

Editorial

Editorial for Special Issue “Remote Sensing of Precipitation Extremes”

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1. Introduction

Recent years have seen tremendous advancements in the field of extreme precipitation monitoring, particularly through the application of remote sensing technologies. With the increasing frequency and intensity of hydro-meteorological extremes under a changing climate, there is an urgent need to strengthen our capacity to monitor, understand, and manage extreme rainfall and snowfall events globally. Satellite-based precipitation products, offering high spatial and temporal resolution, broad coverage, and near-real-time availability, are playing an increasingly central role in addressing gaps left by traditional in situ observation networks, especially in data-sparse regions.

Despite significant progress, several critical challenges remain. These include calibration and integration of different data sources, improving the accuracy of quantitative precipitation estimation (QPE), especially for extremes, and understanding the complex processes underlying extreme precipitation in diverse climatic and topographic settings. Additionally, translating satellite-based precipitation information into actionable knowledge for hydrological applications and disaster risk management is still an ongoing challenge. The use of advanced data fusion techniques, machine learning algorithms, and integrated approaches to downscaling and bias adjustment have shown promise, but further development is needed for reliable operational applications.

This Special Issue hosts nine papers devoted to remote sensing applications in precipitation, bringing together a diverse collection of studies that address many of the above challenges. These contributions span a range of topics, including the following:

- Calibration and evaluation of ground-based radar networks using satellite data;
- Fusion of radar and gauge data to enhance QPE reliability;
- Performance assessment and bias characterization of satellite precipitation products such as GPM IMERG and TRMM in various climatic regions, including complex terrain;
- Analysis of extreme precipitation events in the context of floods, droughts, and tropical cyclones;
- Case studies on precipitation monitoring in areas with limited in situ data.

Section 2 summarizes the individual articles hosted in this Special Issue in alphabetical order based on the first author's name, and Section 3 outlines some concluding remarks.



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2. Overview of Contributions

The paper authored by Biondi et al. (Contribution 1) presents a comprehensive comparison of various rainfall estimation methods, specifically those relying on weather radar data, rain gauge data, and their fusion. This study evaluates the accuracy and reliability of each method in estimating rainfall for a severe event that occurred in Tuscany, Italy. The results confirm that merging radar and rain gauge data outperforms both individual approaches by reducing errors and improving the overall reliability of precipitation estimates. This study highlights the importance of data fusion in enhancing the accuracy of QPE and supports its application in operational contexts, providing further evidence for the greater reliability of merging methods.

The aim of the study by Keikhosravi-Kiany and Balling (Contribution 2) is to comprehensively evaluate the performance of GPM IMERG Early (IMERG-E), Late (IMERG-L), and Final Run (IMERG-F) in precipitation estimation and their capability in detecting extreme rainfall indices over southwestern Iran from 2001 to 2020. The Asfezari gridded precipitation data, which were developed using a dense network of ground-based observations, were utilized as the reference dataset. The findings indicate that IMERG-F performs reasonably well in capturing many extreme precipitation events. All three products showed a better performance in capturing fixed and non-threshold precipitation indices across the study region. The findings also revealed that both IMERG-E and IMERG-L have problems in rainfall estimation over elevated areas. Examining the effect of land cover type on the accuracy of the precipitation products suggests that both IMERG-E and IMERG-L show large and highly unrealistic overestimations over inland water bodies and permanent wetlands. The results of the study highlight the potential of IMERG-F as a valuable source of data for precipitation monitoring in the region.

In their study, Kim et al. (Contribution 3) examine the influence of water vapor on heavy rainfall events over the complex mountainous terrain of the southern Korean Peninsula using rawinsonde and global navigation satellite system (GNSS) datasets from a mobile observation vehicle (MOVE). The results demonstrate that the prevailing southeasterly winds enhanced precipitation on the leeward side of the mountainous region. The probability of severe rainfall increases in correspondence with the highest precipitable water vapor (PWV) bin (>60 mm). A lead–lag analysis demonstrates that the atmosphere remained moist for 1 h before and after heavy rainfall events. The temporal behavior of PWV retrieved from the MOVE-GNSS data demonstrates that during Changma (the summer monsoon), heavy rainfall events experience a steep decrease after a long increasing trend in PWV. However, the most intense rainfall events occurred after a rapid increase in PWV, along with a strong southwesterly water vapor flow during convective instability.

Loulli et al. (Contribution 4) compare and evaluate volume-matching thresholds and data filtering schemes for the two radars of the Cyprus weather radar network from October 2017 to May 2023. Excluding reflectivities below and within the melting layer with a 250 m buffer yielded consistent results for both ground radars. The selected calibration schemes were combined, and the resulting offsets were compared with stable radar parameters to identify stable calibration periods. The consistency of the wet hydrological year October 2019 to September 2020 suggests that radar calibration results are prone to differences in meteorological conditions, as scarce rainfall can result in insufficient data for reliable calibration.

