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Potential of IRS-P4 microwave radiometer data for soil moisture estimation over India

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सार – विभिन्न अनुप्रयोगों के लिए भिन्न कालिक और स्थानिक मापक्रमों पर मृदा में नमी का आकलन करना अत्यंत महत्वपूर्ण है। छोटे स्थानिक मापक्रमों में इसका महत्व कृषि मौसम विज्ञानिक अनुप्रयोगों के लिए होता है, जबकि बड़े स्थानिक मापक्रमों में यह मासिक से मौसमी समय–अवधि समाकलनों के लिए वुायमंडल के संख्यात्मक पूर्वानुमान निदर्शों में महत्वपूर्ण परिसीमा प्राचल है। इन स्थानिक मापक्रमों पर मृदा में नमी का निरंतर स्वस्थाने भूमंडलीय मापन वस्तुतः असंभव है क्योंकि मृदा के प्रकारों में अधिक विषमता के कारण इन प्रेक्षणों को लेना अत्याधिक महंगा पड़ता है और इसमें समय भी अधिक लगता है। उपग्रह पर आधारित सूक्ष्मतरंग विकिरणमापी जलवायु निदर्शों (50–100 कि.मी.) के अनुरूप विभेदनों पर मृदा में नमी का अप्रत्यक्ष आकलन उपलब्ध करा सकता है। इस शोध–पत्र में भारतीय उपग्रह आइ.आर.एस.–पी 4 में बहु–आवृति क्रमवीक्षण सूक्ष्मतरंग विकिरणमापी (एम.एस.एम.आर.) के विभव को बड़े क्षेत्र में मृदा में नमी के औसत के आकलन का मूल्यांकन किया गया है। इनकी तुलना भारत मौसम विज्ञान विभाग (भा.मौ.वि.वि.) की कुछ वेधशालाओं में लिए गए साप्ताहिक–प्रेक्षित स्वस्थाने मृदा में नमी के आँकड़ों से की गई है।

ABSTRACT. Soil moisture at different temporal and spatial scales is very important for various applications. At smaller spatial scales it has importance for the agro-meteorological applications, whereas at large spatial scales it is an important boundary parameter in the numerical prediction models of atmosphere for monthly to seasonal time-scale integrations. Frequent *in situ* global measurements of soil moisture at these spatial scales are virtually impossible because large heterogeneity of soil types makes these observations highly expensive and time consuming. Satellite based microwave radiometers can provide indirect estimates of soil moisture at resolutions compatible to that of climate models (50-100 km). In this paper the potential of Multi-frequency Scanning Microwave Radiometer (MSMR) onboard Indian satellite IRS-P4 is assessed for large area averaged soil moisture estimation. These are compared with the weekly-observed *in situ* soil moisture data over a few observatories of India Meteorological Department (IMD).

Key words – Soil moisture, IRS-P4 MSMR, Microwave radiometer, Brightness temperature, Remote sensing.

1. Introduction

Numerical studies based on General Circulation Models (GCMs) have provided more and more evidence that climate is determined by a dynamic equilibrium in which the atmosphere affects the land surface and is affected by them. From the point of view of large-scale modeling, it is important to have observation values (*e.g.*, soil moisture) on scales comparable to model scales.

Several modeling studies have focused on soil moisture, showing that land surface hydrology is a crucial component of the climate system (Dirmeyer and Shukla, 1993). Shukla and Mintz (1982) suggested that soil moisture anomalies could persist long enough to modify the atmospheric circulation over seasonal to interannual time-scales. Such anomalies could be sustained through an evaporation feedback mechanism, which would be particularly efficient in the interior of the continents due to the strong recycling of precipitation (Serafini, 1990). Fennessy and Shukla (1999) showed the significant impacts in several tropical and extratropical regions with realistic soil moisture initialization and concluded that using a realistic initial state of soil wetness could enhance seasonal atmospheric prediction.

Real-time analysis of land surface state, *e.g.*, distribution of soil wetness, temperature, snow cover and depth, and large-scale properties of the vegetation, has historically received less emphasis. There are two main reasons. First, there is a dearth of useful data collected on the land surface, and most data that are collected are not disseminated due to lack of a well-developed real-time global network like that which exists for atmospheric observations. Also, due to large heterogeneity hundreds of measurements for soil wetness may be necessary to arrive at an accurate, representative estimation at the resolution of the model (typically 10^2 to 10^5 km^2), which is typically near to the characteristic spatial scale of soil moisture variations on monthly to seasonal timescales (Vinnikov *et al.*, 1996). Second, most emphasis has historically been on the needs of short term weather forecasting, where the initial atmospheric conditions is the major determinant of the evolution of weather over periods from hours to a few days. For medium range weather forecasting and climate simulation and prediction, the land surface and ocean boundary conditions play a more important role.

Global Soil Wetness Project (GSWP) has produced a two-year (1987-88) global dataset of soil wetness, temperature, surface fluxes, and other land surface variables using various land surface schemes and a common set of soil and vegetation parameter and meteorological forcings (Dirmeyer *et al.*, 1999). This dataset represent the current state of the art in global quality and consistency for quantities such as soil wetness. Recently, Robock *et al.*, (2000) has taken initiative to create a soil moisture data bank with observations from about 600 stations covering a large variety of climate. However, due to the high spatial variability of both precipitation and land surface properties it is not feasible to derive global soil moisture climatology from *in situ* measurements.

