Long-term Analysis of Rainfall Variability and Gridded Precipitation Product Performance in Coastal Southeast China

Yuli Wang[1], Joseph Awange[1, *], Ting On Chan[2]

[1] Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, 999077 Hong Kong (SAR), China - wangyuli.wang@connect.polyu.hk, joseph.awange@polyu.edu.hk
[2] School of Geography and Planning, Sun Yat -sen University, 510275 Guangzhou, China - chantingon@mail.sysu.edu.cn
* Corresponding Author: joseph.awange@polyu.edu.hk

Keywords: Gauge-based validation, Precipitation products, Rainfall analysis, Southeast China.

Abstract:

Accurate precipitation estimation is essential for hydrological applications and hazard monitoring in coastal regions characterized by complex terrain and strong land–sea interactions. This study analyzes long-term rainfall variability and evaluates the performance of six widely used gridded precipitation products, namely PERSIANN, IMERG, CHIRPS, ERA5-Land, GSMaP, and MSWEP, over the Guangdong–Hong Kong–Macao region during 2001–2023, using rain gauge observations as a reference. The results reveal pronounced spatial heterogeneity in precipitation trends, with coastal subregions showing a clear drying tendency, whereas the inland mountainous region remains relatively stable. Despite these differences, all regions exhibit highly synchronized interannual variability, indicating the dominant influence of large-scale climatic drivers. All products reproduce the unimodal seasonal cycle associated with the South China monsoon, with peak rainfall occurring in June. However, discrepancies increase during the peak rainy season, when intense convective precipitation enhances estimation uncertainty. Among the evaluated datasets, GSMaP and IMERG consistently outperform the others, with higher correlation coefficients and lower RMSE across most months, demonstrating strong capability in capturing complex precipitation dynamics. In contrast, PERSIANN shows substantial limitations, particularly during low-intensity rainfall periods, while ERA5-Land systematically underestimates peak rainfall intensity despite relatively stable performance. Product uncertainties also exhibit clear seasonal dependence, with the largest errors occurring during the pre-monsoon and monsoon periods. Overall, this study highlights the importance of long-term, region-specific evaluations of precipitation products in complex coastal environments and provides practical guidance for dataset selection in hydrological modeling and disaster risk management.

1. Introduction

Accurate precipitation estimation is critical for hydrological monitoring, flood and landslide early warning, and climate diagnostics in densely populated coastal megacity regions (Awange et al., 2016; Awange et al., 2019; Wang et al., 2026). Guangdong Province, together with Hong Kong and Macao, features strong land–sea contrasts, complex terrain, and frequent typhoon influences, resulting in highly heterogeneous rainfall patterns (Yan et al., 2020). While rain gauges provide reliable point-scale measurements, effective decision-making increasingly relies on spatially continuous gridded precipitation products.

The gridded precipitation products include satellite-based data such as the Integrated Multi-satellite Retrievals for GPM (IMERG) (Huffman et al., 2020), Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Arregocés et al., 2023), the Global Satellite Mapping of Precipitation (GSMaP) (Kubota et al., 2020), and the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks–Climate Data Record (PERSIANN-CDR) (Ashouri et al., 2015), the multi-source blended Multi-Source Weighted-Ensemble Precipitation (MSWEP) product (Beck et al., 2019), as well as the reanalysis product ERA5-Land (Jiang et al., 2021). However, their performance can vary markedly across temporal scales, terrain complexity, and regional rainfall regimes (Khandu et al., 2016; Wang et al., 2025). This highlights the need for gauge-based, long-term evaluations tailored to the Guangdong–Hong Kong–Macao region to clarify the strengths and limitations of these products for both scientific research and operational applications.

Numerous studies have evaluated the performance of satellite-based and reanalysis precipitation products across different climatic regions worldwide, including tropical, arid, and mountainous environments. These studies have demonstrated that product accuracy is strongly influenced by regional climate conditions, terrain complexity, and precipitation regimes, leading to considerable spatial variability in performance (e.g., Beck et al., 2019; Khandu et al., 2016; Maggioni and Massari, 2018).

However, despite these efforts, evaluations specifically focused on coastal regions of Southeast China remain relatively limited. In particular, the Guangdong–Hong Kong–Macao region, characterized by complex land–sea interactions, monsoon dynamics, and frequent typhoon activity, poses unique challenges for precipitation estimation that have not been systematically addressed in existing studies. This highlights the need for a dedicated, long-term assessment to better understand product performance under such complex coastal conditions.