Pang et al. (Contribution 5) contribute with a study that takes a rare historical event of extreme, heavy precipitation that occurred in the Henan Province, China, in July 2021. By analyzing the distribution of the spatial and temporal characteristics of precipitation errors, using a probability density function of the occurrence of precipitation and the daily variation pattern, the authors assess the capability of a radar precipitation estimation prod-

uct (RADAR), satellite precipitation products (IMERG and GSMAP), a reanalysis product (ERA5) and a precipitation fusion product (CMPAS) to monitor an extreme rainstorm in the region. The CMPAS has the best fit with the gauge observations in terms of the precipitation area, precipitation maximum, and the evolution of the whole process, with a low spatial variability of errors. However, the CMPAS slightly underestimates the precipitation extremum at the peak moment (06:00–08:00). The RADAR product is prone to a spurious overestimation of the originally small rainfall, especially during peak precipitation times, with deviations concentrated in the core precipitation area. The IMERG, GSMAP, and ERA5 products have similar performances, all of which fail to effectively capture heavy precipitation in excess of 60 mm/h, with negative deviations in precipitation at mountain front locations west of northern Henan Province.

The study by Peinó et al. (Contribution 6) evaluates the performance of Integrated Multi-satellite Retrievals for GPM (IMERG V06B) at the sub-daily and daily scales. Ten years of half-hourly precipitation records aggregated at different sub-daily periods were evaluated over the Western Mediterranean. The analysis at the half-hourly scale examines the contribution of passive microwave (PMW) and infrared (IR) sources in IMERG estimates, as well as the relationship between various microphysical cloud properties using Cloud Microphysics (CMIC–NWC SAF) data. The results show the following: (1) a marked tendency to underestimate precipitation compared to rain gauges which increases with rainfall intensity and temporal resolution; (2) a weaker negative bias for retrievals with PMW data; (3) an increased bias when filling PMW gaps by including IR information; and (4) an improved performance in the presence of precipitating ice clouds compared to warm and mixed-phase clouds.

Ullah et al. (Contribution 7) carried out a study that determined the record-breaking impacts of drought events (1998–2002) and flooding (2010) and analyzed a 12-year period, including the follow-on period wherein the winter wheat crop was grown. The study identified the drought, flood, and warm and cold edges over the plain of Punjab Pakistan based on a 12-year time series (2003–2014), using the vegetation temperature condition index (VTCI) approach based on Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) data products. In 2010, the Global Flood Monitoring System (GFMS) model applied to the real-time Tropical Rainfall Measuring Mission (TRMM) rainfall incorporated data products into the TRMM Multi-Satellite Precipitation Analysis (TMPA) for measuring the flood detection/intensity, stream flow, and daily accumulative precipitation, presenting the plain provisions to wetlands. This study tested drought severity, warm and cold edges, and flood levels using the VTCI drought-monitoring approach, which utilizes a combination of the normalized difference vegetation index (NDVI) with land surface temperature (LST) data products.

Binary tropical cyclones (BTCs) typically refer to the coexistence of two tropical cyclones (TCs) within a specific distance range, often resulting in disastrous rainstorms in coastal areas of China. However, the differences in rainfall and underlying causes between BTC-influenced typhoons and typhoons in general remain unclear. In the article by Wang et al. (Contribution 8), the TC closer to the rainfall center in the BTC is referred to as the target typhoon (tTC), while the other is termed the accompanying typhoon (cmp_TC). This study compares and analyzes the rainfall differences and potential causes of tTCs and similar typhoons (sim_TC) that have a comparable track but were unaffected by BTCs from 1981 to 2020. The results show that (1) on average, tTCs and cmp_TC experience 18.79% heavier maximum daily rainfall compared to general TCs, with a significantly increased likelihood of rainfall ≥ 250 mm. (2) Given similar tracks, the average rainfall for tTCs (212.62 mm) is 30.2% heavier than that for sim_TC (163.30 mm). (3) The analysis of potential impact factors on rainfall (translation speed, intensity, direction change) reveals

that sim_TCs move at an average of 21.38 km/h, which is about 19.66% faster than the 17.87 km/h of tTCs, potentially accounting for the observed differences in rainfall. (4) Further investigation into the causes of west–east-oriented BTC rainfall in the Northern Fujian region suggests that water vapor transport and slowing down of the translation speed are the possible mechanisms of BTC influence.

