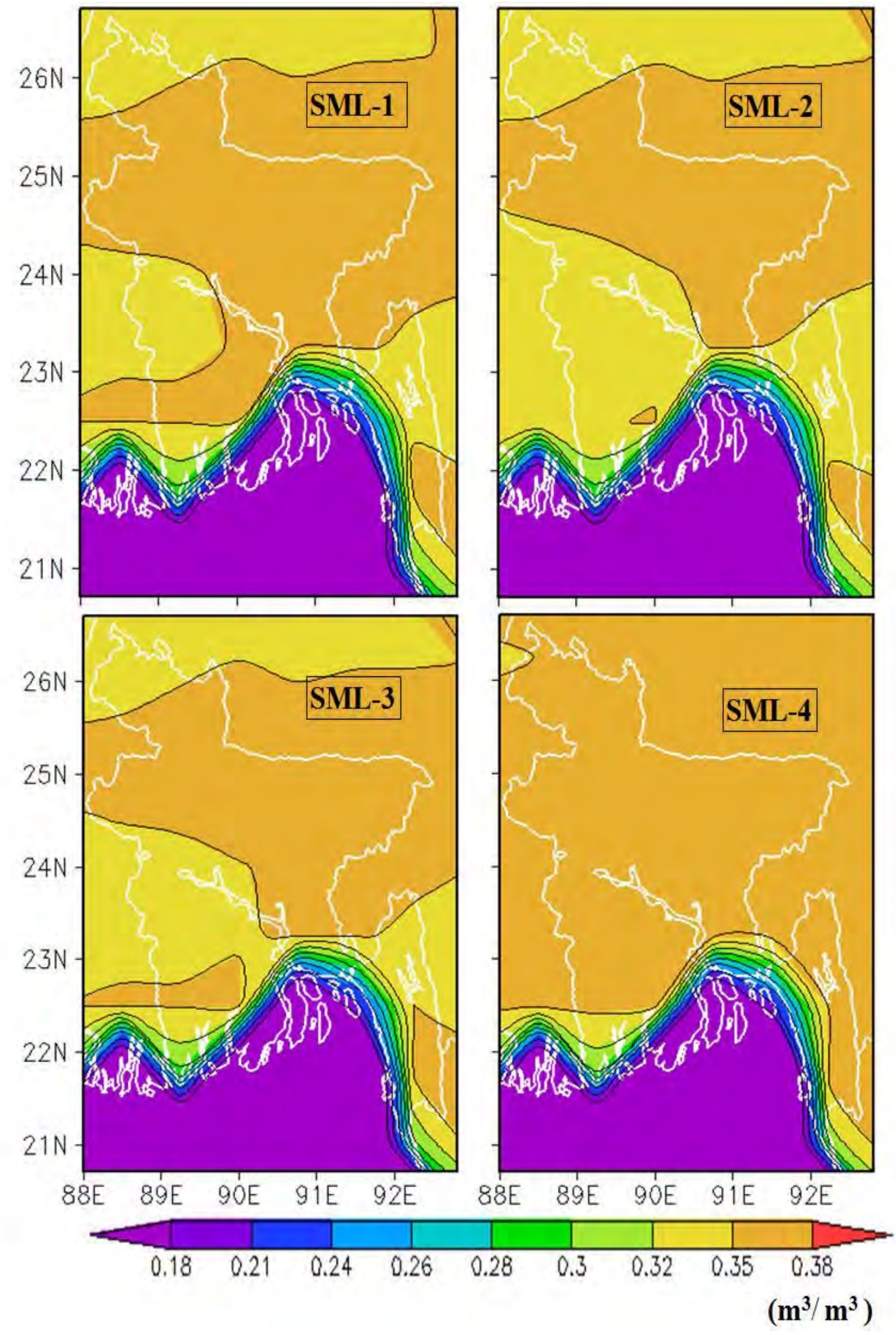

Fig. 4.13: Distribution of averaged soil moisture (m^3m^{-3}) for different layers over Bangladesh in September during the period of 1979-2014.

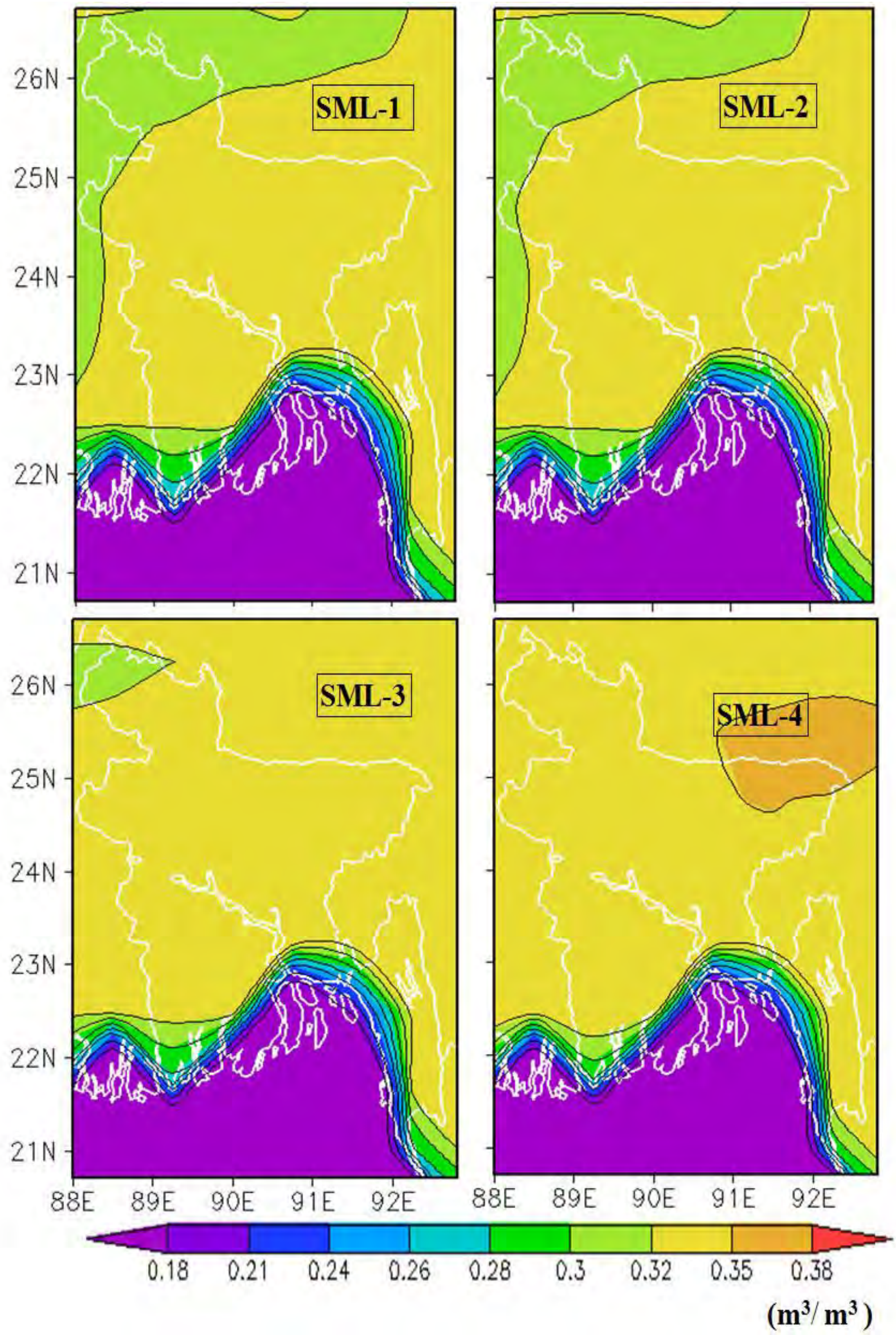

Fig. 4.14: Distribution of averaged soil moisture (m^3m^{-3}) for different layers over Bangladesh in October during the period of 1979-2014.

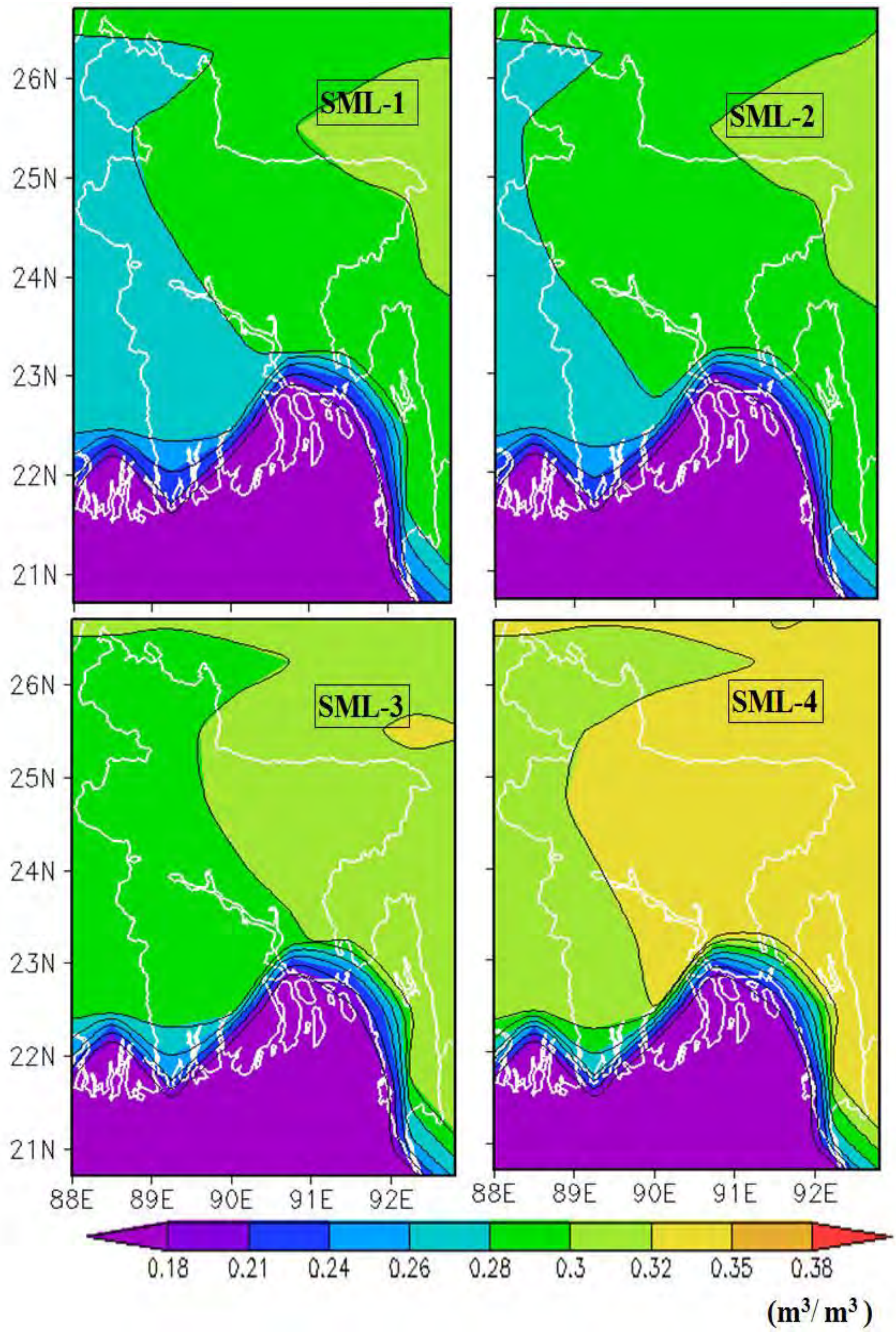

Fig. 4.15: Distribution of averaged soil moisture (m^3m^{-3}) for different layers over Bangladesh in November during the period of 1979-2014.

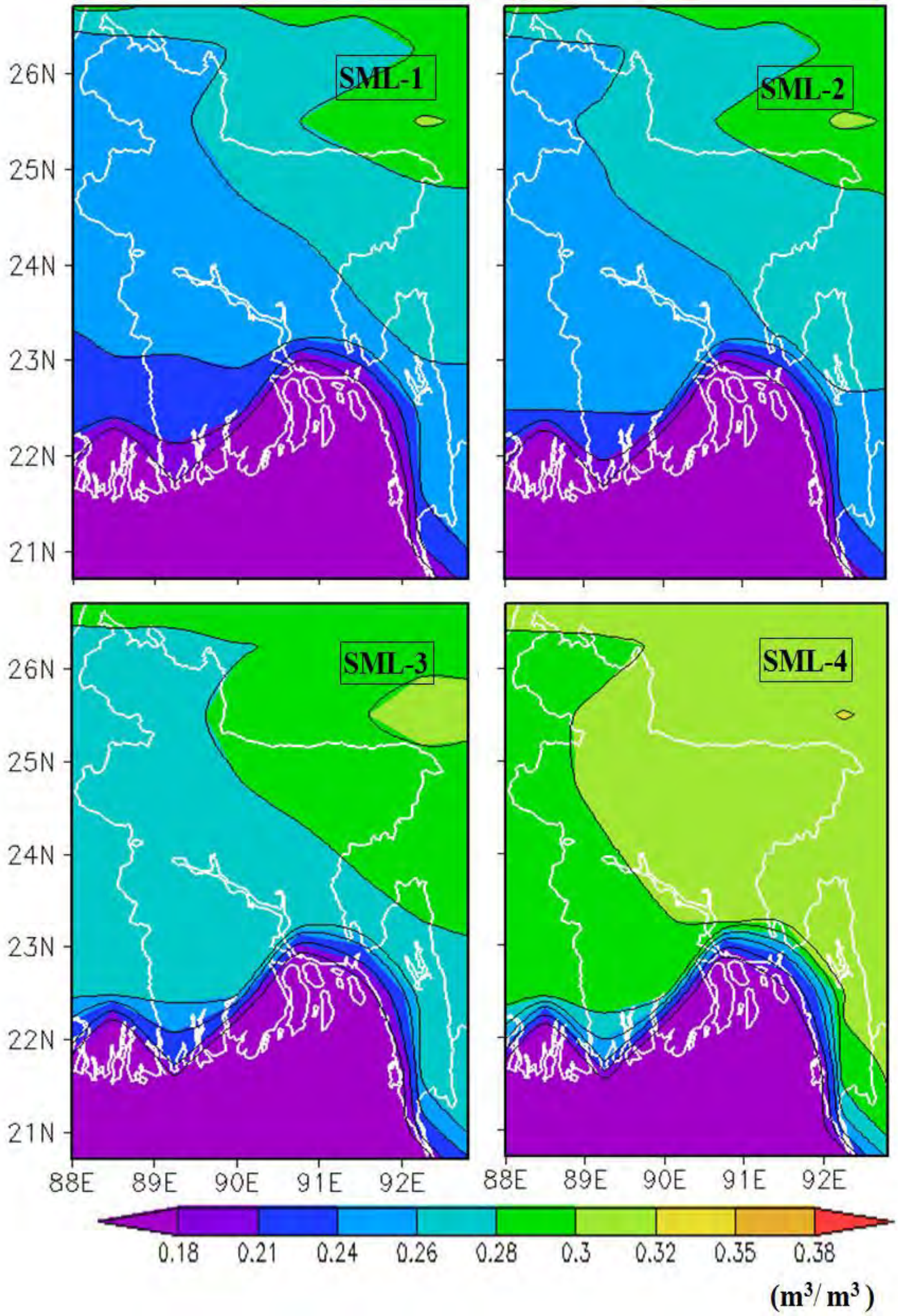

Fig. 4.16: Distribution of averaged soil moisture (m^3m^{-3}) for different layers over Bangladesh in December during the period of 1979-2014.

The bars diagram in Fig. 4.17 shows the monthly comparison of soil moisture for each layer for Bangladesh during 1979-2014. Soil moisture in the first layer starts to decrease from January and reaches minimum in March. Then it starts to increase and gets maximum in July. Then again it starts to decrease up to December. Soil moisture in the rest of the three bottom layers maintain the same phenomena like the first layer but with different values.

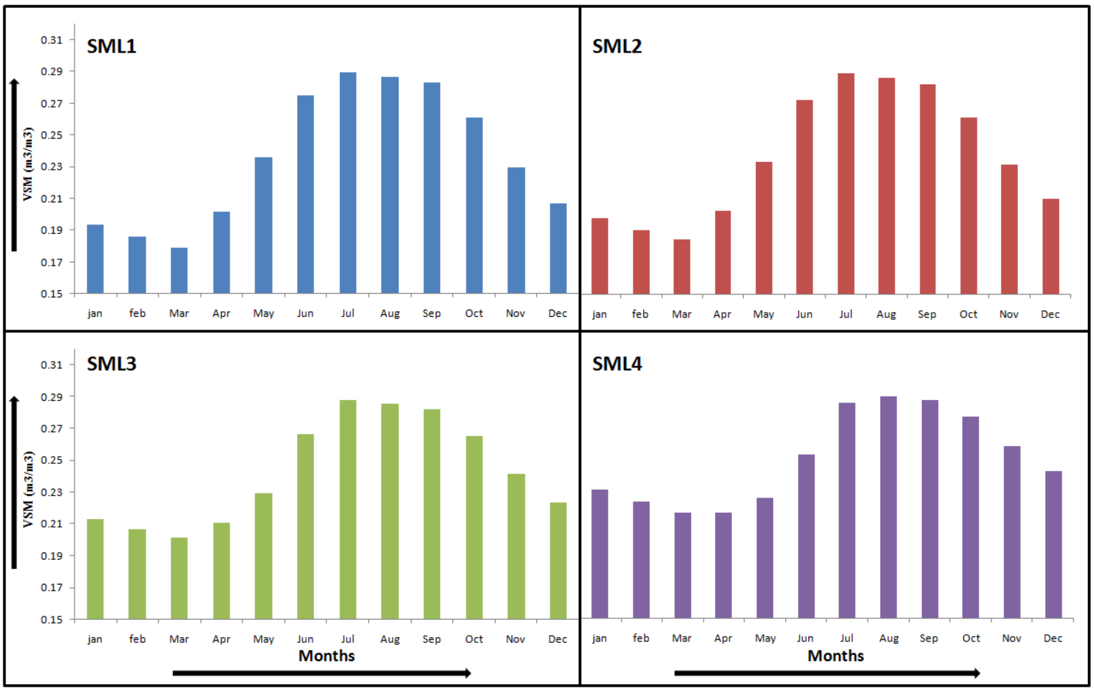

Fig. 4.17: Monthly country-averaged soil moisture (m^3m^{-3}) in four layers in Bangladesh.

The monthly variability of soil by month for different layers is shown in Fig. 4.18. The 36-year averaged soil moisture for all four layers shows the same periodic phenomena throughout the twelve months. Soil moisture is lowest (0.180 m^3m^{-3} for SML1, 0.184 m^3m^{-3} for SML2, 0.201 m^3m^{-3} for SML3 and 0.217 m^3m^{-3} for SML4) in March for all layers. Whereas highest value (0.287 m^3m^{-3} for all layers) is noticed in July or August. In May all four layers are almost coincided to each other with the value of (0.24 m^3m^{-3}). So, May is considered as the transition month in this study. In June, soil moisture is decreasing from the surface layer to the bottom layer i.e. surface layer holds more moisture (0.274 m^3m^{-3}) than the bottom layer (0.253 m^3m^{-3}). All four layers having low moisture (<0.26) during November to May and relatively high moisture (>0.26) during June (except the fourth layer) to October. Therefore, the moisture characteristics of soil layers are divided into two parts and analyzed for the dry (November-May) and wet (June-October) seasons. Distinct variations within the moisture layers are found in the dry season; in contrast, moisture layers are approximately identical in the wet season which behaves like one saturated layer after the month of May.

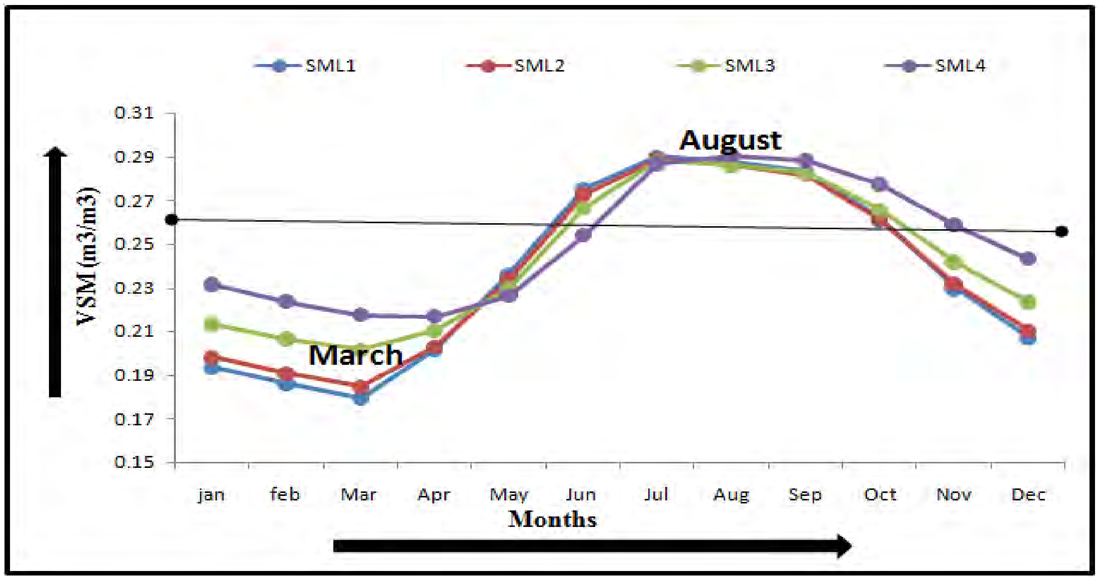

Fig. 4.18: Monthly averaged of soil moisture (m^3m^{-3}) for 1979-2014.

Considering May as a transition Month in this study, November to May is considered as a dry season whereas June to October is considered as a wet season (Fig. 4.19).

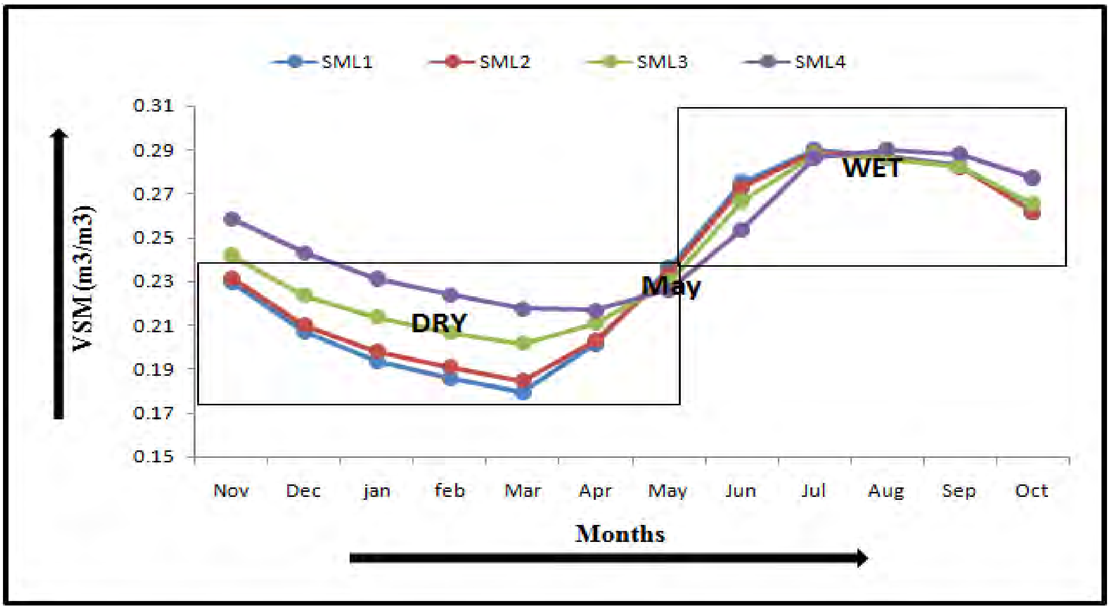

Fig. 4.19: Monthly country-averaged soil moisture (m^3m^{-3}) for 1979-2014 (according to season) in Bangladesh.