Therefore, a comprehensive, gauge-based long-term evaluation is essential for the Guangdong–Hong Kong–Macao region to systematically assess product performance and to better understand their applicability under complex coastal conditions. This study aims to quantify the accuracy and uncertainties of

https://doi.org/10.5194/isprs-archives-XLIX-B3-2026-295-2026

multiple precipitation products and to provide practical guidance for their use in hydrological and climate-related applications.

2. Study area and data

This study focuses on the Guangdong–Hong Kong–Macao region along the southern coast of China, characterized by sharp land–sea contrasts, complex terrain, and strong monsoonal influence. The area spans coastal plains, the highly urbanized Pearl River Delta, inland hills, and the Nanling mountains. Seasonal rainfall is dominated by the East Asian monsoon, with a wet season from late spring to early autumn, while frequent tropical cyclones bring short-duration intense precipitation and elevated flood risks (Liu et al., 2012; Lai et al., 2021).

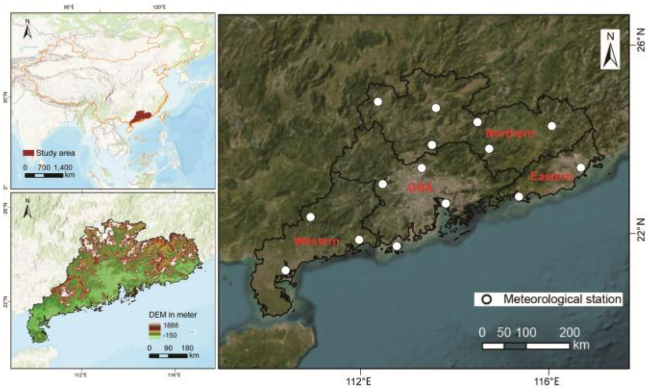

Figure 1. Geographic and topographic characteristics of the coastal regions of Southeast China and the spatial distribution of major meteorological stations.

To ensure the credibility of station-based validation, a comprehensive quality screening was applied to all available rain gauge records using precipitation observations from the National Oceanic and Atmospheric Administration (NOAA). Data completeness was assessed by counting the number of valid daily records for each station–year pair, thereby evaluating both temporal coverage and data continuity.

Following this screening, stations were retained according to three conditions: (i) at least 200 valid observation days per year for most years, (ii) observation records spanning two decades or longer with limited gaps, and (iii) representative spatial coverage across key geomorphic units, including coastal plains, inland hills, and mountainous regions. Based on these criteria, 15 stations were selected, and their spatial distribution is presented in Figure 1.

Table 1. Summary of satellite and reanalysis precipitation products used in this study.

Product	Resolution	Reference
IMERG V07	0.1°/0.5 h	Huffman et al., (2020)
CHIRPS	0.05°/1 d	Funk et al., (2015)
GSMaP	0.1°/1 h	Japan Aerospace Exploration Agency (JAXA), (1998)
PERSIANN-CDR	0.25°/1 d	Ashouri et al., (2015)
ERA5-Land	0.1°/1 h	Hersbach et al., (2020)
MSWEP v2.8	0.1°/1 d	Beck et al., (2019)

Meanwhile, six widely used gridded precipitation products were included in this study, covering satellite-based products, reanalysis products, and multi-source blended products, as summarized in Table 1. To ensure inter-product comparability, all products were harmonized to a common framework by aggregating them to monthly time steps and resampling them onto a unified 0.25° spatial grid. The analysis period (2001–2023) was determined by the maximum overlap among all products.

3. Methods

Product performance was assessed using standard statistical metrics, including the correlation coefficient (CC) to evaluate temporal consistency, the root mean square error (RMSE) to measure magnitude accuracy. These metrics collectively characterize different aspects of model performance, including temporal agreement and error magnitude (Cheng et al., 2025).

$$\mathrm{CC} = \frac{\sum_{i=1}^{n}(P_i-\bar{P})(G_i-\bar{G})}{\sqrt{\sum_{i=1}^{n}(P_i-\bar{P})^2}\sqrt{\sum_{i=1}^{n}(G_i-\bar{G})^2}}, \tag{1}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i-G_i)^2}, \tag{2}$$

where P_i and G_i denote the estimated and observed precipitation at time step i, $\bar{P}$ and $\bar{G}$ are their mean values, and n is the total number of samples. Higher CC and lower RMSE values indicate better performance.