Microwave remote sensing provides a unique capability for direct observation of soil moisture (Schmugge *et al*., 1986; Jackson and Schmugge, 1986; Njoku and Entekhabi, 1996). Remote measurements from space afford the possibility of obtaining frequent, global sampling of soil moisture. Remotely sensed soil moisture observations reflect areally averaged conditions and are therefore better representative than averaged point measurements and may serve an essential role to improve and validate land parameterization in climate models. Microwave measurements have the benefit of being largely unaffected by cloud cover and variable surface solar illumination, but accurate soil moisture estimates are limited to the regions that have either bare soil or low to moderate amounts of vegetation cover.

Many studies (Choudhury and Golus, 1988; Ahmed, 1995) have examined the potential of passive microwave observations to measure soil moisture over large regions using the Scanning Multi-channel Microwave Radiometer (SMMR) on Nimbus-7, which operated from 1978 to 1987. SMMR had the lowest frequency at 6.6 GHz with spatial resolution of 150 km. These studies suggested that under moderate vegetation conditions the 6.6 and 10.7 GHz channels have adequate sensitivity to surface soil moisture. Most of these studies were based on the regression analysis of microwave brightness temperatures with the proxy estimates of the soil moisture, *e.g.* Antecedent Precipitation Index (API) estimated using daily rainfall and surface temperature observations. However, over Indian region there were no attempts to estimate soil moisture using satellite data in the past. Recently, Rao *et al*., (2001) used API for the regression analysis with the Nimbus-SMMR brightness temperature data over Indian region and found very good correlation with 6.6 and 10.6 GHz brightness temperatures at horizontal polarizations.

Recently there have been several studies using *in situ* observed soil moisture to calibrate the satellite observations. Vinnikov *et al*., (1999) used the observations of soil moisture over Illinois, United States, to correlate with the SMMR brightness temperatures and found very good correlation between them. Jackson and Hsu (2001) used TRMM Microwave Imager (TMI, 10GHz) and Special Sensor Microwave Imager (SSM/I, 19 GHz) brightness temperatures to compare with the observed soil moisture over Southern Great Plains of USA and found that TMI 10 GHz data provides great potential for soil moisture estimation.

India launched the Indian Remote Sensing Satellite IRS-P4 (also known as Oceansat-1) in 1999, which has a 4-channel dual polarized Multifrequency Scanning Microwave Radiometer (MSMR). Though the primary mission objectives of IRS-P4 are to gather systematic data for oceanographic, coastal and marine atmospheric applications, here an attempt is made to look into the potential application of MSMR data over land for estimation of large area soil moisture. In the present study IRS-P4 MSMR brightness temperature data at 6.6 GHz for the monsoon period of 1999-2001 (June-August) is used to establish an empirical relationship with the observed *in situ* soil moisture over India.

2. Physical basis for microwave remote sensing of soil moisture

The relationship of the brightness temperature T_b of a thermally radiating body to its physical temperature T_s at microwave frequencies is given by simple expression:

$$T_b = \varepsilon T_s$$

where, ε is emissivity of the surface and T_s is the surface temperature. This is most basic equation for soil moisture estimation at microwave frequencies. The emission of thermal microwave radiation from soils is strongly dependent on the moisture content. Due to the large difference between the dielectric constant of water (~80)

TABLE 1

Grid	Frequency	Grid size
Grid-1	6.6, 10.65, 18, 21 (H & V)	150 km
Grid-2	10.65, 18, 21 (H & V)	75 km
Grid-3	18 & 21 (H & V)	50 km

and that of dry soil (~3.5), the emissivity of soils varies over a wide range from approximately 0.6 for wet (saturated) soils to greater than 0.9 for dry soils. For a soil at temperature of 300°K this variation in emissivity corresponds to the brightness temperature variation of 90°K (270 °K for dry soil and 180°K for wet soil), thereby, covering a range of wetness from approximately 40% to 5% moisture by volume, depending on soil type. This variation in the brightness signal is very much larger than the noise sensitivity of a microwave radiometer, which is typically less than 1°K. The large available signal-to-noise ratio is a major advantage of the passive microwave technique for soil moisture remote sensing.

Theoretically, for a bare smooth soil surface, moisture estimation accuracies of better than 1-2% by volume should be feasible in principle. However, such accuracies are difficult to achieve in practice. The brightness temperature of the soil is also affected by soil surface roughness (Choudhury *et al*., 1979; Mo *et al*., 1987), attenuation and emission by vegetation cover (Jackson *et al*., 1982; Jackson and Schmugge, 1991), surface and subsurface heterogeneity (Tsang *et al*., 1975), and to a lesser degree by soil texture and variability in temperature of the soil and vegetation (Schmugge, 1980). These perturbing factors introduce varying amounts of uncertainty into the relationship between brightness temperature and soil moisture, thereby limiting the accuracy with which soil moisture can be estimated. However, towards the shorter frequency region of the microwave spectrum (< 5 GHz) the effects of vegetation and roughness are much reduced. At these wavelengths, and in the areas of low to moderate vegetation, soil moisture has a dominant effect on the brightness temperature. Further, atmospheric attenuation is negligible at these low frequencies.