4.1.3 Seasonal Variation of Soil Moisture

Spatial distributions of averaged soil moisture in four layers (i.e. SML1, SML2, SML3 and SML4) during dry and wet seasons are shown in Fig. 4.20 and Fig. 4.21 respectively. It has been seen that during dry season first two layers almost have same variations of soil moisture whereas the third and fourth layers have different distributions all over Bangladesh, soil moisture is decreasing from northeast to southwest and horizontal gradient of moisture is prominent in the upper two layers than that in the lower layers. On the other hand, during wet season each of the four layers maintains the identical and saturated distributions of soil moisture.

Fig. 4.22 shows the comparison of soil moisture among different layers for dry and wet seasons. The soil layers contain more moisture (56% of the total layer moisture) in the wet season than that of in the dry season (44%). Percentage of individual layer during dry and wet seasons shows in the Fig. 4.22. It shows that percentage difference of soil moisture between dry and wet seasons are 31%, 29%, 24%, and 19%, respectively for the four layers. So, the moisture difference between dry and wet seasons is decreasing from the surface layer to the bottom layer. The comparison between the moisture during dry and wet seasons indicates that the moisture in the layers behave similar to overall characteristics of the soil moisture over Bangladesh (Fig. 4.2). Therefore, moisture in the dry season is important because it significantly contributes to the total moisture pattern over Bangladesh.

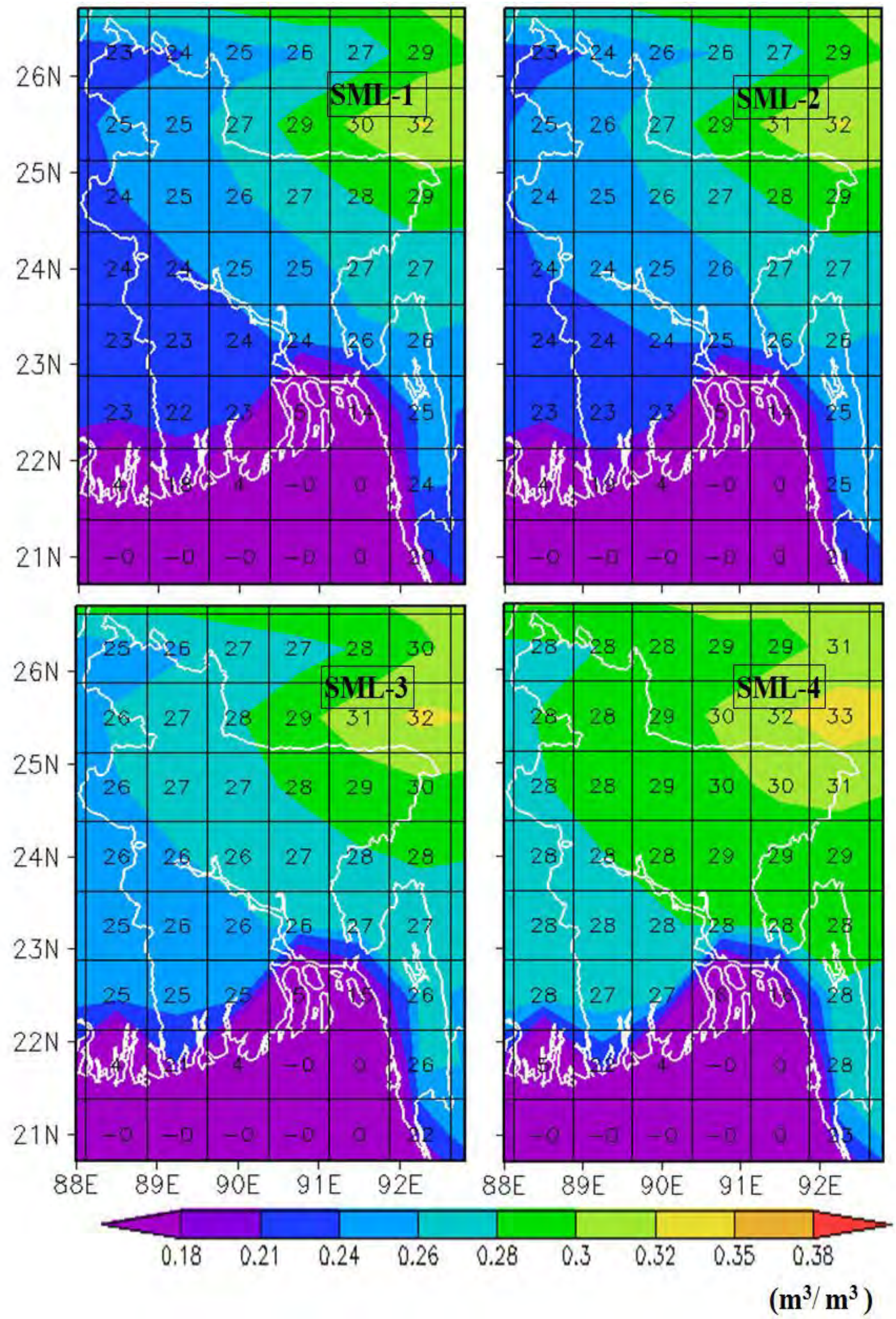

Fig. 4.20: Distribution of averaged soil moisture value (m^3m^{-3}) for different layers over Bangladesh in the dry season during the period 1979-2014. (Moisture values $\times 10^{-2}$) are also indicated in the grids.

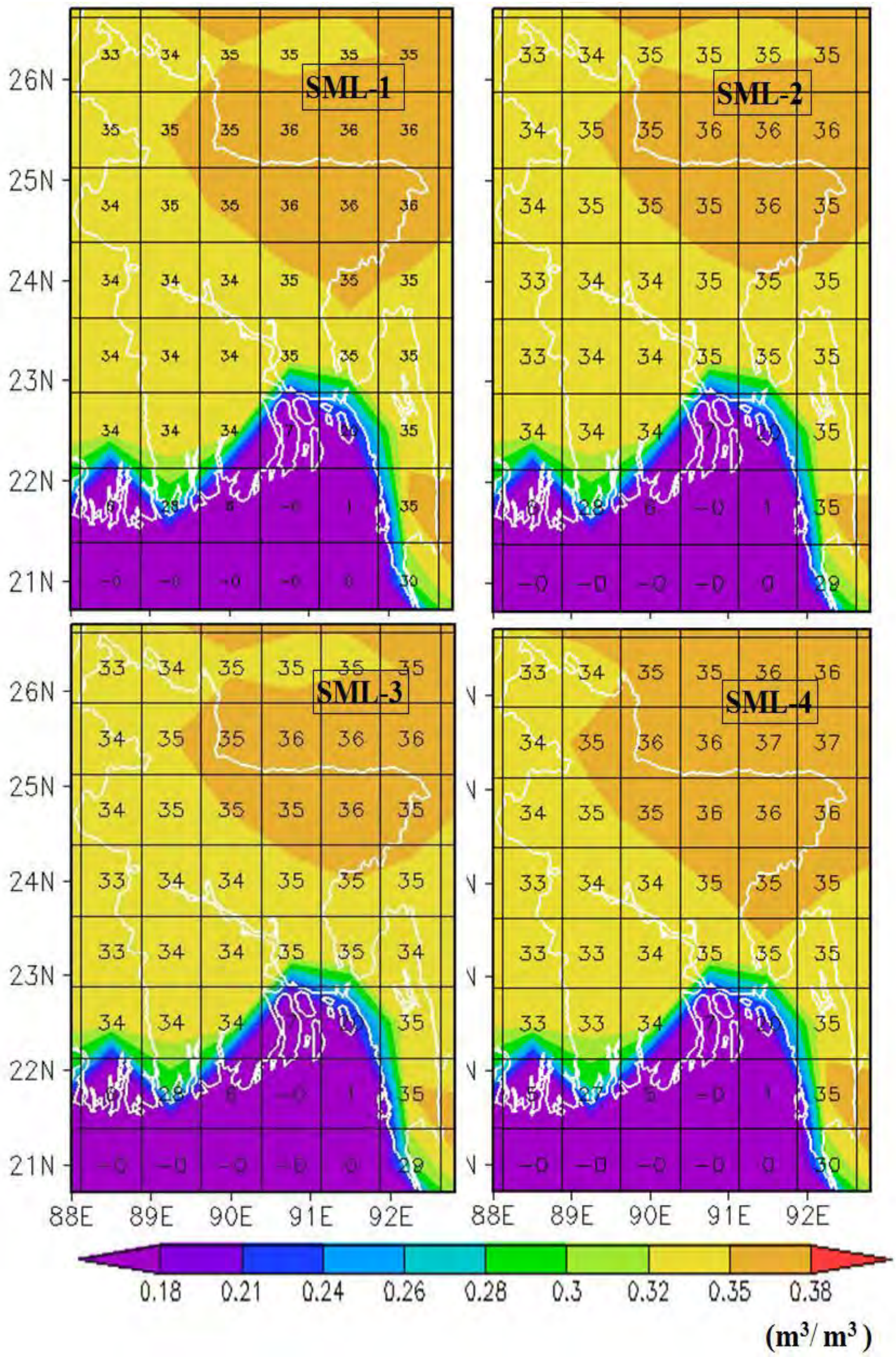

Fig. 4.21: Distribution of averaged soil moisture value (m^3m^{-3}) for different layers over Bangladesh in the wet season during the period of 1979-2014. (Moisture values $\times10^{-2}$) are also indicated in the grids.

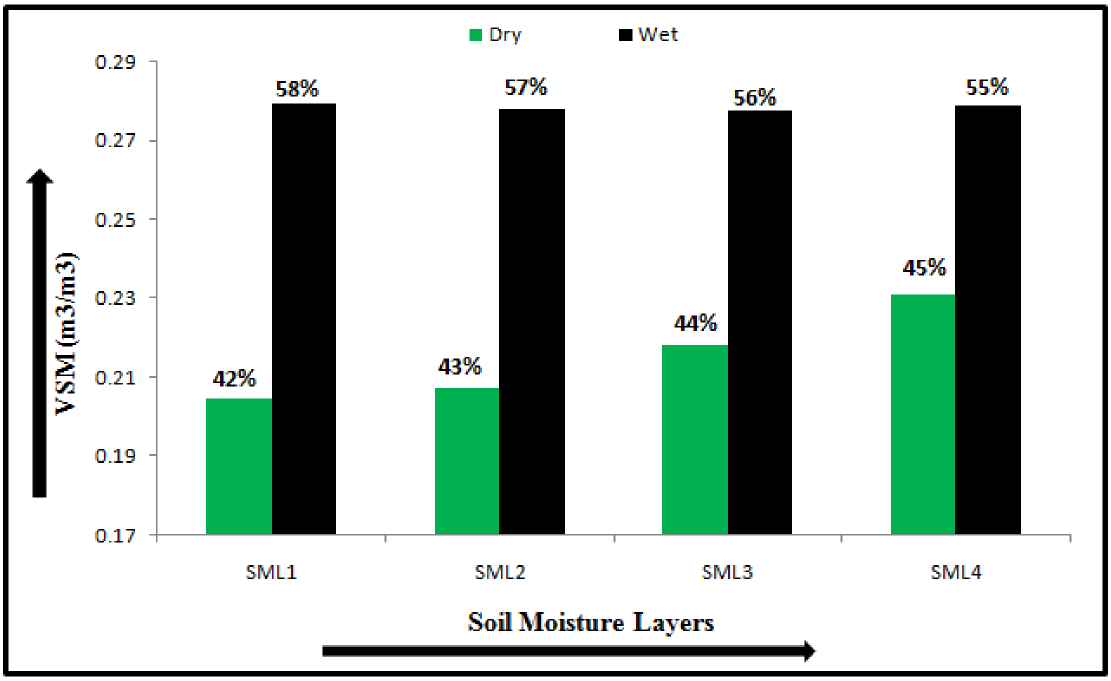

Fig. 4.22: Average soil moisture (m^3m^{-3}) in the four layers according to the dry and wet seasons for 1979-2014.

4.1.4 Annual Variability of Soil Moisture in Dry and Wet season

In this section annual variability of soil moisture for different layers during dry and wet seasons are discussed. In the dry season, soil moisture is increasing significantly as R^2 value for the top to bottom layer are 0.56, 0.56, 0.67 and 0.61, respectively (Fig. 4.23). In the wet season, soil moisture has positive trend where R^2 value for top to bottom layer are 0.18, 0.21, 0.19 and 0.19, respectively (Fig. 4.24) which are not significant. Increased amount of soil moisture in the dry season contributes maximum in the yearly increased soil moisture than that in the wet season (Fig. 4.25). It is also seen from the Table-2 and 3 that soil moisture in each of the four layers during dry season, annual moisture increasing rate is reduced from the upper layer to the bottom layer and moisture difference between two layers is increasing from the upper to bottom the layer. On the other hand, total increasing rate of soil moisture in the wet season is not significant in amount and there is no significant soil moisture difference between the two layers.

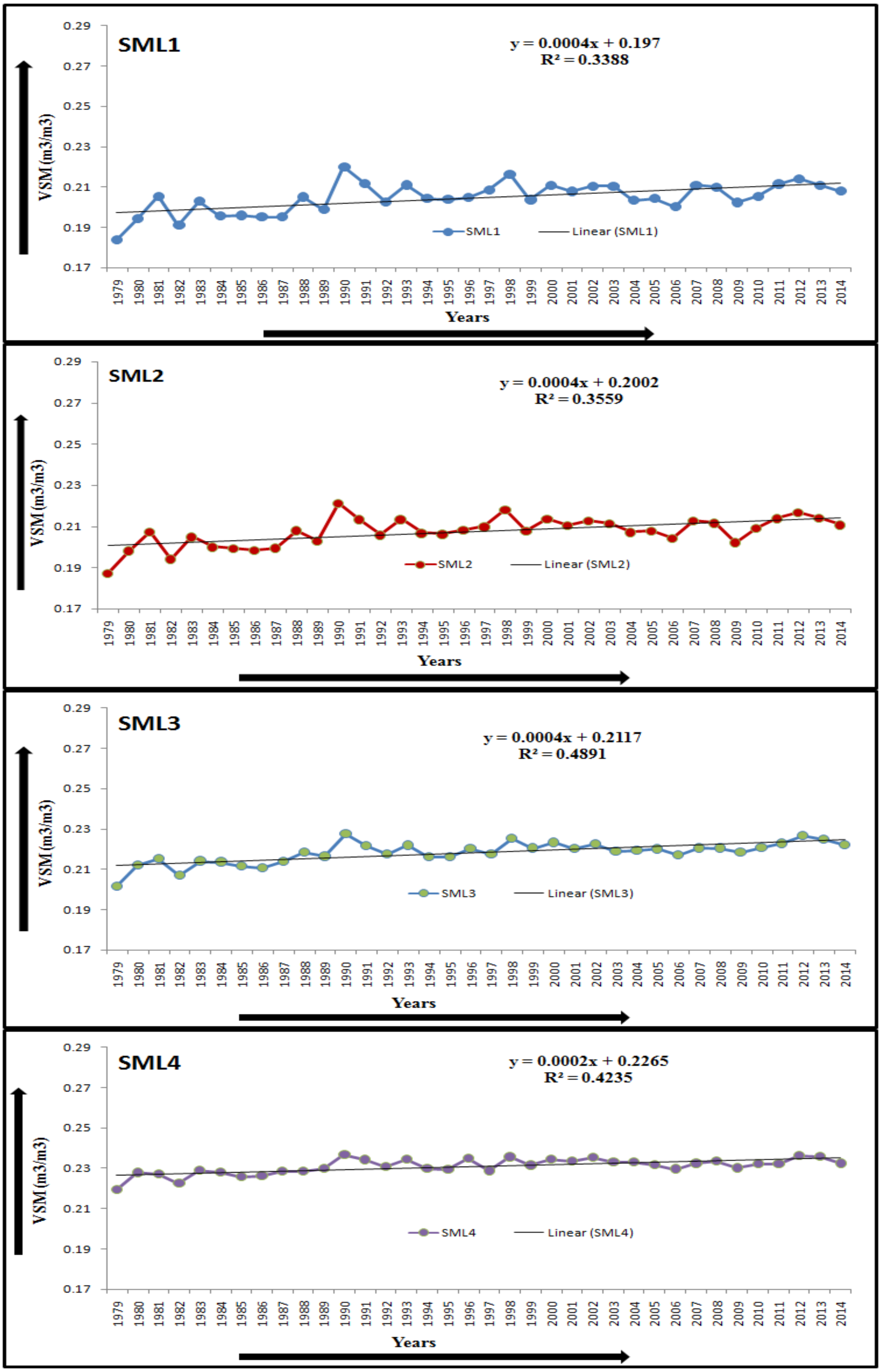

Fig. 4.23: Annual variation of soil moisture (m^3m^{-3}) during dry season for the period of 1979-2014.

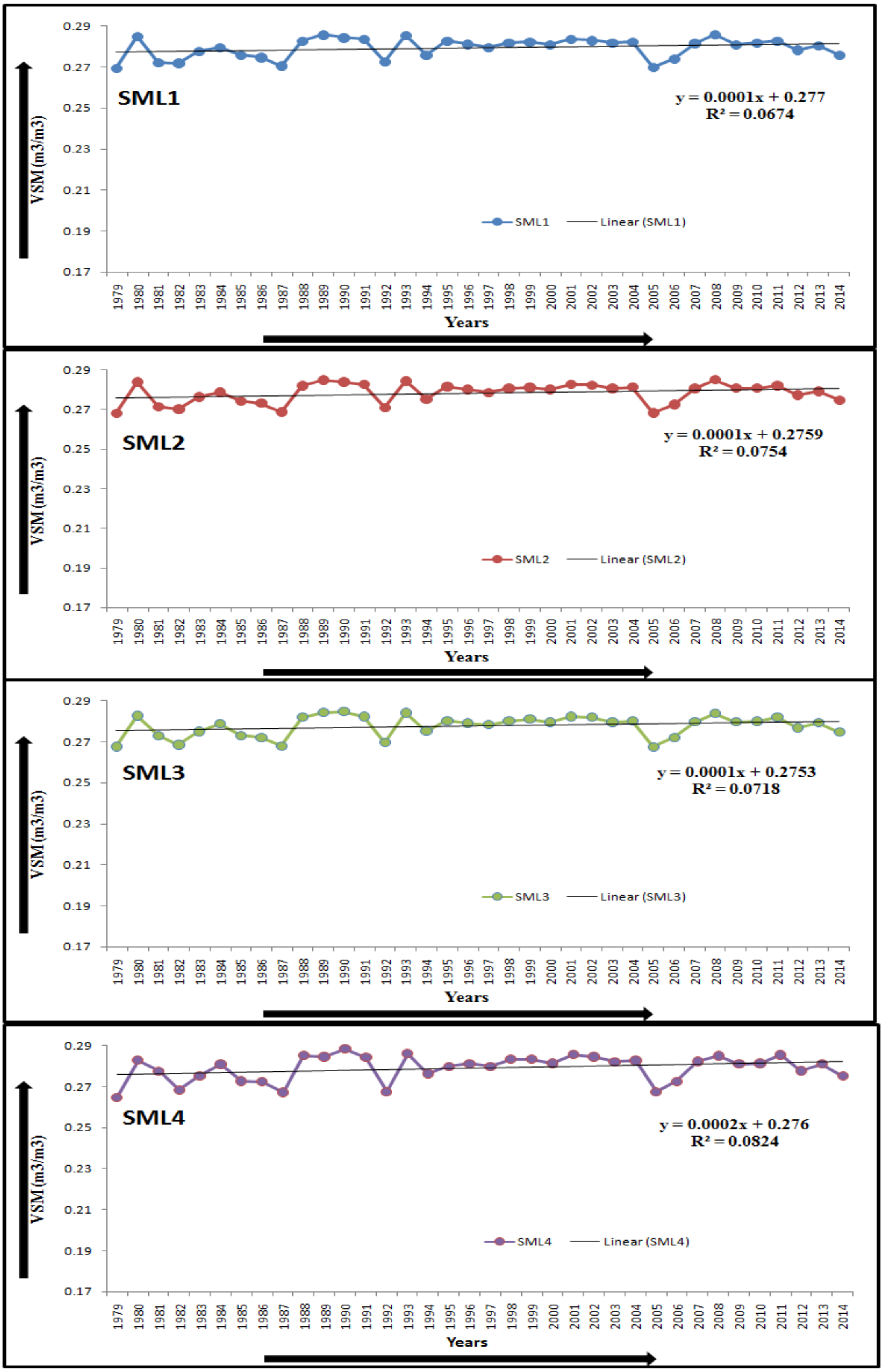

Fig. 4.24: Annual variation of soil moisture (m^3m^{-3}) during wet season for the period of 1979-2014.

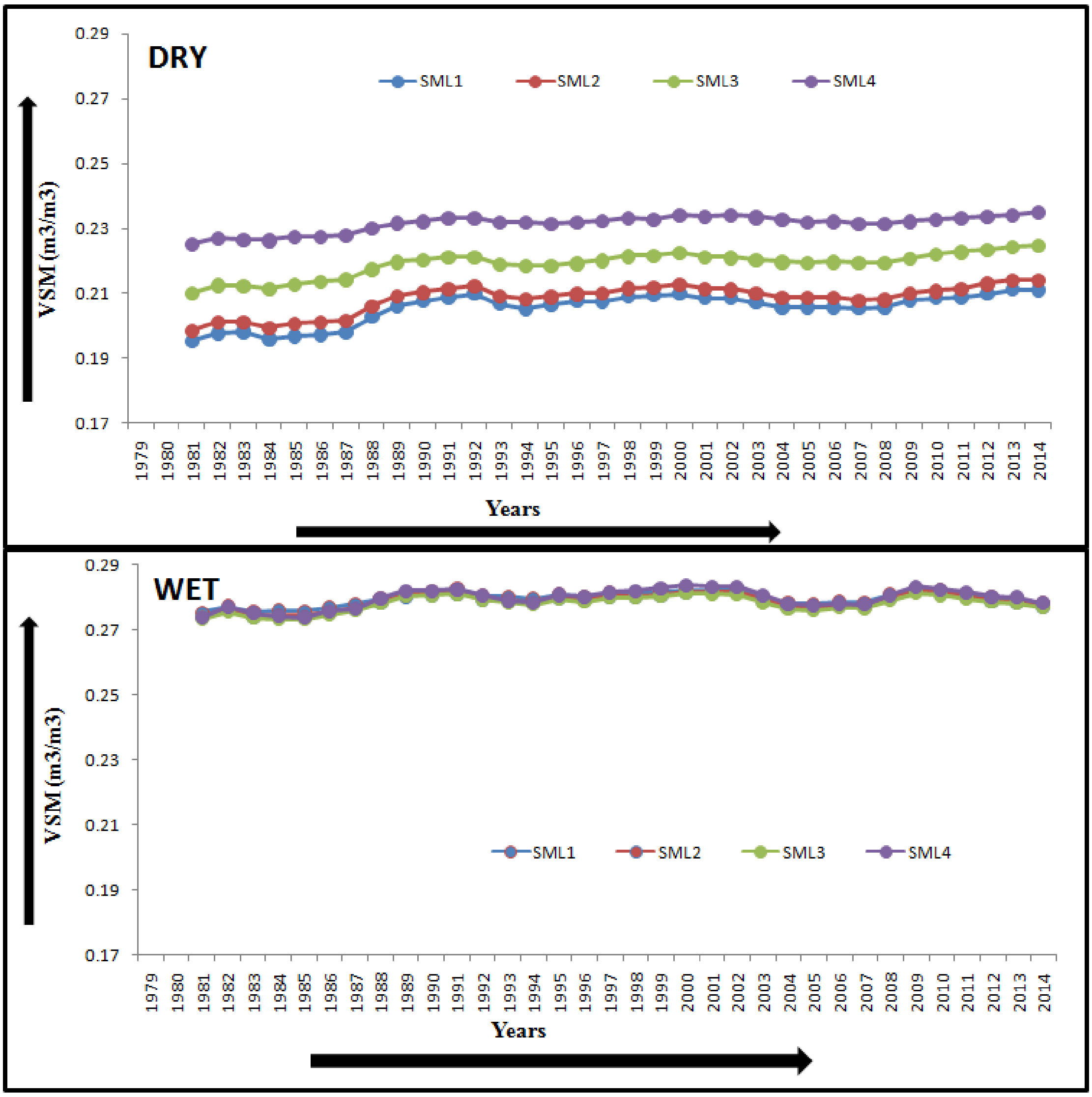

Fig. 4.25: 5-year running means of soil moisture (m^3m^{-3}) during dry and wet seasons in 1979-2014.

