Downscaling satellite-based precipitation over Germany using a fingerprint method

The thesis will develop a downscaling technique that combines the long, spatially complete IMERG satellite precipitation time-series with DWD rain-gauge information. The goal is to test the capability of this technique to downscale satellite-based precipitation products and test whether this high-resolution product can better represent heavy rainfall over Germany.

Scientific motivation

Satellite precipitation products such as IMERG provide a valuable, homogeneous record from 2000 onward at approximately 0.1° resolution and half-hourly temporal resolution, but this grid is too coarse to resolve locally heavy-rainfall structures, hampering a use in water-related applications. Rain gauges in contrast provide trustworthy point measurements but cannot describe the full spatial footprint of an event. Ground-based radar systems are also very valuable, and can provide high spatio-temporal resolution data, but are not feasible for most developing and less developed countries due to high upfront cost and maintenance difficulties. The central question of this thesis is whether we can reconstruct sub-pixel precipitation variability by combining coarse IMERG pixel-scale precipitation with rain-gauge point constraints in a mass-conserving, smoothness-constrained downscaling framework?

Core idea

The starting point is a so-called VERA-style variational formulation. The unknown high-resolution field is estimated by minimizing a cost function that balances four terms: conservation of the IMERG pixel-average precipitation, agreement with available rain gauges, spatial smoothness/curvature constraints, and non-negativity. In practical terms, the method asks: Among all fine-scale precipitation fields that are consistent with the coarse satellite pixel and nearby gauges, which field is the most physically plausible?

Figure 1 summarizes the proposed workflow. IMERG provides the coarse precipitation field, gauges provide local point constraints, and the VERA-type reconstruction produces a fine-grid field. Independent validation is performed primarily by withholding some gauges from the reconstruction and testing whether the method can predict them.

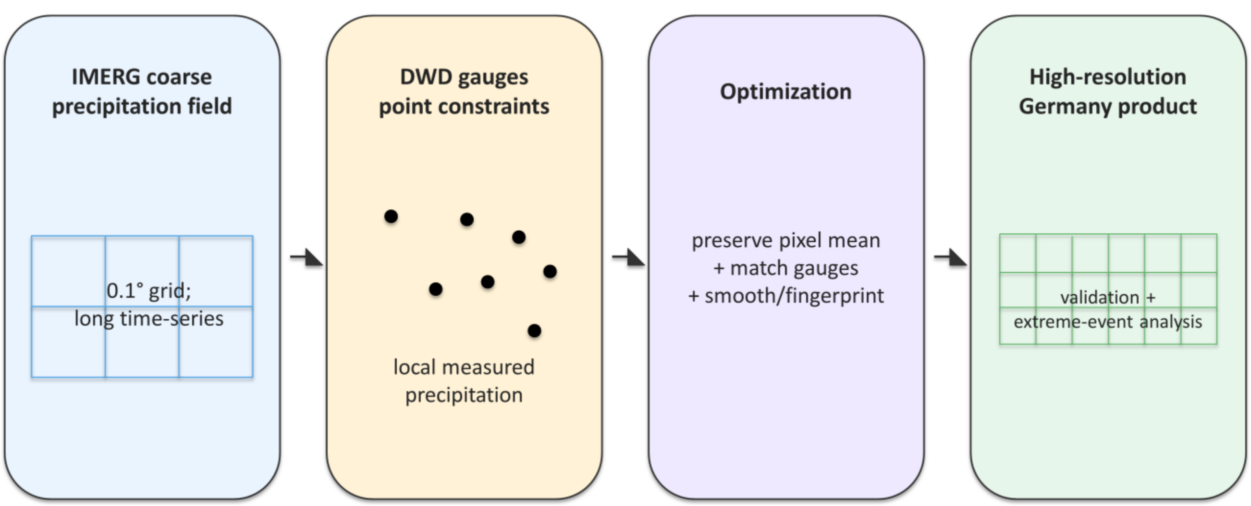

Figure 1. *Proposed workflow: Use the satellite field as the large-scale fingerprint and rain gauges as local anchors.*

Figure 2 illustrates the same idea in one dimension, because the real two-dimensional problem (spatial precipitation field) is easier to understand after this simplification. A standard interpolation method, such as a cubic spline, can produce a smooth curve through rain-gauge observations or satellite grid points, but it ignores the requirement that the average precipitation within each satellite pixel should remain consistent with IMERG, or the interpolation goes through the rain-gauge values. The proposed method therefore adds a coarse-scale constraint: the fine-grid values inside each IMERG pixel should average back to the original satellite value.

