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Geoscientific
Model Development

Supplement of

EMMA-Tracker v1.0: a mesoscale convective system tracker and 27-year European observational climatology

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Section 1: Input Data Morphology Comparison

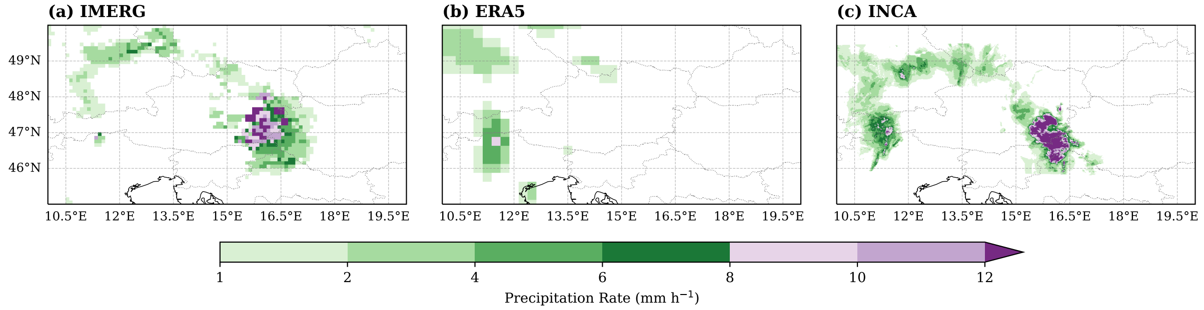

Figure S1: Comparison of a single precipitation event as captured by (a) IMERG (0.1°), (b) ERA5 (0.25°), and (c) INCA (1 km). The color bar indicates precipitation rate in mm/hr. Example from 10 August 2015 for the 19:00 UTC timestep.

The EMMA-Tracker's detection algorithm is sensitive to the morphology (shape and structure) of precipitation plumes. IMERG was selected as the primary input dataset based on its ability to resolve these structures, particularly when compared to coarser reanalysis products. Figure S1 compares the same MCS as represented by IMERG, ERA5, and the INCA radar product with a 1 km horizontal grid (1 km) [1]. Although INCA resolves finer-scale details and higher peak intensities, the general shape, size, and location of the precipitation system are well-captured by IMERG. In contrast, the ERA5 precipitation field is much coarser and more diffuse, lacking the defined structure necessary for the EMMA-Tracker's core detection and merging steps. This demonstrates the necessity of IMERG-resolution data for this methodology.

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[1] GeoSphere Austria: INCA v1 1h 1km. Available at https://data.hub.geosphere.at/dataset/inca-v1-1h-1km. Accessed August 2025.