Table-2: Soil moisture characteristics during dry season from 1979- 2014.

Soil layers	Total increase in soil moisture (%)	Difference in moisture between layers (%)
SML1	13.18	
SML2	12.50	1.37
SML3	10.17	5.18
SML4	6	5.82

Table-3: Soil moisture characteristics during wet season from 1979- 2014.

Soil layers	Total increase in soil moisture (%)	Difference in moisture between layers (%)
SML1	2.33	
SML2	2.45	-0.33
SML3	2.61	-0.20
SML4	3.90	0.50

4.2 Effects of Atmospheric Variables on Soil Moisture

Atmospheric variables i.e. precipitation (P), evaporation (E), surface air temperature, relative humidity are analyzed for the study area and compared with the soil moisture.

4.2.1 Precipitation

Spatial distribution of averaged precipitation (1979-2014) over Bangladesh is shown in Fig. 4.26. It has been seen that eastern part of Bangladesh has greater precipitation rate (>5 mm/day) than western part of the country (<5 mm/day).

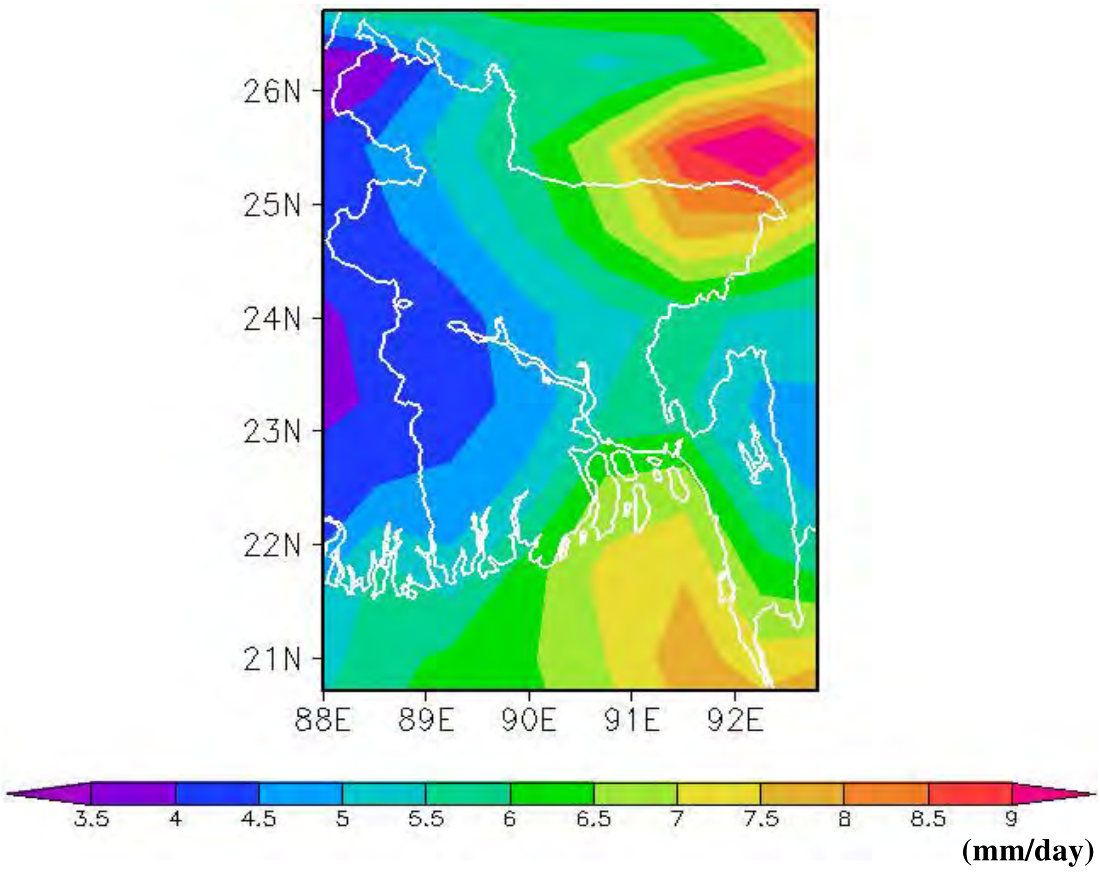

Fig. 4.26: Average precipitation distribution (mm/day) over Bangladesh for 1979-2014.

Fig. 4.27 shows the scatter plots between monthly precipitation and the soil moisture of different layers for 36-years. Co-relation co-efficients 'r' are found to be 0.89, 0.89, 0.85, and 0.69 respectively for four layers (Table-4). The co-efficient of determinant value are also found, R^2= 0.80, 0.79, 0.72 for first three layers of soil moisture which are significant (Fig. 4.27). It indicates that the influences of precipitation on soil moisture are decreasing from the top layer to the bottom layer.

Monthly average of 36-years data for precipitation and soil moisture in the first layer is plotted in Fig. 4.28. As soil moisture is the storage of water in the soil layer so when precipitation rate is low soil moisture in the layer is low (November - May). Conversely, soil moisture is increased when precipitation rate is getting higher and it happens from June to October (Fig. 4.28).

Yearly average of precipitation rate is 5.76 (mm/day) where 1.84 mm/day is the rate in the dry season and 11.26 mm/day in the wet season. About 16.76% of yearly average precipitation (5.76 mm/day) storages in the ground as total water content in the four layers of soil. Maximum precipitation (46.71%) among (1.84 mm/day) storages in the ground as soil moisture in the dry season where 9.9% among (11.26 mm/day) is used as soil moisture in wet season (Fig. 4.29).

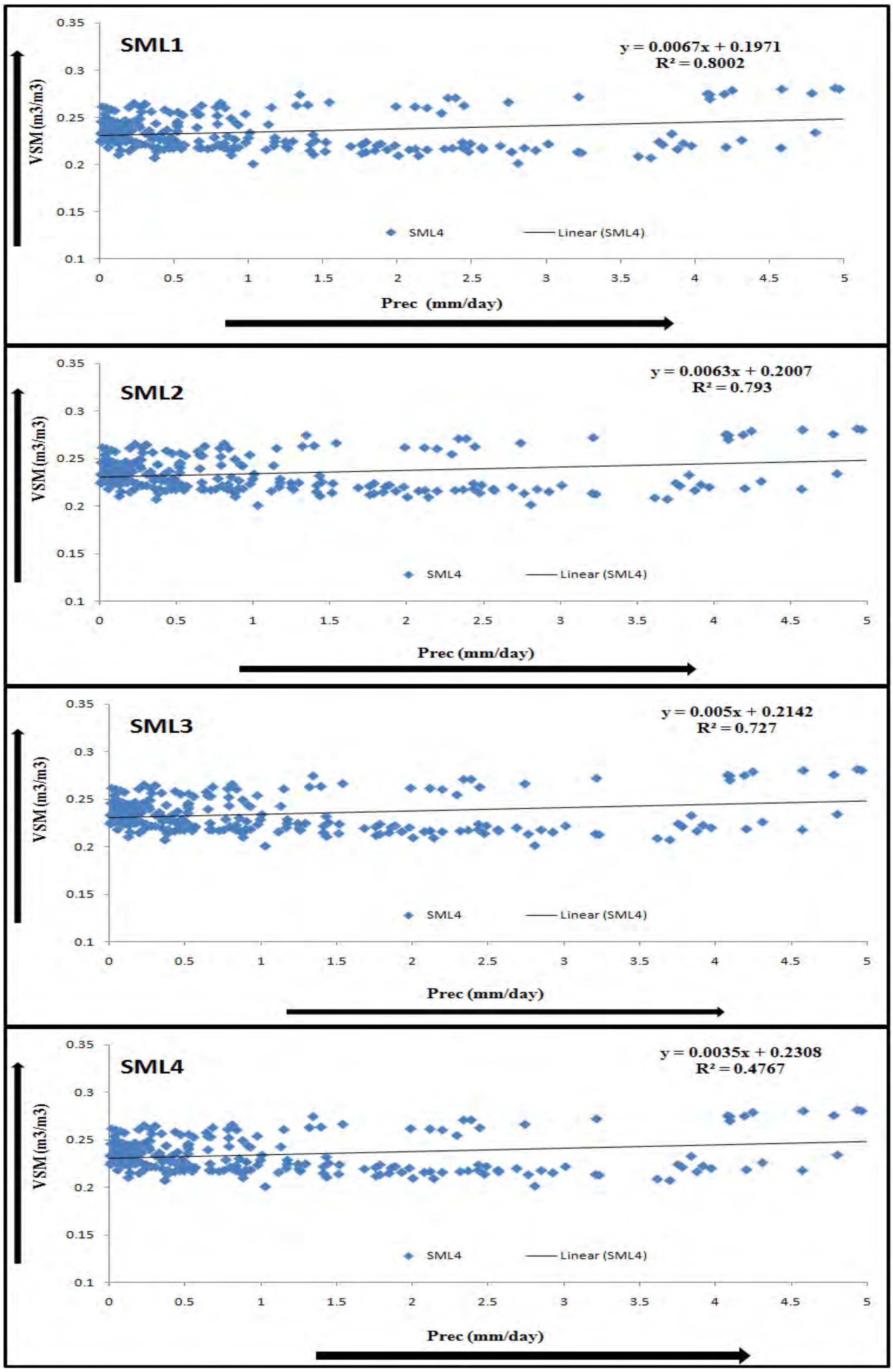

Fig. 4.27: Scatter plot between precipitation and soil moisture for the four layers in 1979-2014.

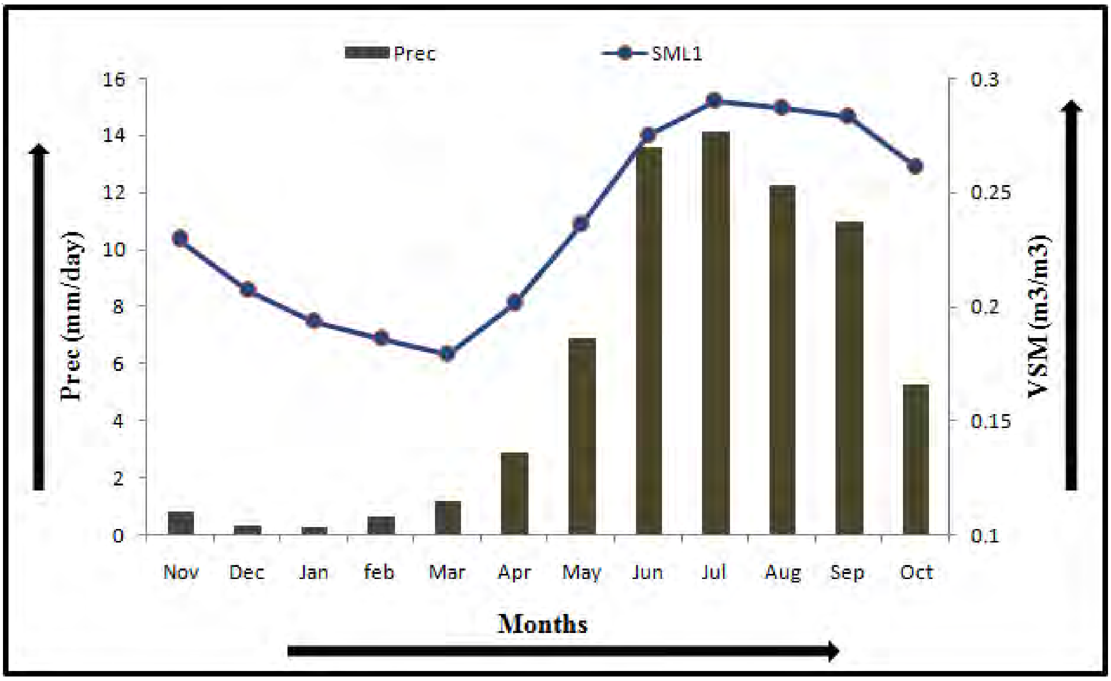

Fig. 4.28: Monthly average of precipitation (mm/day) with soil moisture (m^3m^{-3}) in the first layer.

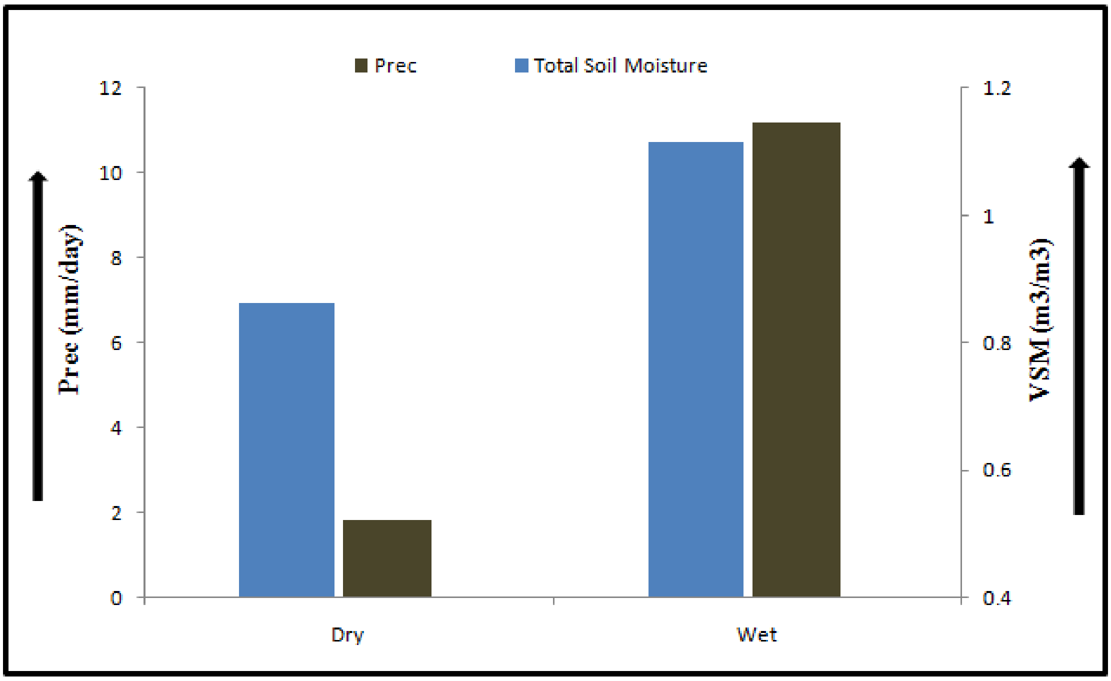

Fig. 4.29: Average precipitation (mm/day) and total soil moisture (m^3m^{-3}) in the four layers during dry and wet season.

4.2.2 Evaporation

Spatial distribution of averaged evaporation over Bangladesh is shown in Fig. 4.30. It has been seen that North-western part of Bangladesh has less evaporation rate (<2.8 mm/day) and it is increasing (>2.8 mm/day) toward the south-eastern part of Bangladesh.

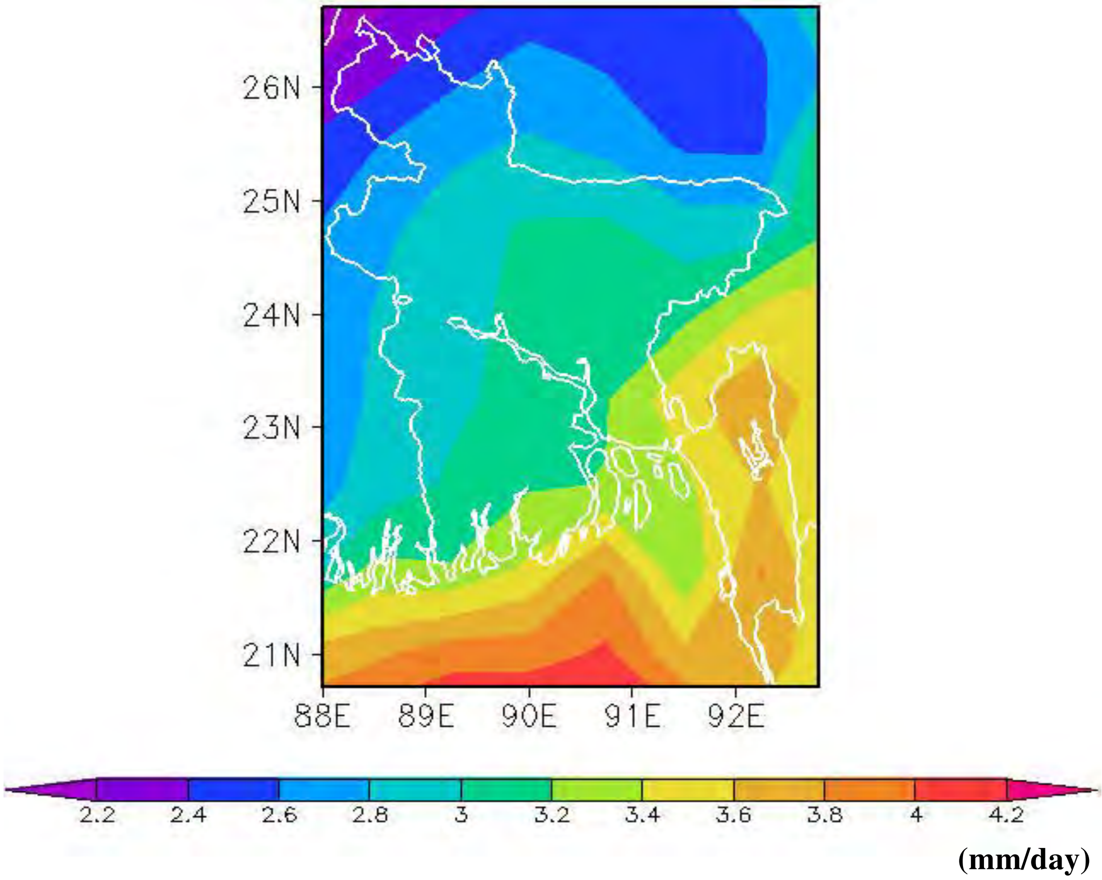

Fig. 4.30: Average distribution of evaporation (mm/day) over Bangladesh for 1979-2014.

In Fig. 4.31 the average evaporation rate is 2.57 (mm/day) in the dry season where in the wet season evaporation rate is 3.81 (mm/day). Evaporation rate is higher in wet season (60% of total) than the dry season (40% of total). In this study, the value of evaporation has found to be very little influence on soil moisture (Fig. 4.32). Mainly, Evaporation depends on temperature. Highest evaporation (4.34 mm/day) takes place in the month of May when temperature remains maximum value (28.18 ^{0}C) and lowest value (1.6 mm/day) is found in the month of January when minimum temperature (17.71^{0}C) is observed (Fig. 4.33).

Fig. 4.34 shows the scatter plots of monthly evaporation and soil moistures for different layers. Evaporation interacts with the first two layers significantly as co-efficients of determination values are R^2 = 0.52, 0.50 for the first two layers of soil and co-relation co-efficients 'r' are found to be 0.72 and 0.70, respectively for first two layers (Table-4). Evaporation eventually decreases the soil moisture but the amount of soil moisture not depends on individual precipitation or evaporation. Precipitation and evaporation both are simultaneously important to the amount of soil moisture. Therefore, the effect of evaporation-precipitation (E-P) to the soil moisture will be discussed in the next section.

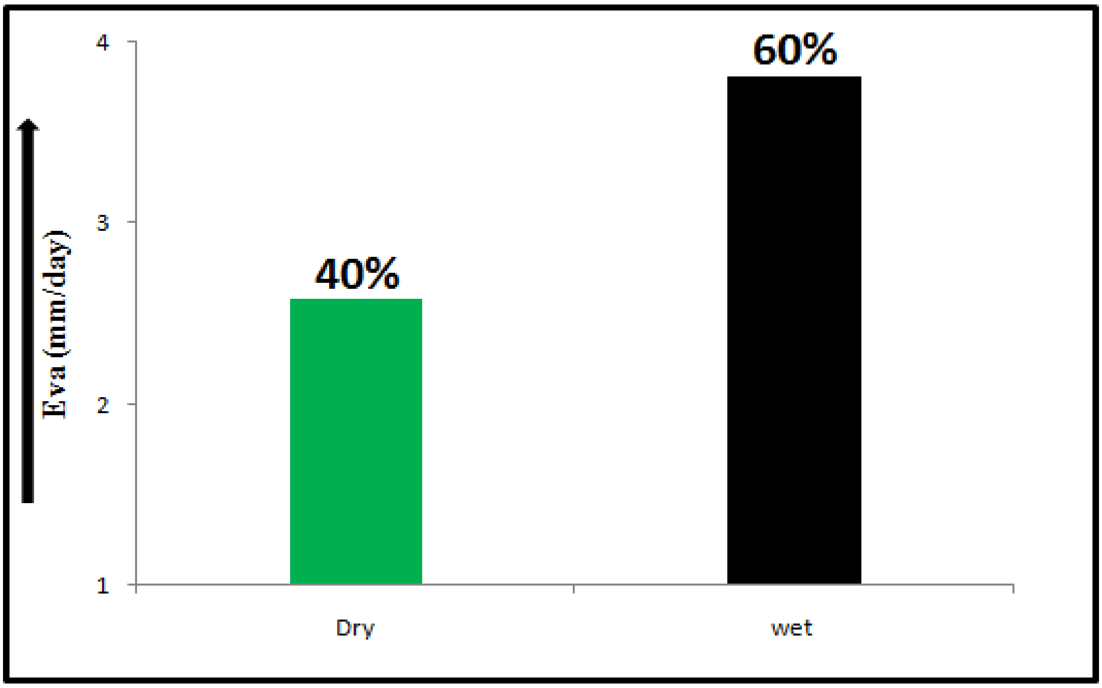

Fig. 4.31: Average evaporation (mm/day) during dry and wet seasons.

