Soil moisture variability across different scales in an Indian watershed for satellite soil moisture product validation

Gurjeet Singh^{*a}, Rabindra K. Panda^a, Binyak P. Mohanty^b, Raghavendra B. Jana^c

^aSchool of Earth Ocean and Climate Sciences, IIT Bhubaneswar, India; ^bDepartment of Biological and Agricultural Engineering, Texas A&M University, USA; ^cWater Desalination and Reuse Centre, King Abdullah University of Science and Technology

ABSTRACT

Strategic ground-based sampling of soil moisture across multiple scales is necessary to validate remotely sensed quantities such as NASA's Soil Moisture Active Passive (SMAP) product. In the present study, in-situ soil moisture data were collected at two nested scale extents (0.5 km and 3 km) to understand the trend of soil moisture variability across these scales. This ground-based soil moisture sampling was conducted in the 500 km² Rana watershed situated in eastern India. The study area is characterized as sub-humid, sub-tropical climate with average annual rainfall of about 1456 mm. Three 3x3 km square grids were sampled intensively once a day at 49 locations each, at a spacing of 0.5 km. These intensive sampling locations were selected on the basis of different topography, soil properties and vegetation characteristics. In addition, measurements were also made at 9 locations around each intensive sampling grid at 3 km spacing to cover a 9x9 km square grid. Intensive fine scale soil moisture sampling as well as coarser scale samplings were made using both impedance probes and gravimetric analyses in the study watershed. The ground-based soil moisture samplings were conducted during the day, concurrent with the SMAP descending overpass. Analysis of soil moisture spatial variability in terms of areal mean soil moisture and the statistics of higher-order moments, i.e., the standard deviation, and the coefficient of variation are presented. Results showed that the standard deviation and coefficient of variation of measured soil moisture decreased with extent scale by increasing mean soil moisture.

Keywords: Soil moisture, Soil Moisture Active Passive (SMAP), Eastern India, satellite remote sensing, soil moisture variability

1. INTRODUCTION

Surface soil moisture is widely recognized as a prime environmental variable related to land surface climatology, hydrology and ecology because of its control on the land surface energy balance [1]. Variations in soil moisture have a strong impact on land surface energy dynamics, atmospheric variations (e.g., rainfall patterns), regional and local runoff generation, ground water recharge, and vegetation productivity (actual crop yield). Spatial and temporal variability of soil moisture is caused by the spatio-temporal variation in rainfall, vegetation cover, soil properties and topography, thus making it difficult to accurately quantify using models [2]. Knowledge of soil moisture with reasonable spatial and temporal resolution is, therefore, required to improve hydrologic and climatic modeling and prediction [3], [4]. A growing need of soil moisture information over a broad range of scales poses many challenges to the scientific community. There is currently a gap in the ability to routinely measure soil moisture at point, field, watershed and regional scale for hydro-metrological and ecological studies.

*gs17@iitbbs.ac.in; phone: +91-674-2576122

Currently, in-situ point scale measurement methods (e.g., gravimetric, neutron probe, time/frequency domain reflectometry and capacitance probe) are being used throughout the world for continuous monitoring but are suitable only for field plots. These methods rarely provide adequate information at the watershed or regional scales since maintaining high density in-situ networks for soil moisture measurement at such large scales is highly expensive. The growing need for soil moisture observation at large scale, motivated the development of satellite microwave sensors [5]. Global soil moisture observations have been available from passive microwave sensors such as the C/X-band ($\sim 6/10$ GHz) Advanced Microwave Scanning Radiometer (AMSR-2) as well as active microwave sensor like the C-band Advanced Synthetic Aperture Radar (ASAR) [6]. The Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) missions are currently providing soil moisture content estimates for near-surface soils (0-5 cm) using L-band radiometer (1.4 GHz) at spatial resolution of approximately 40 km and 36 km respectively. These satellite based soil moisture measurements show promise in assisting researchers to describe soil moisture dynamics for large areas, but do not capture the significant amount of variability within the remote sensing footprint [7], [8]. Remotely sensed soil moisture represents an average value within a footprint and its scale ranges from several hundred square kilometers to several thousand square kilometers. For this reason, a large number of distributed ground-based soil moisture sampling is needed to accurately validate the mean soil moisture content within a remotely sensed footprint.