Section 2: Postprocessing Filter Sensitivity Analysis

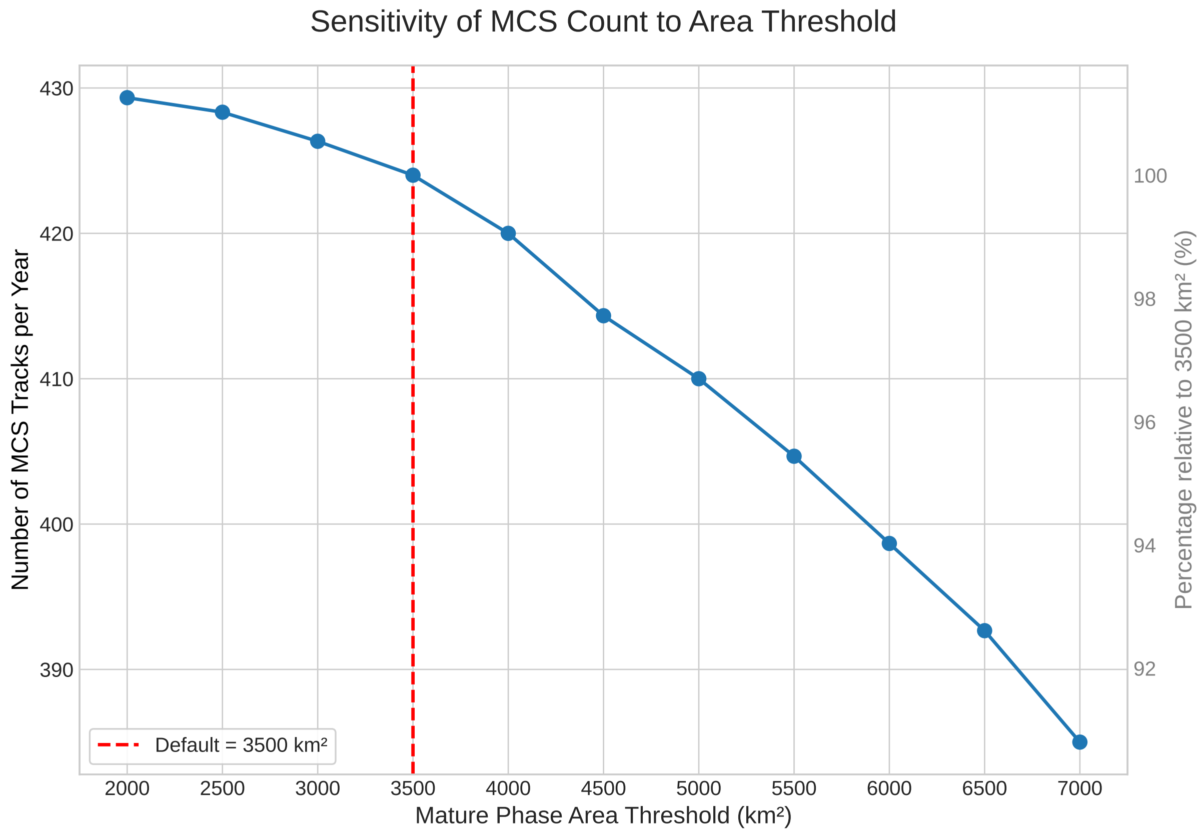


Figure S2: Sensitivity analysis of the area threshold. The red dashed line shows the default setting (3500 km^2) used for creating the dataset. Percentage values are relative to this default value. The tracking for this analysis covers the years 2015–2017.

Figure S2 presents the sensitivity of the raw tracking output (prior to the postprocessing filter) to the area threshold. Direct comparisons of area thresholds between different tracking algorithms are difficult due to varying MCS definitions and the use of different input variables (e.g., infrared brightness temperature vs. precipitation). The tracking for this sensitivity analysis was performed for the years 2015–2017. The algorithm's output remains highly stable for thresholds between 2000 km^2 and 7000 km^2. The overall variation in tracked systems between these two values is less than 10%.

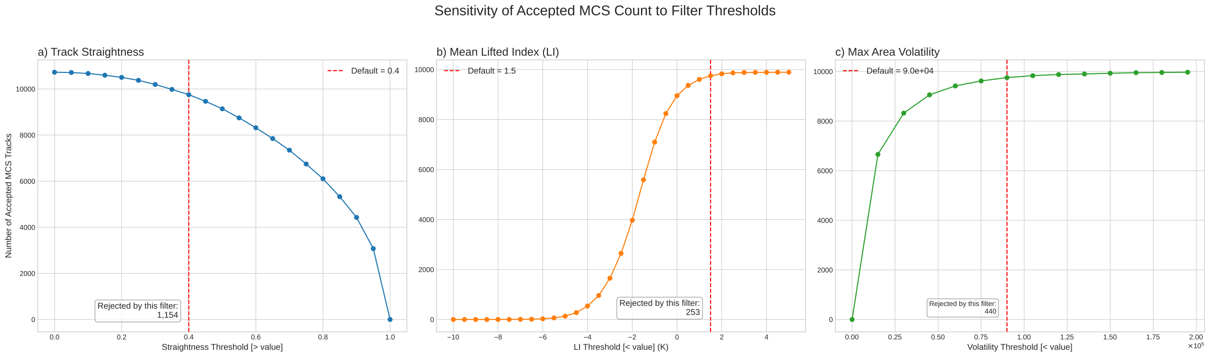


Figure S3: Sensitivity analysis for MCS track acceptance based on postprocessing filter thresholds. (a) Track Straightness, (b) Mean Lifted Index (LI), and (c) Max Area Volatility. The red dashed line indicates the default threshold value selected for the EMMA-Tracker.