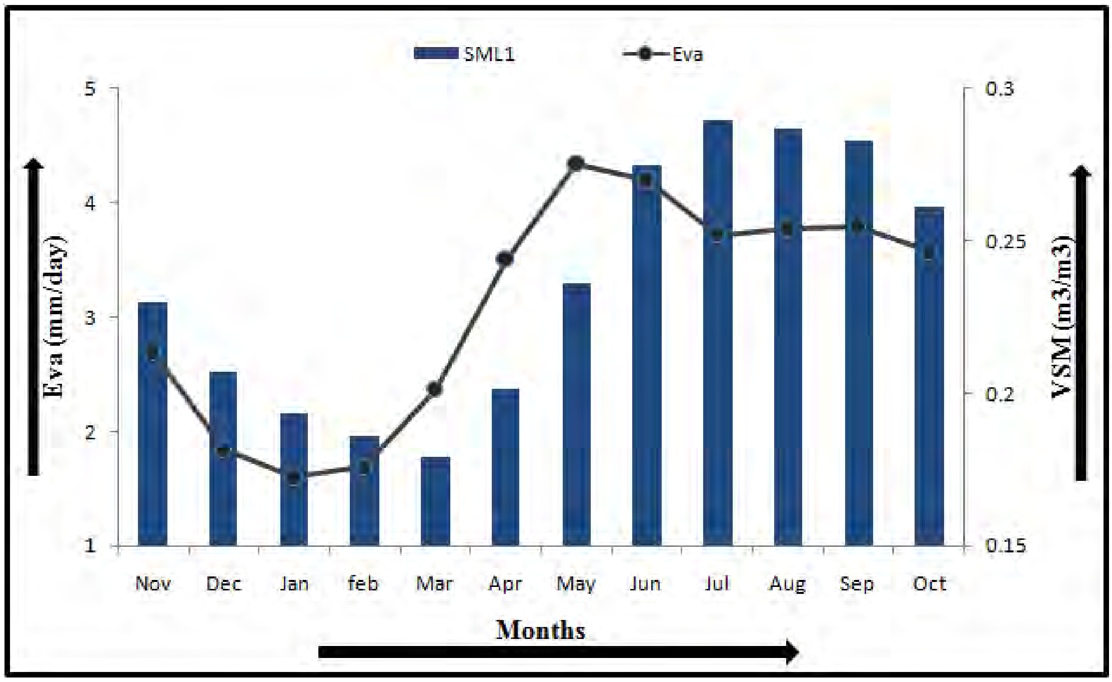

Fig. 4.32: Monthly average evaporation (mm/day) with soil moisture (m^3m^{-3}) in the first layer.

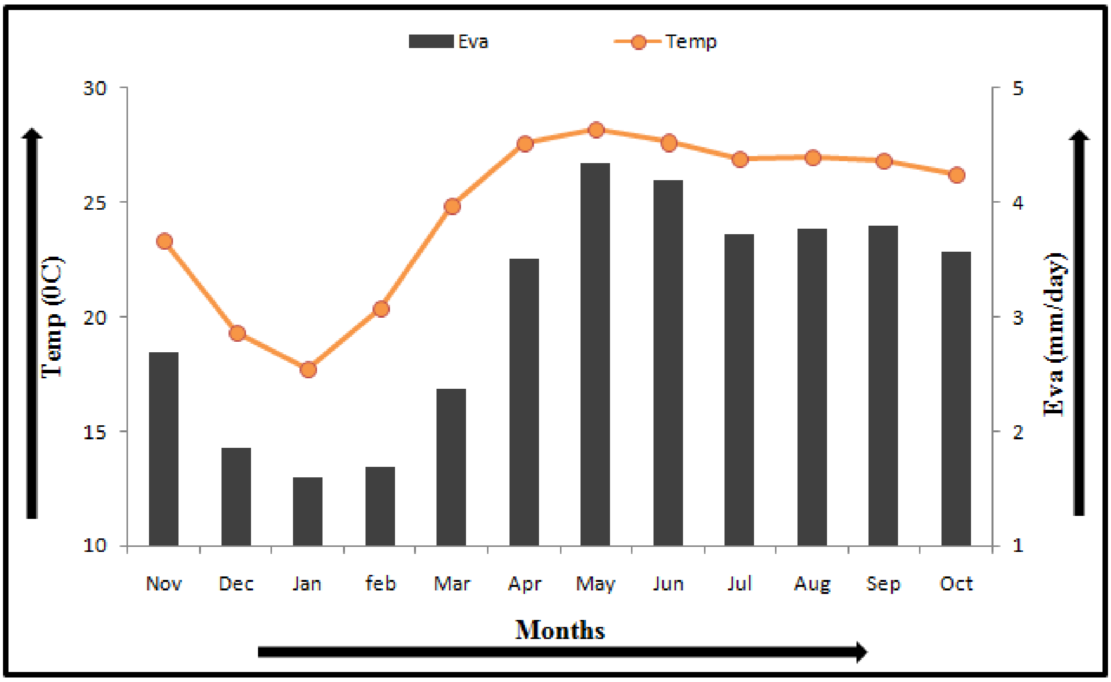

Fig. 4.33: Monthly average evaporation (mm/day) with temperature (^{0}C).

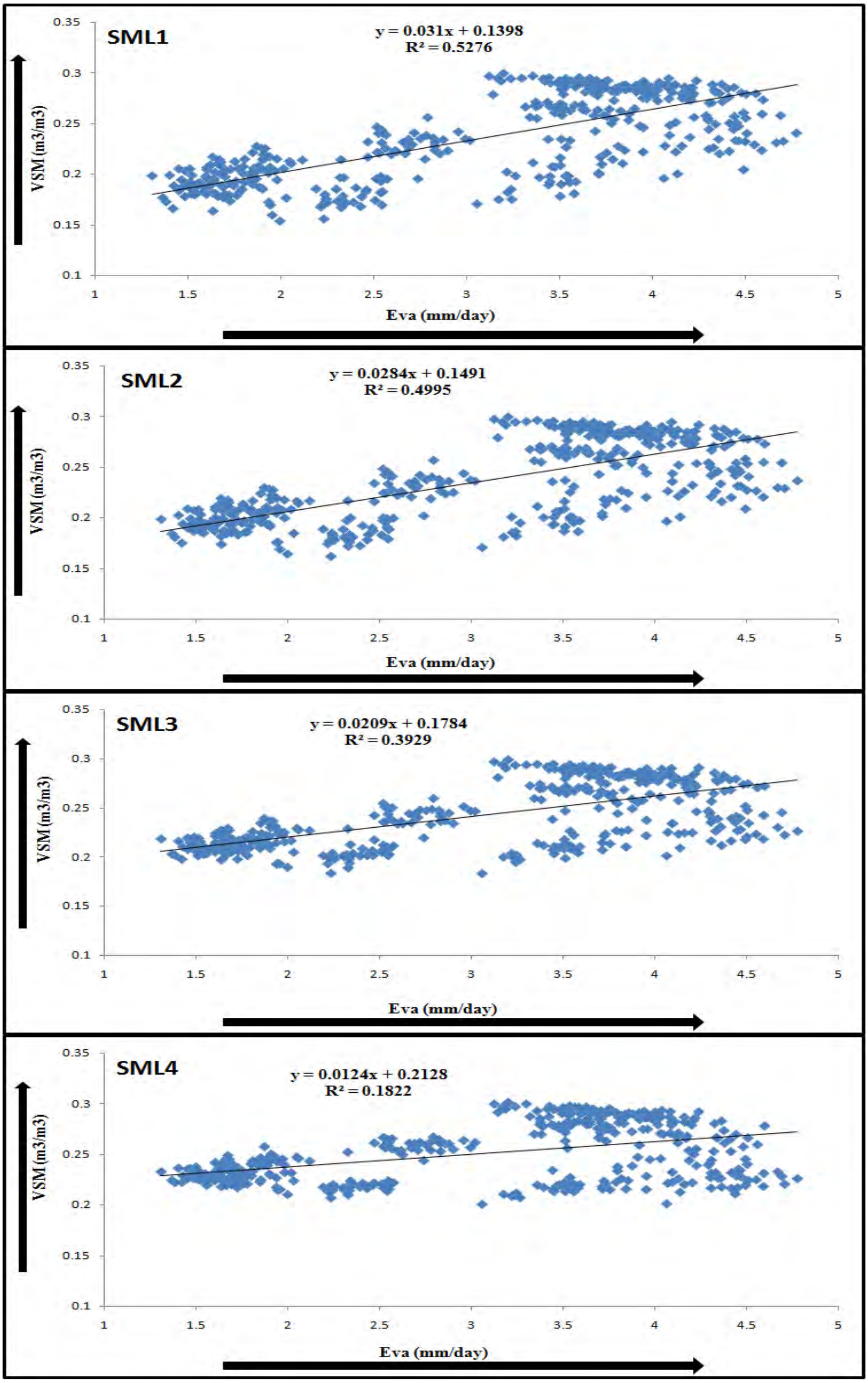

Fig. 4.34: Scatter plot between evaporation and soil moisture for the four layers.

4.2.3 Evaporation minus Precipitation

Spatial distribution of Evaporation minus Precipitation (E-P) averaged (1979-2014) over Bangladesh is shown in Fig. 4.35. As the difference of evaporation and precipitation (E-P) gives the exact information about soil moisture i.e. higher values of E-P contributes to the higher moisture in the soil. It has been seen that the higher value (<-2 mm/day) is found in eastern part and it is decreasing toward the western part of Bangladesh.

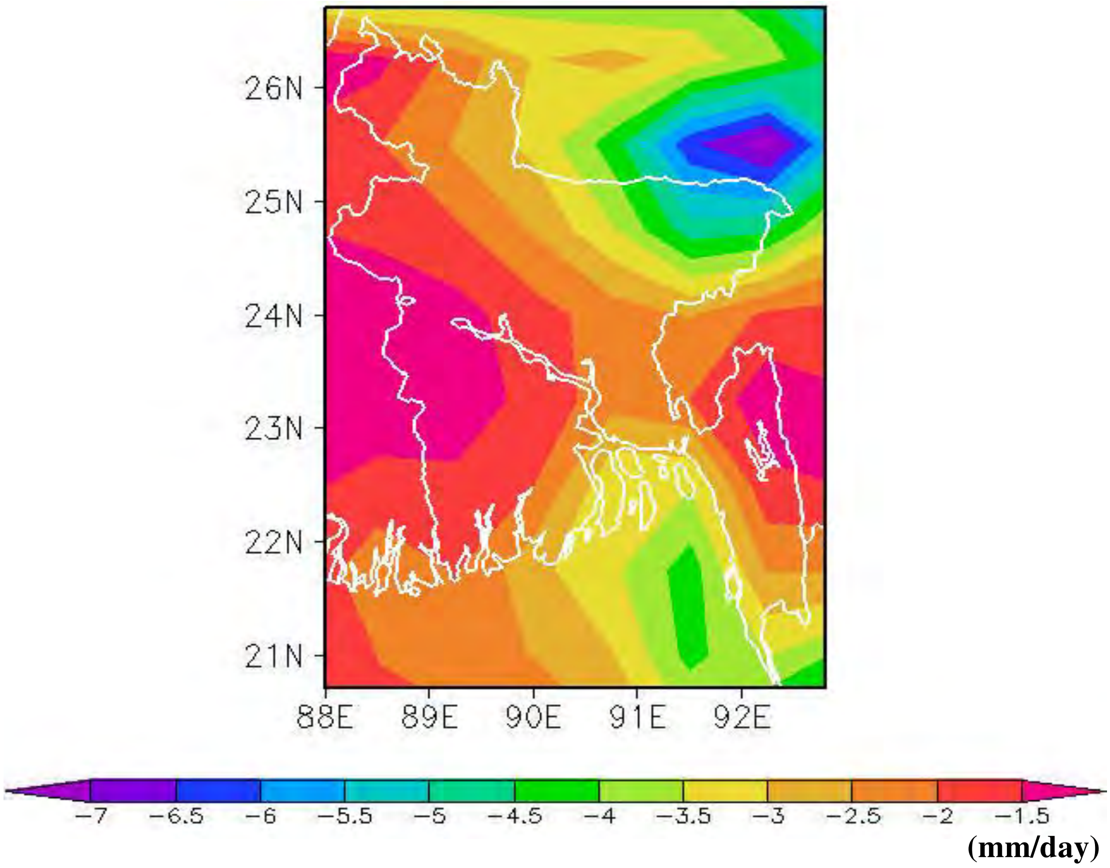

Fig. 4.35: Averaged distribution of E-P (mm/day) over Bangladesh for1979-2014.

Fig. 4.36 shows the scatter plots for the relation between E-P and the soil moisture for different layers. Co-efficient of determination value for the layer-1, 2, 3 and 4 of soil moisture with (E-P) values are R^2 = 0.76, 0.76, 0.71, 0.49 which gives more significant value for the upper three layers. The negative trend line indicates that soil moisture is inversely proportional to the value of E-P. Co-relation co-efficients 'r' are found to be -0.87, -0.87 and -0.82 respectively for first three layers (Table-4).

Co-relation between different layers of soil moisture and atmospheric variables of evaporation, precipitation, E-P, relative humidity at surface, surface temperature are summarized in table-4.

Table-4: Correlation coefficient between atmospheric variables and soil moisture for the four layers.

Soil layer	Evaporation (E)	Precipitation (P)	(E-P)	Relative humidity (Rh)	Temperature	Temperature with two months shifting
SML1	0.72	0.89	-0.87	0.88	0.57	0.80
SML2	0.7	0.89	-0.87	0.87	0.55	0.80
SML3	0.62	0.85	-0.84	0.81	0.49	0.80
SML4	0.42	0.69	-0.7	0.64	0.3	0.78

The monthly average value for evaporation (E), precipitation (P) and the difference between them (E-P) are calculated and presented in Fig. 4.37. The evaporation rate and the precipitation rate are much lower in the dry season than that in the wet season. In dry (wet) season, the evaporation rate is 2.5 mm/day (3.8 mm/day) and the precipitation rate is 1.8 mm/day (11.2 mm/day). The difference of evaporation and precipitation (E-P) has the lower positive value (<2 mm/day) in the dry season and higher negative value (~ -10 mm/day) in the wet season.

Evaporation minus precipitation (E-P) provides the information about how much water comes to the soil that actually measures the value of soil moisture. Therefore, negative value of E-P gives excess of water where positive value indicates the dryness of the soil. The 36-year averaged data of E-P and soil moisture perfectly coincide with each other shown in Fig. 4.38.

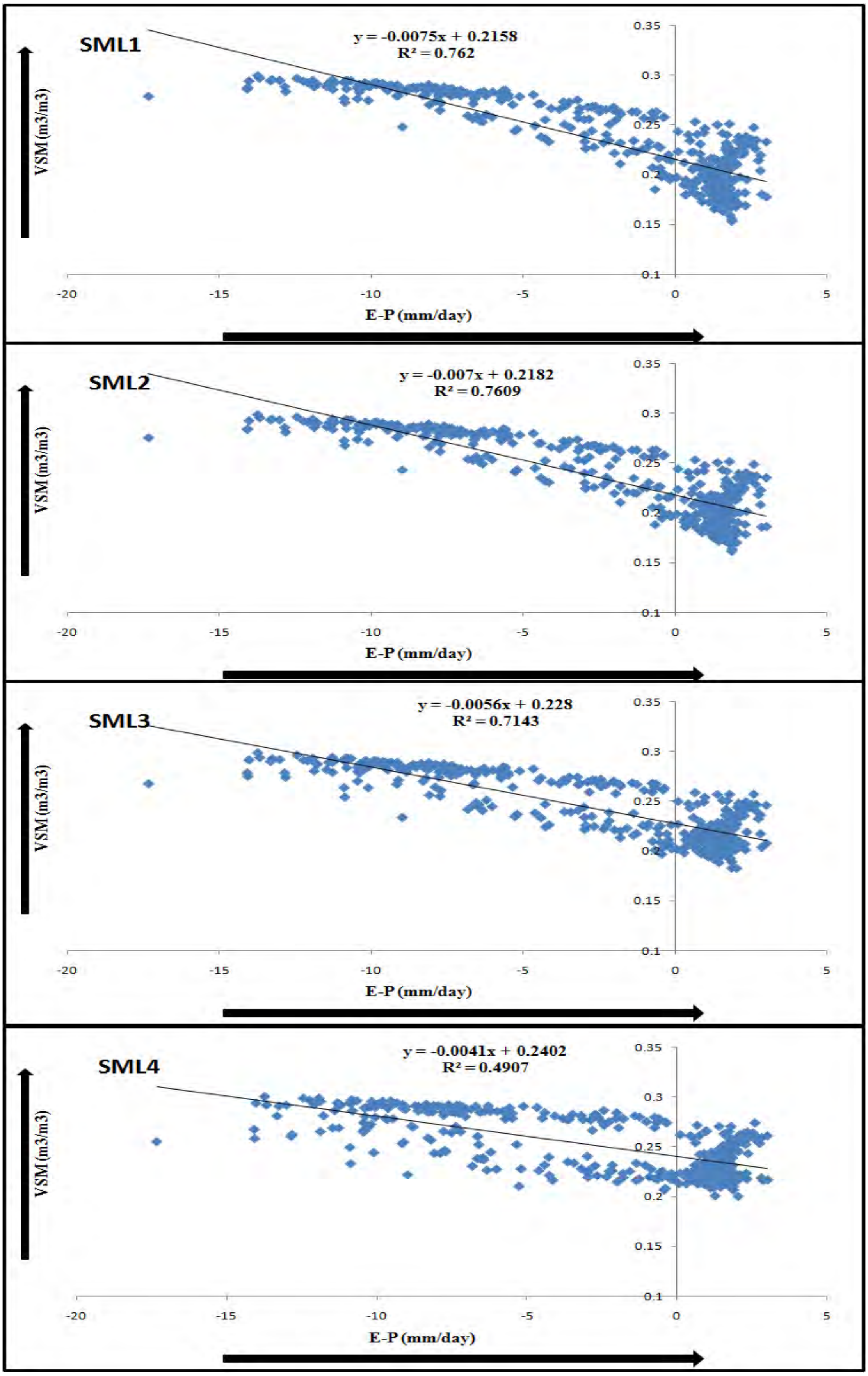

Fig. 4.36: Scatter plot between (E-P) with the four soil moisture for the four layers.

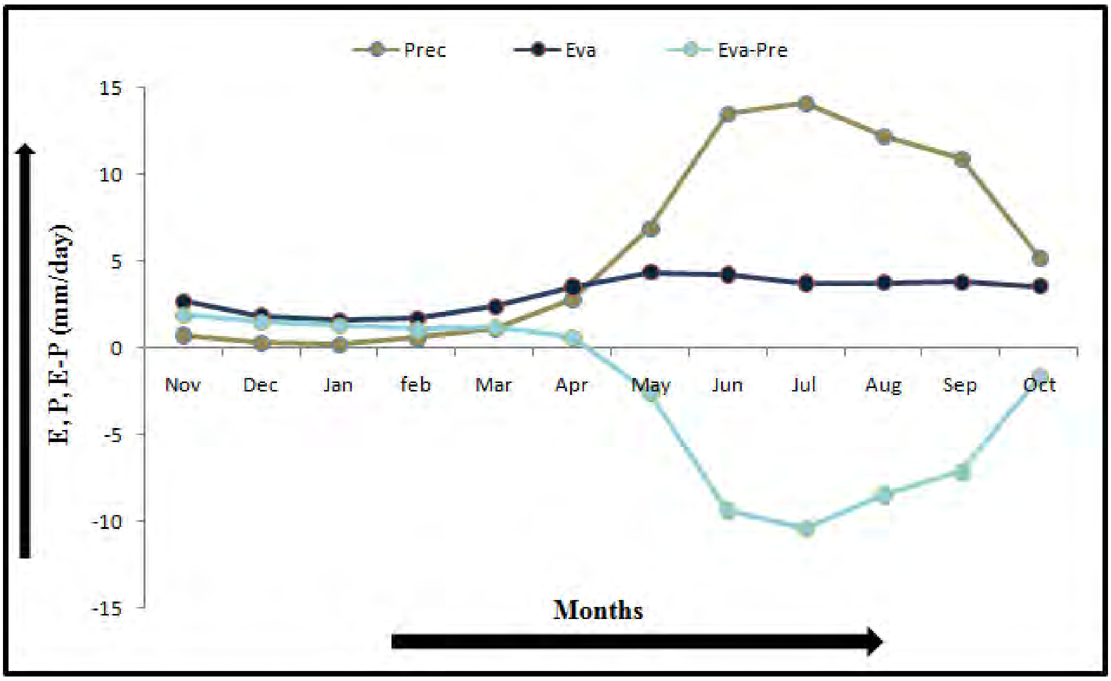

Fig. 4.37: Monthly Evaporation (E), Precipitation (P) and Evaporation minus precipitation (E-P) for 1979-2014.

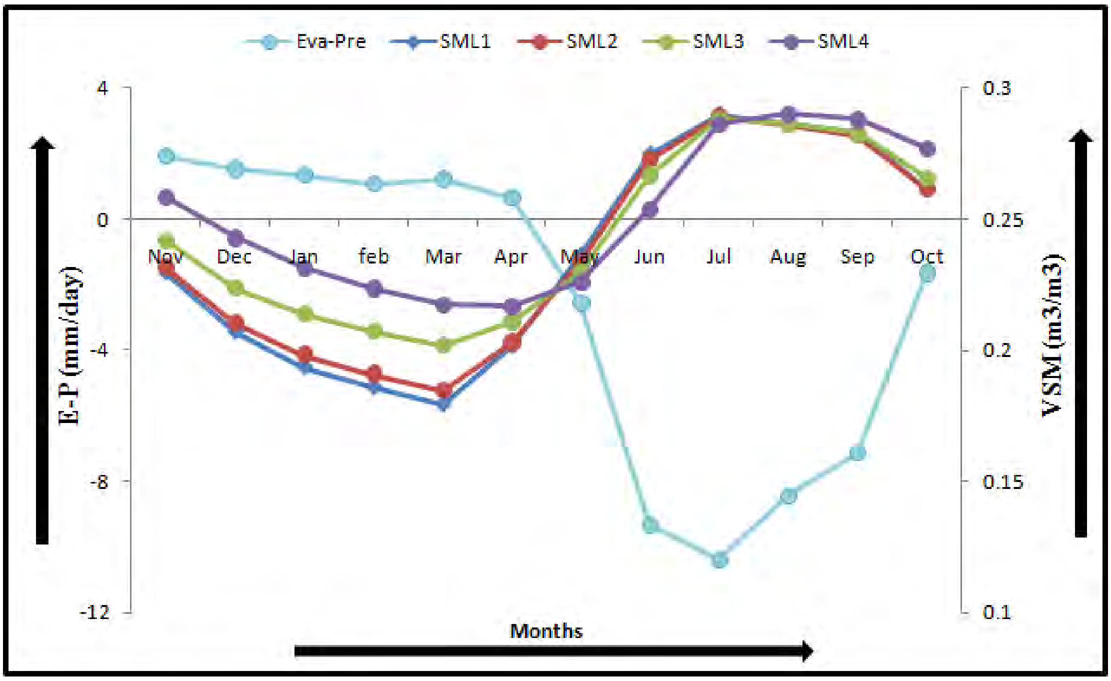

Fig. 4.38: The value of E-P (mm/day) and soil moisture (m^3m^{-3}) in the different layers.

4.2.4. Relative Humidity at Surface

Spatial distribution of averaged (1979-2014) surface relative humidity over Bangladesh is shown in Fig. 4.39. It is seen that relative humidity (%) is getting increased from western part to eastern part of Bangladesh which is similar to the soil moisture patterns of Bangladesh.

