

High-Dynamical-Fidelity Precipitation (HiDF-P) satellite estimates informed by atmospheric and land surface variables within a video diffusion framework

Runze Li¹, Yan Xia², Yongquan Qu^{3,4}, Dongwei Fu⁵, Clement Guilloteau¹, Efi Foufoula-Georgiou^{1,2}

¹ Department of Civil and Environmental Engineering, University of California, Irvine, CA, USA

² Department of Earth System Science, University of California, Irvine, CA, USA

³ NSF Center for Learning the Earth with Artificial Intelligence and Physics (LEAP), Columbia University, New York, NY, USA

⁴ Department of Earth and Environmental Engineering, Columbia University, New York, NY, USA

⁵ Space Science and Engineering Center, University of Wisconsin-Madison, Madison, WI, USA

Hydrometeorological research and operations hinge on accurate precipitation observations with high spatiotemporal fidelity, e.g., faithful multi-scale storm organization, propagation, and lifecycle evolution. Despite being the sole globally available observational source, satellite precipitation products still fall short of reproducing the spatiotemporal structure of ground-based observations, due in significant part to severe temporal discontinuities and dynamical distortions arising from the intrinsic inhomogeneity, intermittency, and indirectness of passive microwave retrievals. To address this gap, we propose a video-diffusion framework for probabilistic generation of satellite-based High-Dynamical-Fidelity Precipitation (HiDF-P) estimates and demonstrate its superior performance in improving accuracy and spatio-temporal coherence across a range of scales as compared to current satellite retrievals and baseline Deep Learning models. The video diffusion framework allows for explicit spatiotemporal modeling of precipitation fields constrained by novel loss functions and informed by the rich physical information from ~40 4-dimensional atmospheric/land environmental fields, with this extra information compensating for the inherent temporal deficit in satellite observations. A comprehensive process-oriented diagnostic suite of metrics, e.g., wavenumber-frequency spectral analysis and object-based storm tracking, is established to rigorously interrogate products' multiscale dynamical fidelity. IMERG precipitation and ERA5/ERA5-Land environmental variables were used as inputs, with MRMS precipitation as the reference, over the CONUS. Our results show that HiDF-P faithfully reproduces the observed spectral energy distribution and storm propagation characteristics. It substantially improves precipitation event properties (e.g., duration, peak timing, short extremes contribution), precipitation system attributes (e.g., scale, radial decay rate, convective-core fraction), and precipitation track kinematics (e.g., path length, curvature, and area-evolution rate) relative to IMERG and baseline models, approaching ground-truth realism. Transferability experiments further demonstrate robust spatial generalization to unseen regions. This work advances a new paradigm leveraging video diffusion models for developing satellite precipitation datasets that simultaneously target spatial and temporal patterns, and it provides algorithmic foundations for long-term, global satellite-based precipitation products with high dynamical fidelity.