Reply to Reviewer comments

Reviewer 1

Summary

The paper addresses the critical importance of accurately estimating global precipitation, especially at the sub-daily scale, where uncertainties are typically higher than daily, monthly, or annual estimates. The study has been conducted on satellite-based and reanalysis products on a global scale. The study specifically investigates the diurnal cycle of precipitation using a comprehensive analysis of five global precipitation products that provide at least hourly resolution data: The analysis focuses on three key parameters of the diurnal variability of precipitation: precipitation amount, frequency, and intensity. The study highlights the need for integrating diverse datasets to minimize uncertainties and ensure a more accurate analysis of global precipitation patterns. Relying on a single precipitation product can lead to misrepresentations due to the inherent discrepancies in the diurnal cycle estimates.

We thank the reviewer for his/her constructive and encouraging comments, and truly appreciate for the time and efforts to review the manuscripts. We paid detailed attention to all the reviewer's comments/suggestions and have responded accordingly.

Major Comments:

If the primary goal is a relative comparison among the products (e.g., to understand differences in product outputs without focusing on absolute accuracy), then comparing the products directly to each other is acceptable. However, for a comprehensive evaluation of accuracy and applicability, it is ideal to use a reliable benchmark dataset. This provides valuable insights into the behavior of each product with respect to the intensity and frequency, allowing for a more robust assessment.

We completely agree with the reviewer that the comparing the datasets with a benchmark

would have definitely added further insights into their accuracy and applicability. However, the lack of a global benchmark product at such high spatial and temporal resolution hinder such studies at the global level.

Indeed, we are interested here in relative comparison, and finding the uncertainties among the estimates rather than finding out the best product. The same is also exclusively highlighted in the conclusion section of the study as; P-23 Line 529 'Overall, the study provides an overview of the agreements and disagreements among the precipitation products at a sub-daily scale on a global level, rather than making claims about the superiority of any one product.'

Why did you not use the latest version of the IMERG product (v07) in this study? Using the most recent version is crucial, as updates in IMERG v07 may include improvements in algorithm accuracy, enhanced calibration, and adjustments based on newer gauge corrections. These enhancements can significantly impact the reliability and precision of precipitation estimates, which is particularly important for a robust inter-comparison of precipitation products. I strongly encourage you to consider using IMERG v07 that has been released in 2023, in your analysis to ensure that your findings are based on the most accurate and current data available.

The study was carried out early in 2023, prior to the release of IMERG V07. Due to certain circumstances the manuscript was postponed. Nonetheless, since IMERG V07 is now available, we agree with the reviewer suggestion that ensuring our findings are based on most accurate, we decided to replace IMERG V06 with IMERG V07 in the revised manuscript.

Minor Comments:

For PERSIANN, and CMORPH the link where the data have been downloaded are mentioned, please do the same for IMERG and GSMaP:

The reviewer's remarks will be added in the revised manuscript as follows; "The IMERG precipitation datasets are accessed from the NASA Goddard Flight Center (https://gpm1.gesdisc.eosdis.nasa.gov/data/GPM_L3/)."

"The GSMaP estimates are obtained from the JAXA G-Portal (https://earth.jaxa.jp/gpr/)."

Line 136-139: please add a reference

The following reference will be added in the revised manuscript; "Subsequently, they are further refined to the desired 0.25° × 0.25° resolution through the nearest neighbour interpolation technique (Thiessen, 1911; Berndt and Haberlandt, 2018)".

Line 170-172: This statement is not fully clear to me. Does it mean that in this case, adding more than 4 clusters improved WSS by less than 7%? And based on that the additional clusters did not significantly enhance clustering quality. Selecting k=4, avoids overfitting while preserving meaningful pattern distinctions in the diurnal precipitation data. Is it correct? If yes, I suggest rephrasing your statement to be more clear.

Indeed, the reviewer understanding is correct. Adding more than 4 cluster resulted in reduction of WSS of less than 7%, which indicate the additional clusters did not significantly improve the clustering quality. To clarify this point to the readers, we have rephrased the sentence as follows: "To determine the optimal number of clusters, the process was iterated from K = 1 to K = 15. Ultimately, k = 4 was selected as the appropriate number of clusters because the reduction in the within-cluster sum of squares (WSS) for additional clusters was below 7%."

Line 216-217: Please mention which index you are referring to, here you refer to intensity, am I right? Do you have an idea of what might be the possible causes for the sharp decline

of GSMaP over south hemisphere?

No, we are refereeing to precipitation amount index in that context. There are three paragraphs, each addressing a different index: the first and second paragraphs refers to precipitation amount and frequency, while the third one focuses on intensity. To make this clear we will cite the figure number there.

