Digging Deep: Field-Scale Soil Moisture Monitoring in Optimizing Agro-Hydrological Systems

Aju CD[1], Milind Mujumdar[1], Bhupendra Bahadur Singh[1], Mangesh Goswami[1], Madhusudan Ingale[1], and Naresh Ganeshi[1,2]

[1]Center for Climate Change Research, Indian Institute of Tropical Meteorology
[2]Department of Atmosphere, Ocean and Earth System Model-ling Research, Meteorological Research Institute

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Authors

Aju C.D[a],

Milind Mujumdar[a*],

Bhupendra Bahadur Singh[a],

Mangesh Goswami[a],

Madhusudan Ingale[a],

Naresh Ganeshi[b]

Host Institutions

[a]*Center for Climate Change Research, Indian Institute of Tropical Meteorology, Pune*

[b]*Department of Atmosphere, Ocean and Earth System Modelling Research, Meteorological Research Institute, Tsukuba, Japan*

**Corresponding author email: mujum@tropmet.res.in*

The increasing impact of climate change on agriculture, particularly in India, poses a significant threat to farmers and other involved communities. A neglect of soil health and reliance on fertilizers make the sector more vulnerable to extreme weather events. A recent climate change assessment report by the Ministry of Earth Sciences, India (Dhara et al., 2020) highlighted rising temperatures, declining summer monsoon rainfall, and a heightened risk of drought and floods across India. In this regard, it is important to examine the soil moisture (SM) variability which regulates or expedites the impact of hydrometeorological extremes via its control on evapotranspiration and thus surface fluxes. Recognizing the importance of SM and its memory is therefore crucial for identifying resilient regions and making informed agricultural decisions in the context of a changing climate. Insufficient observational networks for crucial climate variables, such as SM, hinder our understanding of complex multiscale interactions in the climate system. This limits our ability to comprehend the changing patterns of floods and droughts in India. SM, integral for moderating weather and climate, faces challenges in measurement at the intermediate scale from few hundred meters to few kilometres, impacting land-surface models and agricultural applications. In this context, IITM Pune set up a non-invasive Cosmic ray soil moisture monitoring, system based (COSMOS, Figure 1) on a network of the newly developed neutron scattering method which potentially helps to bridge the gap between