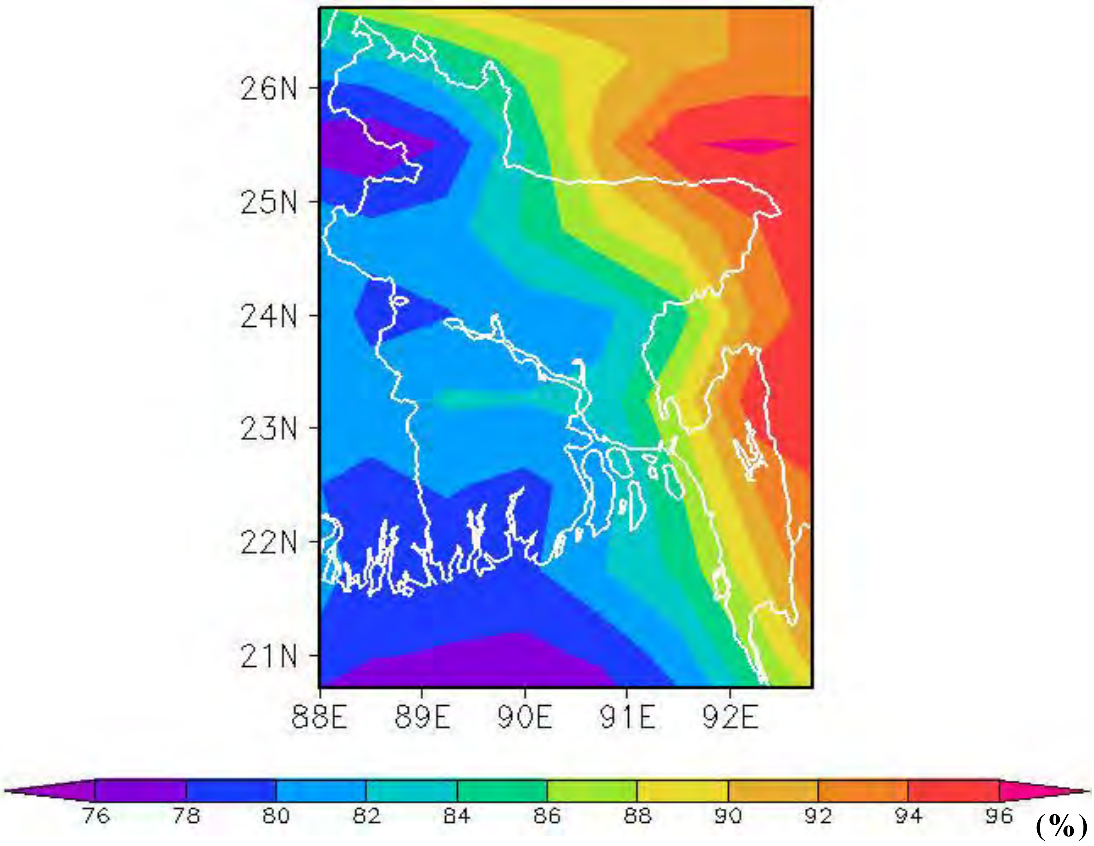

Fig. 4.39: Distribution of averaged (1979-2014) relative humidity (%) at surface over Bangladesh.

It is observed that the average value of relative humidity is low (77%) in the dry season as compared to that in the wet season (92%). However, relative humidity over Bangladesh is almost ~84% averaged for all months. Percentage difference between dry and wet season is 18% (Fig. 4.40).

The scatter plot of Fig. 4.41 represents how relative humidity relates with soil moisture throughout the thirty six years. The co-efficient of determinations R^2 for the layer-1, 2, 3 and 4 are found to be significant with the values of 0.78, 0.75, 0.66 and 0.41, respectively. Co-relation co-efficients 'r' are found 0.88, 0.87, 0.81 and 0.64, respectively for the layer-1, 2, 3 and 4 of soil moisture (Table-4).

Fig. 4.42 indicates that how monthly average soil moisture of the first layer (interactive layer to the atmosphere) is correlated with the relative humidity. Here, First layer is considered as this layer has more direct contact with the atmosphere. It is seen that when relative humidity is low (73.19%) and soil moisture is getting low (0.185 m^3m^{-3}) and it acts completely reverse way (high value of soil moisture 0.289 m^3m^{-3}) in case of high relative humidity (93.81%). It is because of when relative humidity is low it carries moisture from the surface to atmosphere, so soil moisture is getting low and when it is high, its carries less amount of moisture to atmosphere.

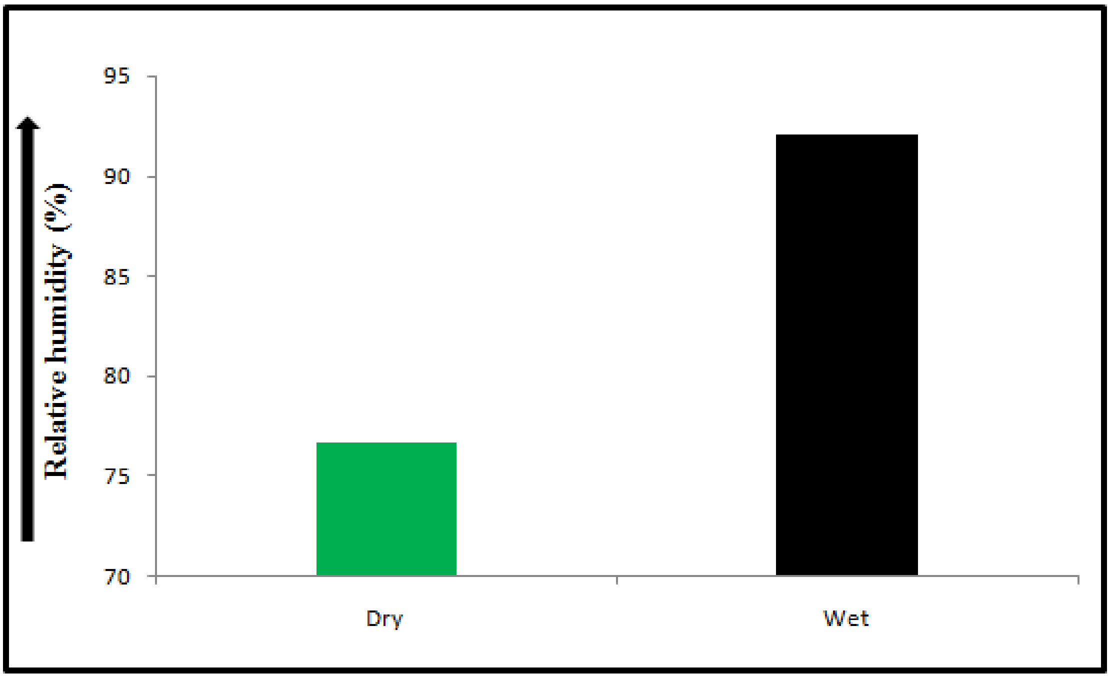

Fig. 4.40: Average (1979-2014) relative humidity (%) for dry and wet seasons.

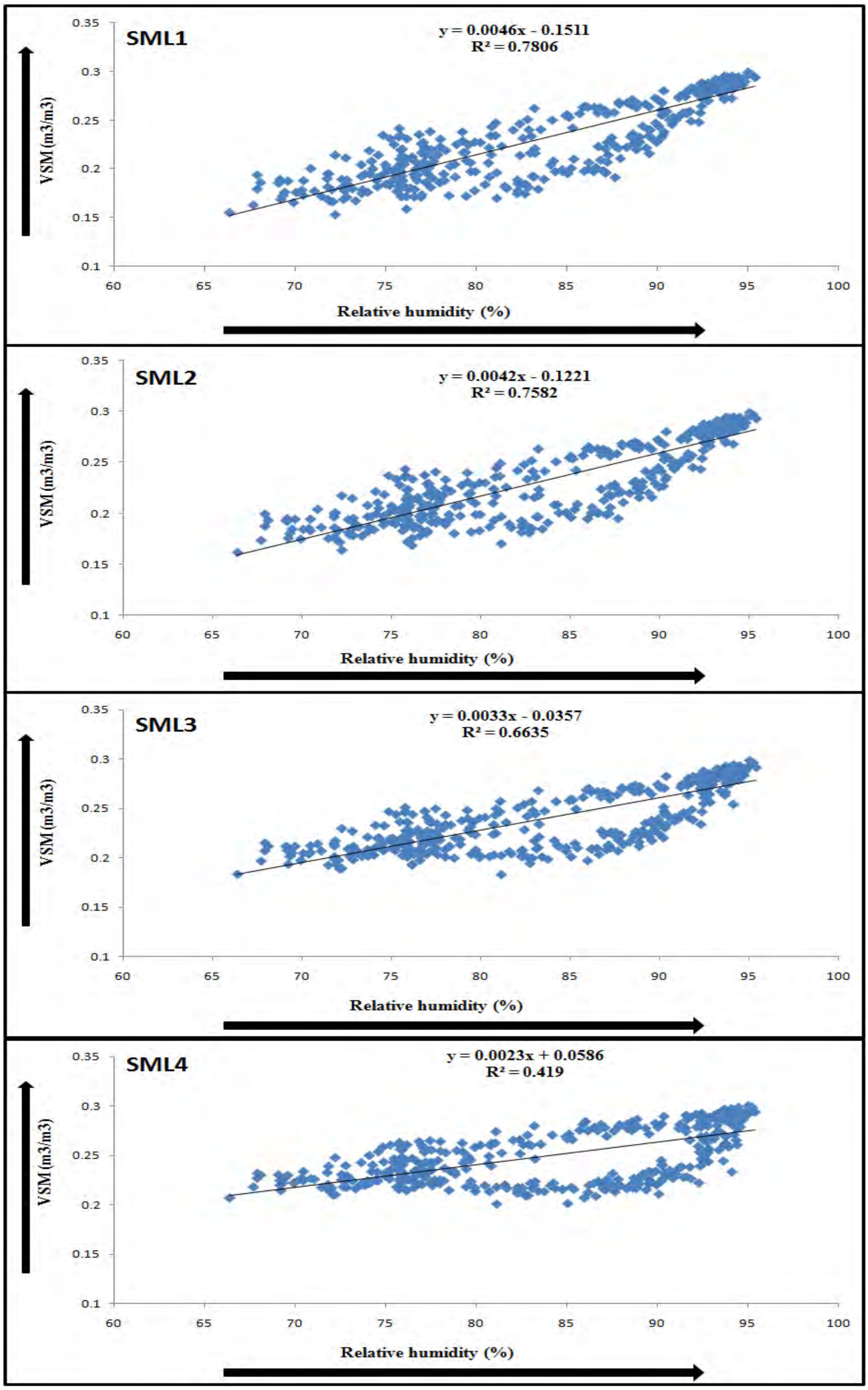

Fig. 4.41: Scatter plot between soil moisture in the four layers and relative humidity.

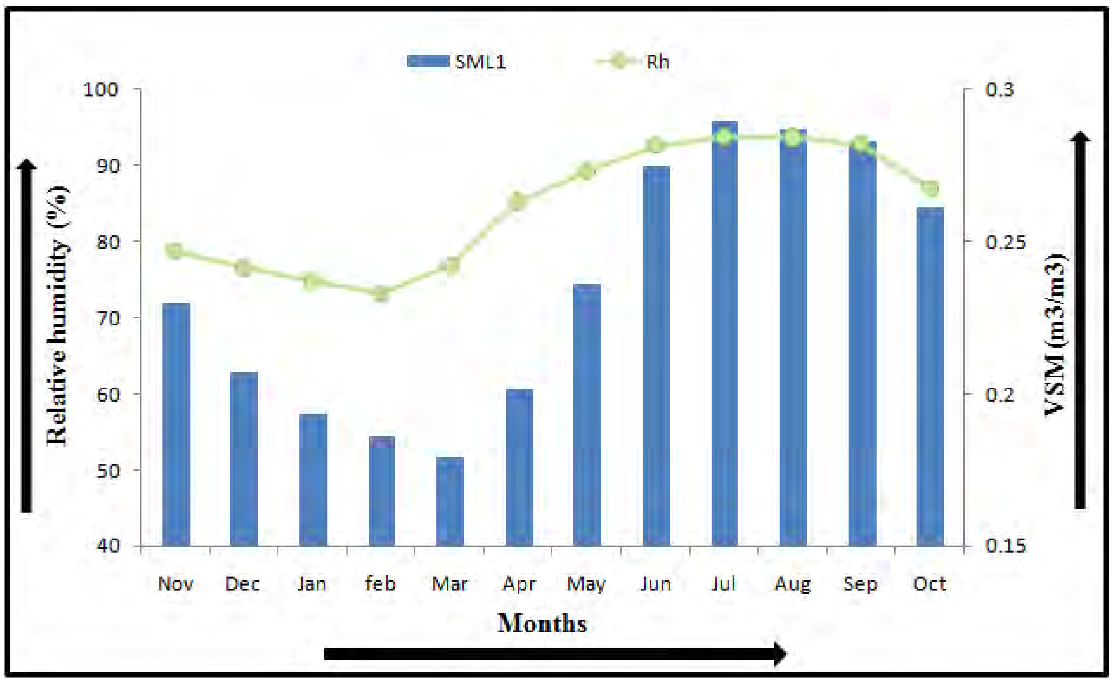

Fig. 4.42: Relative humidity (%) vs soil moisture (m^3m^{-3}) for the first layer.

4.2.5 Surface Temperature

Spatial distribution of averaged (1979-2014) surface temperature over Bangladesh is shown in Fig. 4.43. It is seen that surface temperature is getting increased towards eastern part to western part of the Bangladesh. It is observed that eastern part holds almost 24^0C where in western part holds ~26^0C.

Fig. 4.44 shows the temperature amount according to the dry and wet seasons. It is seen that average temperature in the dry season is 23^0C and in the wet season of 27^0C. Temperature is higher in the wet season by 15.5% of that in the dry seasons.

The variation of monthly average surface temperature with the soil moisture for the first layer is displayed in Fig. 4.45. It is found that soil moisture is changed with the change of temperature by two months later. Minimum temperature is found in January whereas soil moisture becomes the minimum value in March. Similarly maximum temperature is attained in May whereas maximum soil moisture is found in July.

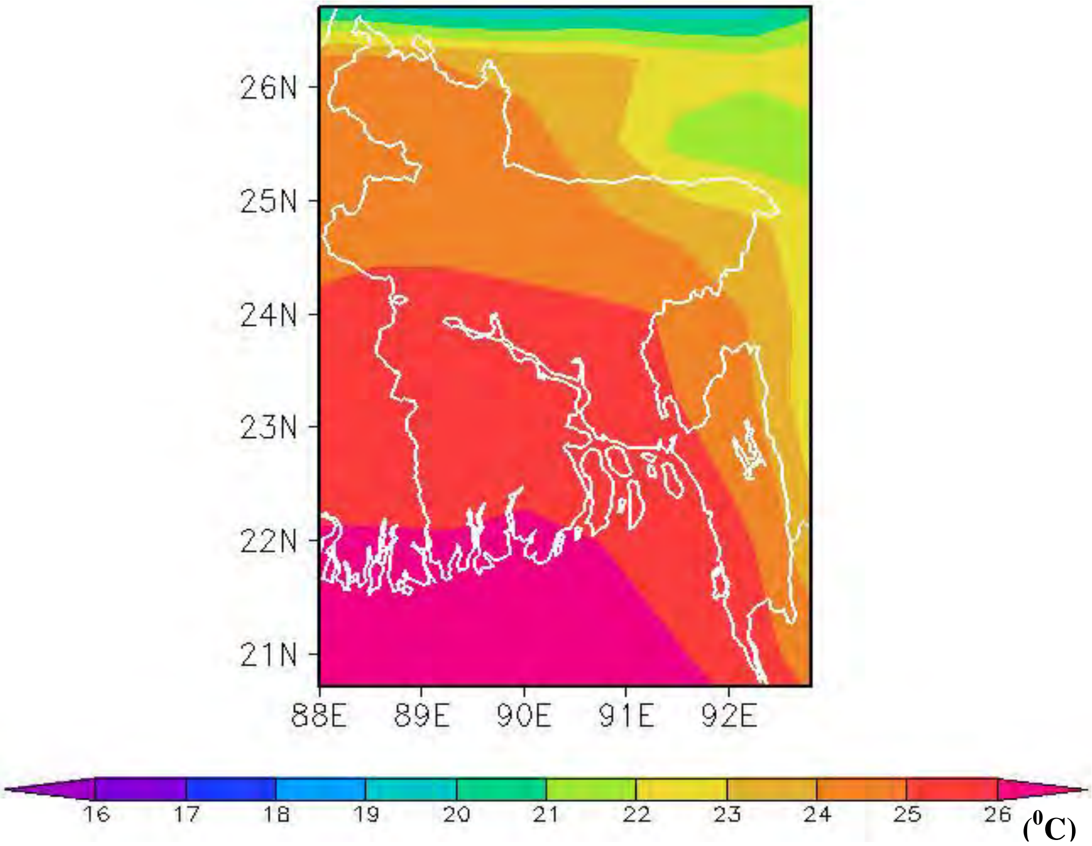

Fig. 4.43: Average (1979-2014) distribution of temperature (^{0}C) over Bangladesh.

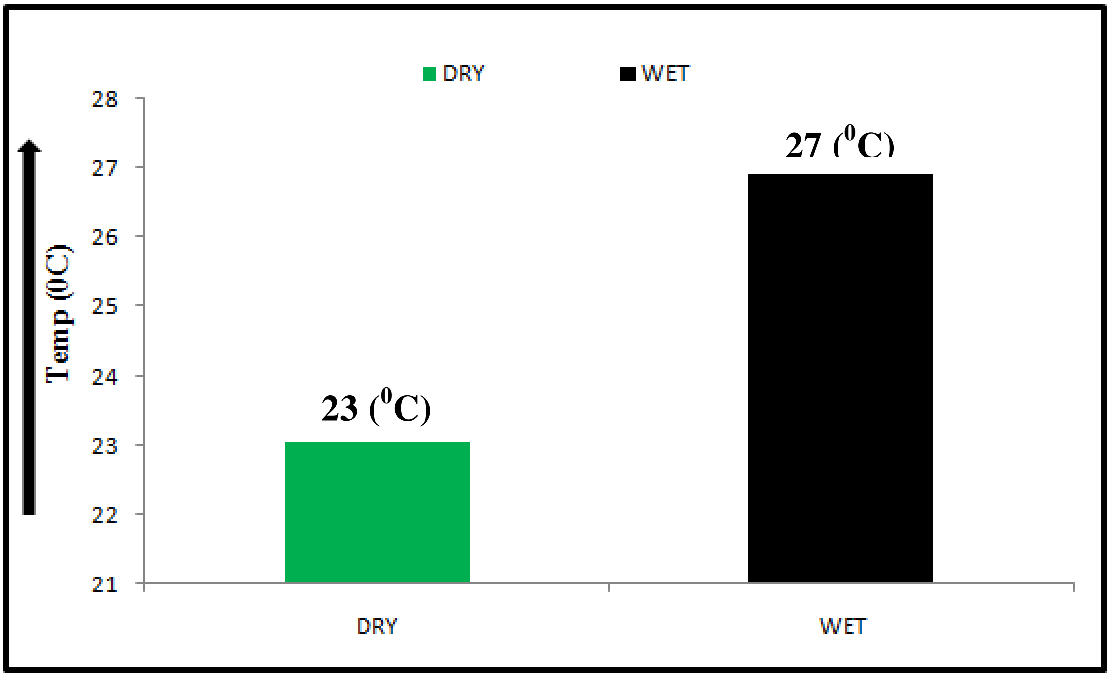

Fig. 4.44: Average surface temperature (^{0}C) according to the dry and wet seasons.

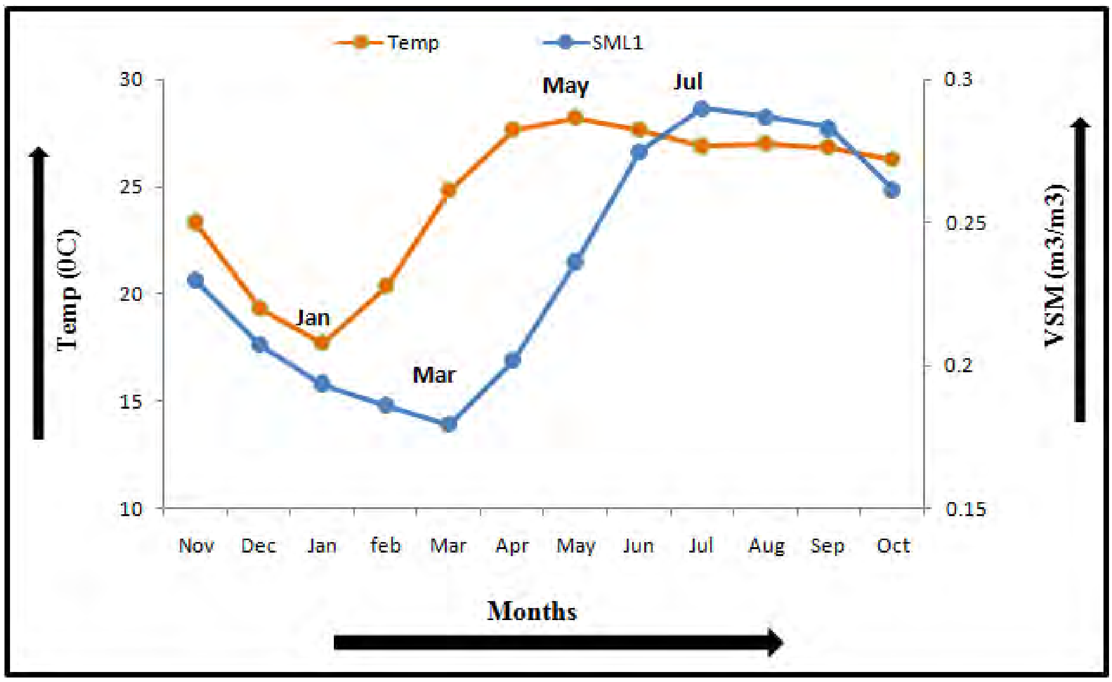

Fig. 4.45: Surface temperature (^{0}C) vs soil moisture (m^3m^{-3}) for the first layer.

The correlation between surface temperature and soil moisture in the first layer has the value of 0.57 (Table-4) which would be much better (0.80) if the correlation could be redrawn by the two months forwarding of temperature data. Also trend line is not significant (co-efficient of determinant, R^2 = 0.32) if surface temperature and soil moisture are plotted (Fig. 4.46), however, it gives the significant value of R^2= .65 if temperature value is shifted two months ahead from the actual one (Fig. 4.47). Therefore, soil moisture has two months delay response with temperature.

Considering the delay response, per month the change of soil moisture with respect to surface temperature is found 0.01 on average (m^3m^{-3}) i.e. 1 degree change of surface temperature changes the value of soil moisture by 0.01 (m^3m^{-3}) after 2 months. This change is highly significant because the global mean annual soil moisture varies only from 0.23-0.24 m^3 m^{-3} [31].

