

## **Advancing Global Precipitation Monitoring Products for Science and Applications**

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*To those who have not tried it, measuring rainfall might seem simple. It is not.*

—National Academies report on Extreme Precipitation Events<sup>1</sup>

### **Synopsis**

NASA's satellite precipitation products provide global coverage at a high resolution and a consistent long-term record, and have been instrumental for scientific research and societal applications. However, these products have limitations in their representation of intense and light precipitation, snowfall, orographic precipitation, and uncertainties, all of which hinder effective use, most acutely in the hydrology community. This white paper addresses these limitations with a set of recommendations on implementation approaches within NASA's Hydrosphere research area. These recommendations focus on priorities for future satellites, continued investment in algorithm development, and a multi-source data processing system.

Specific recommendations are:

1. Maintain a satellite reference standard with sufficient channel diversity and resolution.
2. Enhance the imager capabilities on the reference satellite with hyperspectral sounding and coincident soil moisture and snowfall observations.
3. Study the impact of upcoming and commercial satellites on multi-satellite precipitation products and advance the low-frequency technology to complement these satellites.
4. Sustain support for precipitation rate retrieval algorithm improvement.
5. Improve snowfall retrievals and phase-discrimination models.
6. Provide a better representation of precipitation extremes.
7. Tackle the longstanding challenge of quantifying uncertainty.
8. Collaborate with international partners on analysis-ready geostationary data.
9. Create a modern multi-source data processing system.

These recommendations would allow NASA to address user needs in the next decade in a realistic framework, thus ensuring NASA's continued global leadership in satellite precipitation monitoring.

## **1 Importance of Global Satellite Precipitation Products for Science and Applications**

Rainfall and snowfall are necessary for life on Earth but are highly variable and difficult to estimate. They are also among the forms of weather that regularly threaten life, property, and prosperity. NASA has been at the forefront of global research both to understand the processes affecting precipitation and to develop global multi-satellite precipitation monitoring products that provide a long-term program of record at a high resolution. In particular, the Integrated Multi-satellite Retrievals for GPM (IMERG) precipitation products<sup>2</sup> from the Global Precipitation Measurement (GPM) mission<sup>3</sup> and the predecessor TRMM Multi-satellite Precipitation Analysis (TMPA) from the Tropical Rainfall Measuring Mission (TRMM) have been cornerstones of scientific research and societal benefits. Enabled by the coordination of satellite data from domestic and international agencies, IMERG (0.1°, ½-hour, global coverage) and TMPA (0.25°, 3-hour, 50°N/S) have been used in scientific research and societal applications. This focus on applications (Figure 1) began well before NASA formally adopted its Earth Science to Action strategy in 2024 to provide actionable information to decision-makers.

The Web of Science citation index includes over 1,700 peer-reviewed journal articles referencing IMERG, with about 2,000 additional technical articles related to the GPM mission. Among other things, IMERG has been used to characterize extreme events, model streamflow, analyze precipitation variability, and evaluate global models. IMERG is also used in a range of societal applications, including the estimation of drinking-water supply recharge, agriculture, drought monitoring, disaster response, disaster readiness, and reinsurance underwriting<sup>6–8</sup>. IMERG also supports other agencies such as the Department of Defense through the Global Hydrology Information<sup>9</sup>, which reduce duplication of effort across the U.S. government and thus increase the value to taxpayers. Table 1 provides a partial list of key on-going applications users for GPM data.

Why are observations important given numerical modeling advances and why should NASA fulfill this role? While numerical global models—including reanalysis products and Artificial Intelligence models—are playing an increasingly important role in quantifying the Earth system, they currently fall short when it comes to precipitation<sup>10–14</sup>. It is unlikely that models alone can approach the skill of satellite retrievals in convective environments during the next decade. While NOAA does produce satellite precipitation products, their primary emphasis is on supporting forecasters with real-time observations, so consistency in the entire record is not a focus. In contrast, NASA prioritizes maintaining a record with minimal artifacts arising from changes in the observing system. This enables support for research and applications that require long-term observations at sub-daily resolutions, from calculating recurrence intervals to pricing parametric insurance premiums.

