Using SMAP soil moisture to optimize the design of in situ soil moisture observation networks

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National Aeronautics and Space Administration

H53A-1068

Abstract

The design of in situ soil moisture networks is crucial for optimizing their impact on various applications. This study is the first attempt to use data-driven soil moisture (SM) dynamics as a foundation for such network design. Using SMAP L4 and time stability analysis, we tested our approach in the newly developed Upper Missouri River Basin (UMRB) network. We found that the current UMRB network development (as of January 2024) covers the full range of SM variation, with the Mean Relative Difference (derived from time stability analysis) used as a proxy. The findings of this work demonstrate a complementary approach to network design, which is often based on auxiliary datasets. More importantly, the success of this approach requires a careful integration of modeled and satellite-derived SM data to leverage consistent spatial and temporal coverage.

Background

Since 2020, a new UMRB Soil Moisture Monitoring Network (hereafter referred to as UMRB SMMN) has been under development across the UMRB basin. These stations represent grid cells of 25 miles (~40 x 40 km, see Figure 1). The UMRB SMMN aims to improve "total water" monitoring, including year-round precipitation, evapotranspiration, snow, and soil moisture, for a total of 540 grid cells. As of January 2024, 170 grid cells are covered by at least one in situ station. Prior to this network's development, an existing network with soil moisture records was already in place.

Our analysis focuses on the 540 grid cells and shallow SM (0–5 cm). Shallow SM estimate are obtained from satellite observations and outputs from a land surface hydrological model. However, multiple stations from the older network only recorded deeper SM data (10 cm and 20 cm). To increase the availability of shallow SM data from in situ network for our analysis, we extrapolated it from deeper SM measurements and climate variables derived from NLDAS forcings. These estimated shallow SM values are treated as in situ data with high accuracy.

To this end, we aim to evaluate the representativeness of the current UMRB SMMN based on shallow SM time series analysis.