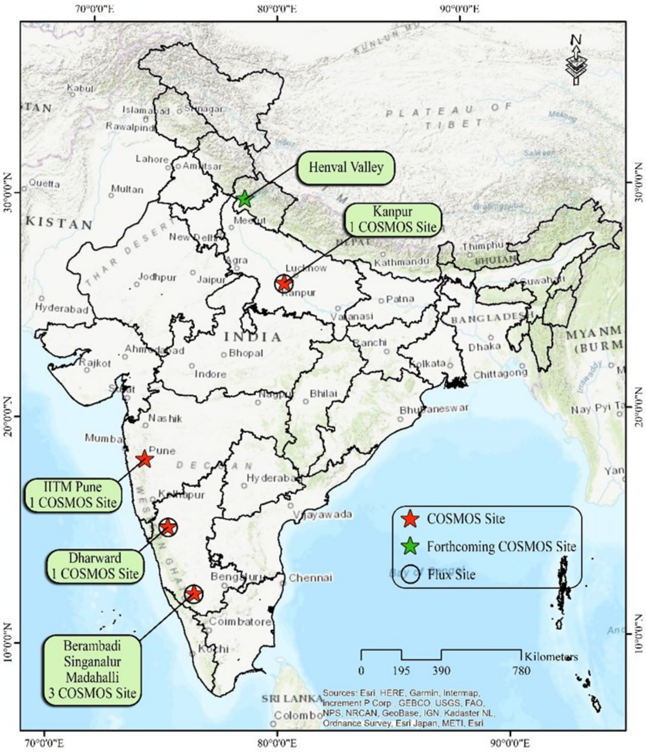


Figure 1: Map showing current and forthcoming COSMOS-India sites

the conventional point scale, remote sensing techniques, bridge the gap between the conventional point scale, remote sensing techniques and model simulations of surface soil moisture (Mujumdar et al. 2017). The non-invasive COSMOS system provides a field scale measure of soil moisture, effectively addressing spatial heterogeneity by averaging over the entire area. **This method is inevitable for accurate computations** since the SM variations are sensitive to spatial heterogeneity. Also, the COSMOS system estimates the area-averaged soil moisture, which avoids the challenge of extensive horizontal variability in surface soil moisture fields due to complex interactions between pedologic, topographic, vegetative, and meteorologycal factors while obtaining area-representative soil moisture using the network of point measurements.

Principle of measuring the soil moisture using the COSMOS technique

The cosmic rays were first discovered in 1912 by Victor Hess. Compton and Eastman (1935) later revealed that the ionization observed by Hess was caused by secondary radiation, primarily consisting of electrically charged particles penetrating the atmosphere. Subsequent measurements (Hendrick and Edge, 1966) indicated a correlation between the intensity of "fast" neutrons above the ground and the water content of the soil. Initially considered noise by cosmic-ray physicists, this phenomenon is now recognized by hydrologists as a signal providing information about surface water content (Zreda et al., 2012). The COSMOS technique harnesses the natural occurrence of cosmic rays to measure soil moisture content. Originating from space, cosmic rays interact with atmospheric molecules, generating secondary particles, including neutrons. These neutrons penetrate the Earth's surface and are sensitive to the presence of hydrogen atoms, abundant in soil water. By detecting and analyzing the flux of these neutrons returning to the surface, COSMOS offers continuous, non-invasive measurements of soil moisture across vast areas. This method boasts various advantages, including its capability to monitor soil moisture at different depths and its independence from ground-based sensors or weather conditions. The secondary cosmic ray neutrons cascade through the atmosphere in stages of high energy, fast (epithermal) neutrons, and finally thermalizes, with the epithermal neutrons crucial in determining water content due to their modulation by hydrogen atoms above and within the Earth's surface (Zreda et al., 2012).

Calibration of volumetric water content

A correction for atmospheric moisture content should be included in the conversion of measured neutron intensity to soil moisture. The effect of location and soil chemistry are also accounted for by making a local calibration to define the relationship between the fast neutron intensity, ϕ (normalized for variations in pressure, atmospheric water vapor, and solar activity), and soil moisture, SM. Other sources of hydrogen existing in and near soils, including lattice water, atmospheric water vapor, snow cover, water in and on vegetation, etc., should be considered when converting neutron intensitly to soil moisture. At COSMOS-IITM site, SM or volumetric water content (VWC - θ) is calculated using the following calibration function (Desilets et al., 2010)

$$\theta = \frac{a_0}{N/N_0 - a_1} - a_2\#(1)$$

where N: Fast neutron count, N_0: neutron count in the air above dry soil and a0, a1 and a2 are the fitting parameters.

Field-scale soil moisture time series (COSMOS-IITM)

The daily variations of COSMOS field-scale soil moisture (SM) and its effective measurement depth at COSMOS-IITM site from January 31, 2017, to November 10, 2023, are shown in Figure 2. Validation against in-situ profiles (yellow dots, Zreda et al. 2012) shows satisfactory agreement. The study utilizes a best-fit N_0 value of 1194 to derive volumetric water content (VWC) from the Cosmic-ray method. Validation with in-situ observations at the IITM site indicates a root mean square error (RMSE) in the range of 1-2% (Mujumdar et al., 2021).

The annual cycle of SM and effective depth mirrors the monsoon cycle, with notable variations exceeding 20% VWC and almost 20 cm in effective depth around monsoon onset and withdrawal phases. During wet periods, SM is around 30% and above, with an effective depth <15 cm, while dry periods exhibit SM below 15%, with rising effective depth above 25 cm. Intriguingly, within the monsoon season, field-scale SM and its effective depth show significant variations.