3. Data

3.1. *Satellite data*

MSMR onboard IRS-P4 is configured as a 4-channel radiometer with both vertical and horizontal polarization at frequencies 6.6, 10.65, 18 and 21 GHz with spatial resolutions of 120, 80, 40 and 40 km respectively for the various channels. It is a conical scan system, having a

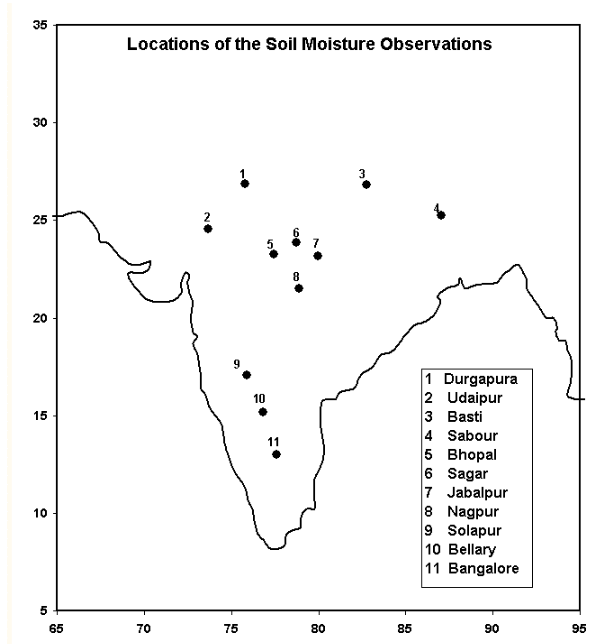


Fig. 1. Map depicting the locations of *in situ* soil moisture observations

constant incidence angle of 49.7º at each scan position. The satellite is in a near circular, sun-synchronous orbit at an altitude of 720 km with the local time of equatorial crossing in the descending node of 1200 hr ± 10 minutes. MSMR has a swath of 1360 km and the repetivity (global coverage cycle) is of 2 days. Dynamic temperature range is 10-330 °K and sensor sensitivity is 0.6 °K. Brightness temperature datasets are provided in three grids summarized in Table 1.

Here BT data of 6.6 GHz (150-km grid) at horizontal polarization has been analyzed for monsoon season of 1999-2001 (June-August) and compared with the observed soil moisture data. BT data are also compared with the rainfall data, which is the major forcing factor to the soil moisture during monsoon season.

3.2. *Observed soil moisture data*

Observed soil moisture data over a few observatories of India Meteorological Department have been obtained during the monsoon season of 1999-2001. These observations are point measurements and are made once every week. Locations of these observations are indicated on Fig. 1. The observations are given as volumetric soil moisture content (%) at two levels, *i.e*., at surface and at 7.5 cm depth. We have analyzed only the surface soil moisture observations because microwave radiations at 6.6 GHz can give information only about top few centimeter surface soil layer.