In the present study, field experiments were designed to provide an extensive data set of ground-based soil moisture across different scales in the Rana watershed of eastern India. The aim of soil moisture sampling across different scales is to validate the soil moisture products provided by latest satellite (SMAP). This paper describes the study area, ground sampling strategies, and provides an overview of the data collected. Soil moisture standard deviation, coefficient of variation versus the mean moisture content is also presented across different scales.

2. STUDY AREA AND EXPERIMENTAL DESIGN

2.1 Study area

The ground-based soil moisture sampling was carried out in an agricultural watershed located in the Mahanadi River Basin of eastern India (Figure 1). The watershed covers an area of 500 km² and the elevation ranges from 22 to 299 m with an average elevation of 57.32 meter. The study area is characterized as sub-humid, sub-tropical climate with average annual rainfall of about 1456 mm. During different parts of the year, the study area suffers from both extreme events such as flood and drought. Soil moisture was measured at multiple depths (5, 15, 30, 60 and 100 cm from surface) at three locations in the study watershed. The major crop of the study area is paddy/rice, which is usually cultivated during the rainy season.

2.2 Experimental Design

Experiments were designed to capture the surface soil moisture distribution in dry and wet periods of the year. The ground-based measurements of surface soil moisture (0-5 cm) were conducted at two nested scale extents (0.5 km, 3 km) to understand the trend of soil moisture variability across these scales (Figure 2). Three 3x3 km focus area (F1, F2 and F3) were selected for intensive sampling, on the basis of different topography, soil properties, vegetation characteristics and availability of profile soil moisture monitoring stations. Figure 3 shows that the selected focus areas have different topography, with focus area F3 having the highest average elevation (61.66 m) followed by F2 (42.97 m) and F1 (35.54 m). These 3x3 km square grids were sampled intensively once a day at 49 locations each, at a spacing of 0.5 km. In addition, 9 locations were also selected at 3 km spacing around each intensive sampling grid to cover a 9x9 km square grid. Sixteen locations with 9 km spacing were also selected to cover a 36x36 km square grid, corresponding to the coarse resolution SMAP footprint. At present the ground-based soil moisture measurements were taken only at 0.5 and 3 km scales in the months of February and March which are dry periods of the year. The soil moisture measurements at 9 km scale were not taken due to logistics issues.

Figure 1. Location of (a) Mahanadi river Basin in India (b) Watershed in Mahanadi river basin (c) Watershed with a hillshade, representing the topography

Figure 2. (a) Digital elevation model with intense soil moisture monitoring focus areas F1, F2 and F3 (b) Nested sampling grids for soil moisture measurement at three scale extents: 0.5, 3 and 9 km.

Figure 3. Elevations of focus areas, F1 (Minimum: 30 m, Maximum: 43 m, Average: 35.54 m), F2 (Minimum: 29 m, Maximum: 94 m, Average: 42.97 m), and F3 (Minimum: 48 m, Maximum: 79 m, Average: 61.66 m) with average slope of 0.94 %, 1.59% and 1.63% respectively.

During the field experiments, both volumetric and gravimetric measurements were made using impedance probes (Theta probe soil moisture sensor, type ML3, Delta-T Devices, Cambridge, England) and soil sampling tools respectively. The gravimetric soil moisture sampling provides reliable moisture content measurements. Therefore, 14 of the 49 intensive sampling locations (within the 3x3 km square grids) and all the sampling locations at 3 km spacing were sampled with both Theta probe and soil sampling tools during each sampling for calibration purposes. The calibration of each Theta probe was done on the basis of field-specific calibration method [9], which compares probe measurements with adjacent gravimetric measurements. In order to reduce the possible impact of soil moisture heterogeneity, three measurements were taken (~ 1 m distance) at each sampling locations where each measurement consists of three repetitions. The averaging of the three measurements at each sampling location can reduce the uncertainty in the estimates of mean soil moisture for validation.