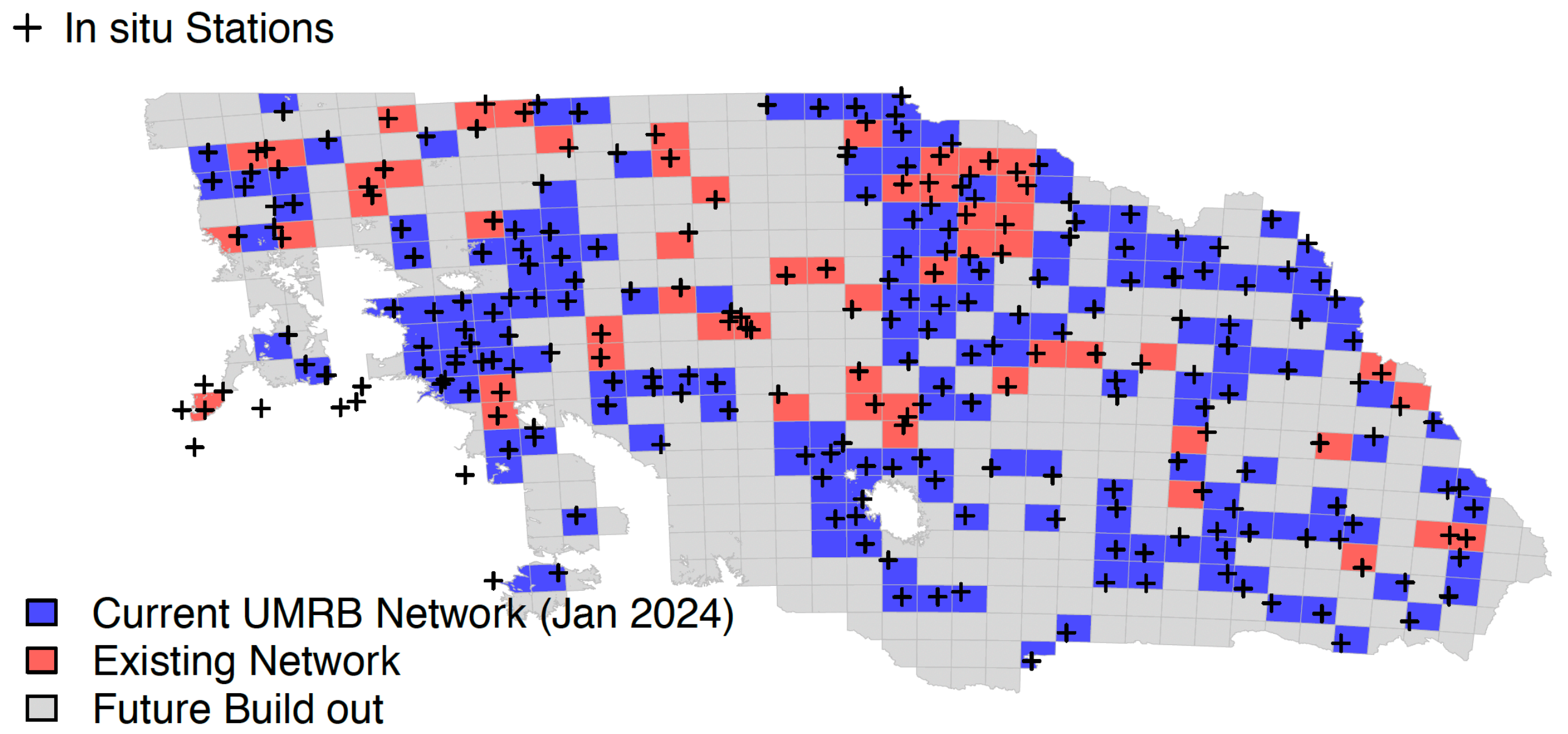

Figure 1. Distribution of 540 grid cells that will have at least one in-situ soil moisture (SM) station across the UMRB. **As of January 2024, 170 grid cells (blue) have completed in situ SM installations. There are 56 grid cells (red) with data from existing networks from various Mesonet. All red and gray grid cells are candidates for building the remaining in situ stations as part of the UMRB SMMN project.**

References

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Primary Datasets for Developing SMAP-based Time Stability Analysis

Data	Original Data	Data Processing	Source
Surface soil moisture (SSM, 5 cm) derived from SMAP L4 product	3-hour/ 2015-2024	daily (DOY 100 to DOY 330) / 2015-2024	Reichle et al., 2022
SSM observed from in situ stations	Hourly or daily / 2015-2024	daily (DOY 100 to DOY 330) / 2015-2024	Mesonet (MT, ND, SD, WY, NE)
UMRB Grid Network			USACE

For rescaling SMAP L4, NLDAS forcings , soil texture, and topography are also required.

Method

SMAP-based Time Stability Analysis

In spatial scale, **a sampling location** represents a USACE network grid cell. In temporal scale, **a sampling day** represents the average daily soil moisture estimate derived from satellite- and model-based SMAP L4. The watershed-mean soil moisture of k^th^ sampling day, $\bar{\theta}_k$ is defined as

$$\bar{\theta}_k = \frac{1}{N}\sum_{j=1}^{N}\theta_{jk}$$

θ_{jk} is the volumetric soil moisture measurement at sampling location j and sampling day k. Temporal mean for each sampling location $\bar{\theta}_j$ can be defined as

$$\bar{\theta}_j = \frac{1}{M}\sum_{k=1}^{M}\theta_{jk}$$

For each sampling location j and total sampling days M, the mean relative difference, $\bar{\delta}_j$ (%v/v) is estimated as follows

$$\bar{\delta}_j = \frac{1}{M}\sum_{k=1}^{M}\frac{\theta_{jk}-\bar{\theta}_k}{\bar{\theta}_k}$$

Rescaling SMAP L4

This task was performed to adjust SMAP L4 SSM data to better align with the SM variance observed at the UMRB, leveraging the in situ SM network. A Random Forest model was first trained using data from in situ locations, with the labels being daily observed soil moisture content at 5 cm. The predictors included daily SMAP L4 SSM, daily NLDAS forcing data (*U and V wind component at 10 meters, air temperature at 2 meters, specific humidity, surface pressure, surface downward longwave and shortwave, precipitation, convective available potential energy, and potential evapotranspiration*), and site characteristics (*geographic information, soil texture, and topography*). The trained model was then applied to grid cells across the basin to adjust SMAP L4 SSM values (hereafter referred to as SMAPL4-RF).