The linear relationship between soil moisture in the first layer and temperature can be set up by the following equation

Y/X = 0.01 ……………….. (1)

Y=X× 0.01 ……………….. (2)

Where, **X = Temp ($^\circ$C) in t months**

Y = Soil moisture (m^3m^{-3}) in (t+2) months

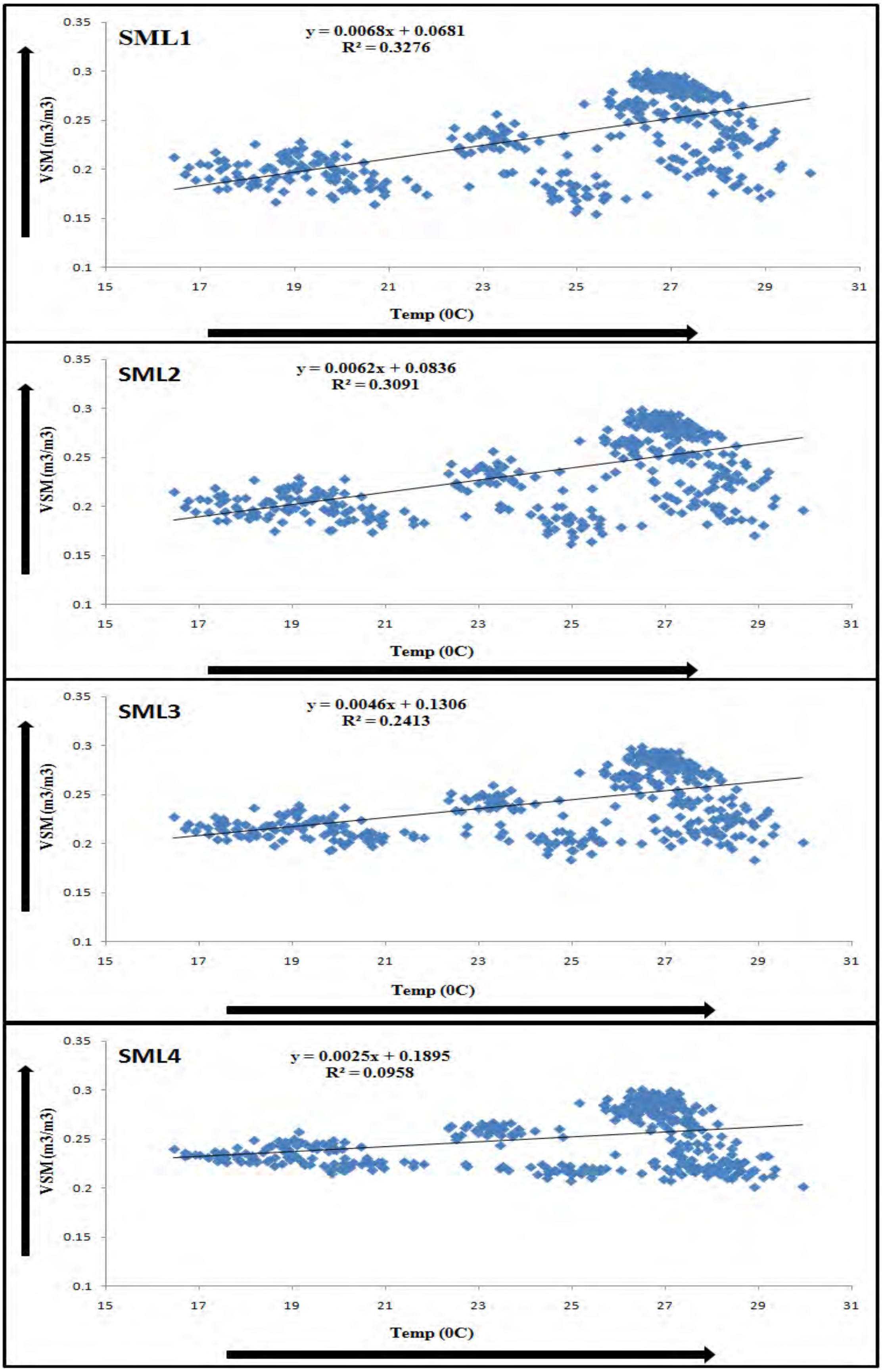

Fig. 4.46: Scatter plot of surface temperature with soil moisture (m^3m^{-3}) for the four layers.

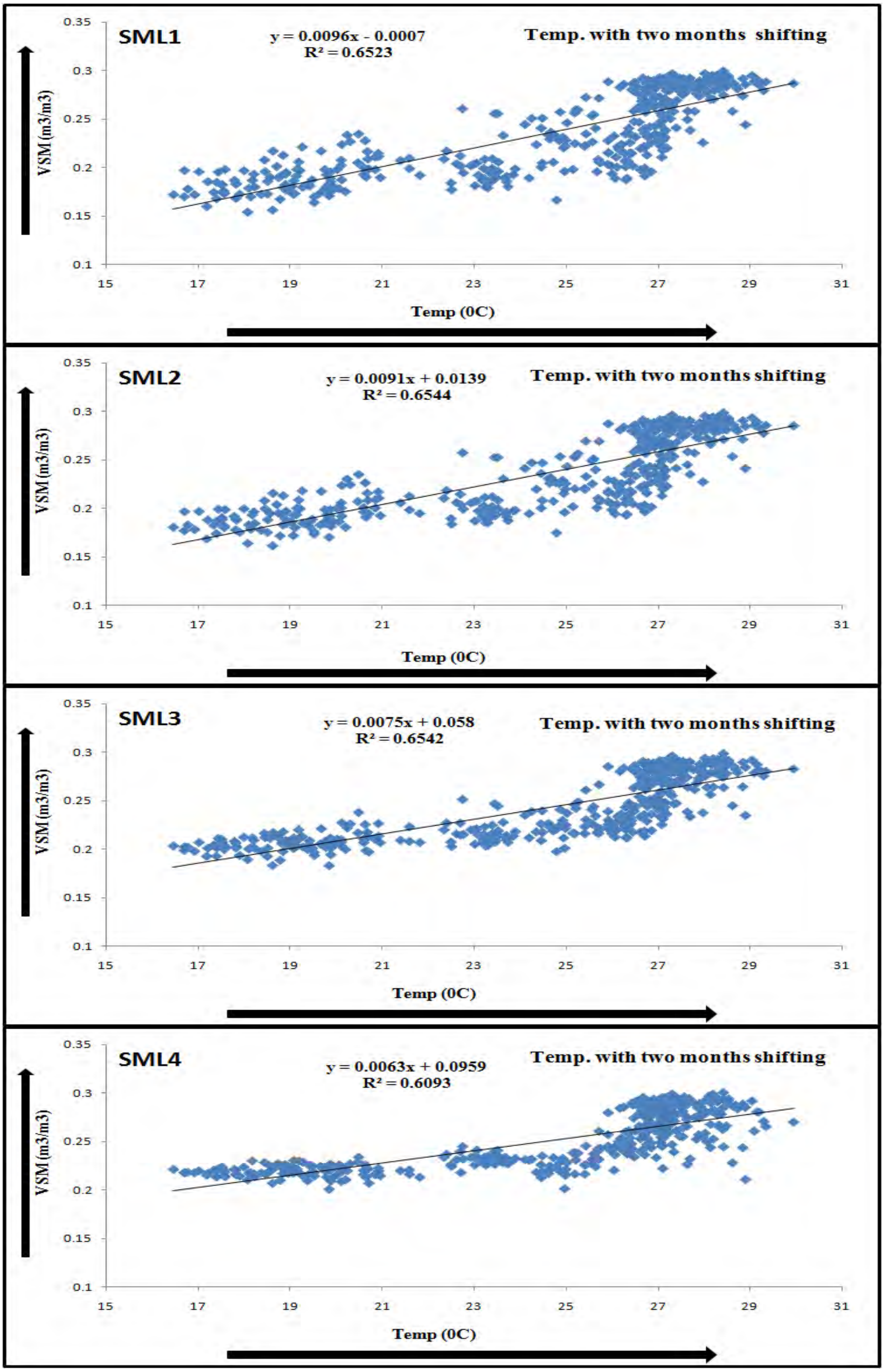

Fig. 4.47: Correlation of surface temperature (two months shifting) with soil moisture for the four layers**.**

4.2.5.1 Verification for the Relationship of Soil Moisture with Temperature

The verification between the actual value of soil moisture for 36-year average and that of the predicted value using equation (2) is shown in Fig. 4.48. The predicted value is similar to the actual value except for the months of November, December and January. In these three months predicted values are 0.002 m^3m^{-3} higher than the actual values.

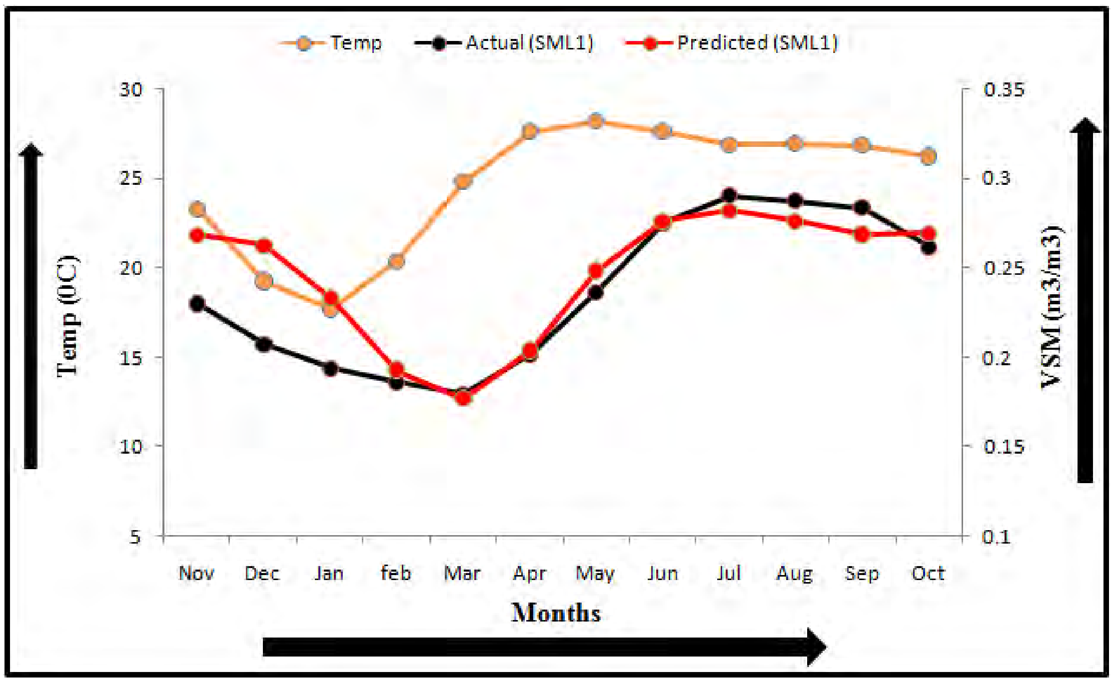

Fig. 4.48: Relationship between soil moisture (m^3m^{-3}) in the first layer (actual and predicted value) and temperatures (^{0}C).

Therefore, to minimize the errors in these months, the predicted equation is modified by multiplying the average value of temperature for the months of September, October and November by 0.008 and that for the rest of the months by 0.01 i.e. the equation (2) will be

$$\left.\begin{aligned} Y &= X \times 0.008 \quad \text{for SON, (S= Sep, O= Oct, N= Nov)} \\ &= X \times 0.01 \quad \text{for Rest of months} \end{aligned}\right\} \quad \text{.......... (3)}$$

Where, **X = Temp ($^\circ$C) in t months**

Y = Soil moisture (m^3m^{-3}) in (t+2) months

Using this modified equation, the actual value and predicted value of soil moisture is calculated and shown in Fig. 4.49. The equation is also used for the entire study period from 1979-210 which is shown in Fig. 4.50. The result is found very similar to the actual one which is further verify by the statistical methods.

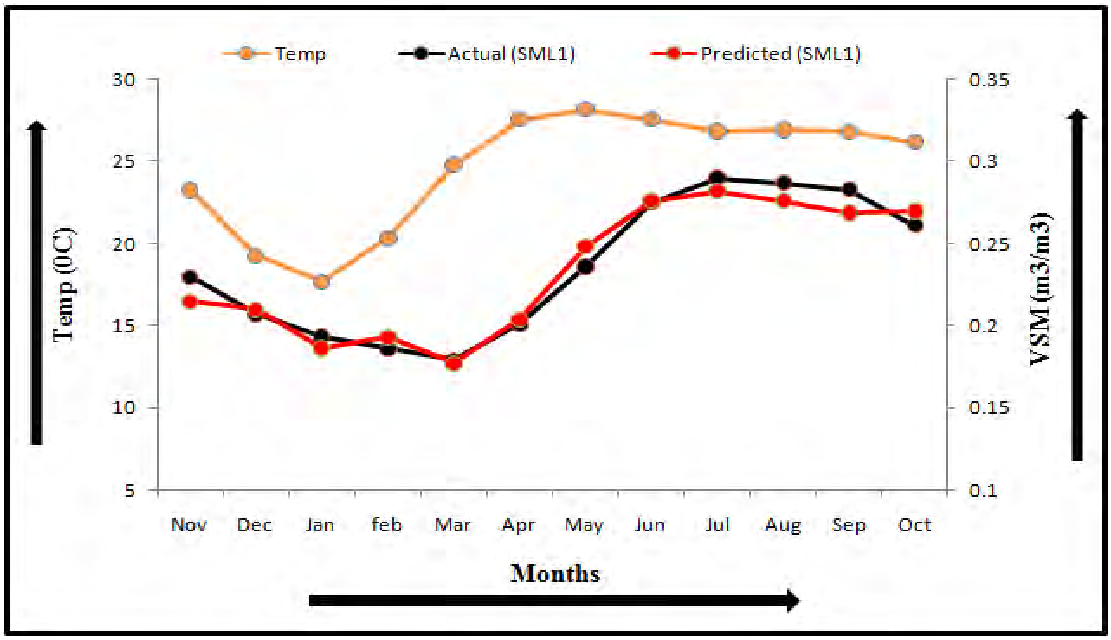

Fig. 4.49: Relationship between soil moisture (m^3m^{-3}) in the first layer (actual and predicted value) and temperatures (^0C) with correction.

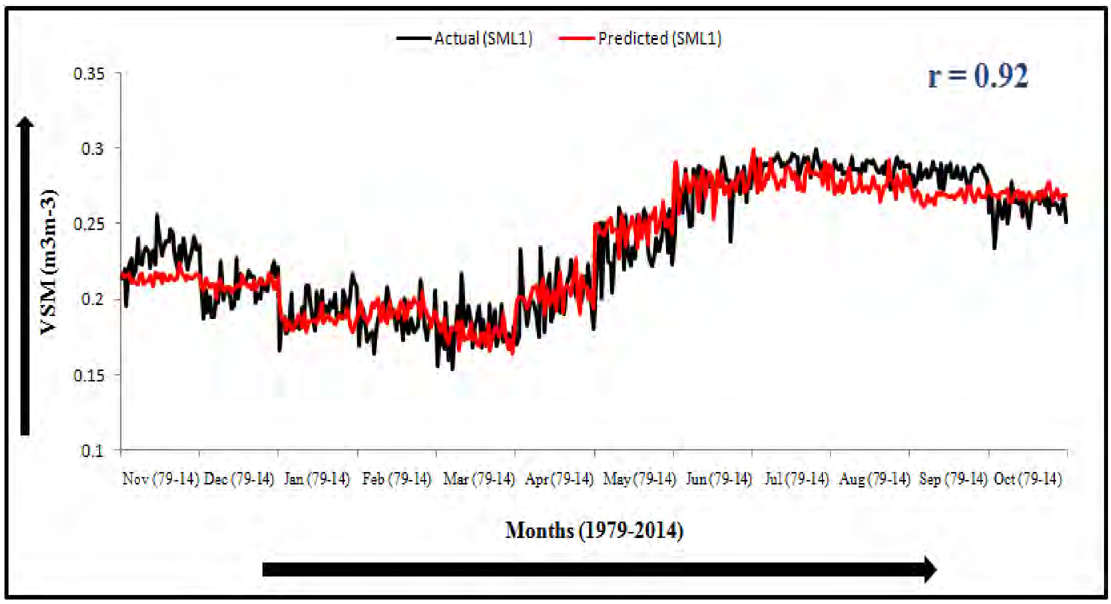

Fig. 4.50: Actual value vs predicted value of soil moisture in the first layer for the whole study period (1979-2014).

Here, the Co-relation co-efficient and T-test between actual and predicted values of soil moisture in the first layer is analyzed which have been shown below:

Test-1		
Co-relation Co-efficient		
Actual and Predicted value	r =0.92	
Test-2		
T-Stat: Two-Sample (Actual and Predicted value) Assuming Equal Variances		
	Actual value (SML1)	Predicted value (SML1)
Mean	0.235786841	0.233762283
Variance	0.001756057	0.001500855
Observations	432	432
Hypothesized Mean Difference	0	
df	857	
t Stat	0.737342421	
P(T<=t) one-tail	0.230557981	
t Critical one-tail	1.64663359	
P(T<=t) two-tail	0.461115962	
t Critical two-tail	1.9627359	

Test-1 indicates that the predicated value is very significant to actual value as r gives extremely significant value.

Test-2 shows, that there is no significant difference between actual and predicted value of soil moisture in the first layer as t Stat< t Critical for one-tail and t Stat< t Critical for two-tail.

Therefore, the predicted equation and corresponding result is significant and remarkably acceptable. The soil moisture for month (t+2) can be measured efficiently from the surface temperature of month (t) by using linear equation (3).

4.3 Soil Moisture in the North Eastern (NE) and South Western (SW) Sides of Bangladesh

4.3.1 Spatial Distribution

Spatial distribution indicated by the boxes in Fig. 4.51 represents the averaged (1979-2014) soil moisture of the NE (D1) and SW (D2) sides of Bangladesh. It has been seen that the value of soil moisture in the first layer is high (>0.3 m^3m^{-3}) in the NE which is decreasing with the value of <0.3 m^3m^{-3} towards the SW sides of Bangladesh. Other three layers follow the same pattern but with different values. Soil moisture for the first two layers is almost same for the respective domain area. Soil moisture is increasing from the third to the fourth layer for the respective sides of Bangladesh.

4.3.2 Monthly Soil Moisture Variation

Monthly average of soil moisture of four layers in the NE and SW sides of Bangladesh is shown in Fig. 4.52. The patterns of soil moisture for the NE and SW sides are seemed to be similar but the amounts of moisture have shown noticeable difference particularly from the month of November to June. In the NE sides, soil moisture gets its minimum (maximum) state in the month of February (July) with the value of 0.250 m^3m^{-3} (0.365m^3m^{-3}) in the first layer whereas, in the SW sides, soil moisture gets its minimum (0.203 m^3m^{-3}) value in the first layer in the month of March and maximum (0.352 m^3m^{-3}) value attain in the first layer in the month of July. Averaged soil moisture is increased from the top layer to the bottom layer by 4.4% in the NE sides whereas, it is increased by 8.6% in the SW sides. Percentage differences between NE to SW sides are found 12.4%, 11.8%, 9.6% and 8.5%, respectively from the upper layer to the bottom layer (Fig. 4.53).

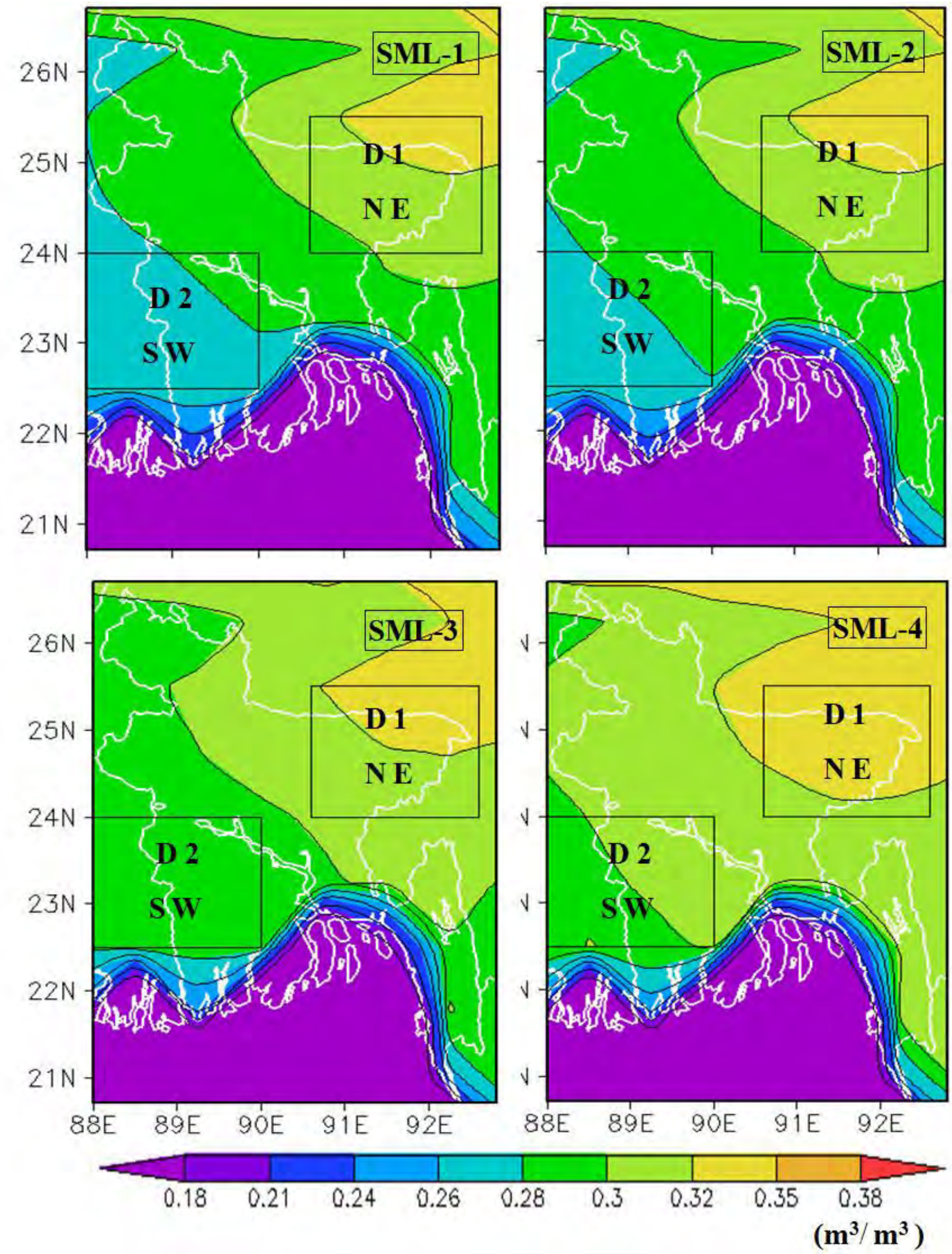

Fig. 4.51: Boxes in the figure indicate the distribution of averaged soil moisture (m^3m^{-3}) for different layers over the north eastern and south western sides of Bangladesh during the period of 1979-2014.

