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EGU26 GENERAL ASSEMBLY

This presentation participates in OSPP — Outstanding Student & PhD candidate Presentation contest

Diffusion-Based Physics-Aware Modeling of Subsurface Soil Moisture

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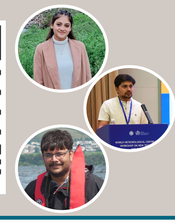


1. Summary

What does this study proposes?

A probabilistic, physics-aware denoising diffusion model to estimate soil moisture at subsurface depths using only surface moisture measurements.

Core of the study: Integrates smoothness and curvature regularization terms inspired by Fickian diffusion theory as weak physics to guide the learning process, without requiring explicit or site-specific physical parameters.

Study sites: 20 global ISMN (International Soil Moisture Network) sites spanning six distinct Köppen-Geiger climate classes.

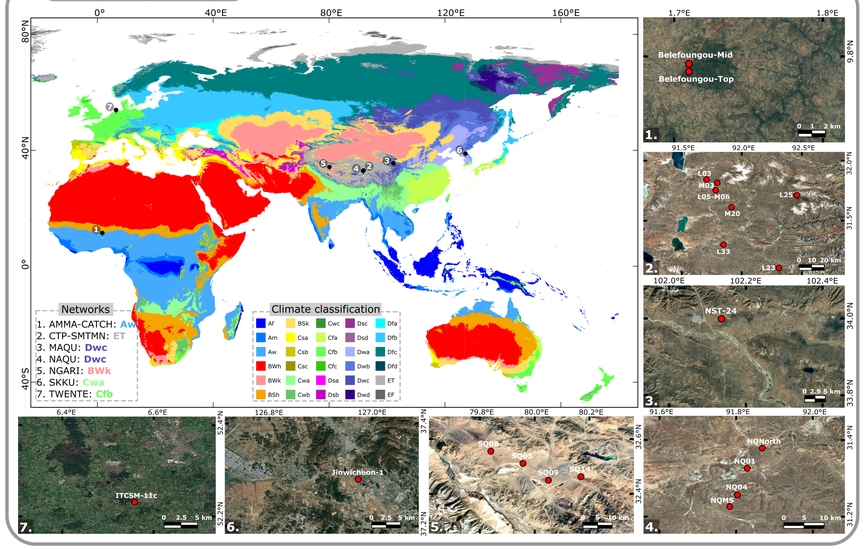
Dataset: Model is trained and evaluated at 10, 20 and 40 cm depths using 5 cm data with hourly observations.

Highlight: Model validation at high-resolution African stations with 10-min data.

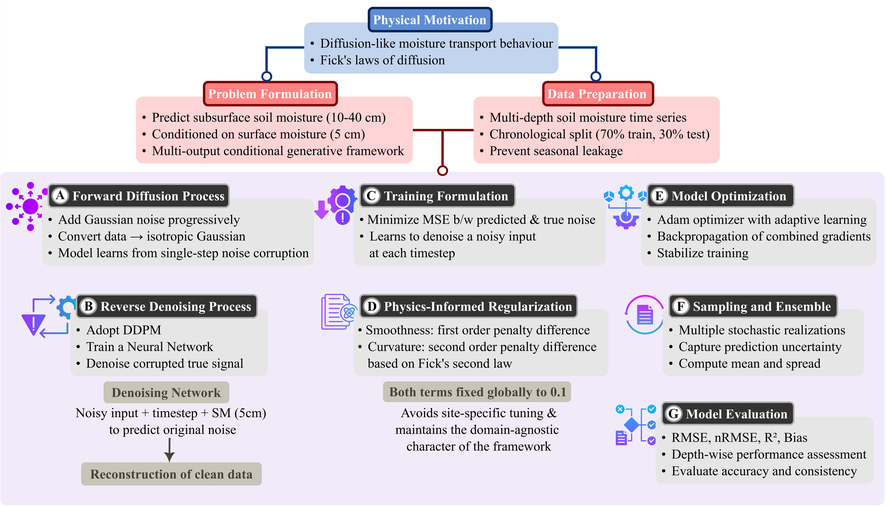
Research Questions:

- Can a purely data-driven model, augmented with physics-inspired regularization, generalize across diverse hydro-climatic conditions?
- How does the ensemble size affect the stability and reliability of predictions?
- What is the sensitivity of the model to input uncertainty?
- Can the model maintain predictive performance when applied to high-frequency input data?