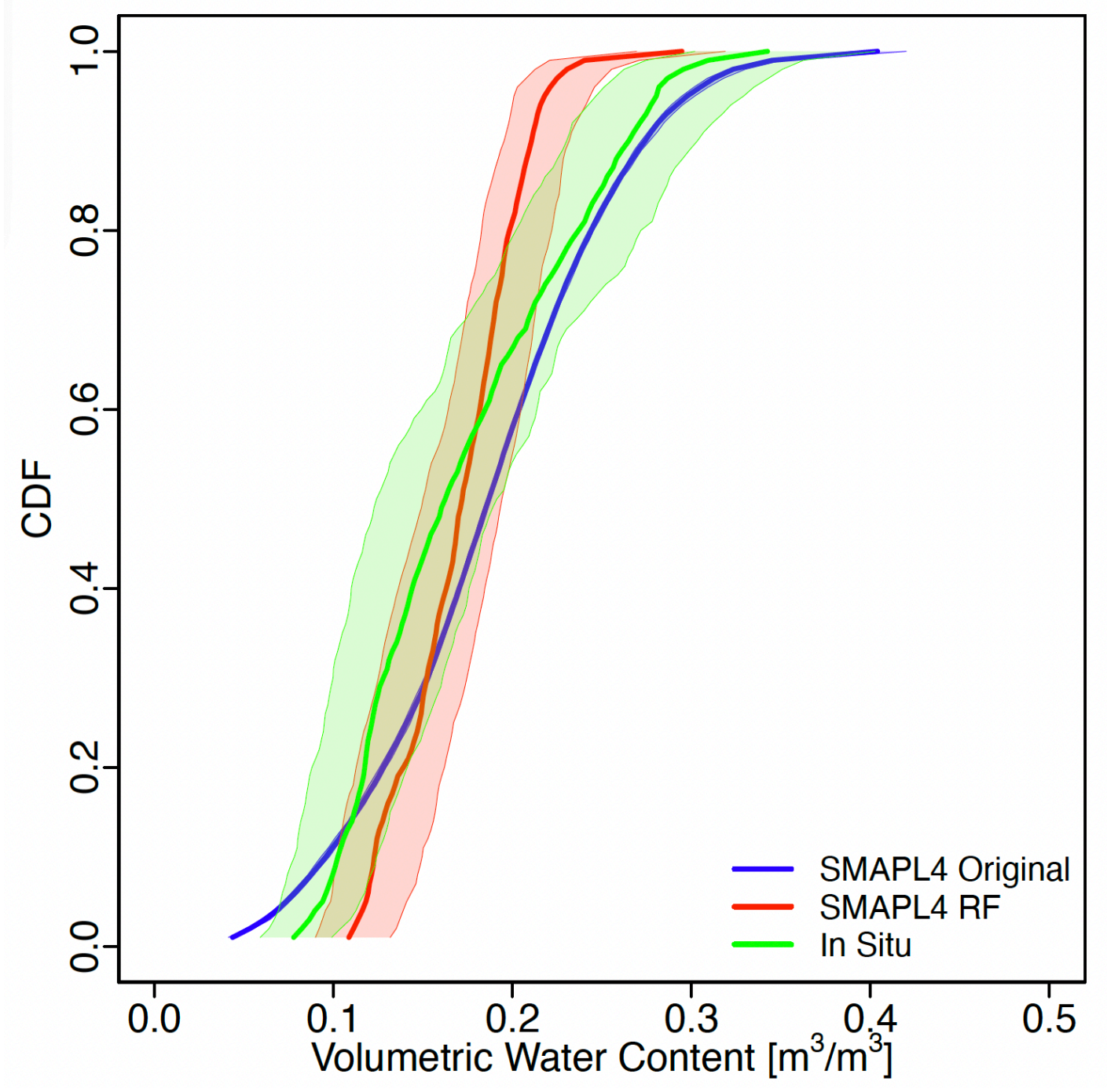

Figure 2. Cumulative Distribution Function comparing observed SM from in situ measurements, estimated SM from the original SMAP L4, and estimated SM from SMAP L4-RF. Shaded areas represent the 25th to 75th percentile range of these CDFs, while bold dashed lines denote the median values. **Generally, the RF algorithm increases the variance of SMAP L4 and provide closer median values with the in situ stations.**