The study further investigates long-term rainfall variability using gauge observations in Southeast China. Trends in annual precipitation were estimated using Sen's slope, a non-parametric approach that quantifies the magnitude of change (mm year^{-1}) while being robust to outliers. The Sen's slope (β) is defined as the median of all pairwise slopes (Abu Arra et al., 2025):

$$\beta = \mathrm{median}\left(\frac{X_j - X_i}{j-i}\right), \quad \forall j > i \tag{3}$$

where X_i and X_j represent precipitation values at time steps i and j, respectively.

4. Results and discussion

To establish a performance baseline, this section evaluates the multi-year precipitation trend in Southeast China. Figure 2 illustrates the interannual variability of regional mean annual precipitation across the four study subregions, together with the corresponding Sen's slope trends. Between 2001 and 2023, the four sub-regions of Guangdong Province exhibited distinct spatial heterogeneity and strong interannual fluctuations in precipitation trends. The East_GD region experienced the most pronounced decline with a Sen's slope of -9.8 mm/yr, followed by the GBA at -7.5 mm/yr, indicating a significant drying trend in the eastern and central coastal sectors over the past two decades. While West_GD also showed a moderate decrease of -4.2 mm/yr, the inland mountainous North_GD remained relatively stable with a near-stationary trend of $+0.5$ mm/yr, suggesting that topographical factors may play a role in buffering the broader regional decline (Zhang et al.,

https://doi.org/10.5194/isprs-archives-XLIX-B3-2026-295-2026

2023a). Despite these varying slopes, all four regions demonstrate highly synchronized temporal oscillations, with prominent rainfall peaks in 2008 and 2016 and synchronized troughs in 2004, 2011, and 2021. This high degree of correlation across the sub-regions suggests that large-scale climatic drivers are the primary determinants of precipitation uncertainties in the area (Zhang et al., 2023b). The contrast between the stable hydrological regime in the north and the accelerating moisture deficit in the coastal southeast highlight a potential shift in the regional moisture transport or monsoon influence that warrants further investigation.

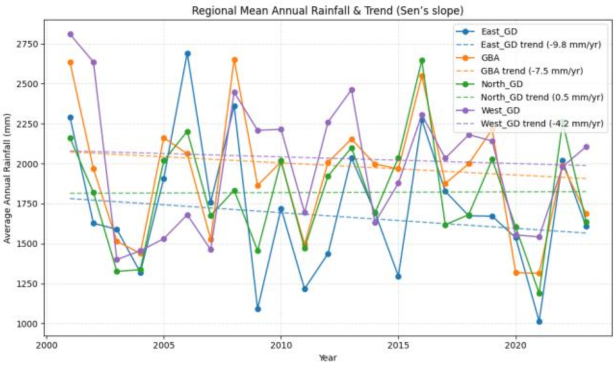

Figure 2. Precipitation trend of Guangdong Province–Hong Kong–Macao.

Figure 3 illustrates the monthly validation of six prominent precipitation products (PERSIANN, IMERG, CHIRPS, ERA5-Land, MSWEP, and GSMaP) against gauge observations. The products demonstrate high performance in capturing monthly rainfall variations, with GSMaP, IMERG, and MSWEP consistently achieving superior correlation coefficients (R > 0.90) across most months, particularly during the transitional seasons of March–May and September–November. While all products align closely with the 1:1 line during low-rainfall periods in January and February, PERSIANN exhibits notably lower reliability in early winter, with an R value as low as 0.21 in January, which indicates significant uncertainties in detecting light or cold-season precipitation.

As rainfall intensity increases during the peak monsoon season (June–August), the dispersion of scatter points expands across all datasets, signaling a decline in estimation accuracy for heavy precipitation events. In June, although most products maintain R values above 0.85, the increased spread suggests that satellite-based and reanalysis products still struggle to precisely capture extreme or convective rainfall totals. Among the compared products, ERA5-Land provides a robust and steady performance throughout the year, yet it generally lags behind top-tier merged satellite products like IMERG and GSMaP in terms of peak correlation, highlighting the inherent trade-offs between reanalysis modeling and direct remote sensing observations.