## **2 Challenges and Gaps in Current Global Satellite Precipitation Products**

### **a) Science and Applications Needs**

Precipitation is a key component of the Hydrosphere program within NASA, with a mission statement focused on “Monitoring and predictive understanding of the Earth’s water supply across the land, ocean, and atmosphere”<sup>15</sup>. In addition, NASA’s Multi-source Integrated Observatory (MIO) will have “Water” as one of its major themes. The atmospheric part of the water cycle is a primary means by which water is redistributed around the globe through evaporation from the surface, transport within the atmosphere, cloud and precipitation formation and evolution, and removal to the surface in precipitation. Precipitation also ties into land surface processes such as water runoff, streamflow, and changes in soil moisture. Thus, accurate long-term precipitation information is an important part of a holistic view of the water cycle. This long-term record, though, faces challenges related to calibration differences across sensor generations and types, varying sensor channel sets,

coarse spatial and temporal resolution, high uncertainty over complex terrain or snow-covered surfaces, and a relatively short observation record that limits the detection of climate trends.

The applications community is one of the largest users of precipitation data. A key part of that community is the hydrology community, which uses precipitation as input to drive applications-related to storm runoff, flash floods, streamflow, and so on. Many other applications flow down from hydrological models, including those in the areas of water resources, emergency management, disaster response, reinsurance, agriculture, and disease monitoring. The hydrology community focuses on land areas where gaps in precipitation estimates discussed below are felt most acutely. These gaps lead to large uncertainties in the various hydrological applications. In particular, higher resolution observations are required to resolve convective-scale storms and associated short-duration, high-intensity events that drive the largest impacts such as flash floods and urban flooding. As such, accurate estimation of timing, peak rate, and storm structure at sub-hourly scales and capturing accurate depictions of the convective cores are needed. Another critical gap is reliable snow-rain-mixed phase partitioning and snowfall rate estimation, particularly when the surface temperature is near 0°C. Errors in phase propagate directly into streamflow and water availability forecasts. Scientific innovation to improve phase detection and develop uncertainty quantification are a high priority to advance these hydrological applications<sup>16</sup>.

As summarized below, currently available satellite observing systems and algorithms struggle at low precipitation rates, yet light precipitation strongly affects soil moisture, ecosystem stress, and the onset or recovery of drought. Better detection of low precipitation rates and clearer separation of no-precipitation vs trace cases, and more consistent performance across stratiform regimes where drizzle is common, is necessary.

## **b) Gaps in Satellite Precipitation in Addressing these Needs**

### **i) Extremes**

Both very large amounts of precipitation and prolonged absences of precipitation are “extreme”, but shortcomings in our ability to analyze satellite observations for these limiting cases of the precipitation spectrum differ. Drought is persistent lack of precipitation, and a key difficulty is in correctly capturing occasional, likely isolated light precipitation. More generally, the problem of both ends of extremes is one of getting the correct distribution, which is important in itself for scientific studies, and also because precipitation retrievals use total volume as a constraint, so deficiencies at one end affect the other. Conversely, as excessive rainfall is often driven by individual convective storm systems that typically have small space and time scales or by precipitation that is augmented by ascent over significant topographic features, they are also hard to observe accurately.

Observations of both heavy and very light precipitation suffer from coarse spatial and temporal sampling. The variety of microwave sensor types and capabilities leads to a heterogeneous set of measurements of varying quality and resolution. The spatial scale of smaller showers and convective storms and the scale of variability within larger precipitation systems are typically smaller than the footprint sizes of many spaceborne sensors, significantly limiting accurate characterization of precipitation at local scales. Improvements in precipitation retrievals depend critically on developing advanced radiometer technologies and passive microwave (PMW) retrieval algorithms with a focus on small scales. Meanwhile, the discrete and often widely separated overpasses by satellites carrying PMW sensors give no direct information about the evolution of precipitation systems between the observed times. Current multi-satellite schemes fill these gaps with some form of Lagrangian interpolation between PMW observations, but these do not account for storm lifecycles between overpasses. Figure 2 provides one estimate of the sampling interval required to adequately capture hydrologically important events.