3. METHODS OF ANALYSIS

The main goal of the present study is to examine variation in the measured soil moisture content across two nested scale extents (0.5 km and 3 km). In addition, ground-based soil moisture measurements at 0.5 km scale were also regrouped into 1 km scale, to analyse the variability at 1 km within the 3x3 km square grid. The soil moisture mean, standard deviation, coefficient of variation were calculated using a set of ground measurements of each day, separately in each grid.

Let θ_i be the soil moisture measured at point i and day j , the spatial mean of each sampling day, $\bar{\theta}_j$, for N number of measurement points is given as:

$$\bar{\theta}_j = \frac{1}{N} \sum_{i=1}^N \theta_{ij} \quad (1)$$

The standard deviation of each sampling day, σ_j , is calculated as follows:

$$\sigma_j = \frac{1}{N-1} \sum_{i=1}^N (\theta_{ij} - \bar{\theta}_j)^2 \quad (2)$$

The coefficient of variation of each sampling day CV_j , is given by:

$$CV_j = \frac{\sigma_j}{\bar{\theta}_j} \quad (3)$$

4. RESULTS AND DISCUSSION

In this section, the statistics of soil moisture content variation across scale are presented. A brief description of data collected during the field campaign is provided. The analysis of soil moisture spatial variability in terms of areal mean soil moisture $\bar{\theta}_j$ and the statistics of higher-order moments, i.e., the standard deviation, σ_j and the coefficient of variation, CV_j are presented.

4.1. Ground Measurements

The ground-based soil moisture campaigns were undertaken for 3 days and each day one of the three 3x3 km focus areas was monitored. The measurements were also made on the same day at 9 locations around each focus area at 3 km spacing to cover a 9x9 km square grid. The days for the campaign were decided based on the SMAP descending overpass (6:00 AM) at the study area. A sample of the soil moisture data collected is shown in Figure 4 and 5. Ancillary information on surface temperature, land cover, vegetation type, vegetation height and dew presence were also collected at each sampling location. The sampling locations were slightly changed from the designed plan for some of the places where monitoring is not possible due to disagreeable surface condition such as: presence of waterbody, very dense forest, road etc. The top left sampling location in Figure 5 was changed due to presence of Mahanadi river. The spatial distribution of measured soil moisture in the focus areas at 0.5 km scale and around these focus area at 3 km scale is presented in the Figure 4 and 5 respectively.

Figure 4. Spatial distribution of the measured soil moisture at 0.5 km spacing over 3x3 km focus areas F1, F2 and F3.

Figure 5. Spatial distribution of the measured soil moisture at 3 km spacing around the focus areas F1, F2 and F3 to cover 9x9 km square grid.

4.2 Spatial Variability of Soil Moisture Content

The spatial distribution of soil moisture content for the focus areas F1, F2 and F3 at different scales during the ground-based soil moisture campaigns are presented in the Figure 6. The boxplots display the inter-quartile (IQR) range (first quartile to the third quartile) of soil moisture. The horizontal line inside the box indicates the median and the filled circles indicate the mean. The whiskers above and below the boxes shows the full range of the soil moisture values. Any data observation which lies 1.5 IQR lower than the first quartile or 1.5 IQR higher than the third quartile can be considered an outlier in the statistical sense, marked as crosses.

Figure 6. Box plots of soil moisture contents for the ground-based sampling measurement at 0.5, 1 and 3 km scales.

The range of variation of soil moisture contents was maximum in the focus area F1 at 0.5 km scale and reduced across the scales 1 km and 3 km respectively. In some pockets of the focus area F1, soil moisture content was very high (Figure 4) due to presence of paddy fields which are fully saturated. These paddy fields were present only near the Rana river, where sufficient water was available for irrigation, but most part of this focus area was dry with fallow land due to non-availability of water. Due to this large variation in the magnitude of soil moisture between saturated and dry soil, the range of soil moisture was quite high. The soil moisture contents of the focus areas F2 and F3 varied within relatively narrower ranges, and the ranges at different scales were similar to each other. The F2 focus area had almost similar soil moisture values across the 3x3 km square grid except at three locations, which were shown as outliers in Figure 6. The focus area F3 had similar mean and median values of soil moisture at 0.5 km scale, which showed that the soil moisture content was relatively uniform across this focus area. However the focus areas F2 and F3 showed dry patterns due to non occurrence of rainfall during the study period.