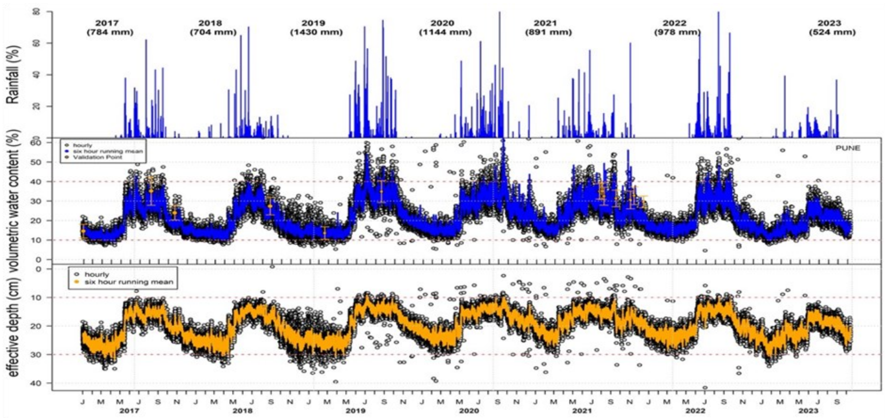


Figure 2: *Time series for the period 2017–2023 (a) COSMOS-IITM field-scale soil moisture and (b) effective depth estimated using equation proposed by Franz et al. (Franz et al., 2012).*

The hourly, six-hourly and validation points of SM are represented by a grey circle and blue line, orange circle respectively. Similarity the hourly and six-hourly effective depth of SM is represented by grey circle and orange line respectively. Orange dots superimposed on soil moisture time series indicate the area-averaged soil moisture values obtained from manual volumetric soil sampling, using the gravimetric method.

COSMOS-IITM field-scale SM data is compared with various available coarser-resolution products comprising coarser-resolution satellite (SMOS, SMAP, AMSR2), reanalysis (ERA5, MERRA-2), and modelled (GLDAS) data products during 2017–2020 (Figure 3).

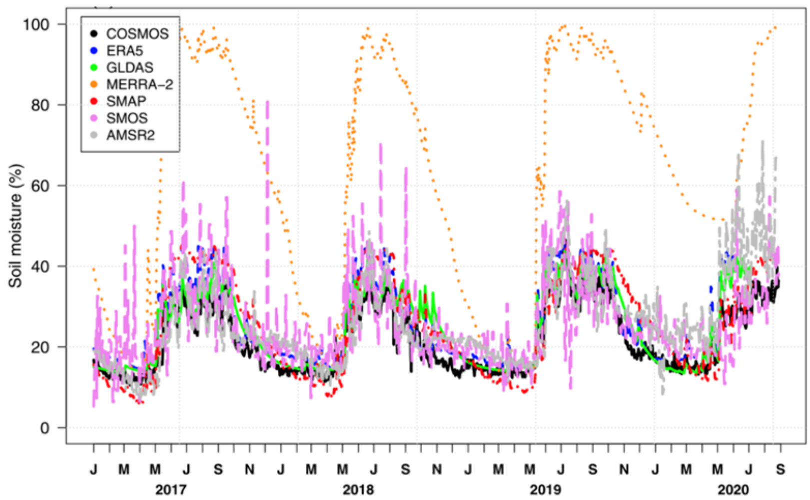
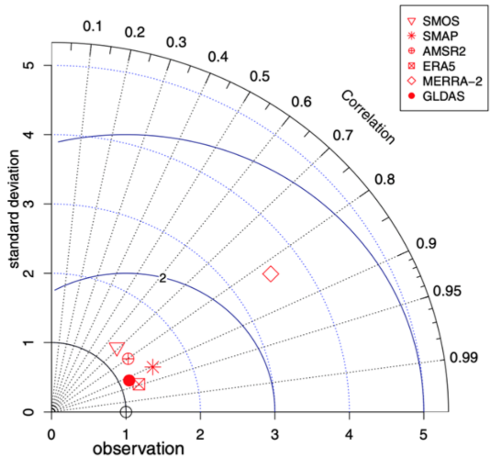
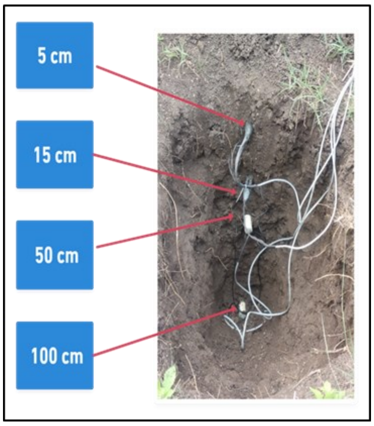