A significant challenge for retrieving scattered light precipitation is to better discriminate between light and zero precipitation, including in situations where light rain evaporates before reaching the surface. Current PMW retrievals do not emphasize this distinction, typically depending on simple thresholding schemes to approximate the division. The heavy-precipitation challenge is that current retrievals for each individual sensors treat heavy precipitation as a simple continuation of the retrieval algorithm for all nonzero precipitation rates, meaning that the developmental statistics are dominated by the much more common low and medium precipitation rates.

## **ii) Snowfall**

Snowfall remains difficult to estimate because snow- and ice-covered surfaces hamper the ability of PMW sensors to correctly detect and measure falling snow<sup>17,18</sup>. In addition, radar signals within ice-phase precipitation are often too weak and/or shallow for satellite-based precipitation radars to accurately estimate light to moderate snowfall rates<sup>19</sup>. This weak/shallow signal issue extends to PMW retrievals as well. The need to closely monitor snowpack, including through improved snowfall observations, has become urgent in recent years as low snowpack threatens drinking and agricultural water supplies in snowmelt-dominated areas such as the Western and Southwestern United States.

## **iii) Orography**

Satellite precipitation products have long struggled to capture orographic precipitation<sup>20–25</sup> because the dynamic enhancement of surface precipitation rate, often involving the liquid phase and warm rain processes<sup>26</sup>, is not captured in PMW retrievals over land, which depends on the ice-scattering signals. While PMW retrieval schemes have incorporated corrections, e.g., by including an explicit orographic index based on wind motions near mountainous terrains<sup>27,28</sup>, their success is thus far unclear, especially when incorporated into Level 3 products<sup>29</sup>. Alternatively, orographic enhancement correction schemes using machine learning (ML) techniques have demonstrated promise<sup>30</sup>, but their generalizability beyond the specific training region remains to be determined. The regions affected by issues in Sec. 2bi–iii are depicted in Figure 3.

## **iv) Uncertainty**

Efforts to quantify the errors and uncertainties in precipitation estimates have lagged significantly over the last three decades. Aside from the basic scientific imperative that we must provide such information, uncertainty estimates are needed by researchers and applications developers who combine satellite precipitation estimates with estimates from local sources such as rain gauges and weather radar, or who use the precipitation estimates in models, in decision support systems, and in combination with other (uncertainty-informed) datasets. Recent developments provide promising avenues for progress in the coming decade<sup>31–35</sup>.

Gaps in current satellite precipitation for user needs include:

- homogeneity in the long-term precipitation record,
- consistency across the full distribution of precipitation,
- correct detection of light precipitation,
- accurate phase partitioning and snowfall rates,
- quantified orographic precipitation,
- ability to quantify small-scale systems,
- short sampling intervals for PMW sensors,
- correct timing, peak rate, and structure in storms, and
- user-relevant uncertainty quantification.

### **3 Recommendations for Addressing these Gaps in the Next Decade**

Progress in precipitation science and observation is key to supporting many of the societal applications that critically depend on NASA's precipitation products. The PMW program of record is a heterogeneous mix of sensors of varying capabilities, often with highly constrained measurement capabilities. The Decadal Survey offers the opportunity to identify future directions for NASA observational technologies and to identify high-priority pathways for integrating the program of record for improved precipitation science and better connection to other communities. The sections below identify some of these future directions as well as important areas for improvement in observational technologies and algorithms that can realistically be achieved in the next decade.

#### **a) Priorities for Future Satellites**

The best payoffs for improved precipitation observations are achievable only if NASA invests in future assets. Computing integrated global precipitation observations requires a reliable reference satellite for calibration and training of ML algorithms. In the GPM mission, this role is served by the GPM Core Observatory with its active and passive instruments and a non-sun-synchronous orbit. A non-sun-synchronous orbit is essential for a reference satellite to collocate observations across the entire globe with sun-synchronous satellites. The active instrument should have at least the Ku-band (13.6 GHz) with a horizontal resolution of 5 km and a swath of 245 km (matching GPM KuPR). The passive instrument should have a broad range of channel frequencies for observing liquid and frozen precipitation, high accuracy, and high spatial resolution—similar to GMI or better. For nearly 30 years, the TRMM and GPM satellites served as references. JAXA's upcoming Precipitation Measuring Mission (PMM) may be insufficient to serve as the next reference since in its current formulation the radiometer lacks the low-frequency channels (19–37 GHz) required for accurately retrieving liquid phase precipitation. Maintaining a high-quality satellite that can serve as a reference standard for a constellation is necessary for optimizing the value of precipitation products.