4.3 Standard deviation and coefficient of variation of soil moisture content

Standard deviation versus mean soil moisture content in the focus areas across 0.5, 1 and 3 km scales is presented in the Figure 7a. Although standard deviation of the ground-based soil sampling did not show a clear trend with increasing mean soil moisture, the standard deviation decreased with extent scale. The reason for this uncertain trend may be due to less number of data points being available as the monitoring was done only for the dry period. It was also observed from the figure that even though the standard deviations were calculated using soil moisture measurements taken at different sites with varying land cover conditions, they were spread within a similar range at 0.5 and 3 km scales, respectively. Figure 7b shows the coefficient of variation versus mean soil moisture across 0.5, 1 and 3 km scales. This pattern also did not show a clear trend due to limited range of mean soil moisture content monitored. However, it was seen that the coefficient of variation decreased with extent scale as a whole.

Figure 7. Soil moisture (a) standard deviation verses mean moisture content (b) coefficient of variation (CV) verses mean moisture content in the focus areas across the 0.5, 1 and 3 km scales.

4.4 Variability across scales

In order to understand the variation of soil moisture with respect to mean soil moisture across the scales, the range of mean soil moisture from 0 to $0.5 \text{ m}^3/\text{m}^3$ was divided in to ten bins of size $0.05 \text{ m}^3/\text{m}^3$, and the soil moisture data were averaged within each bin. Figure 8 shows the bin averaged soil moisture versus coefficient of variation (CV) at the three scales. It was observed from Figure 8, that the CV increased with increasing scale. Spatial variability of the surface soil moisture can be affected by number of parameters such as precipitation, soil texture, topography, vegetation, evapotranspiration, etc. These parameters can either enhance or reduce the spatial variability of soil moisture which depends on their spatially distribution and combination with other factors [5]. The results of present study reveals that the behaviors of soil moisture variability with mean soil moisture content have a good relationship across the scales. The study area did not receive any rainfall over a long period during the field compaign. It was also observed during the compaign that most of the agriculture fields were uncultivated due to the lack of water availability. However, the reason of increase variability across the scales may be due to spatial heterogeneity of soil texture and varying elevation across the scales.

Figure 8. Coefficient of variations of soil moisture contents at the 0.5, 1 and 3 km scales averaged within $0.05 \text{ m}^3/\text{m}^3$ wide bin of mean soil moisture contents.

The validation of satellite based soil moisture observations requires a large number of ground-based samples to accurately determine the footprint-scale mean soil moisture content. The empirical relationships between standard deviation and mean soil moisture can be developed to calculate the uncertainty of the large area mean using a certain number of ground-based soil moisture measurements [5]. The temporal stability analysis of ground-based soil moisture measurement is also an alternative for validation of satellite footprints. The temporal stability of soil moisture [10], [11] helps to identify the representative sampling locations where the local value of soil moisture content can be considered representative of footprint scale mean. However, the ground-based soil moisture measurements are required for both dry and wet periods of the year for development of the reliable empirical relationships and for time stability analysis. The results shown in the present study are based on the field campaigns in the dry period only which do not show a clear trend, and require more data set to capture the long term variability. Future field campaigns are planned to measure soil moisture across 0.5, 3 and 9 km scales during the wet and crop growing seasons to develop empirical relationships and for time stability of soil moisture.