Figure S3 illustrates the sensitivity of the final accepted MCS track count to the thresholds chosen for the three postprocessing filters. These curves were used to identify physically meaningful and robust cutoffs:

1. **Track Straightness (Fig. S3a):** The threshold of 0.4 (red dashed line) was selected as it corresponds to the ’elbow’ in the sensitivity curve. At this point, the number of accepted tracks decreases sharply, effectively separating the main population of tracks exhibiting coherent propagation (values > 0.4) from the population of stationary or erratically moving tracks (values < 0.4).
2. **Mean LI (Fig. S3b):** The number of accepted tracks nearly saturates (flattens) for mean LI values ≤ 1.5 K. This indicates that 1.5 K serves as a robust physical boundary, separating the vast majority of identified systems (which exist in neutral or unstable mean environments) from a small population persisting in a more stable mean conditions.
3. **Max Area Volatility (Fig. S3c):** The curve flattens significantly for threshold values above 9.0×10^4 km^2. This value was chosen to remove a small population of extreme outliers (e.g., spurious mergers of frontal systems) while retaining the core population of MCS tracks that exhibit more plausible size changes.

Section 3: Morphological Implications for Filtering

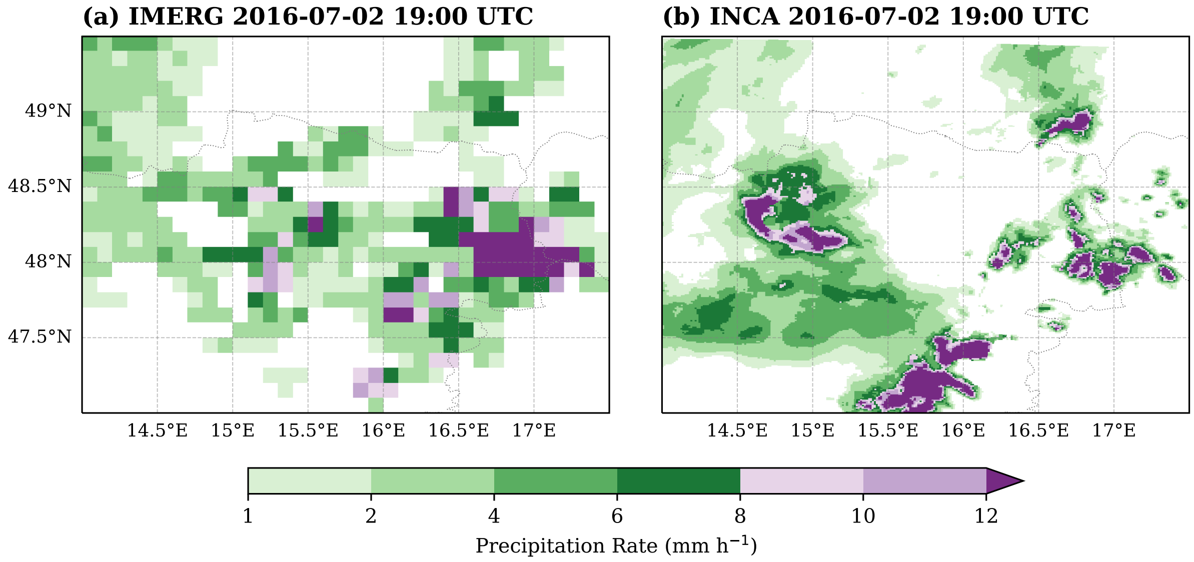
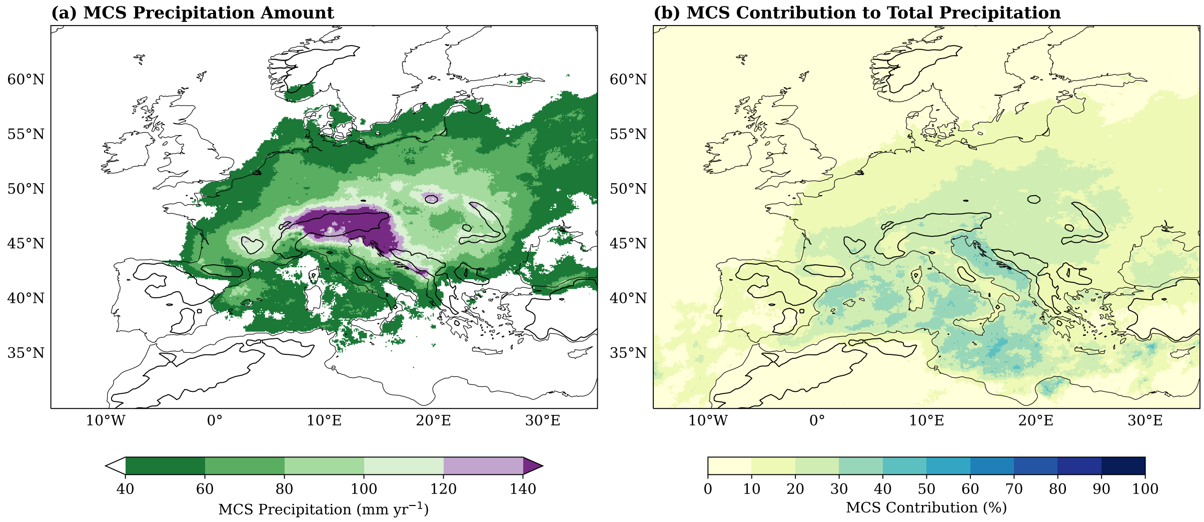