Results

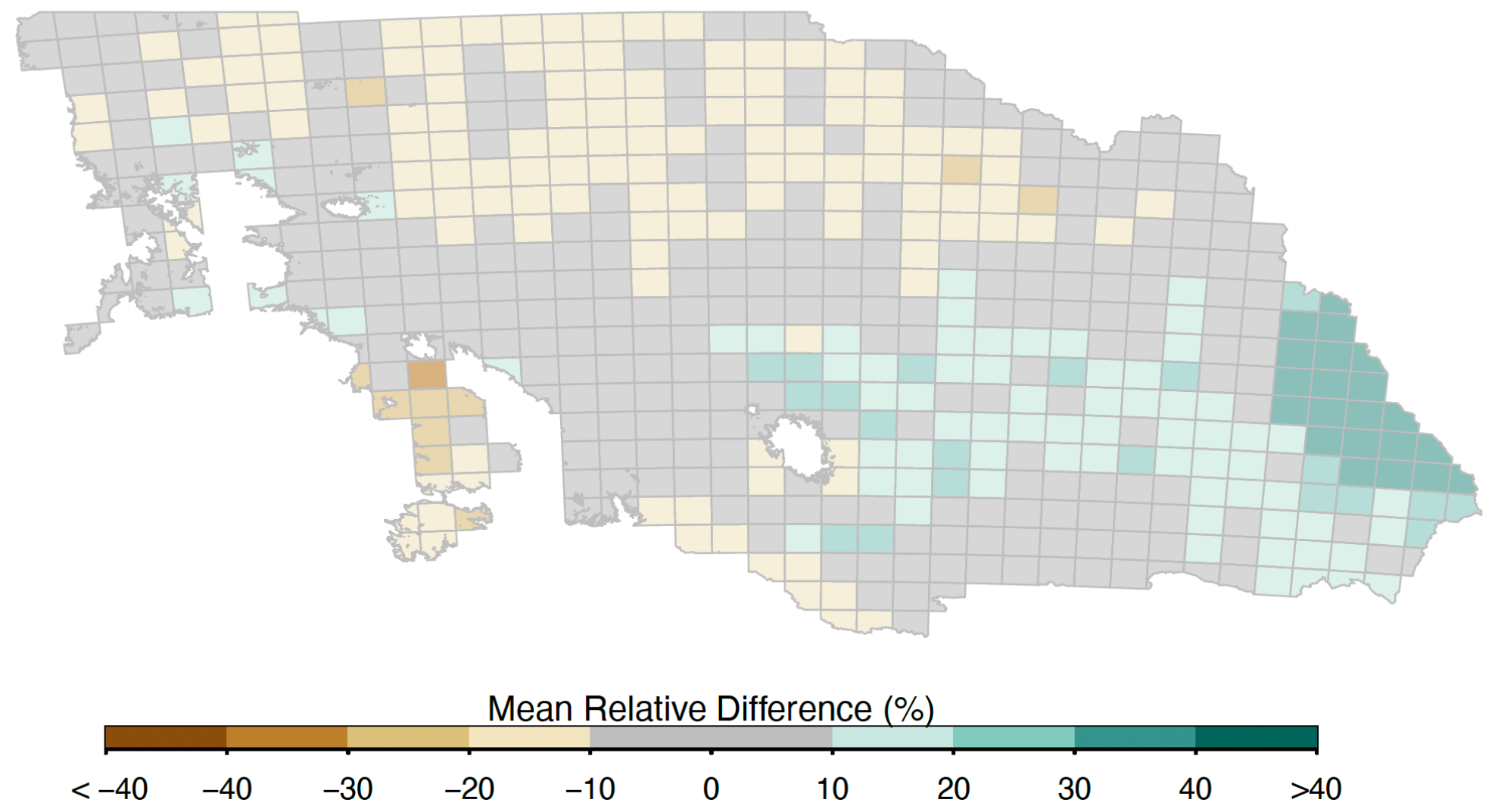

Figure 3. Spatial distribution of SMAP L4-RF-based MRD across 540 grid cells. **The low plains in the eastern basins are "wet" representative grid cells, while the northern basins are generally "dry" representative grid cells. However, extreme dryness is observed in the southwestern part.**