Figure 3: *Time series comparison of daily soil moisture (% of VWC) from SMOS (pink), SMAP (red), AMSR2 (grey), ERA5 (blue), MERRA-2 (orange), and GLDAS (green) with COSMOS-IITM (Mujumdar et al., 2021).*

Among all the SM data products GLDAS and ERA5 have relatively close resemblance to the COSMOS-IITM observations. Also, MERRA-2 SM products show maximum bias, whereas GLDAS exhibits the least bias over the Pune region. A comparison of SM data of various methods is shown in Figure 4.





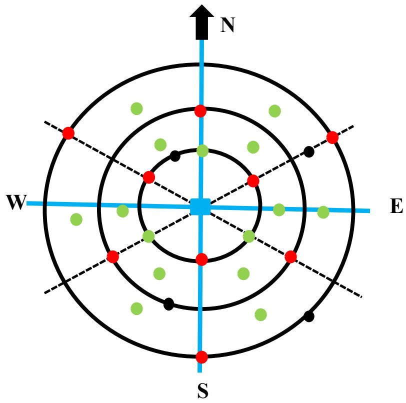


Figure 4: *Taylor Diagram presents the comparison of six different soil moisture data sets (SMOS, SMAP, AMSR2, ERA5, MERRA-2, and GLDAS; represented by distinct symbols) with vali- dation reference to COSMOS-IITM observation in terms of centred Root Mean Square Error (RMSE) Correlation Coefficient and Standard Deviation (Mujumdar et al., 2021)*

Field-scale hydrometeorological observations

The automated system developed at the Centre for Climate Change Research, Indian Institute of Tropical Meteorology (CCCR, IITM), Pune, regularly monitors the meteorological variables like soil moisture and temperature in four different layers of the soil. Collected data for different hydrometeorological variables is stored and communicated via Bluetooth low energy (ble), email, and short message service (SMS). A field photograph is shown in Figure 5 (Technical report, IITM). At the latest around 280 profiles are analysed, starting from March 21, 2022 to November 29, 2023.

Figure 5.: *Low cost soil profile sensors (red dots) at various depths and schematic map with three concentric circles at 5 m, 25 m and 75 m (inner to outer).* The green dots (right-hand side picture) indicates locations at which soil samples were collected and a gravimetric analysis is carried out to infer the volumetric water content.

Research Implications

The surface -subsurface coupling of SM observations from IMD stations across the core monsoon zone (CMZ) of India and COMSOS-IITM, Pune site, has shown an enhanced or near to void of convective activities during succeeding winter and pre-monsoon seasons of the excess and deficit years, respectively.

Figure (6) (Goswami et al., 2023) indicates the soil water dynamics in terms of the ridgeline plots of surface and subsurface SM and soil temperature (ST) as a function of time at the COSMOS-IITM site. This is in line with the above results based on coupling and memory analysis for the same period but only on a much larger extent – CMZ of India.