Just as the GPM Microwave Imager (GMI) advanced on TRMM's imager by adding frequencies near 166 and 183 GHz, there are important opportunities to enhance imager capabilities on the reference satellite. Sounding channels near 50–60, 118, and 183 GHz, including hyperspectral capability, could add valuable information about the thermodynamic conditions in and around precipitation. L-band (1.4 GHz) and C-band (4–8 GHz) could provide concurrent information on both soil moisture and precipitation, enabling computing coupled land-atmosphere interactions and giving insight into moisture availability, precipitation runoff, and floods. Sub-mm frequencies (> 300 GHz) are very sensitive to ice scattering and could improve snowfall retrievals, especially when coupled with 183 GHz channels. Not only will this improve the reference satellite capabilities to advance precipitation science, but it will also enhance our understanding of retrieval physics, thus strengthening the foundation of multi-satellite products.

A constellation of low-Earth orbit (LEO) PMW sensors continue to provide the backbone of global satellite precipitation products since they offer a good balance between sampling and accuracy. Expanding the constellation of PMW sensors in space, perhaps by intelligently taking advantage of growing capabilities in smallsat technologies, can reduce the current reliance on Lagrangian interpolation to fill temporal gaps. However, current plans to focus upcoming PMW satellites on higher channel frequencies may reduce retrieval skill, especially over the ocean where the low-frequency channels add valuable information. This issue is particularly relevant as NASA begins to use commercial PMW smallsats that—while having the potential to greatly expand the coverage and improve revisit rates in conjunction with agency satellites—are currently limited to high frequencies. It is unclear what impact this combination of increased sampling and reduced skill will have on the identified gaps in satellite precipitation, so research on this front is urgently needed, especially in the

ML framework. At the same time, NASA must invest in technological research to develop low-cost PMW sensors with low-frequency channels (19–37 GHz) that can complement the expected smallsat constellation.

Investing in future assets involves:

- maintaining a high-quality reference satellite,
- enhancing channel capability on the reference satellite's PMW sensor, and
- enabling low-frequency technologies complementary to PMW smallsats.

## **b) Continued Investment in Algorithm Development**

Some of the gaps discussed in Section 2 require continued investment in algorithm development and data integration. It is crucial that we remain grounded in the physics of the retrieval process even as ML techniques have demonstrated excellent progress when applied to retrieval algorithms. But all such algorithms are essentially in their first generation, so there is much room for further adoption and refinement. For example, the GPM PMW retrieval scheme uses a radar-radiometer algorithm for its training reference, but this reference has known deficiencies. It is plausible that greater use of ML techniques can help with these deficiencies. ML techniques have also demonstrated promise in related quantities such as downscaled precipitation<sup>36</sup>, snowfall retrievals<sup>37</sup>, and convective or stratiform type<sup>38</sup>. Similarly, better use of low-frequency channel information and footprint oversampling through ML approaches can facilitate progress on orographic precipitation, which often involve warm rain seeder-feeder processes associated with emission rather than scattering signals in the microwave<sup>26</sup>. Meanwhile, in IMERG, the morphing technique and the Kalman filter merging scheme almost certainly would benefit from ML approaches such as incorporating multispectral geosynchronous Earth orbiting (GEO) infrared (IR) data and information on the evolution of precipitation systems into the morphing process<sup>39</sup>. At the same time, whether ML schemes can incorporate or replace the brightness temperature calibration and the precipitation rate calibration—both currently essential in the GPM family of products—is a matter of research, a topic that is central to whether changes in the observing system manifest as artifacts in the long-term precipitation record. All of these algorithm investments should improve the overall accuracy of satellite precipitation, but they require sustained support.