2. Study Area

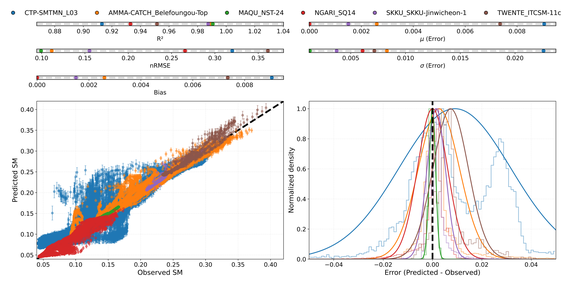


3. Methodology

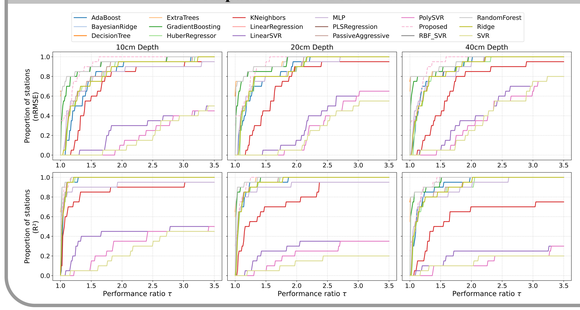


4. Results

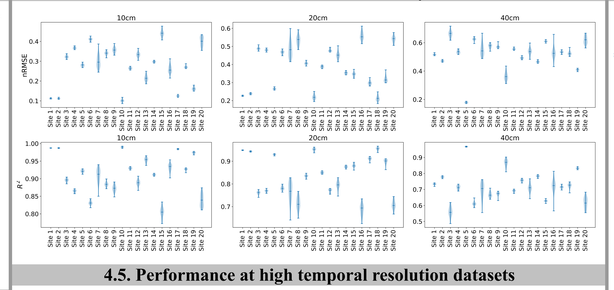
4.1. Model performance



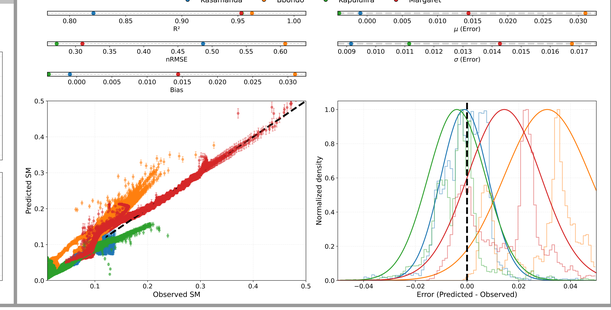
4.2. Comparison with Benchmark



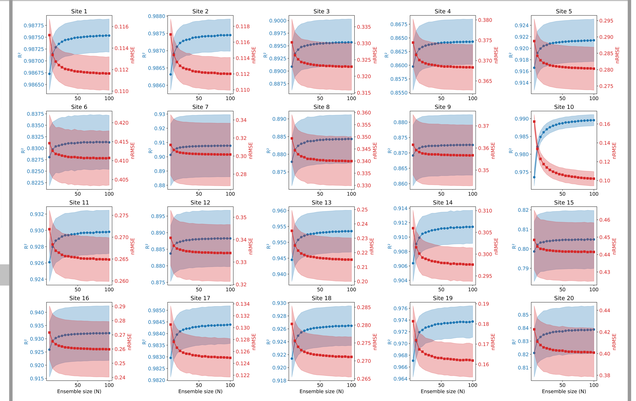
4.3. Stochastic Robustness Analysis



4.5. Performance at high temporal resolution datasets



4.4. Performance at different N at 10 cm



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Physics-Aware Probabilistic Modeling of Subsurface Soil Moisture Using Diffusion Processes Across Different Climate Settings

Key Points:
- A physics-aware generative model to estimate subsurface soil moisture using only surface observations
- The ensemble size plays a critical role in improving the stability and reliability of predictions, with diminishing gains beyond a certain threshold

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5. Conclusions

- **Model performance:** R^2 ranges from 0.91 to 0.99
  Climates with stable seasonal patterns (Aw, Dwc, and Cfb): lower errors
  Climates with freeze-thaw dynamics (ET) and monsoonal variability (Cwa): higher uncertainty
- **Benchmark comparison:** Strong performance against 17 state-of-the-art algorithms.
- **Stochastic robustness analysis:** Testing across 30 random seeds and varying ensemble sizes indicated that moderate-sized ensembles provide an effective balance between accuracy and stability.
- **Uncertainty analysis:** White, Autocorrelated, and Structured noise revealed that the 20 cm layer is most susceptible to surface-level perturbations, while deeper layer remain comparatively resilient.
- **Performance on higher-resolution datasets (10-min):** Prediction errors tightly centered around zero and very low standard deviation.

Acknowledgement

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विज्ञान एवं प्रौद्योगिकी मंत्रालय MINISTRY OF SCIENCE AND TECHNOLOGY — सत्यमेव जयते

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