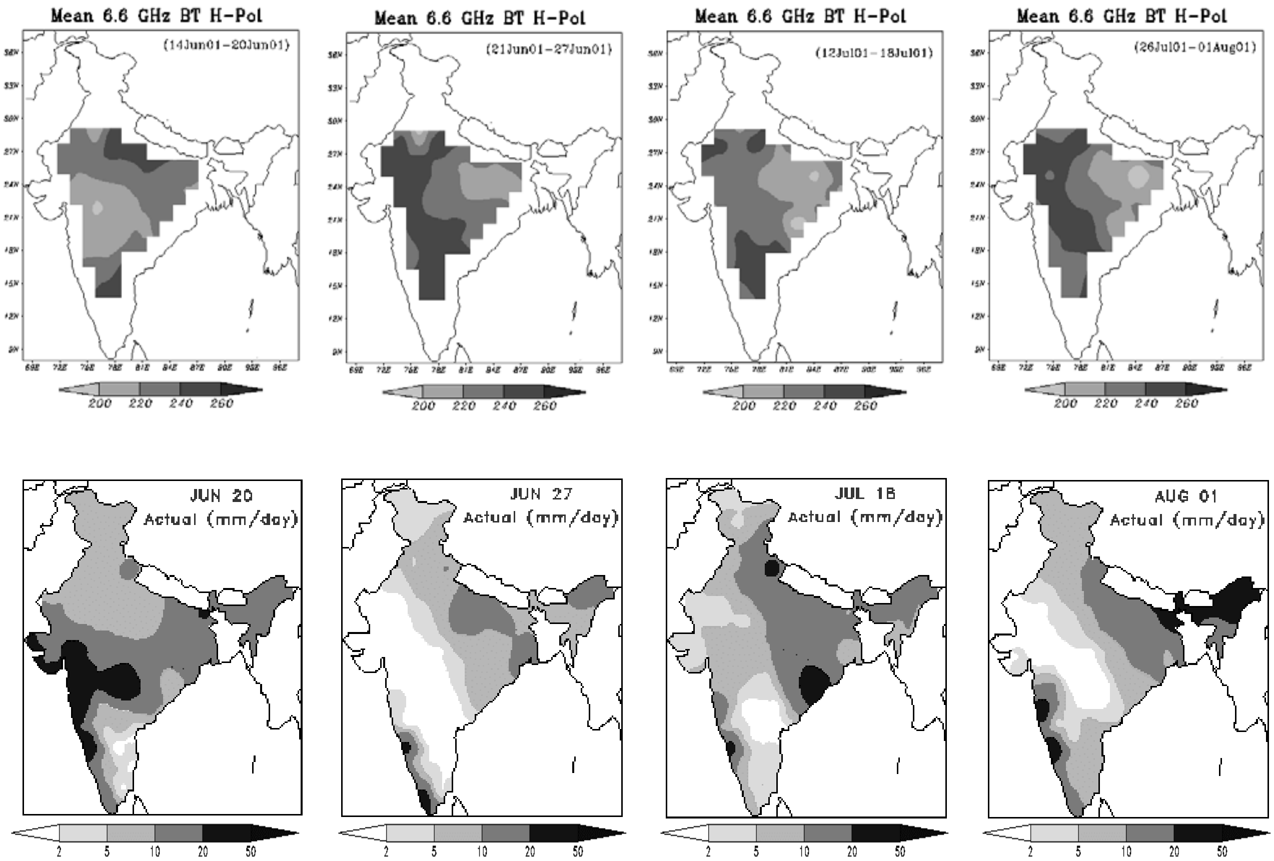


Fig. 2. Maps of mean T6H for the weeks ending on 20 June, 27 June, 18 July and 1 August 2001. Rainfall for the corresponding weeks are given in bottom panels

3.3. *Rainfall data*

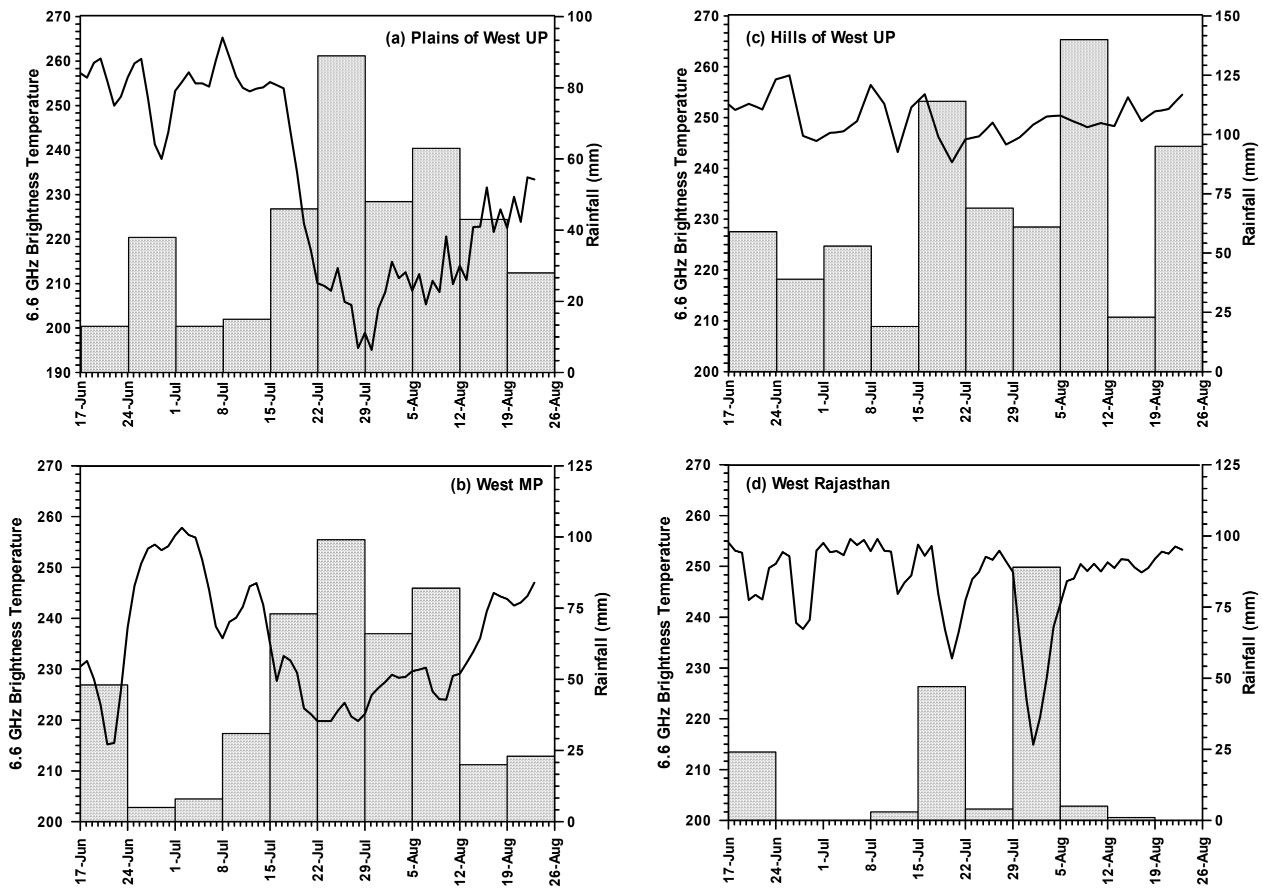
Weekly rainfall maps are taken from the website 'Monsoon On Line' maintained by D. B. Stephenson, K. Rupa Kumar and E. Black. These maps are generated using IMD's observed rainfall data (*http://www.tropmet.res.in/~kolli/MOL*). Weekly rainfall data over Indian subdivisions are taken from the Weekly Weather Reports (Published by IMD).