Figure 4 illustrates the monthly mean precipitation captured by gauge observations and these products. All products successfully reproduce the unimodal seasonal cycle characteristic of the South China Monsoon, with rainfall peaking in June (exceeding 300 mm). While the products show high consistency during the pre-monsoon and post-monsoon periods, noticeable uncertainties emerge during the peak rainy season (May–August), where CHIRPS and IMERG tend to slightly overestimate the monthly totals compared to the gauge data, whereas ERA5-Land consistently underestimates the peak intensity in June. These discrepancies highlight the varying performance of different algorithms in capturing convective and frontal rainfall dynamics over complex coastal terrains.

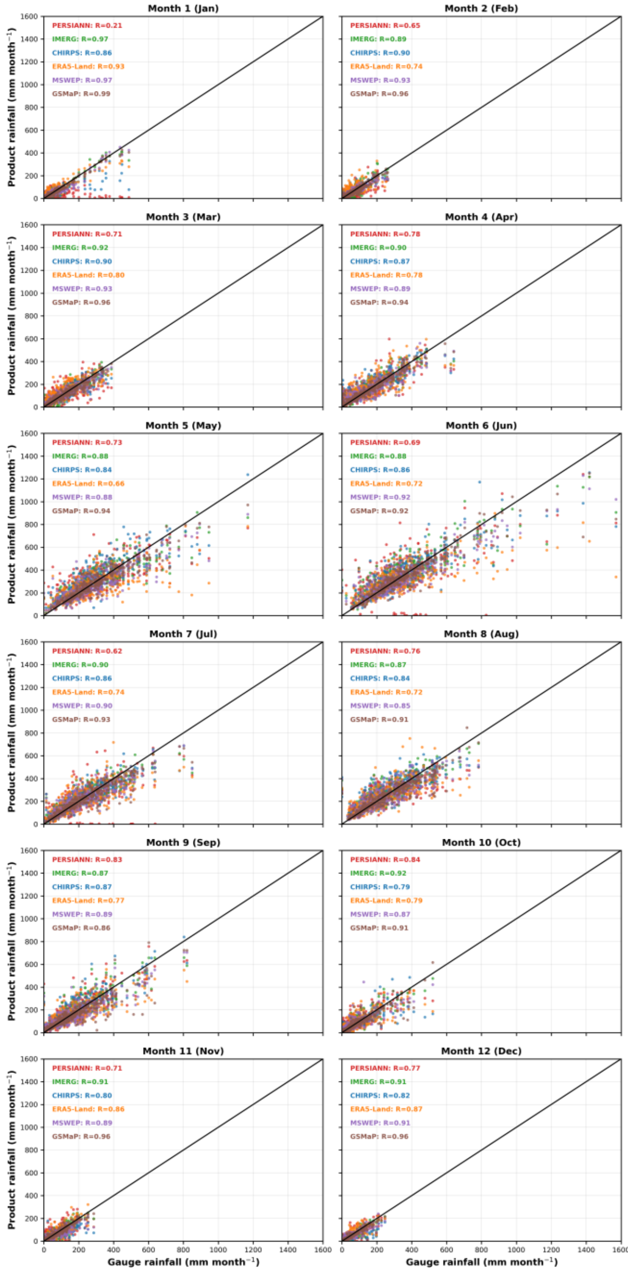

Figure 3. Scatter plots of monthly rainfall between in-situ observations and gridded precipitation products.

The reliability of the six gridded precipitation products in capturing these dynamics is further evaluated through monthly RMSE analysis, as shown in Figure 5. The uncertainties associated with all products exhibit a clear seasonal pattern, with RMSE values peaking during the pre-monsoon and peak monsoon months (May–June) before declining in the dry season. GSMaP and IMERG consistently demonstrate superior performance with the lowest RMSE across most months, indicating their robustness in tracking Guangdong’s complex rainfall patterns. Conversely, PERSIANN and ERA5-Land show substantially higher uncertainties during the peak rainy season, with RMSEs exceeding 150 mm in June, highlighting the persistent challenges satellite and reanalysis products face in accurately quantifying high-intensity convective rainfall over complex coastal and mountainous terrains.