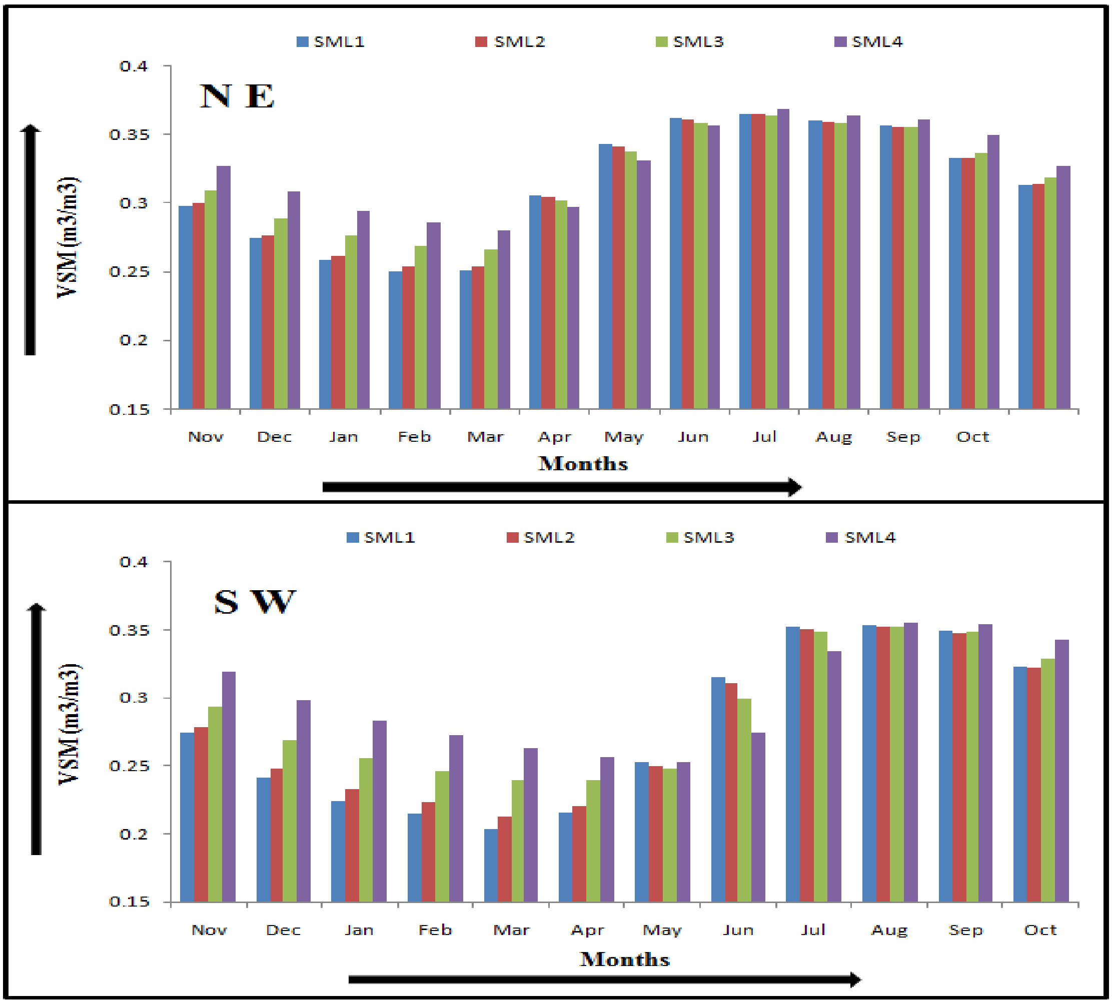

Fig. 4.52: Monthly average of soil moisture (m^3m^{-3}) in the NE and SW sides for 1979-2014.

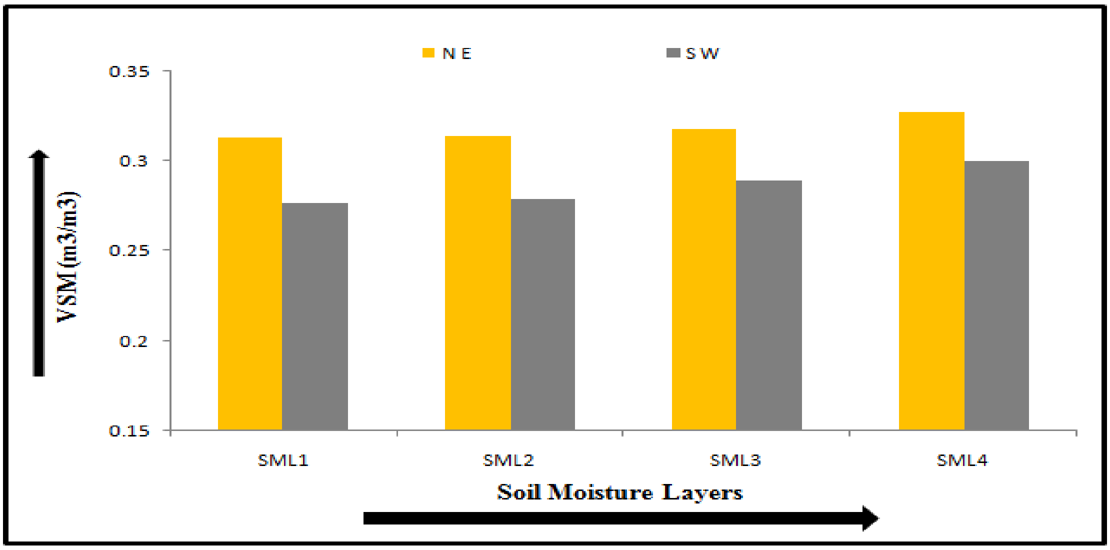

Fig. 4.53: Average soil moisture (m^3m^{-3}) for four layers in the NE and SW sides of Bangladesh for 1979-2014.

4.3.3 Seasonal Soil Moisture Variation

The difference of soil moisture for each layer in the NE and SW parts according to dry and wet season is represented in Fig. 4.54. The distinct characteristics of soil moisture in the four layers are observed in the dry season over the NE and SW sides of Bangladesh. In the dry season, the percentage difference of soil moisture in the four layers between the NE to SW are found 19.7%, 17.9%, 13.3% and 8.8% respectively, for the upper layer to the bottom layer. On the other hand, in wet season these percentage differences are found less (4.8%, 5.3%, 5.6% and 8.1%, respectively for the upper layer to the bottom layer) corresponds to dry season.

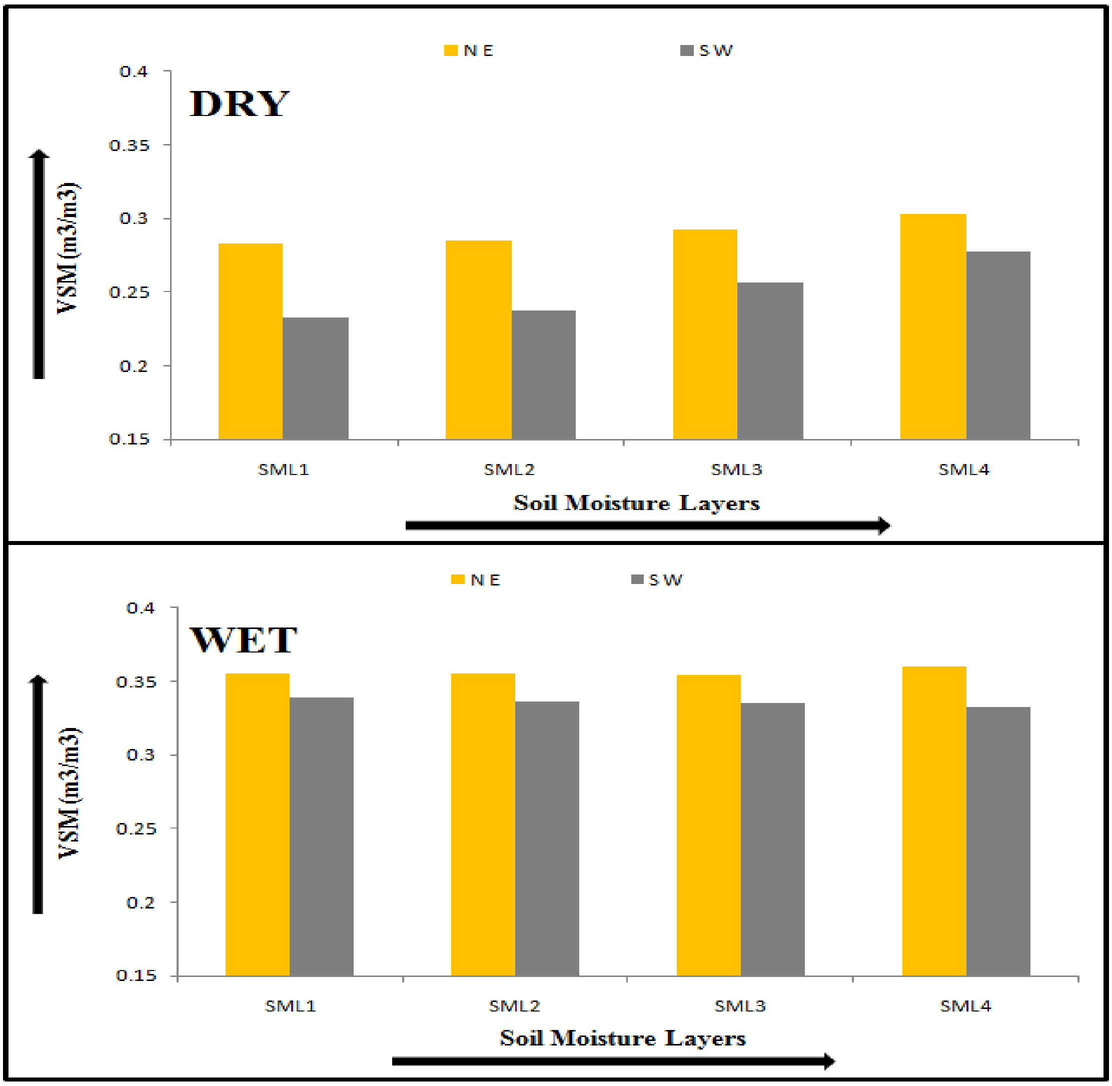

Fig. 4.54: Averaged soil moisture (m^3m^{-3}) in four layers according to dry and wet season in the NE and SW sides of Bangladesh for 1979-2014.

4.3.4 Effects of Atmospheric Variables on Soil moisture in the NE and SW Sides of Bangladesh

4.3.4.1 Surface Temperature

Monthly average of Surface temperature and soil moisture of first layer in the NE and SW sides of Bangladesh is shown in Fig. 4.55. From November to March temperature of the NE area has lower value (20^{0}C) than the SW (21.2^{0}C) area and the percentage of difference during these months between NE and SW is 5.7%. From April to October temperature increases to (26^{0}C) in the NE area and in the SW area to (28.6^{0}C) and the percentage of difference between NE and SW during these months is 9.6%. It has been observed that soil moisture in the first layer for both sides act with two months delay response to the temperature.

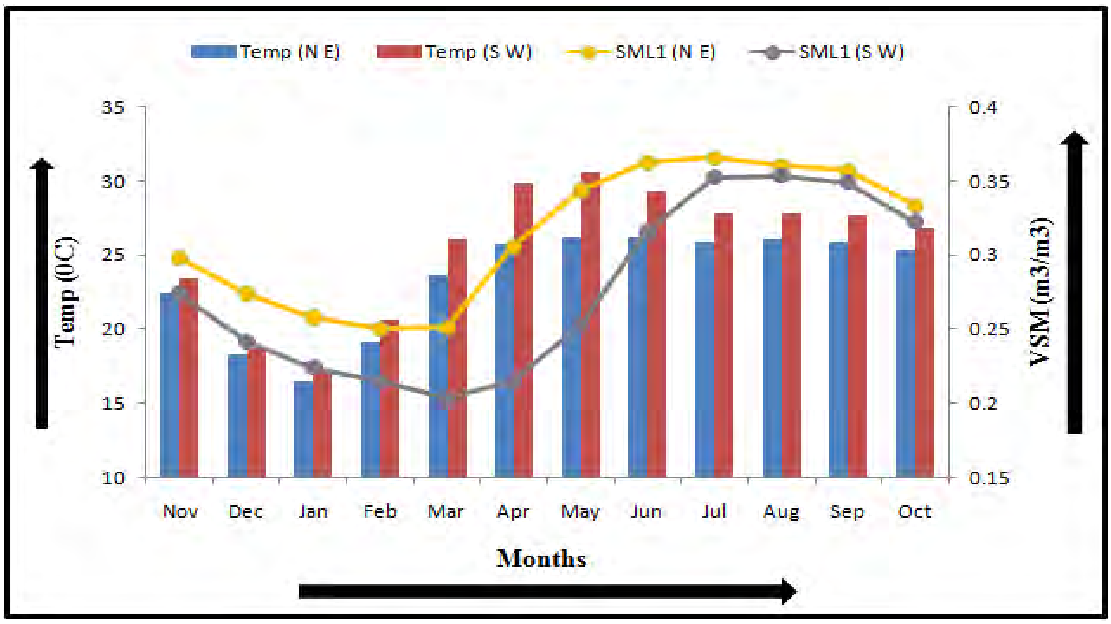

Fig. 4.55: Monthly average of temperature (^{0}C) and soil moisture (m^3m^{-3}) in the first layer of NE and SW sides of Bangladesh for 1979-2014.

4.3.4.2 Evaporation and Precipitation

Monthly average evaporation and soil moisture in the first layer for the NE and SW sides of Bangladesh is shown in Fig. 4.56. Average Evaporation rate almost carries greater value (2.41 mm/day) in the NE area than the SW area (2.10 mm/day) and the percentage difference between NE to SW is 13.5% in the dry season. In the wet season, this percentage difference is reduced to 10.5% between SW to NW area.

Soil moisture in the first layer for the two areas is approximately related in proportion to the each parts of the evaporation rate.

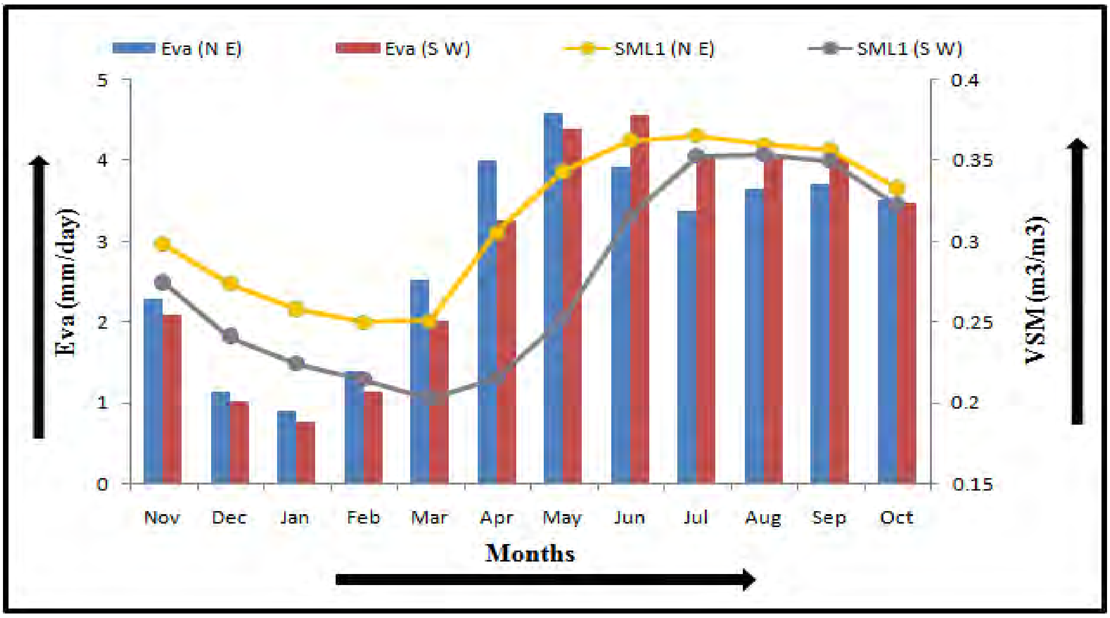

Fig. 4.56: Monthly average of evaporation (mm/day) and soil moisture (m^3m^{-3}) in the first layer of the NE and SW sides of Bangladesh for 1979-2014.

Monthly average precipitation and soil moisture in the first layer for the NE and WS sides of Bangladesh is represented in Fig. 4.57. In the dry season, precipitation rate in the NE area (3.75 mm/day) is higher than the SW area (0.90 mm/day) and in the wet season precipitation rate is (12 mm/day) in the NE area which is greater value than that of the WS area (9.15 mm/day). The percentage difference of precipitation between NE to SW is found 49.7% throughout the twelve months. As precipitation is highly co-related with soil moisture, soil moisture gets its highest (lowest) value in maximum (minimum) precipitation rate for both of the sides.

Monthly average value of evaporation minus precipitation (E-P) and soil moisture in the first layer for the NE and SW sides of Bangladesh is displayed in Fig. 4.58. In case of evaporation minus precipitation (E-P) which actually indicates the amount water partly stay in the soil, the NE area always has higher negative value (-4.24 mm/day) than that in the SW area (-1.40 mm/day) throughout the year. This result indicates that NE side of Bangladesh contains higher amount of soil moisture than the SW side.

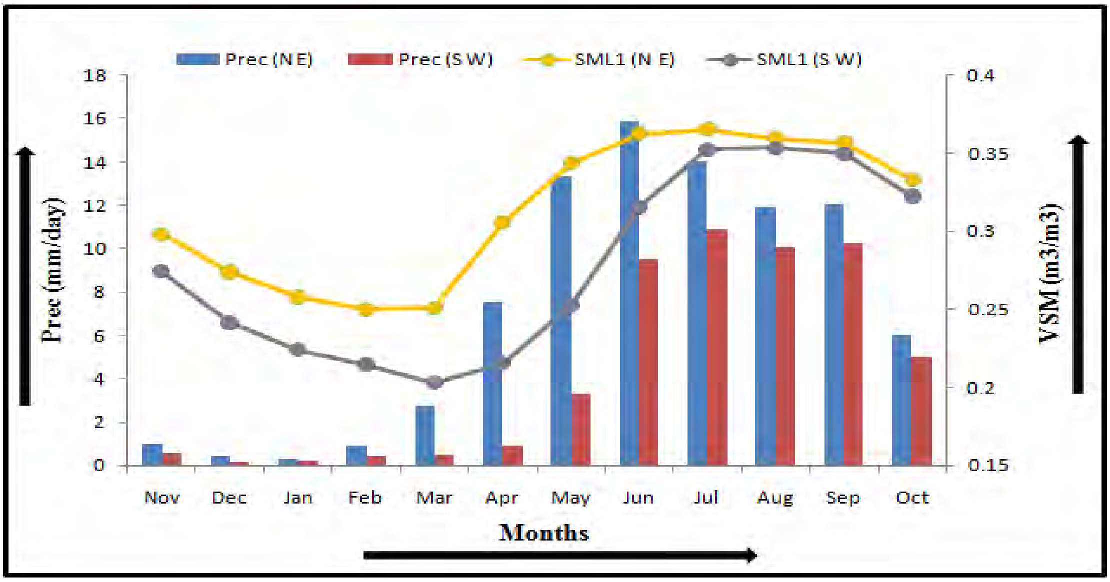

Fig. 4.57: Monthly average of precipitation (mm/day) and soil moisture (m^3m^{-3}) in the first layer of the NE and SW sides of Bangladesh for 1979-2014.

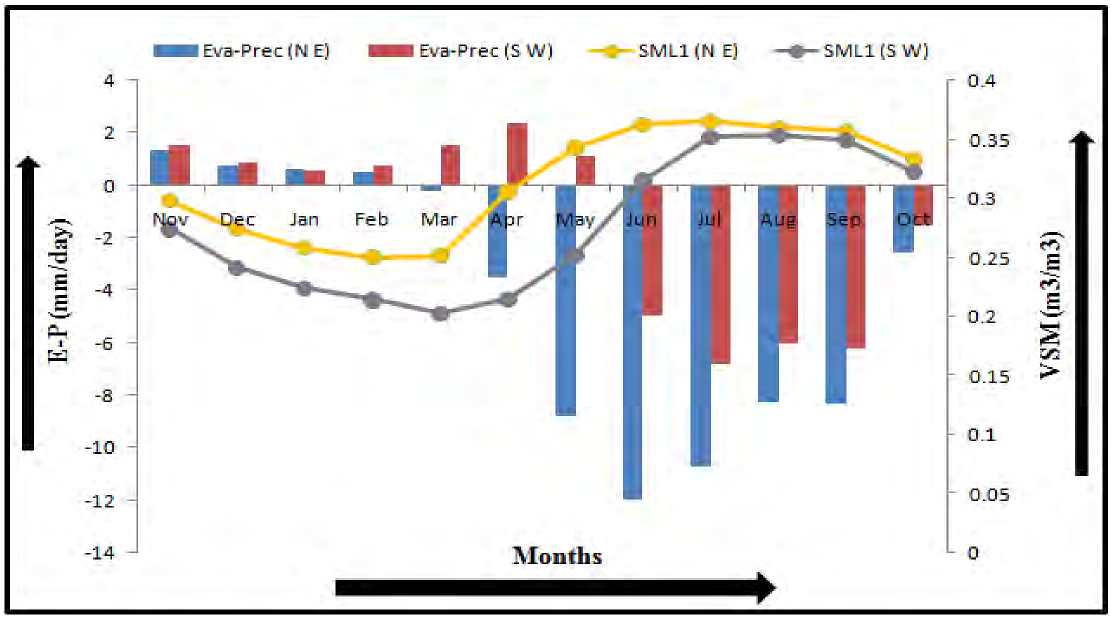

Fig. 4.58: Monthly average of E-P (mm/day) and soil moisture (m^3m^{-3}) for the first layer in the NE and SW sides of Bangladesh for 1979-2014.

CHAPTER 5

CONCLUSIONS

Now a days, soil moisture is an important climate predictor. So, long-term moisture contents in the four different soil layers from surface to 255 cm depth for the land of Bangladesh are examined. For this purpose the 36-years reanalysis data from ECMWF are used from 1979 to 2014. According to climatological point of view, soil moisture over Bangladesh is increasing significantly since 1979 to 2014 for all layers. However, within these 36-years average soil moisture in the surface layer (0-7cm) is increased by 7.6% and this annual increasing rate is gradually decreasing toward the bottom layer (100-250 cm) with the value of 5%. Average soil moisture is also increasing downward non-linearly. Percentage differences in moisture between successive layers are found 0.53%, 2.54%, and 3.28% from upper to bottom layer, respectively.

Soil moisture in each of the four layers maintains a periodic pattern throughout the twelve months of the year with a minimum value in March and maximum in July or August. Seasonal variability of moisture shows a dissimilar behavior of soil moisture between dry (November-May) and wet (June-October) seasons. Moisture in all different soil layers increasing downward in the dry season with the average value of 0.23 m^3m^{-3} in the bottom layer and 0.20 m^3m^{-3} in the surface layer ; whereas, it behaves like one moist layer in the wet season. Because after the month of May soil moisture in all layers are saturated with an approximate value of 0.28 m^3m^{-3}. Soil in Bangladesh has 25.6% more moisture in the wet season than that of dry season. Therefore, comparison between the moisture layers during the dry and wet seasons indicates that dry season contributes to the total vertical moisture pattern over Bangladesh. In addition, annual increase of soil moisture in the dry season has significant R^2 value (0.56, 0.56, 0.67 and 0.61, respectively for four layers) than that of the wet season (R^2=0.18, 0.21, 0.19 and 0.23, respectively for four layers). This result indicates about the importance of soil moisture during the dry season as it contributions to the total annual soil moisture characteristics.

Chapter 5

Horizontal Moisture from surface to 100 cm soil depth is not uniformly distributed in Bangladesh which shows dry in the west side (<0.3 $m^3 m^{-3}$) than the east side. Below 100 cm, moistures are almost uniform all over Bangladesh. Soil in the north eastern side of Bangladesh holds more moisture than the south western side with percentage difference of 12.4% in the surface layer.

Different atmospheric parameters over Bangladesh are examined and compared with the characteristics of soil moisture, especially with the surface layer. Evaporation minus precipitation (E-P) is negatively correlated with the monthly average soil moisture (r=-0.87 for the surface layer) moisture i.e. negative value of E-P provides excess of water whereas the positive value indicates the dryness of soil. Moreover, Relative humidity and precipitation have strong positive correlations of r=0.89 and r=0.88, respectively over 36-years for the first soil layer. Soil moistures in the other layers are also significantly changed with the parameters but the value of r is less than the first layer. Surface temperature has the minimum (maximum) value in January (May) where the moisture in soil contains the minimum (maximum) value in two months later i.e. in March (July). Therefore, the change in temperature is strongly correlated (r=0.80) with the change of soil moisture in the first layer after two months. The moisture value of 0.01 (m^3m^{-3}) is changed for per degree change of temperature. So if temperature is known for a particular month, soil moisture of Bangladesh after 2 months can be predicted which will be helpful for agriculture and related disciplines. In addition, the information of moisture in different layers during the dry season could help to take decision about different type of crop production. Increasing of soil moisture indicates about the climate change. Increase in soil moisture could enhance the possibility of flood over Bangladesh.