4. Soil moisture estimation from MSMR data

A database of daily 6.6 GHz brightness temperatures at horizontal polarization (T6H) is created over India for the period of June-August 1999, 2000 and 2001. Since the MSMR measurements have repetivity of 2 days the daily dataset is created using 3 days running mean. For the comparison and regression with the observed soil moisture the T6H data within 1° search radius is interpolated to the station location. We have used only mid-night data because during the night-time (predawn hours) the soil profile is most likely to be in hydraulic equilibrium and also the soil temperature profile is more likely to be closer to uniform during this time (Jackson and Hsu, 2001; Ahmed, 1995). Other factors that make nighttime data more useful include lower variation in the nighttime surface temperature within a particular season (June-August). This makes brightness temperature measurements more sensitive to the emissivity (and hence soil moisture) and minimizes the surface temperature dependency. On the other hand daytime observations will depend not only on the physical features and antecedent conditions but also on the pattern of drying and heating as it occurred that particular day.

4.1. *Soil moisture signal in MSMR data*

To evaluate the MSMR data for its suitability to estimate large area average soil moisture, 6.6 GHz H-Polarization brightness temperature data is compared with the corresponding rainfall data. Here it is assumed that rainfall is directly linked with the soil moisture, *i.e.*,



Figs. 3(a-d). Time series (for 1999) of T6H (solid curve) with the rainfall (Bars) for (a) Plains of west U.P., (b) west M.P. (c) Hill of west U.P. (Uttaranchal) and (d) west Rajasthan

higher rainfall will contribute to higher soil moisture amount. Similarly, prolonged dry spell will lead to the drying of the soil surface. Therefore, the regions, which experienced high rainfall over a period, will have high soil moisture and hence the brightness temperature must show low values due to lower emissivity. Conversely, the areas with low rainfall should have higher brightness temperature.

First, the spatial distribution of T6H over India is compared with the corresponding week's rainfall distribution. Fig. 2 shows a sample plot of T6H and rainfall for the weeks ending on 20 June, 27 June, 18 July and 1 August 2001 to show different patterns of rainfall distribution. In the maps T6H is plotted only over central India and peninsula, because microwave radiometer data can be used to estimate soil moisture only over plain regions with moderate vegetation cover; hence mountainous regions with high forest cover and also coastal regions (to avoid the ocean contamination due to large footprint size ~150 km × 150 km) are excluded in the analysis.

From these maps it can be observed that the areas with high rainfall (and hence high soil moisture) are having low values of T6H and over the regions with moderate or low rainfall the T6H values are higher. The negative relation between the T6H and rainfall amount (indicating soil moisture conditions) clearly indicates the potential of microwave radiometric measurements for soil moisture delineation over Indian region. Moreover, the temporal variations as seen in T6H clearly brings out the variations in the soil wetness, as inferred from the rainfall maps. For the week ending 20 June 2001, high rainfall values (upto 50 mm/day) are seen over Maharashtra, the T6H values over this regions range between 200-220 °K. Similarly, the lower rainfall values over the Gangetic plains correspond to T6H values in the range of 240-260 °K. Similar behaviour is noted in other weeks also. Here it may be noted that the 6.6 GHz measurements