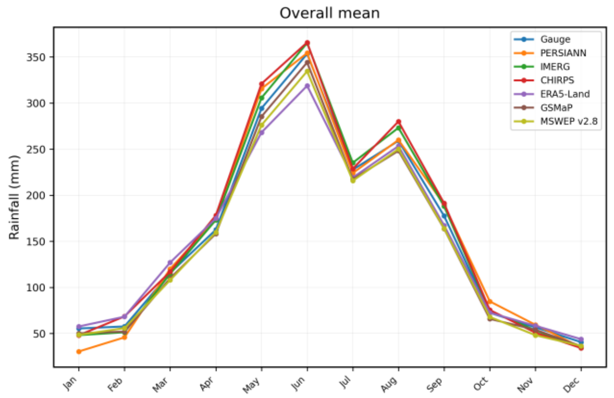

Figure 4. Monthly mean precipitation captured by gauge observations and six gridded precipitation products.

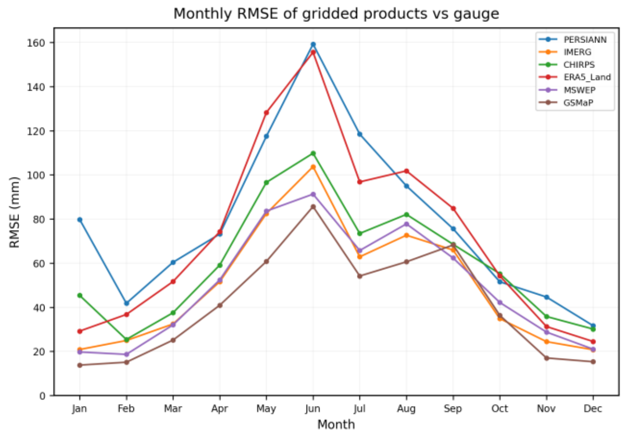

Figure 5. Monthly RMSE of Gridded Precipitation Products.

The comparative validation reveals a clear hierarchy in the performance of gridded precipitation products over Guangdong's complex terrain. GSMaP and IMERG consistently outperform other products, demonstrating superior precision with the highest correlation coefficients (R > 0.90) and the lowest RMSE across most months. This enhanced accuracy can be attributed to their advanced multi-sensor merging algorithms and the integration of high-frequency microwave (MW) samples, which are more physically direct in capturing the liquid water content of monsoon-driven convective systems (Ning et al., 2016; Tang et al., 2016; Bouizrou et al., 2023). In contrast, PERSIANN shows significant uncertainties, particularly during the dry season (e.g., R = 0.21 in January), likely due to its heavy reliance on infrared (IR) cloud-top temperature data. IR-based retrievals often struggle to distinguish between non-precipitating cold clouds and light-rain systems, leading to the observed "near-blindness" during low-intensity winter rainfall (Ashouri et al., 2015).

Furthermore, the notable performance gap during the peak monsoon (May–June) highlights the inherent trade-offs between satellite remote sensing and reanalysis modeling. While satellite-based products like CHIRPS tend to overestimate peak rainfall, which is likely due to challenges in filtering warm orographic clouds, ERA5-Land consistently exhibits a negative bias and higher RMSE exceeding 150 mm in June (Arregocés et al., 2023). This systematic underestimation by ERA5-Land suggests that despite its high-resolution land surface modeling, the underlying reanalysis system may still smooth out extreme, localized convective bursts that are characteristic of the South China rainy season (Jiang et al., 2021). These results indicate that while GSMaP and IMERG are most suitable for tracking high-intensity events, ERA5-Land remains a steady but conservative estimator that requires bias correction when applied to regional flood or extreme weather studies in coastal-to-mountainous transitions (Tarek et al., 2020).

5. Conclusion

This study conducted a comprehensive evaluation of long-term rainfall variability and the performance of six widely used gridded precipitation products over the Guangdong–Hong Kong–Macao region from 2001 to 2023. The results reveal pronounced spatial heterogeneity and strong interannual variability in regional precipitation, with coastal subregions exhibiting a clear drying tendency, while the inland mountainous region remains relatively stable. Despite these differences, all subregions display highly synchronized temporal fluctuations, suggesting that large-scale climatic drivers dominate precipitation variability across the study area .