The included research by Zhang et al. (Contribution 1) aims to evaluate the effectiveness of five satellite precipitation products (SPPs)—CMORPH, IMERG-Final, PERSIANN-CDR, TRMM-3B42V7, and TRMM-3B42RT—in identifying variations in the occurrence and distribution of intense precipitation occurrences across the Qinghai–Tibet Plateau (QTP) during the period from 2001 to 2015. To evaluate the effectiveness of the SPPs, a reference dataset is generated by utilizing rainfall measurements collected from 104 rainfall stations distributed across the QTP. Ten standard extreme precipitation indices (SEPIs) are the main focus of the evaluation, which encompasses parameters such as precipitation duration, amount, frequency, and intensity. The findings reveal that (1) geographically, the SPPs exhibited better retrieval capability in the eastern and southern areas over the QTP, displaying lower detection accuracy in high-altitude and arid areas. Among the five SPPs, IMERG-Final outperformed the others, demonstrating the smallest inversion error and the highest correlation. (2) In terms of capturing annual and seasonal time series, IMERG-Final performs better than other products, followed by TRMM-3B42V7. All products performed better during summer and autumn compared to spring and winter. (3) The statistical analysis reveals that IMERG-Final demonstrates exceptional performance, especially concerning indices related to precipitation amount and precipitation intensity; moreover, it demonstrates a slight advantage in detecting the daily rainfall occurrences and occurrences of intense precipitation.

3. Concluding Remarks

The papers included in this Special Issue collectively demonstrate that while significant advances have been made, especially in multi-source data fusion and the use of high-resolution satellite products, challenges remain in capturing extremes in regions with complex topography, diverse climate regimes, or sparse ground-truth data. Several studies highlight the value of integrating satellite, radar, and ground observations for improved QPE, as well as the importance of tailored bias adjustment for different event types and locations. Others emphasize the need for further refinement in retrieval algorithms, calibration methods, and the application of advanced statistical and machine learning techniques.

Looking ahead, several future research directions emerge from this Special Issue:

- Enhanced data fusion could be achieved via further development of multi-source fusion algorithms combining satellite, radar, and gauge data, especially for extreme and localized events.
- The development of machine Learning and AI could lead to broader application of deep learning and AI for both QPE and the classification/forecasting of extreme precipitation.
- Regarding, extreme event characterization, improved methods for identifying and attributing extremes, particularly under changing climate conditions and in ungauged basins, could be developed.
- In terms of operational implementation, translating research advances into robust, user-friendly operational tools for hydrological forecasting and disaster risk reduction could be a key area in future.
- With respect to bias adjustment and downscaling, a key area could be the continued refinement of downscaling and bias adjustment techniques for satellite precipitation data, particularly to support local water management and impact modeling.

- Improving stakeholder Integration and ensuring closer collaboration with end-users and stakeholders could help to ensure that satellite-based precipitation information is accessible, actionable, and relevant for decision-making.

Recent studies also illustrate both the opportunities and challenges associated with these directions. For example, the evaluation of satellite-based precipitation retrievals derived from soil moisture observations (e.g., SM2RAIN-ASCAT) against regional reference datasets has shown promise for certain indices but persistent underestimation or overestimation for several extreme precipitation indicators, particularly in regions with complex terrain or near coastlines. This underlines the need for improved methodologies to capture the intensity and frequency of extremes at regional scales [1].

Beyond their role in characterizing extremes, satellite-based precipitation estimates (SPEs) are increasingly applied in a wide range of operational and societal contexts. They provide critical inputs for water resource management (e.g., irrigation advisory systems), drought monitoring, river flow and flash-flood forecasting, landslide early warning systems, etc. Furthermore, the assimilation of SPEs into numerical weather prediction models has been shown to reduce systematic errors and improve precipitation forecasts. These examples highlight the essential role of SPEs not only for scientific research but also for supporting decision-making in agriculture, disaster risk reduction, and weather services [2,3].

In parallel, artificial intelligence (AI) is increasingly being recognized as a powerful tool to advance our understanding and modeling of extreme weather and climate events. Beyond improving prediction, AI approaches offer potential for more transparent and explainable models, better integration of heterogeneous datasets, and enhanced communication of risk to stakeholders—critical for disaster preparedness and response [4].

The progress highlighted in this Special Issue underscores the importance of interdisciplinary collaboration and the ongoing need to bridge the gap between remote sensing science and practical water management.

This Special Issue showcases the work of those in the scientific community involved in precipitation science. The papers included within highlight the current progress in important areas of precipitation remote sensing, through the presentation of state-of-the-art data sources; technological advances; and relevant methodological approaches. This collection of papers strives to stimulate further research in the field of precipitation remote sensing.

However, it is relevant to note that the community is engaged in using satellite data to improve our understanding of changes in daily precipitation. This necessitates the introduction of new statistical approaches, such the non-asymptotic one proposed by Marra et al. [5]. Studies on the diurnal variability of global precipitation are necessary, especially those using hourly satellite and reanalysis datasets [6]. One final crucial aspect is the investigation of extreme precipitation in poorly gauged areas to derive return levels of extremes in such difficult situations [7], which are very common.

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