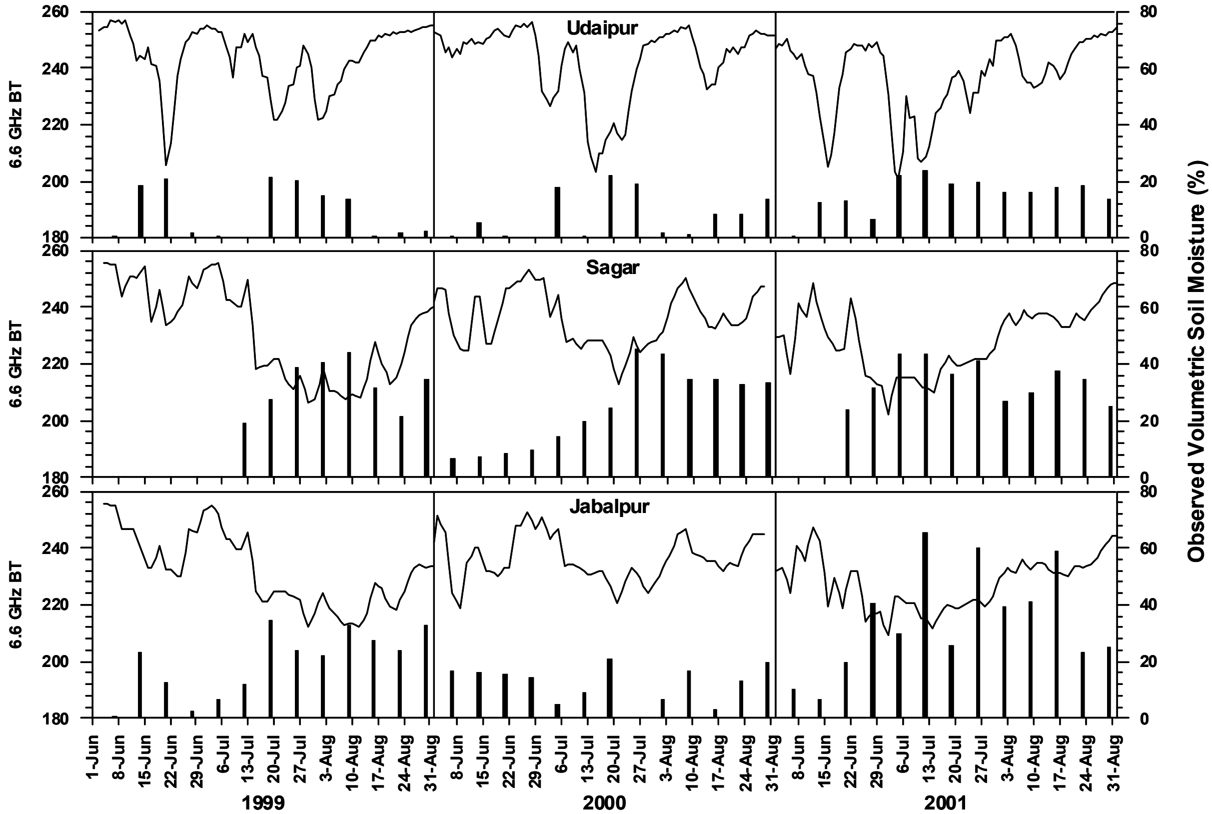


Fig. 4. Time series of T6H (solid curve) with observed soil moisture (vertical bars) for Udaipur, Sagar and Jabalpur

among all MSMR channels are least affected by the most atmospheric conditions including the light drizzle and are least sensitive to vegetation, thereby, most sensitive to the moisture in the top soil layer.

Next, time series of T6H is plotted against weekly rainfall over all subdivisions. Periods corresponding to high rainfall are having very low T6H and periods with low rainfall show higher T6H. Figs. 3(a&b) shows time series of T6H with rainfall for the relatively plain areas with low amount of vegetation (plains of west UP and west MP). For such areas T6H shows very good sensitivity to the soil moisture (inferred by the amount of rainfall fallen on land). However, highly mountainous and densely vegetated regions [Fig. 3(c), Hills of west UP] show very little sensitivity to the soil moisture (inferred by rainfall amount). T6H does not show any contrast with the low or high rainfall events. This is because the dense vegetation obscures the soil layer and emits its own radiation and hence no signal of soil moisture can be obtained over such areas. It is interesting to see the behaviour of time series of T6H with rainfall over desert areas [Fig.3(d), west Rajasthan], where high rainfall events show very sharp and narrow dip in the T6H. This is because desert cannot hold moisture for long period of times at surface levels due to high percolation to deeper layers and quick evaporation.

Thus, it is seen that MSMR data show high sensitivity to the soil moisture over the areas of moderate vegetation and low surface roughness. The mountainous and highly vegetated regions show least sensitivity for soil moisture using microwave radiometer data. Such regions have been excluded from the analysis.

4.2. *Relationship of MSMR 6.6 GHz BT with the observed soil moisture*

For regression analysis with the observed soil moisture, only the T6H data of June-July period are used because beyond this period the vegetation grows and the microwave measurements become more sensitive to the vegetation layer, thereby reducing the sensitivity to the moisture in the underlying soil layer. Also, for this period mid-night surface temperature variations are small (~2-5 °K, Source : NCEP Reanalysis) as compared to the variations in the brightness temperature (> 50 °K from dry to wet soil conditions). This makes it feasible to use direct

TABLE 2

Regression equations for different locations

S. No.	Location	Regression Equation		R	N
		SM as independent variable	T6H as independent variable		
1	Durgapura	T6H= –0.86 SM + 249.8	SM = –0.07 T6H + 20.3	0.25	23
2	Udaipur	T6H= –1.18 SM + 251.2	SM = –0.50 T6H + 130.5	0.77	24
3	Basti	T6H= –1.85 SM + 263.3	SM = –0.08 T6H + 37.5	0.39	24
4	Sabour	T6H= –1.31 SM + 247.9	SM = –0.44 T6H + 118.0	0.76	24
5	Bhopal	T6H= –0.99 SM + 247.0	SM = –0.88 T6H + 220.2	0.93	11
6	Sagar	T6H= –0.77 SM + 248.6	SM = –0.84 T6H + 218.3	0.80	17
7	Jabalpur	T6H= –0.94 SM + 249.3	SM = –0.76 T6H + 193.7	0.84	20
8	Nagpur	T6H= –2.49 SM + 299.0	SM = –0.32 T6H + 100	0.89	7
9	Solapur	T6H= –1.49 SM + 255.6	SM = –0.45 T6H + 120.1	0.82	12
10	Bellary	T6H= –0.31 SM + 242.1	SM = –0.42 T6H + 112.9	0.36	24
11	Bangalore	T6H= –0.52 SM + 255.5	SM = –0.14 T6H + 39.8	0.26	22