The validation of gridded precipitation products demonstrates that most products are capable of capturing the seasonal cycle and monthly variability of rainfall, particularly during low-intensity periods. However, substantial uncertainties emerge during the peak monsoon season, when intense convective rainfall becomes dominant. Among the evaluated products, GSMaP and IMERG consistently outperform others, achieving higher correlation and lower RMSE, indicating their strong capability in representing complex coastal precipitation dynamics. In contrast, PERSIANN shows significant limitations, especially during dry seasons, due to its reliance on infrared-based retrievals. ERA5-Land exhibits stable but conservative performance, with systematic underestimation of peak rainfall intensity.

The results further highlight a clear seasonal dependence of product uncertainties, with errors peaking during the pre-monsoon and monsoon periods. This reflects the inherent challenges faced by both satellite-based and reanalysis products in accurately capturing high-intensity and short-duration rainfall events over regions characterized by strong land–sea interactions and complex terrain.

Overall, this study underscores the importance of region-specific, long-term evaluations for precipitation products in coastal environments. The findings provide practical guidance for selecting appropriate products in hydrological modeling and hazard monitoring applications, particularly in monsoon-influenced coastal regions. Future work should focus on integrating multi-source observations and improving retrieval algorithms to better represent extreme precipitation processes in complex terrains.

References

Abu Arra, A., Keskin, M.Z. and Şişman, E., 2025. Trend analysis of hydro-meteorological variables using Mann-Kendall and Sen's Slope with Standardization (SSS): Case study of the Kızılırmak catchment, Türkiye. *Physics and Chemistry of the Earth, Parts A/B/C*, 141, 104115.

Arregocés, H.A., Rojano, R. and Pérez, J., 2023. Validation of the CHIRPS dataset in a coastal region with extensive plains and complex topography. *Case Studies in Chemical and Environmental Engineering*, 8, 100452.

Ashouri, H., Hsu, K.-L., Sorooshian, S., Braithwaite, D.K., Knapp, K.R., Cecil, L.D., Nelson, B.R. and Prat, O.P., 2015. PERSIANN-CDR: Daily Precipitation Climate Data Record from Multisatellite Observations for Hydrological and Climate Studies. *Bulletin of the American Meteorological Society*, 96(1), 69-83.

Awange, J.L., Ferreira, V.G., Forootan, E., Khandu, Andam-Akorful, S.A., Agutu, N.O. and He, X.F., 2016. Uncertainties in remotely sensed precipitation data over Africa: UNCERTAINTIES IN REMOTELY SENSED PRECIPITATION DATA OVER AFRICA. *International Journal of Climatology*, 36, 303–323.

Awange, J.L., Hu, K.X. and Khaki, M., 2019. The newly merged satellite remotely sensed, gauge and reanalysis-based Multi-Source Weighted-Ensemble Precipitation: Evaluation over Australia and Africa (1981–2016). *Science of The Total Environment*, 670, 448–465.

Beck, H.E., Wood, E.F., Pan, M., Fisher, C.K., Miralles, D.G., van Dijk, A.I.J.M., McVicar, T.R., and Adler, R.F., 2019. MSWEP V2 Global 3-Hourly 0.1° Precipitation: Methodology and Quantitative Assessment. *Bulletin of the American Meteorological Society*, 100(3), 473–500.

Bouizrou, I., Bouadila, A., Aqnouy, M. and Gourfi, A., 2023. Assessment of remotely sensed precipitation products for climatic and hydrological studies in arid to semi-arid data-scarce region, central-western Morocco. *Remote Sensing Applications: Society and Environment*, 30, 100976.

Cheng, Y., Zhang, X., Wang, K., Zhang, Y., Guo, Y. and Shen, Y.-J., 2025. Multidimensional evaluation of satellite-based and reanalysis-based precipitation datasets in the Tibetan Plateau. *Journal of Hydrology*, 660, 133364.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A. and Michaelsen, J., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Scientific Data*, 2, 150066.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S. and Thépaut, J.-N., 2020. The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146, 1999–2049.

Huffman, G.J., Bolvin, D.T., Braithwaite, D., Hsu, K.-L., Joyce, R.J., Kidd, C., Nelkin, E.J., Sorooshian, S., Stocker, E.F., Tan, J., Wolff, D.B., and Xie, P., 2020. Integrated Multi-satellite Retrievals for the Global Precipitation Measurement (GPM) Mission (IMERG). In: Levizzani, V., Kidd, C., Kirschbaum, D.B., Kummerow, C.D., Nakamura, K., and Turk, F.J. (eds.), Satellite Precipitation Measurement: Volume 1. Springer International Publishing, Cham, 343–353.