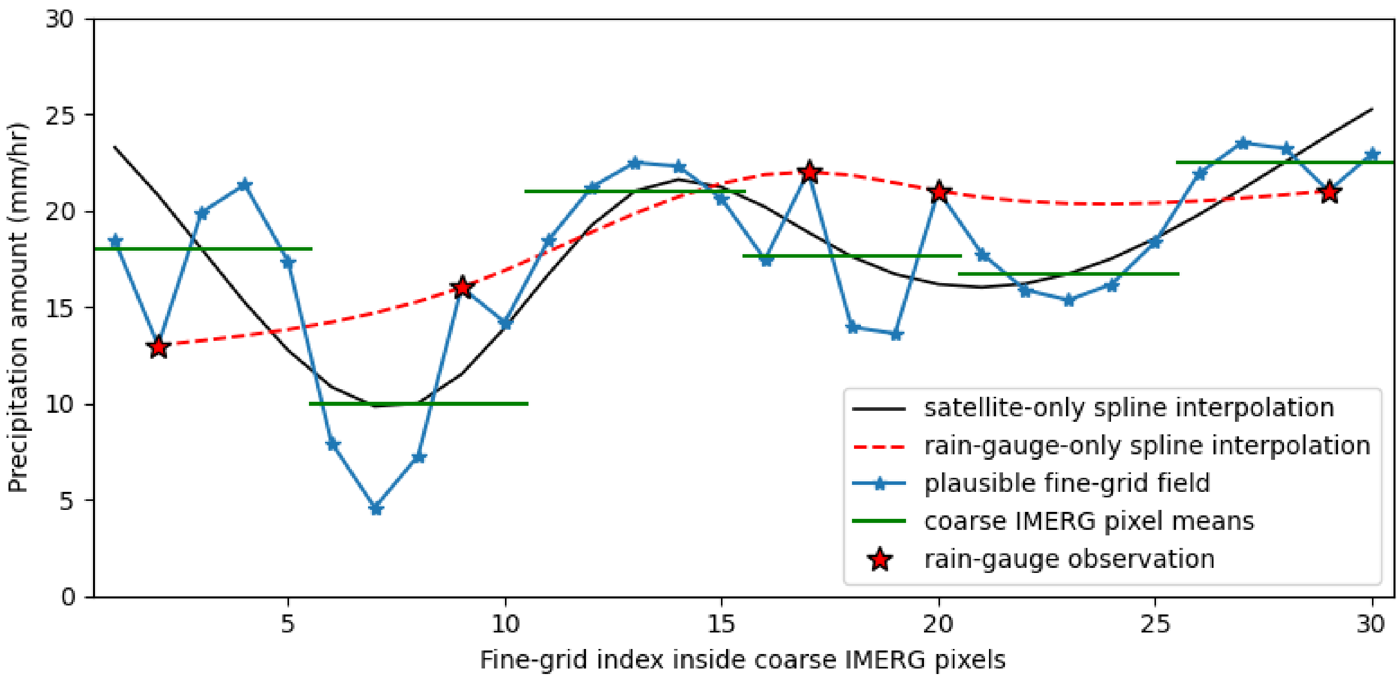

Figure 2. *One-dimensional illustration of the thesis concept: Green horizontal lines show the original coarse IMERG pixel mean, while red stars indicate rain-gauge observations at selected fine-grid locations. The black curve shows a standard cubic-spline interpolation through the satellite pixel centers, and the red dashed curve shows a cubic-spline interpolation through the rain-gauge observations. The blue curve shows a plausible fine-grid precipitation field reconstructed under constrains: it is influenced by the rain-gauge observations while preserving the original coarse satellite-pixel totals. This figure is a simplified one-dimensional example; the thesis would extend the same idea to a two-dimensional grid (spatial precipitation fields) over Germany.*

Research questions

- How can the one-dimensional constrained reconstruction concept be generalized to a robust two-dimensional precipitation downscaling algorithm over Germany?
- Can a mass-conserving, gauge-constrained downscaling method reconstruct precipitation at withheld rain-gauge locations better than the original IMERG field and simple interpolation baselines?
- How sensitive is the method to gauge density, season, precipitation intensity, and the choice of smoothness or curvature constraint?
- Which aspects improve most: mean climatology, wet-day frequency, intensity distribution, or severe-event structure?
- Are the reconstructed spatial patterns of selected heavy-rainfall events physically plausible when compared with RADKLIM and Catalogue of Radar-based heavy Rainfall Events (CatRaRE), while acknowledging that these products are not fully independent validation data?

Methodological plan

- **i**) Build a Python prototype of the downscaling algorithm itself; ii) The prototype will start with a simplified one-dimensional example to demonstrate the mathematical idea: fine-grid precipitation values are estimated so that they preserve the coarse IMERG pixel mean, remain close to available gauge observations, and avoid unrealistic small-scale noise through a smoothness or curvature constraint. In the second step, the method will be extended to the real two-dimensional IMERG grid (spatial coverage) over Germany. The algorithm will then be tested first with daily accumulations and then move to hourly processing if the prototype is stable.
- Define the objective function: station mismatch + IMERG pixel-volume conservation + first- and/or second-derivative smoothness + optional fingerprint weighting. It might be possible to tune the weights via cross-validation.
- Evaluate against leave-one-station-out gauges (k-fold cross-validation) and RADKLIM at common temporal/spatial scales. Metrics: bias, MAE/RMSE, correlation, wet-event frequency, quantile errors, and scores for heavy-rain thresholds.
- Use the final product for a compact scientific analysis: seasonal climatology, 95th/99th percentile maps, the maximum amount of precipitation that falls on a single/five consecutive days within a specified period (RX1day/RX5day), and selected severe-event case studies over Germany.

Data, tools, and expected outcome

Main input	IMERG Final Run precipitation over Germany
Ground information	DWD rain-gauge precipitation
Reference/evaluation	RADKLIM hourly 1 km gauge-adjusted radar precipitation and, optionally, CatRaRE heavy-rain event catalogues
Deliverables	Documented Python package/notebooks, high-resolution test product, validation figures, and a thesis chapter on climatology/extremes

Interested? Please contact ehsan.sharifi@kit.edu and peter.knippertz@kit.edu