5. CONCLUSIONS

The ground-based soil moisture measurements were taken using impedance probe and gravimetric sampling in the selected focus areas. The ground-based soil moisture measurements were regrouped into 0.5, 1 and 3 km scales and analyzed in order to characterize soil moisture variability with changing focus area mean moisture content and across the scales. The range of variation of soil moisture contents was found maximum in the focus area F1 at 0.5 km scale, which reduces across the extent scales 1 km and 3 km respectively. The soil moisture contents of the focus areas F2 and F3 vary within relatively narrow ranges, and the ranges at different scales are similar to each other. The soil moisture variations in term of standard deviation and coefficient of variation do not show a clear trend with increasing mean soil moisture, but decreases with extent scale as whole. The coefficient of variations of soil moisture contents at the 0.5, 1 and 3 km scales averaged within 0.05 m³/m³ wide bin of mean soil moisture contents show that the CV increase with increasing scale. The more number of ground-based soil moisture measurements are required in both dry and wet season, to develop empirical relationships between standard deviation and mean soil moisture for calculating the uncertainty of the large area mean. The future campaigns for ground-based soil moisture measurement during the wet and crop growing seasons can provide extensive data to develop reliable empirical relationships and time stability analysis for SMAP satellite soil moisture product validation.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Information Technology Research Academy (ITRA), Ministry of Information Technology, Govt. of India, for the financial support as sponsored research project and IIT Bhubaneswar for facilitating the execution of this research project. The authors also wish to thank the participants who have worked diligently for collecting soil moisture data.

REFERENCES

- [1] Vinnikov, K.Y., Robock, A., Qiu, S., Entin, J. K., Owe, M., Choudhury, B. J., Hollinger, S. E., and Njoku, E.G., "Satellite remote sensing of soil moisture in Illinois, USA", *Journal of Geophysical Research*. 104, 4145-4168 (1999).
- [2] Dubayah, R., Wood, E. F., and Lavalley, D., " Multiscaling analysis in distributed modeling and remote sensing: an application using soil moisture", In: Quattrochi, D.A., and M. Goodchild (Eds), *Scale in Remote Sensing and GIS*. Lewis Publishers, New York, 93-112 (1997).
- [3] Western, A. W., Grayson, R. B. and Blöschl, G., "Scaling of soil moisture: A hydrologic perspective", *Annual Review Earth Planet Sciences*. 30, 149-180 (2002).

- [4] Koster, R. D., et al., "Regions of strong coupling between soil moisture and precipitation", *Science*. 305, 1138-1140 (2004).
- [5] Famiglietti, J. S., Ryu, D., Berg, A. A., Rodell, M. and Jackson, T. J., "Field observations of soil moisture variability across scales", *Water Resources Research*. 44, W01423 (2008).
- [6] Panciera R., Walker, J. P. and Jackson, T. J. "The Soil Moisture Active Passive Experiments (SMAPEX): Towards soil moisture retrieval from the SMAP mission", *IEEE Transaction on Geoscience and Remote Sensing*. 52 (1), 490-507 (2014).
- [7] Famiglietti, J. S., Devereux, J. A., Laymon, C. A., Tsegaye, T., Houser, P. R., Jackson, T. J., Graham, S. T. and Rodell, M., "Ground-based investigation of soil moisture variability within remote sensing footprints during the Southern Great Plains 1997 (SGP97) Hydrology Experiment", *Water Resources Research*. 35, 1839-1851(1999).
- [8] Mohanty, B. P., Famiglietti, J. S. and Skaggs, T. H., "Evolution of soil moisture spatial structure in a mixed vegetation pixel during the Southern Great Plains 1997 (SGP97) Hydrology Experiment", *Water Resources Research*. 36, 3675-3686 (2000).
- [9] Cosh, M. H., Jackson, T. J., Bindlish, R., Famiglietti, J. S. and Ryu, D., "Calibration of an impedance probe for estimation of surface soil water content over large region", *Journal of Hydrology*. 311, 49-58 (2005).
- [10] Mohanty, B. P., and Skaggs, T. H., "Spatio-temporal evolution and time stable characteristics of soil moisture within remote sensing footprints with varying soil slope, and vegetation", *Advance in Water Resources*. 24, 1051-1067 (2001).
- [11] Cosh, M. H., Jackson, T. J , Bindlish R. and Prueger, J. H., "Watershed scale temporal and spatial stability of soil moisture and its role in validating satellite estimates", *Remote Sensing of Environment*. 92, 427-435 (2005).