Figure S4: Comparison of precipitation rate (mm/hr) for an event on 2 July 2016 for the 19:00 UTC timestepbetween (a) IMERG and (b) INCA datasets. This case highlights how IMERG's horizontal grid spacing can merge distinct, smaller convective cells (seen in INCA) into a single larger cluster.

Figure S4 further illustrates the morphological differences between IMERG and high-resolution radar, and the implications for the EMMA-Tracker filters. The INCA radar data (b) shows several distinct, intense, and relatively small precipitation cells associated with a local thunderstorm. In the IMERG data (a), the 0.1° horizontal grid spacing and retrieval process merge these distinct cells into a single, larger precipitation "blob". This artificial merging can cause localized, quasi-stationary thunderstorms to meet the MCS area threshold (5000 km^2) in the raw tracking output. However, these systems do not propagate coherently, and their centroids move erratically. They are therefore effectively identified and removed by the Track Straightness filter, ensuring that only genuinely propagating systems are retained in the final climatology.

Section 4: Supplementary Precipitation Statistics



(a) MCS Precipitation Amount

(b) MCS Contribution to Total Precipitation

Figure S5: (a) Total warm-season (May-September) MCS precipitation amount (mm/year) and (b) the corresponding contribution of MCSs to total warm-season precipitation (in %). Data is from 1998–2024.

The following figures provide supplementary context for the precipitation contribution analysis. Figure S5 shows the total absolute precipitation amount from MCSs (a) and their percentage contribution to the total warm-season (May-September) precipitation (b). This map is referenced in the main text to demonstrate that the overall contribution of the filtered MCSs to the total water budget is moderate, generally below 20 to 30% in most of continental Europe.