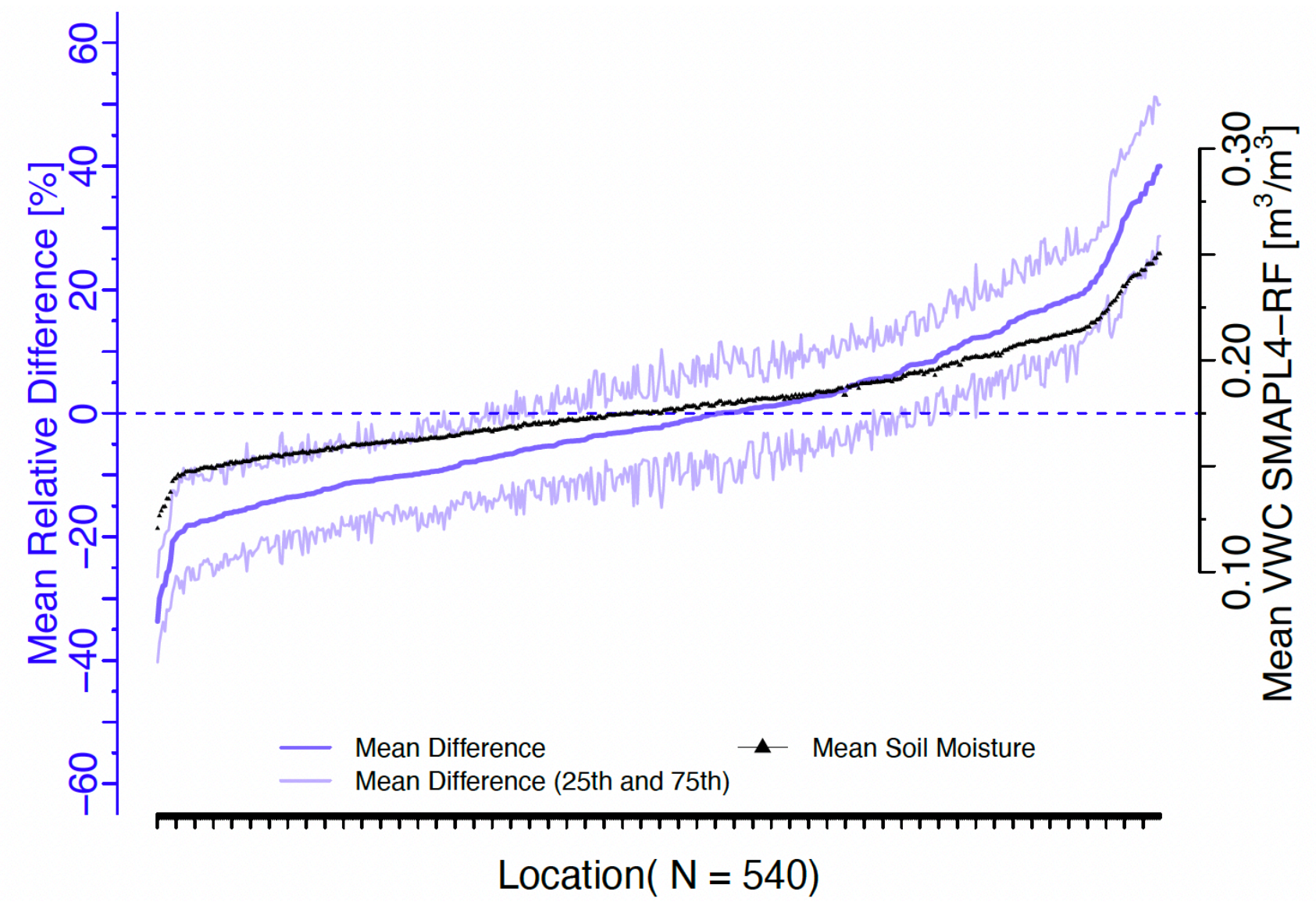

Figure 4: Ranked temporal MRD for 540 grid cells. **Basin-average SM (MRD = 0) is approximately 0.18 m³/m³ based on SMAP L4-RF. The deviation toward wet conditions (right tail) is higher than the deviation toward dry conditions (left tail). Positive MRD values can reach up to 60%, while negative MRD values for dry conditions are about 40%.**