Regarding the sharp decline of precipitation features for GSMaP, although the exact reason is yet unknown, it is could be mainly caused by the underestimation of heavy precipitation. We have added further discussion attributing potential causes as follows: "In the southern hemisphere, GSMaP has shown a sharp decline from -30°S until -60°S which could be attributed to the underestimation of heavy precipitation events over the ocean. GSMaP's tendency to underestimate both the amount and frequency of heavy precipitation has also been reported in previous studies (Weng et al., 2023; Ning et al., 2017)."

Line 284-288: Is the only possible reason for differences between IMERG and GSMaP the use of different gauge corrections? What about the variations in their underlying algorithms? In short, while both IMERG and GSMaP utilize a similar constellation of satellite estimates, they differ in algorithms, processing techniques, and data sources, all of which could contribute to the observed discrepancies in precipitation estimates.

I'm also interested in learning more about any overlap between the GPCC and CPC networks, as well as an approximate count of gauges used by each. Additionally, since GPCC and CPC likely apply different quality control, calibration, and interpolation methods, this could further contribute to differences in their final precipitation products, even when some gauges are shared.

We agree with the reviewer's comment that the difference between the IMERG and GSMaP is more than just solely attributed to the gauge correction. Indeed, there is some overlap

between the GPCC and CPC stations (Kidd et al., 2017). However, estimating the exact number of overlapping stations is challenging due to variations in data sources, quality control procedures, and the number of gauges, which fluctuate over time. GPCC uses a time-varying collection of data from over 86,000 stations across the globe (Sun et al., 2018; Schneider et al., 2014). It requires at least 10 years of continuous data for the station to be included in the database. In contrast, CPC utilizes approximately 30,000 stations globally and incorporates historical data and additional sources (such as radar and satellite) to perform quality control on raw datasets. The following discussion has been added to the revised manuscript;

"This behavior of GSMaP over land is notable, considering both IMERG and GSMaP use a similar constellation of satellite estimates. Nevertheless, it should also be noted that both datasets use different gauge corrections over land. IMERG applies GPCC corrections on a monthly scale, while GSMaP utilizes CPC corrections on a daily scale. GPCC accesses from a time-varying collection over 86,000 stations (Sun et al., 2018; Schneider et al., 2014), whereas CPC uses data from 30,000 stations over the globe (Xie et al., 2010). Although there is some overlap among the data sources, both datasets (i.e., GPCC and CPC) exhibit differences due to their underlying quality control measures, interpolation techniques, and other factors. Moreover, beyond gauge corrections, differences between IMERG and GSMaP in their precipitation retrieval algorithms, sampling frequency, and other aspects could also contribute to the observed discrepancies. Among these factors, gauge correction is likely a major reason, as the differences are more pronounced over land than over the ocean. Similar performance of GSMaP has also been reported over China (Weng et al., 2023), where it failed to detect precipitation events during the wet season and underestimated both the frequency and magnitude of precipitation extremes."

Line 303-306: It might be interesting for some readers to have more information on some of the possible reasons for these phenomena! For example, the interactions between Sea Surface Temperature and Boundary Layer: Over oceans, cooling at night allows for more

stable conditions near the surface, which can promote the formation of precipitation in the early morning hours. The surface cooling also reduces convective inhibition, allowing for nighttime or early morning convection. You can also mention other possible reasons such as "latitudinal differences in sunlight and heat retention" etc.

The same comment applies to the "coastal regions" and "over land" parts. Figures 6, 7, and 8: These are very good figures; they're highly informative and well-designed."

Thank you for the insightful suggestion. We will add the physical mechanism responsible for those as; "The diurnal variation in precipitation is primarily driven by the difference in diurnal temperature variation between land and ocean, owing to the ocean's higher heat capacity compared to land. In general, the afternoon peak in precipitation over land is mainly attributed to daytime solar heating, which destabilizes the atmosphere and triggers convection (Yang and Smith, 2006). In contrast, cloud-top nighttime radiative cooling and the resulting thermal instability of the atmosphere cause nocturnal or early morning precipitation peaks over the ocean (Yang and Smith, 2006). Coastal regions, which experience precipitation peaks between those of land and ocean, are influenced by land-sea breeze interactions. Additionally, other mechanisms such as regional topography (e.g., mountains and valleys), latitudinal differences in solar heating, and complex local atmospheric circulations, either individually or in combination further complicate and influence the diurnal variation of precipitation in specific regions (Wang et al., 2023; Ruiz-Hernández et al., 2021)."