Japan Aerospace Exploration Agency (JAXA), 1998. GSMaP(Hourly). Japan Aerospace Exploration Agency (JAXA) https://doi.org/10.57746/EO.01GS73BKT358GFPY92Y2QNS5E9.

Jiang, Q., Li, W., Fan, Z., He, X., Sun, W., Chen, S., Wen, J., Gao, J. and Wang, J., 2021. Evaluation of the ERA5 reanalysis precipitation dataset over Chinese Mainland. *Journal of Hydrology*, 595, 125660.

Khandu, Awange, J.L. and Forootan, E., 2016. An evaluation of high-resolution gridded precipitation products over Bhutan (1998–2012). *International Journal of Climatology*, 36, 1067–1087.

Kubota, T., Aonashi, K., Ushio, T., Shige, S., Takayabu, Y.N., Kachi, M., Arai, Y., Tashima, T., Masaki, T., Kawamoto, N., Mega, T., Yamamoto, M.K., Hamada, A., Yamaji, M., Liu, G., and Oki, R., 2020. Global Satellite Mapping of Precipitation (GSMaP) Products in the GPM Era. In: Levizzani, V., Kidd, C., Kirschbaum, D.B., Kummerow, C.D., Nakamura, K., and Turk, F.J. (eds.), Satellite Precipitation Measurement: Volume 1. Springer International Publishing, Cham, 355–373.

Lai, Y., Huang, G., Chen, S., Lin, S., Lin, W. and Lyu, J., 2021. Land Use Dynamics and Optimization from 2000 to 2020 in East Guangdong Province, China. *Sustainability*, 13, 3473.

Liu, D., Guo, S., Chen, X. and Shao, Q., 2012. Analysis of trends of annual and seasonal precipitation from 1956 to 2000 in Guangdong Province, China. *Hydrological Sciences Journal*, 57, 358–369.

Maggioni, V. and Massari, C., 2018. On the performance of satellite precipitation products in riverine flood modeling: A review. *Journal of Hydrology*, 558, 214–224.

Ning, S., Wang, J., Jin, J. and Ishidaira, H., 2016. Assessment of the Latest GPM-Era High-Resolution Satellite Precipitation Products by Comparison with Observation Gauge Data over the Chinese Mainland. *Water*, 8(11), 481.

Tang, G., Ma, Y., Long, D., Zhong, L. and Hong, Y., 2016. Evaluation of GPM Day-1 IMERG and TMPA Version-7 legacy products over Mainland China at multiple spatiotemporal scales. *Journal of Hydrology*, 533, 152–167.

Tarek, M., Brissette, F.P. and Arsenault, R., 2020. Evaluation of the ERA5 reanalysis as a potential reference dataset for hydrological modelling over North America. *Hydrology and Earth System Sciences*, 24, 2527–2544.

Wang, J., Awange, J., Shen, Y., Tabatabaeiasl, M. and Song, Y., 2025. Closing Africa's water balance budget: Assessing the suitability of eight latest precipitation products. *International Journal of Applied Earth Observation and Geoinformation*, 142, 104711.

Wang, Y., Ling, Y., Chan, T.O., Ng, A.H.-M., Awange, J., Larouche, C., Shokri, D., Sun, Y. and Xie, J., 2026. Landslide susceptibility under two decades of land use change (2000–2020). *Journal of Maps*, 22, 2633880.

Yan, M., Chan, J.C.L. and Zhao, K., 2020. Impacts of Urbanization on the Precipitation Characteristics in Guangdong Province, China. *Advances in Atmospheric Sciences*, 37, 696–706.

Zhang, A., Chen, C. and Wu, L., 2023a. Regional Variability of Raindrop Size Distribution from a Network of Disdrometers over Complex Terrain in Southern China. *Remote Sensing*, 15(10), 2678.

Zhang, Y., Zheng, X., Li, X., Lyu, J., and Zhao, L., 2023b. Evaluation of the GPM-IMERG V06 Final Run Products for Monthly/Annual Precipitation under the Complex Climatic and Topographic Conditions of China. *Journal of Applied Meteorology and Climatology*, 62(8), 929–946.