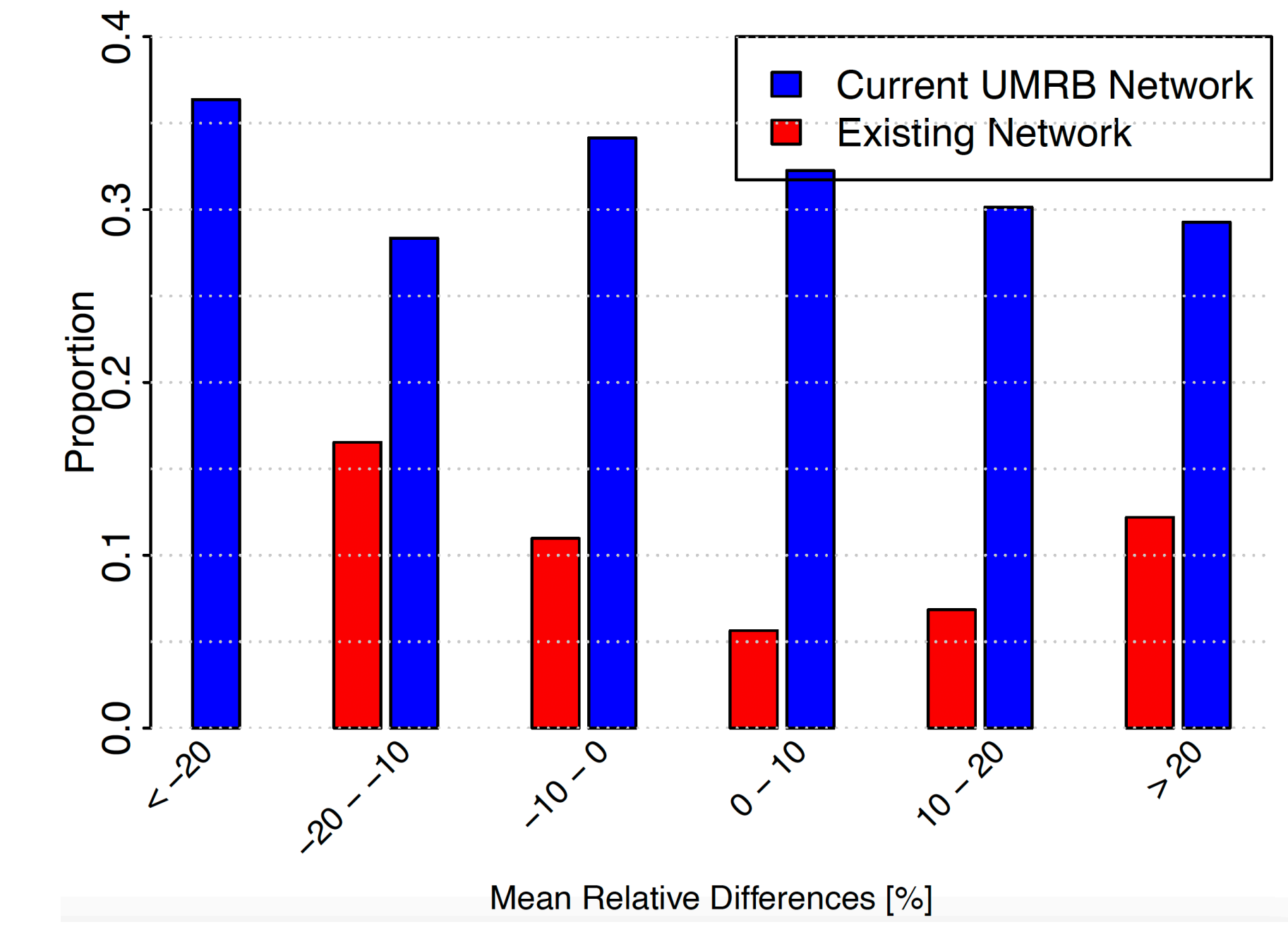

Figure 5. Distribution of the proportion of in situ stations from the UMRB Network and the Existing Network across different MRD bins. **Although only one-third of the stations have been established, the UMRB Network could cover the full range of SM dynamics (using MRD as a proxy).**

Conclusion

- We propose a complementary approach to selecting the ideal placement for in situ soil moisture stations.
- The added value of the SMAP product is demonstrated by evaluating the full soil moisture dynamics, providing insights into the representativeness of an in situ network.
- This method has potential at higher spatial resolutions wherever satellite-based or model-based soil moisture data is available.

Acknowledgements

We thank the NIDIS Data Value Study Project, program coordinators Marina Skumanich and Elise Osenga. We also thank Jared Entin, program manager of the NASA Terrestrial Hydrology Program, for supporting this study.

Contact