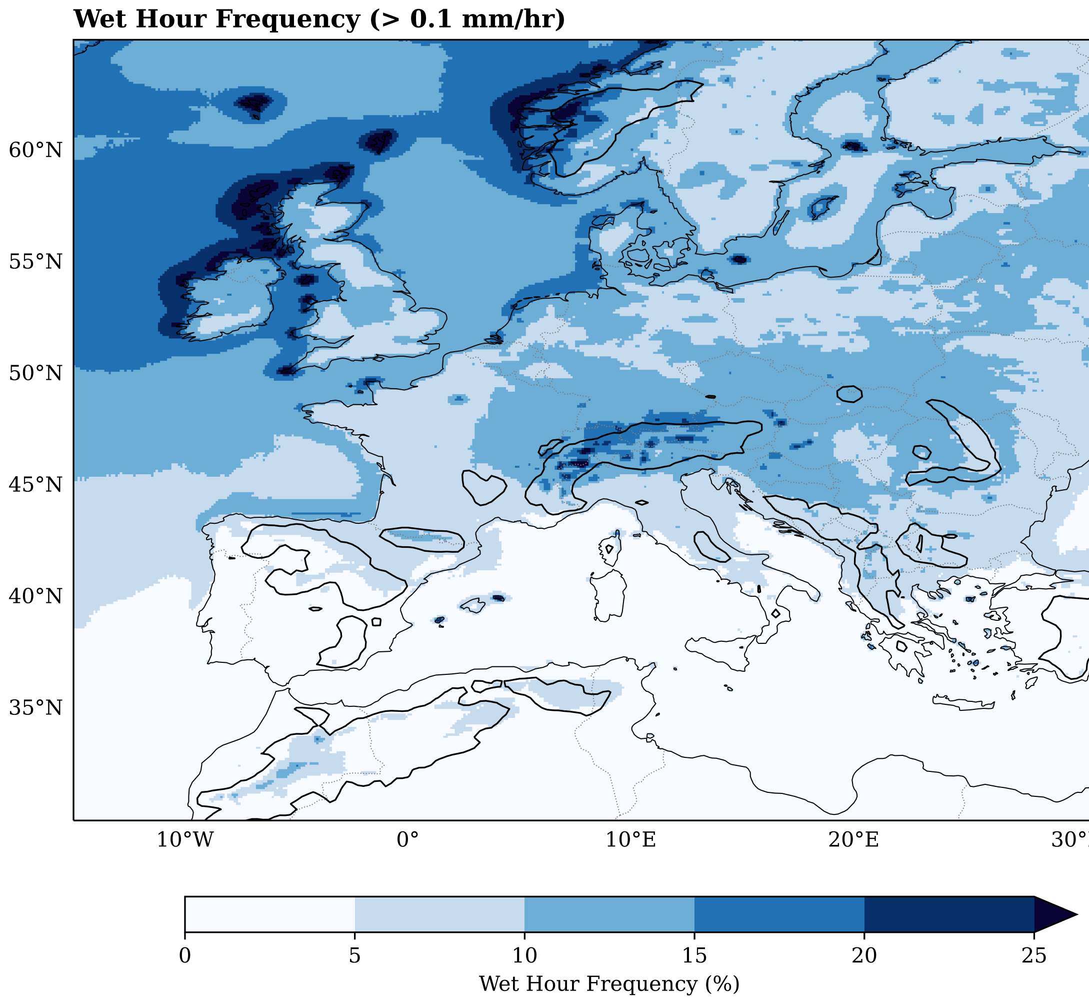


Figure S6: Warm-season (May-September, 1998–2024) WHF over Europe. A wet hour is defined as having IMERG precipitation > 0.1 mm h^{-1}.

Figure S6 provides the climatological Wet Hour Frequency (WHF) for the warm season. This map should provide context for interpreting the heavy precipitation percentiles. The percentiles (P98, P99, etc.) are calculated pixel-wise based on *wet hours only*. Therefore, the local return period of a P99.9 event (a 1-in-1000 wet-hour event) depends on this map. For example, in a region with a WHF of 10%, a P99.9 event corresponds to a 1-in-10,000 *total* hour event, or an average return period of approximately 42 days (10,000 / 24). The WHF over most of continental Europe is between 5% and 15%.