There is significant potential for advances in the determination of precipitation phase. On the one hand, direct retrievals of snowfall from PMW instruments are an area of active research<sup>40</sup>. On the other hand, it is also vital to continue development of a parametric model that determines the phase using environmental conditions. In IMERG, wet-bulb temperature is used to determine the probability of phase based on a database derived from station observations, but avenues for further development can be found using additional variables, ML techniques, and a broader database<sup>41</sup>. Therefore, improving snowfall retrievals requires investments on parallel tracks of snowfall-specific retrieval algorithms and a parametric model, each with different time horizons.

For extremes specifically, ML retrieval schemes can benefit from an investigation into the optimal loss function. The conventional loss function in ML regression—mean squared error—is excellent for minimizing overall biases but may limit the dynamic range of estimates, particularly in situations of limited information content. Evaluation metrics that can represent the skill in quantifying extremes or—even better—the full distribution of values are required. Additionally, these metrics need to move beyond pixel-based quantities and account for spatiotemporal structure. Addressing the full distribution and spatiotemporal structure would allow for a more accurate quantification of both very heavy and very light precipitation. In the presence of a reliable validation reference, metrics and loss functions that go beyond the mean are a step towards a more accurate representation of extremes.

There are fresh approaches that have strong potential to drive progress on the longstanding grand challenge of quantifying uncertainty for precipitation. The central challenge is that precipitation is intermittent and has a highly skewed non-negative distribution of precipitation rates. Furthermore, precipitation retrieval is an underdetermined problem and the merging process introduces additional complexities. Recent promising developments include: (i) ML techniques have demonstrated capability in producing data-driven probabilistic distribution of precipitation rates as opposed to computing a single deterministic value<sup>28</sup>; (ii) studies on precipitation rates have identified suitable distributions to represent these uncertainties in a succinct set of parameters<sup>31</sup>; and (iii) several use cases have demonstrated applying precipitation uncertainties in hydrological applications<sup>34,35</sup>. While these efforts are currently separate, support for a coordinated push in uncertainty quantification should provide scientifically defensible and operationally feasible solutions to this longstanding problem. This work will also open the opportunity to address the spatiotemporal structure of the uncertainties driven by the multi-scale nature of precipitation.

GEO satellites have an important role to play in filling the gaps between LEO swaths, though at the expense of reduced accuracy. While global precipitation retrievals from GEO traditionally rely on the 11- $\mu$ m channel, recent advances have demonstrated the value in other channels onboard the GEO satellites. Up to now, these other channels have lacked utility because there was no analysis-ready archive as has been the case for 11  $\mu$ m (provided by NOAA/NWS/CPC). Fortunately, EUMETSAT is leading an international project to develop GEO-Ring<sup>42</sup>, a consistent, analysis-ready GEO record extending back to the start of GEO data in 1980, which is specifically designed to support work such as multispectral precipitation retrievals. Therefore, NASA should collaborate with the GEO-Ring project and prioritize developing multispectral precipitation retrievals based on the GEO-Ring archive.

Continued investment in algorithm development will:

- improve overall accuracy,
- improve phase distinction and quantify snowfall,
- better represent extremes,
- develop scientifically based uncertainty estimates, and
- leverage the multispectral information in GEO satellites.

### c) Multi-Source Precipitation Data Processing

In the next decade, how will all of these technical and algorithmic innovations in precipitation find their way into the datasets that are actually used in science and applications? The GPM mission currently provides comprehensive support for this computing through the Precipitation Processing System (a Science Investigator-led Processing System). However, such support is not planned for future missions, requiring that precipitation be treated as a fundamental Earth science variable with its own dedicated processing facility. This new processing system should take advantage of efficiencies in NASA's planned shared resources and processing capabilities.

The observations from dozens of individual PMW satellite instruments must be processed on an on-going basis. Channel data from individual satellite sensors are quality-controlled, intercalibrated, and converted to precipitation retrievals. This processing must first occur in near-real time, primarily for Earth Action application use, then be repeated once more-complete input data arrive that are needed for science-quality retrievals. It is a hallmark of NASA data products that the entire data record is recomputed each time a new version of the science algorithm is released. So, this next-generation processing facility must be capable of retrospectively processing petabytes of observations from PMW and GEO IR satellite instruments across the entire period of record (1998–present) when algorithms are improved while also handling the new input data.