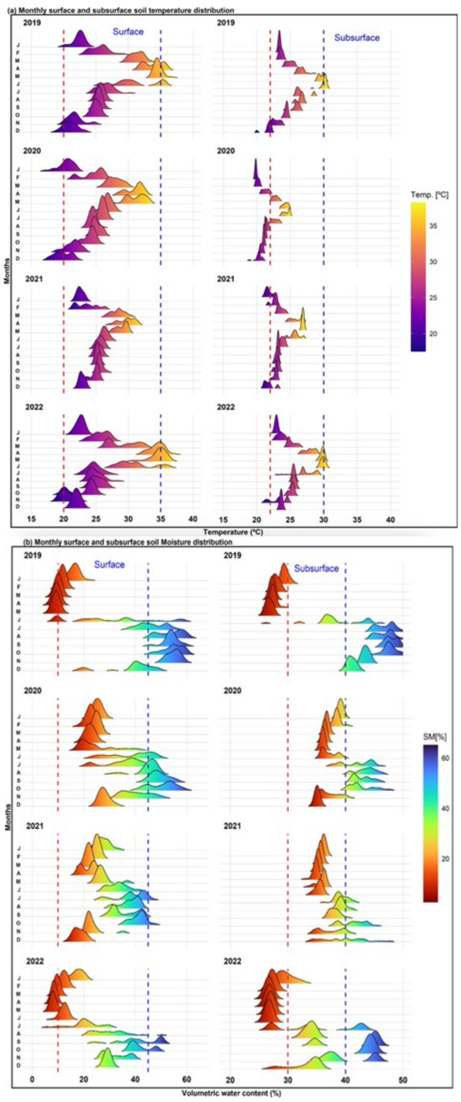


Figure 6: *The density ridgeline plot of surface and subsurface (a) soil temperature (ST, ∘C) and (b) soil moisture (SM, VWC %) for each month of the period between 2019 and 2022, using in-situ measurements at the COSMOS-IITM, Pune. The colour bar (same as x-axis) depicts the variation in ST (SM). The dashed red lines indi*

cate the threshold for extremely dry (warm) SM (ST) conditions, whereas the dotted blue lines, indicate the threshold for extremely wet (cool) SM (ST) conditions.

Also, the role of surface soil moisture variability on the temperature extremes over the Indian region could be emphasized using COSMOS-IITM, Pune site observations with IMD rainfall, and the GLDAS (1948 – 2014), SM observations over India (Ganeshi et al., 2020). Northcentral India could be identified as a hotspot for SM-temperature coupling using Generalized Extreme Value (GEV) distribution to assess the influence of SM on temperature extremes. Based on the results, the duration of temperature extremes (ExTD) could be observed to increase under dry soil moisture conditions.

Further, in a recent study published by Ganeshi et al. in 2023, the critical role of soil moisture variations in shaping temperature extremes has been underscored. Through meticulous sensitivity experiments, researchers examined the effects of increase or decrease in soil moisture by 20% on the frequency, intensity and duration of extreme temperature events across the Indian region. These findings shed light on the intricate relationship between soil moisture dynamics and temperature extremes, offering valuable insights for understanding and managing climate-related risks in the region.

In conclusion, the challenges posed by climate change on agriculture in India necessitate innovative solutions for monitoring soil moisture and its impact on weather patterns. The development of the Cosmic ray soil moisture monitoring system (COSMOS) by IITM Pune offers a promising avenue for accurate and non-invasive assessment of soil moisture, bridging the gap between conventional point-scale measurements and remote sensing techniques.

By leveraging advanced technologies and interdisciplinary research, such as coupling surface and subsurface soil moisture observations, we gain crucial insights into the complex dynamics of the climate system. Moreover, recent studies highlighting the significant influence of soil moisture variability on temperature extremes underscore the importance of integrating soil moisture monitoring into climate risk management strategies. Moving forward, continued collaboration between scientific institutions, policymakers, and agricultural communities will be vital in implementing sustainable practices and mitigating the adverse effects of climate change on agriculture and livelihoods in India.

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