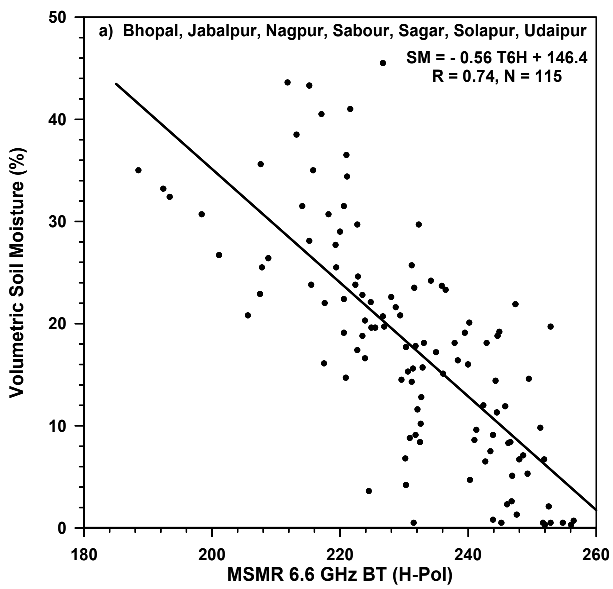
(R – Coefficient of correlation, N – Total number of data points)

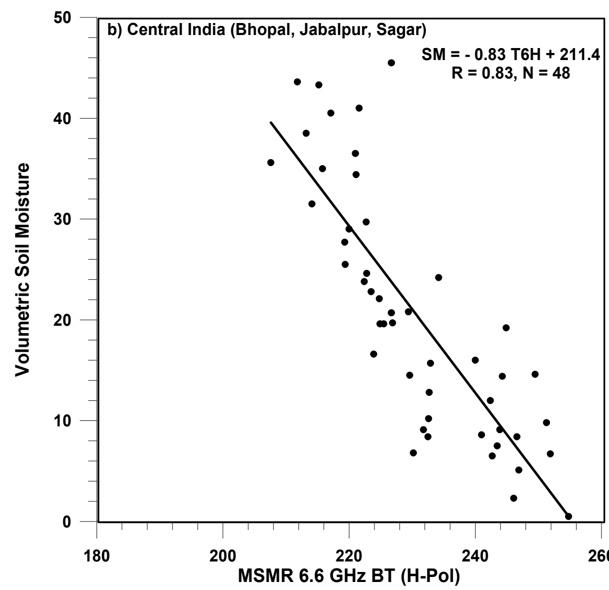
brightness temperature measurements for the regression and calibration with the observed soil moisture data. If surface temperature variations are large, then emissivity ($=T_b/T_s$) is used for regression analysis and calibration with the soil moisture observations instead of direct brightness temperature values (Vinnikov *et al*., 1999). Use of emissivity is always better as it removes the surface temperature component and is sensitive mainly to variations in the soil moisture. However, this will require the knowledge of surface temperatures along with the brightness temperature measurements to compute the soil moisture, and can be achieved with a suitable multichannel algorithm using data from different satellites/sensors.

Comparing the observed soil moisture with the satellite measurement is difficult because of their different times of observations. While soil moisture values are observed once a week (during early hours), the satellite pass may or may not be available for the same day. The orbit of IRS-P4 crosses a particular location at same local time every alternate day (repetivity of two days). For IRS-P4 the local equator crossing time is 1200 (Descending pass) and 2400 (Ascending pass). Therefore, ground measurements do not coincide with the satellite observations in these cases. Heavy rain events between the satellite pass and the ground measurement could introduce large deviations in the scatter plot. Also if there is bright sunshine between the satellite pass and ground observation, then the deviations in the scatter plot will be large if time gap of the observations is very large. However, due to the low frequency of the observed soil moisture data (both temporal as well as spatial) the comparison is done with the nearest satellite observations (in space and time).

Here, we focus on the relationship of the 6.6 GHz brightness temperatures at H-polarization (T6H) with the observed soil moisture over a few Indian observatories. Fig. 4 shows the time-series of observed soil moisture with T6H for four of the locations situated in the central India. It can be noted that the variation in the soil moisture is well reflected in the corresponding variation in the T6H curve. Periods of low (high) soil moisture correspond to the high (low) values of T6H. These variations are similar to those seen in Fig. 3, which were compared with the rainfall values, indicating soil wetness conditions indirectly. Sharp dips in the T6H values for Udaipur corresponding to the high soil moisture values in Fig. 4 is similar to the variation of T6H with rainfall for West Rajasthan as seen in the Fig. 3(d).

We further carried out regression study of the soil moisture with T6H and the regression equations for all these locations are summarized in Table 2 individually. The regression equation in which soil moisture (SM) is





Figs. 5(a&b). Scatter plot and regression equation between observed soil moisture and T6H for (a) Combined dataset (Bhopal, Jabalpur, Nagpur, Sabour, Sagar, Solapur, Udaipur) and (b) Central India (Bhopal, Jabalpur, Sagar)

used as independent variable indicates the sensitivity of T6H to the soil moisture, whereas the equation with T6H as independent variable may be used to convert T6H observations to the satellite derived soil moisture. Most of these stations (7 out of 11) show reasonably high correlation between T6H and the observed soil moisture. It may be noted that all stations with high degree of correlation (> 0.70) are located in the central India and the gangetic plains. Stations in the far north (Durgapura and Basti) and in Southern Peninsula (Bellary and Bangalore) have very poor correlation (R < 0.40) with the observed soil moisture. While Southern Peninsula may have low soil moisture sensitivity due to the high vegetation and forest cover, their northern counterparts may have poor correlation due to the presence of the irrigated fields.