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APPENDIX

1) Conference Abstract

M.Paul and N.Akter, “Long-Term Variability of Soil Moisture over Bangladesh”, Abstracts in the International Conference on Physics-2016, Bangladesh Physical Society, Dhaka, Bangladesh, 10-12 March, 2016.

2) Submitted Article to the Journal ‘ The Atmosphere’, BMD (Accepted)

M.Paul and N.Akter, “The Effect of Atmospheric Variables on Soil Moisture over Bangladesh”, ***The Atmosphere***, BMD, 2016.

Appendix

Abstracts in the International Conference on Physics-2016, Bangladesh Physical Society (BPS)
10-12, March 2016, Atomic Energy Centre, Dhaka.

Long-Term Variability of Soil Moisture over Bangladesh

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Abstract

Soil moisture is the water occupying pore spaces between soil particles, which plays an important role for hydrological cycle. In this study, ERA-Interim reanalysis data collected from European Centre for Medium-Range Weather Forecasts (ECMWF) dataset are used for analyzing soil moisture over Bangladesh for 36 years from 1979 to 2014. From the surface to below, four soil layers of 0-7 cm, 7-28 cm, 28-100 cm, 100-250 cm are considered and measured volumetric soil moisture (VSM) for each layer. Long-term annual variations of soil moisture provide a constant periodic trend having two distinct seasonal characteristics. In wet season (June-October), moistures for all layers are coincided with maximum VSM of 0.28 m^3 water/m^3 soil. In other case, soil moisture in dry season (November-May) is gradually decreased by 13% from the lower level to surface. Monthly surface temperature changed from 17°C to 28°C causes the variation of surface evaporation which results the gradient of soil moisture in dry season. In wet season, temperature (relative humidity) is almost constant with an average value of 27°C (92%). In both cases, evaporation minus precipitation have a strong negative correlation (r = -0.89) with soil moisture which control the exchange of water between land and atmosphere.

Appendix

The Effect of Atmospheric Variables on Soil Moisture over Bangladesh

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Abstract: The moisture for four different depths of soil is analyzed using 36-years reanalysis data. The spatial variation shows that moisture increases with the soil depth. This characteristic is prominent in the dry season (November-May), whereas in the wet season (June-October) moisture reaches the saturated conditions for all layers. The value of soil moisture provides an annual periodicity with maximum value of 0.28 m^3m^{-3} in July and minimum value of 0.17 m^3m^{-3} in March. Atmospheric variables of evaporation minus precipitation and relative humidity are compared to soil moisture in the surface layer which indicates the strong positive relation with the correlation coefficient value of -0.87 and 0.88, respectively. Monthly temperature variation also affects on the amount of soil moisture. The changing of surface temperature changes soil moisture after two months later with an approximate value of 0.01 m^3m^{-3}.The long-term annual variability of soil moisture provides a periodic trend for all layers which indicates about the effect of climate change.

Keywords: Soil moisture, Evaporation, Precipitation, Surface-temperature, Relative humidity.

1. INTRODUCTION

Soil moisture is the water occupying pore spaces between soil particles. The upper 10 cm soil water layer is defined as surface soil moisture, whereas root-zone soil moisture is the upper 200 cm of soil water that is available to plants. Although soil moisture is a small component of the hydrologic cycle, it influences hydrological, biological, biogeochemical and agricultural processes. It is a key variable in controlling the exchange of water and heat energy between land surface and atmosphere through evaporation and plant transpiration [1, 2]. Soil moisture is also recognized as an essential climate variable in 2010 by the Global Climate Observing System (GCOS) because it plays an important role in understanding and predicting climatic patterns [3]. Soil moisture effects on the development of weather patterns and the production of precipitation through atmospheric feedback [4]. Numerical weather prediction models with accurate characterization of soil moisture can lead to significant forecast improvements which can accordingly get better prediction of atmospheric parameters. There are many studies around the world which indicates the importance of relationship between soil moisture and atmospheric variables of evaporation, precipitation, temperature, relative humidity etc. [5-10]. But there are only few studies in Bangladesh which only emphasized the impacts of soil moisture particularly on crops and vegetables [10, 11]. The variability of soil moisture and its distribution over Bangladesh has not been yet studied. For this purpose, the study will emphasized the long-term variations of soil moisture and its seasonal distributions. In addition, to improve climate model over Bangladesh, relations to soil moisture and the atmospheric variables of surface temperature, precipitation, evaporation and relative humidity are examined in this study.

2. DATA USED AND METHOD

In this study, ERA-Interim global atmospheric reanalysis 6-hourly dataset collected from European Centre for Medium-Range Weather Forecasts (ECMWF) is used for analyzing soil moisture for 36 years from 1979 to 2014. The data has 60 levels in the vertical, with the top level at 0.1 hPa and spatial resolution is $0.75^0 \times 0.75^0$ [13]. The reanalysis providing the volumetric soil moisture (VSM) data for soil layer-1 (0-7 cm), soil layer-2 (7-28 cm), soil layer-3 (28-100 cm), and soil layer-4 (100-250 cm) are considered in the study. For analyzing soil moisture and the atmospheric variables, Bangladesh region (20.7°N-26.7°N and 88°E-92.8°E) is selected for study area which is shown in Fig. 1. The VSM data in different layers have been extracted for the study areas and analyzed to find out its spatial and temporal characteristics. Atmospheric variables of precipitation, evaporation, 2-m air temperature, relative humidity at surface have been observed and extracted for the same areas using same data site, and analyzed their effect on the soil moisture.

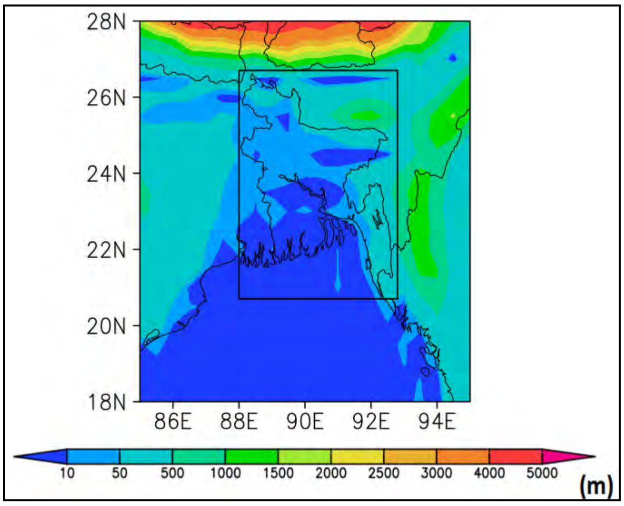

fig. 1: Topography of Bangladesh. The box indicates the study area.

3. RESULTS AND DISCUSSION

3.1 Annual Variation of Soil Moisture:

Spatial distributions of soil moisture averaged for the period from 1979-2014 is shown in Fig. 2 for four layers (i.e. SML1, SML2, SML3 and SML4) mentioned in the previous section. The moisture is increased from the upper layer to the bottom. However, the west side of Bangladesh is dry then the east side up to the third layer. This phenomenon is similar with Nazrul et al. [14] but he studied about the dry and moist air over Bangladesh. The fourth soil layer maintains almost unique value (~ 0.25 m^3 m^{-3}) all over Bangladesh.

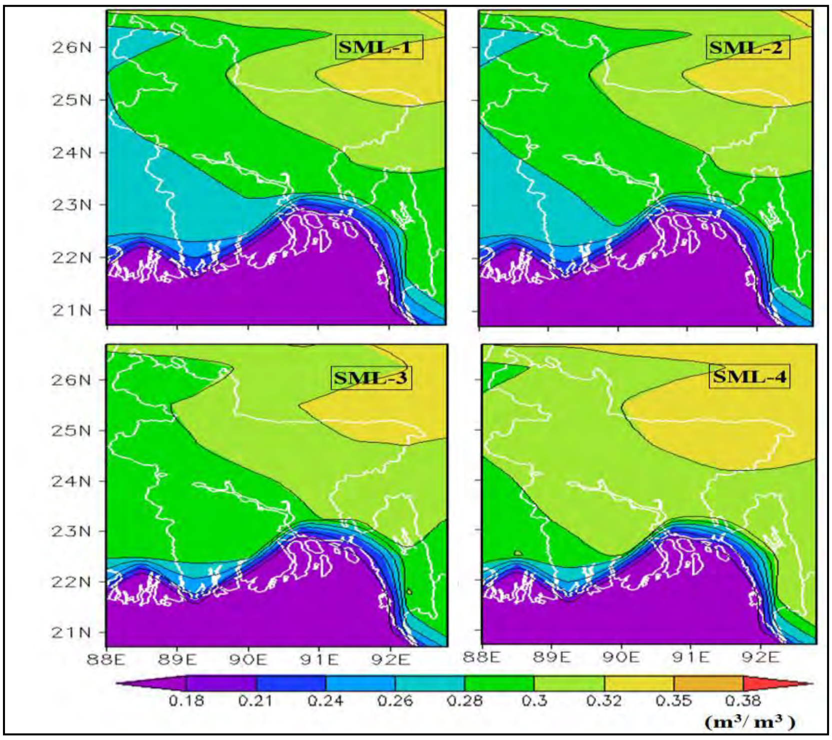

fig. 2: Distribution of averaged soil moisture for 1979-2014.

Appendix

The 36-years average value is calculated in Fig. 3. The figure indicates that soil moisture is increased from the upper layer to the bottom. First two layers almost overlap with each other which mean they contain almost the same quantity of soil moisture (VSM), whereas, the third and fourth layers show distinct difference in terms of having the soil moisture. The average values for the first two layers are found almost same (24.3% and 24.5% of the total soil moisture); where the third and fourth layers have the soil moisture amount of 25% and 26%, respectively. The moisture differences between two successive layers from upper to bottom are found 0.55%, 2.54%, and 3.28%, respectively. Therefore, moisture is increasing to 6.5% from the surface to the bottom layer. Increasing rate of moisture is found positive but not linear one. Moisture is exponentially increased from surface to 250 cm inside the ground.

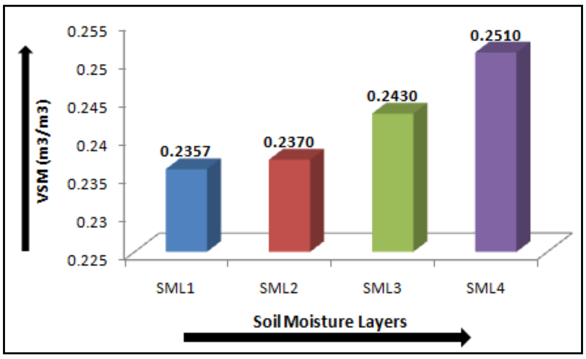

fig. 3: Average value of soil moisture in the four layers for 36 years.

Temporal distribution of soil moisture for the period from 1979-2014 is analyzed by 5-years running mean in Fig. 4**.** Climatologically, each of the four layers represents the rising trends which indicate that soil moisture is increasing day by day but in slower rate. The moisture in each layer is in increasing since 1979 to 2014 as 7.5%, 7.4%, 6.5%, and 5% for the top layer to the bottom layer respectively. Though the percentage of soil moisture is less in surface, however it is increased more because of the climate change.

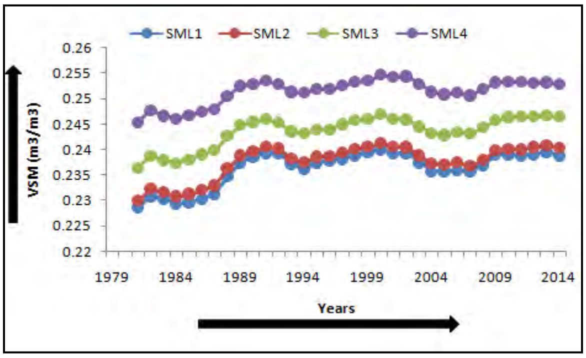

fig. 4: 5-years running mean of soil moisture in the four layers.

3.2 Monthly Variation of Soil Moisture:

Fig. 5 represents the variability of soil moisture by month. Soil moisture for all four layers shows the same periodic phenomena throughout the twelve months having low moisture during November to May (dry season) and relatively high moisture during June to October (wet season). The moisture characteristics of soil layers between the dry and wet seasons are analyzed. Distinct variations within the moisture layers are found in the dry season; in contrast, moisture layers are clearly identical in the wet season which behaves like one saturated layer after the month of May. Soil moisture is lowest in March for all layers i.e 0.17 m^3m^{-3} for SML1, 0.18 m^3m^{-3} for SML2, 0.20 m^3m^{-3} for SML3 and 0.21 m^3m^{-3} for SML4,whereas highest value (0.28 m^3m^{-3} for all layers) is noticed in July or August.

Appendix

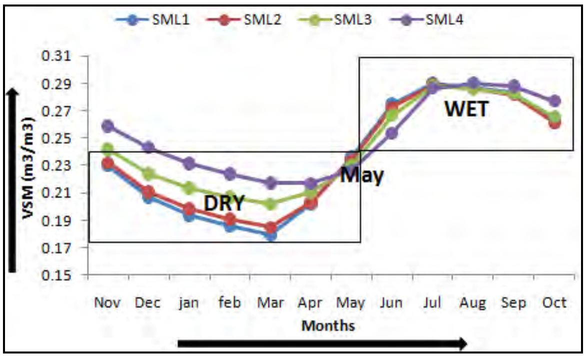

fig 5: Monthly average of soil moisture.

3.3 Seasonally Variation of Soil Moisture:

The bars diagram in Fig. 6 shows the 36-years averaged soil moisture in the dry and wet seasons for different layers. The soil layers contain more moisture (56% of the total) in the wet season than that in the dry season (44%). The comparison between the moisture during dry and wet seasons indicate that the moisture in the layers behave similar to overall characteristics of the soil moisture over Bangladesh (Fig. 3). Therefore, moisture in the dry season is important because it significantly contributes to the total moisture pattern over Bangladesh.

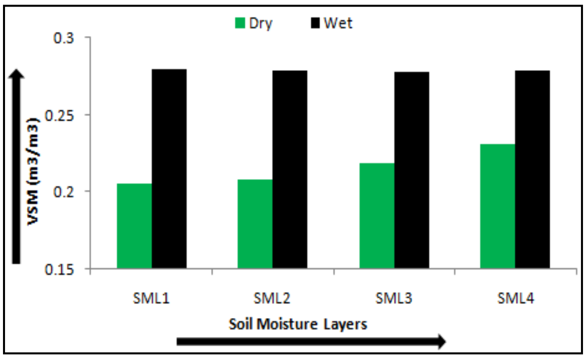

fig. 6: Average soil moisture in the four layers according to the dry and wet seasons for 1979-2014.

3.4 Effects of Atmospheric Variables on Soil Moisture

3.4.1 Precipitation and Evaporation:

The monthly average value for evaporation (E), precipitation (P) and the difference between them (E-P) are calculated and presented in Fig. 7. The evaporation rate and the precipitation rate are much lower in the dry season than that in the wet season. In dry (wet) season, the evaporation rate is 2.5 mm/day (3.8 mm/day) and the precipitation rate is 1.8 mm/day (11.2 mm/day). The difference of evaporation and precipitation (E-P) has the lower positive value (<3 mm/day) in the dry season and higher negative value (~ -8 mm/day) in the wet season.

Appendix

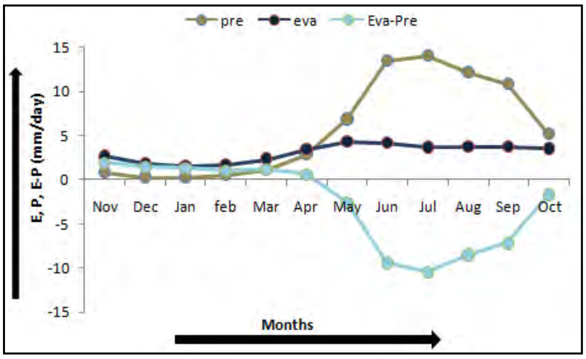

fig. 7: Monthly Evaporation (E), Precipitation (P) and Evaporation-precipitation (E-P) patterns for 1979-2014.

Evaporation minus precipitation (E-P) provides the information about how much water comes to the soil that actually measures the value of soil moisture. Therefore, negative value of (E-P) gives excess of water where positive value indicates the dryness of the soil. The 36-year averaged data of E-P and soil moisture perfectly coincide with each other shown in Fig. 8. The co-relation between E-P and soil moisture in the different layers are calculated in Table-1 and found that all layers are highly correlated except the last layer.

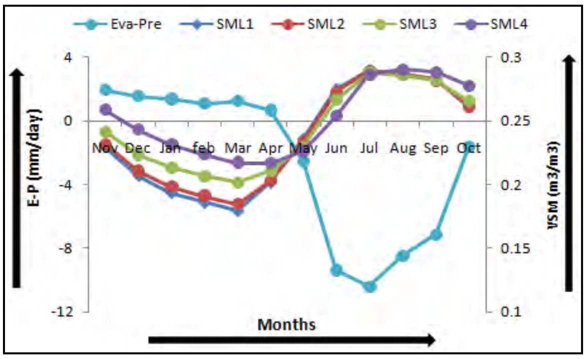

fig. 8: The value of E-P and soil moisture in the different layers.

3.4.2 Relative humidity:

Fig. 9 represents how relative humidity relates or interacts with soil moisture throughout the months. Here, moisture of the first layer is considered as this layer has direct contact with the atmosphere. It is observed that the average value of relative humidity is low (79%) in the dry season compare to the wet season (92%). However, relative humidity over Bangladesh is almost 80% or more for all months. Soil moisture in the first layer is highly correlated (r=.88) with relative humidity (Table-1). Both the atmospheric and soil humidity are less in the dry season and more in the wet season which depend on the values of evaporation and precipitation.

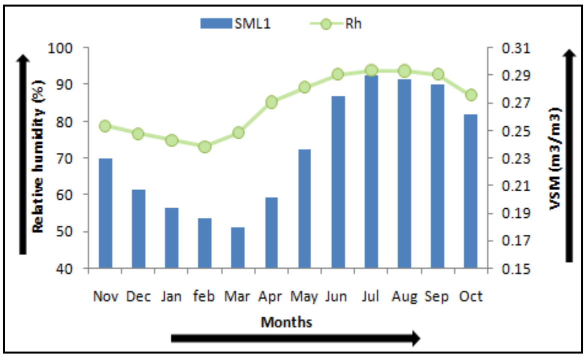

fig. 9: Relative humidity vs soil moisture for the first layer.

Appendix

3.4.3 Surface Temperature:

The variation of average surface temperature with the soil moisture for the first layer is displayed in Fig. 10. It is found that soil moisture is changed with the change of temperature by two months later. Minimum temperature is found in January whereas soil moisture becomes the minimum value in March. Similarly maximum temperature is attained in May whereas maximum soil moisture is found in July. The correlation between surface temperature and soil moisture in the first layer has the value of 0.57 (Table-1) which would be much better (0.80) if the correlation could be redrawn by the two months forwarding of temperature data (Fig. 11). Also trend line is not significant (co-efficient of determinant, R^2 = 0.32) if surface temperature and soil moisture are plotted, however, it gives the significant value of R^2= .65 if temperature value is shifted two months ahead from the actual one. Therefore, soil moisture has two months delay response with temperature.

Considering the delay response, per month the change of soil moisture with respect to surface temperature is found 0.01 on average (m^3m^{-3}) i.e. 1 degree change of surface temperature changes the value of soil moisture by 0.01 (m^3m^{-3}) after 2 months. This value is highly significant because the global mean annual soil moisture varies only from 0.23-0.24 m^3 m^{-3} [15].

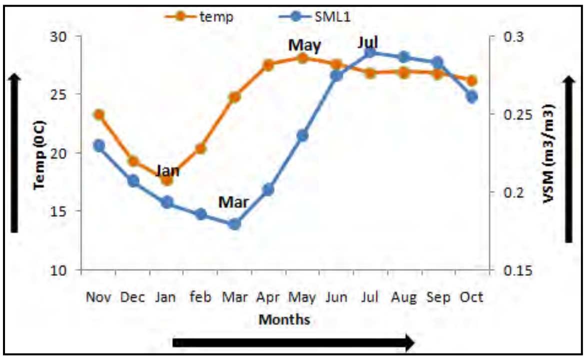

fig. 10: surface temperature vs soil moisture for the first layer.

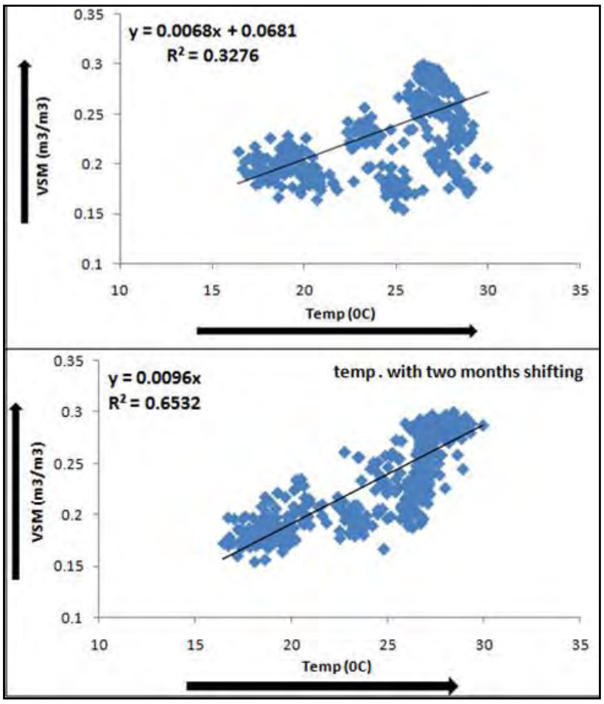

fig. 11: Correlation of surface temperature with soil moisture for the first layer.

Appendix

Table-1: Correlation coefficient between atmospheric variables and soil moisture

Soil layer	Evaporation (E)	Precipitation (P)	(E-P)	Relative humidity (Rh)	Temperature	Temperature with two months shifting
SML1	0.72	0.89	-0.87	0.88	0.57	0.80
SML2	0.7	0.89	-0.87	0.87	0.55	0.80
SML3	0.62	0.85	-0.84	0.81	0.49	0.80
SML4	0.42	0.69	-0.7	0.64	0.3	0.78

4. Conclusions

Now a days, soil moisture is an important climate predictor. So, long-term moisture contents for the land of Bangladesh are calculated in four different soil layers which are gradually increasing from 1979-2014. Annual increasing rate of moisture is higher for the first soil layer. Dissimilar behaviors of soil moisture are observed between dry (Nov-May) and wet (Jun-Oct) seasons. Moisture in all different soil layers increasing downward in dry season, whereas, it behaves like one layer in wet season. Different atmospheric variables are analyzed and compared with soil moisture. Evaporation minus precipitation is negatively correlated with soil moisture while relative humidity and precipitation have strong positive correlations with 36-years monthly average soil moisture. Surface temperature has the minimum (maximum) value in January (May) where soil moisture gets the minimum (maximum) value in two months later in March (July). Therefore, the change in temperature is strongly correlated with the change of soil moisture after two months. On average, the moisture value of 0.01 (m^3m^{-3}) is changed for per degree change of temperature. So if temperature is known for a particular month, soil moisture of Bangladesh after 2 months can be predicted which will be helpful for agriculture and related disciplines. In addition, the information of moisture in different layers during dry season could help to take decision about crop production. Increasing of soil moisture indicates about climate change. Moreover, it is important to find out the reasons why the annual increase of soil moisture in the deeper layer (100-250 cm) is less compared to the surface moisture.

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