Page 15, Figure 7: Do you know why GSMaP displays these north-south striping patterns for the peak precipitation frequency hour?"

Generally, those north-south striping patterns occur in all the datasets, but they are more pronounced in GSMaP. The main reason for this remains unclear, but we will look into it in detail and report the appropriate reasons.

References

Berndt, C., Haberlandt, U., 2018. Spatial interpolation of climate variables in Northern Germany—Influence of temporal resolution and network density. Journal of Hydrology: Regional Studies 15, 184–202. URL: https://www.sciencedirect.com/science/article/pii/S2214581817303361, doi:10.1016/j.ejrh.2018.02.002.

Kidd, C., Becker, A., Huffman, G.J., Muller, C.L., Joe, P., Skofronick-Jackson, G., Kirschbaum, D.B., 2017. So, How Much of the Earth's Surface Is Covered by Rain Gauges? Bulletin of the American Meteorological Society 98, 69–78. URL: https://journals.ametsoc.org/view/journals/bams/98/1/bams-d-14-00283.1.xml, doi:10.1175/BAMS-D-14-00283.1. publisher: American Meteorological Society Section: Bulletin of the American Meteorological Society.

Ning, S., Song, F., Udmale, P., Jin, J., Thapa, B.R., Ishidaira, H., 2017. Error Analysis and Evaluation of the Latest GSMap and IMERG Precipitation Products over Eastern China. Advances in Meteorology 2017, e1803492. URL: https://www.hindawi.com/journals/amete/2017/1803492/, doi:10.1155/2017/1803492. publisher: Hindawi.

Ruiz-Hernández, J.C., Condom, T., Ribstein, P., Le Moine, N., Espinoza, J.C., Junquas, C., Villacís, M., Vera, A., Muñoz, T., Maisincho, L., Campozano, L., Rabatel, A., Sicart, J.E., 2021. Spatial variability of diurnal to seasonal cycles of precipitation from a high-altitude equatorial Andean valley to the Amazon Basin. Journal of Hydrology: Regional Studies 38, 100924. URL: https://linkinghub.elsevier.com/retrieve/pii/S2214581821001531, doi:10.1016/j.ejrh.2021.100924.

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Ziese, M., Rudolf, B., 2014. GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle. Theoretical and Applied Climatology 115, 15–40. URL: https://doi.org/10.1007/s00704-013-0860-x, doi:10.1007/s00704-013-0860-x.

Sun, Q., Miao, C., Duan, Q., Ashouri, H., Sorooshian, S., Hsu, K.L., 2018. A

Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons. Reviews of Geophysics 56, 79–107. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/2017RG000574, doi:10.1002/2017RG000574. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/2017RG000574.

Thiessen, A.H., 1911. PRECIPITATION AVERAGES FOR LARGE AREAS. Monthly Weather Review 39, 1082–1089. URL: https://journals.ametsoc.org/view/journals/mwre/39/7/1520-0493_1911_39_1082b_pafla_2_0_co_2.xml, doi:10.1175/1520-0493(1911)39<1082b:PAFLA>2.0.CO;2. publisher: American Meteorological Society Section: Monthly Weather Review.

Wang, J., Yuan, H., Wang, X., Cui, C., Wang, X., 2023. Impact of Thermally Forced Circulations on the Diurnal Cycle of Summer Precipitation Over the Southeastern Tibetan Plateau. Geophysical Research Letters 50, e2022GL100951. URL: https://onlinelibrary.wiley.com/doi/abs/10.1029/2022GL100951, doi:10.1029/2022GL100951. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2022GL100951.

Weng, P., Tian, Y., Jiang, Y., Chen, D., Kang, J., 2023. Assessment of GPM IMERG and GSMaP daily precipitation products and their utility in droughts and floods monitoring across Xijiang River Basin. Atmospheric Research 286, 106673. URL: https://www.sciencedirect.com/science/article/pii/S0169809523000704, doi:10.1016/j.atmosres.2023.106673.

Xie, P., Chen, M., Shi, W., 2010. CPC unified gauge-based analysis of global daily precipitation (2010 - 90annual_24hydro). URL: https://ams.confex.com/ams/90annual/techprogram/paper_163676.htm.

Yang, S., Smith, E.A., 2006. Mechanisms for Diurnal Variability of Global Tropical Rainfall Observed from TRMM. Journal of Climate 19, 5190–5226. URL: https://journals.ametsoc.org/view/journals/clim/19/20/jcli3883.1.xml, doi:10.1175/JCLI3883.1. publisher: American Meteorological Society Section: Journal of Climate.