The scatter plot and best fit for the combined dataset of all stations with coefficient of correlation greater then 0.70 (Udaipur, Sabour, Bhopal, Sagar, Jabalpur, Nagpur and Solapur) is given in the Fig. 5(a), and the corresponding regression equations are:

T6H = –0.98 SM + 248.6 (SM as independent variable) (1a)

SM = –0.56 T6H + 146.4 (T6H as independent variable) (1b)

The coefficient of correlation for combined dataset is 0.74, which is reasonably high. Here the slope is nearly 1, which indicates that for the change in volumetric soil moisture by 1% the corresponding change in the T6H is 1ºK. It may be noted that the sensitivity of the MSMR is 1ºK which implies that any change in the soil moisture amount greater than 1% can be detected by the corresponding change in the T6H.

It is interesting to note that three stations in the central India (Bhopal, Jabalpur and Sagar) have similar relationship with T6H (similar slopes and intercepts) having very high degree of correlation (R > 0.80). Though Nagpur is also close to these three stations it exhibits a very different relationship with T6H. While temporal variations are matching with T6H variations (R = 0.89), the slope (~2.5) and the intercept (299 ºK) values are very high compared to all other locations with high correlation. This regression equation may not be reliable because of the small sample size (N=7), and the fact that heavy rainfall or prolonged dryness between the satellite observations and the ground measurements, as discussed previously, among the small sample can create large deviations in the regression equation. The scatter plot for the combined central Indian stations (Bhopal, Jabalpur and Sagar) is given in the Fig. 5(b) and the corresponding regressions equations are:

T6H = –0.82 SM + 247.4 (SM as independent variable) (2a)

SM = –0.83 T6H + 211.4 (T6H as independent variable) (2b)

The coefficient of correlation is very high (R = 0.83) compared to combined 7 stations. However, the slope of regression equation (with SM as independent variable) is little lower than the combined 7 stations, which shows little lower sensitivity of T6H to the variations in soil moisture.

Equation (1b) can be used to invert the T6H observations to compute the volumetric soil moisture contents over plains of India, whereas Eqn. (2b) can be used more accurately to derive soil moisture over Central India. This justifies strong need to divide the entire region into several homogenous zones (according to soil properties and vegetation characteristics) and using more number of stations for soil moisture observations within each zone. Since MSMR data are available for only 3 years, 1999-2001, the archived dataset of Nimbus-SMMR (available for the period 1978-1987) can be used to increase the sample numbers. Currently operational satellite TRMM/TMI has the lowest frequency of 10.6 GHz, which can also be used for soil moisture calibration and retrieval. Although the 10.6 GHz has a little lower sensitivity to soil moisture than 6.6 GHz, it has a better spatial resolution (~40 km) and hence can better correlate with the point measurements of the soil moisture. In future ADEOS-II AMSR data of 6.6 GHz with better spatial resolution of 75 km may also be used for the same purpose.

5. Conclusions

Large area average soil moisture is an important boundary forcing for the numerical weather models. Soil moisture at lower spatial scales has importance in Agrometeorology. Direct measurement of the global soil moisture is very expensive and requires dense network of observatories to accommodate the large spatial heterogeneity. Satellites can play an important role in estimating global soil moisture at different spatial scale very frequently.

In the present study potential of satellite microwave radiometer data (IRS-P4 MSMR) for large area average soil moisture estimation is assessed over Indian region. MSMR data at 6.6 GHz (H-Polarization) show very good correlation with the observed soil moisture over most parts of the Indian region. This has been first verified with the help of rainfall and then with the observed soil moisture data.

T6H maps clearly depict the spatial and temporal variability of soil moisture (indirectly through rainfall). The regions of high mountains and with high vegetation show negligible sensitivity to soil moisture. Relatively plain and low vegetated areas show high sensitivity to soil moisture. The *in situ* observed soil moisture shows remarkable correlation with the satellite observed 6.6 GHz brightness temperatures for the entire central India, which further improves when the analysis is restricted to a smaller homogeneous region.

Using a larger database and dividing the entire Indian region into a few homogenous zones (depending upon soil properties and vegetation characteristics) a more reliable working relationship could be established to retrieve soil moisture using satellite microwave radiometer measurements. For this purpose the past data of Nimbus-SMMR (6.6 GHz) and also the current operational satellite TRMM/TMI data at 10.6 GHz are planned to be used.

This study has special significance in view of the satellite missions like ADEOS-2 which have a microwave radiometer Advanced Microwave Scanning Radiometer (AMSR) onboard with lowest frequency of 6.9 GHz at 75 km spatial resolution and the Soil Moisture and Ocean Salinity (SMOS) Mission which will have the best theoretical frequency available for soil moisture sensing, 1.4 GHz at 30-50 km spatial resolution.

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