The processing facility must interact with the input data providers, algorithm developers, and end users. It is mandatory that products from both the on-going and retrospective processing be quality checked, including trending analysis, to ensure the scientific integrity of the data that NASA is providing to user communities. Other essential activities include coordinating with algorithm developers to run long-term tests of potential algorithm upgrades and co-developing value-added datasets with end users to address specific needs in the community.

#### **4 Summary and Recommendations**

Current satellite precipitation products like IMERG have a proven track record for scientific research and societal applications, laying down the trail for subsequent Earth Action activities. However, significant gaps remain in our ability to represent both intense and light precipitation, distinguish between rainfall and snowfall, and quantify uncertainties in a useful way. Fortunately, advances in our understanding and in computation methods provide avenues to address these gaps in the coming decade. Specific recommendations are:

- Prioritize future satellite capabilities needed for precipitation estimation:
  1. Maintain a satellite with sufficient channel diversity and resolution to serve as the reference for the constellation.
  2. Enable new capabilities for the reference imager through hyperspectral sounding and precipitation observations coincident with soil moisture and with snowfall.
  3. Study the impact of varying-quality and often high-frequency PMW platforms on multi-satellite precipitation products and advance the technology for low-cost low-frequency instruments.
- Invest in algorithm development:
  1. Sustain investment on precipitation rate retrieval to maximize returns on existing NASA assets.
  2. Advance snowfall quantification through improved retrievals and parametric models.
  3. Improve the representation of precipitation extremes through better metrics.
  4. Tackle uncertainty quantification by expanding on recent research.
  5. Collaborate with the GEO-Ring project to improve the utility of GEO data for precipitation estimation.
- Create a modern multi-source data processing system capable of both near-real-time and retrospective research-grade processing.

This white paper lays out a path to advance and mature Earth Action-ready satellite precipitation products that provide the longest data record, highest resolution, and lowest latency possible from the available archive of legacy, current, and future satellites, serving both the scientific community and societal applications. This streamlined workflow should be built with the latest ML techniques, ingesting a constellation of full-spectrum PMW on LEO satellites—leveraging NASA-demonstrated low-frequency technology—and multispectral IR on GEO satellites from government and commercial partners. All these input data sets should be anchored to a reference satellite that is tailored for precipitation retrievals in a cost-efficient structure. The driving algorithm should produce precipitation rate estimates that are accurate across the full range of values, with accompanying uncertainty quantification and precipitation phase estimates. When connected to hydrological modeling, this effort would lead to improved streamflow and water availability forecasts, as well as better characterization of soil moisture, ecosystem stress, floods, and droughts. This path is viable and realistic if NASA invests in global satellite precipitation research during the coming decade.

## 5 References

1. National Research Council. *Estimating Bounds on Extreme Precipitation Events: A Brief Assessment*. National Academies Press; 1994:9195. doi:10.17226/9195
2. Huffman GJ, Bolvin DT, Braithwaite D, et al. Integrated Multi-satellite Retrievals for the Global Precipitation Measurement (GPM) Mission (IMERG). In: Levizzani V, Kidd C, Kirschbaum DB, Kummerow CD, Nakamura K, Turk FJ, eds. *Satellite Precipitation Measurement*. Vol 67. Advances in Global Change Research. Springer International Publishing; 2020:343-353. doi:10.1007/978-3-030-24568-9\_19
3. Hou AY, Kakar RK, Neeck S, et al. The Global Precipitation Measurement Mission. *Bull Am Meteorol Soc*. 2014;95(5):701-722. doi:10.1175/BAMS-D-13-00164.1
4. Huffman GJ, Bolvin DT, Nelkin EJ, et al. The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales. *J Hydrometeorol*. 2007;8(1):38-55. doi:10.1175/JHM560.1
5. Kummerow C, Barnes W, Kozu T, Shiue J, Simpson J. The tropical rainfall measuring mission (TRMM) sensor package. *J Atmos Ocean Technol*. 1998;15(3):809-817. doi:10.1175/1520-0426(1998)015<0809:TTRMMT>2.0.CO;2
6. Kirschbaum DB, Huffman GJ, Adler RF, et al. NASA's Remotely Sensed Precipitation: A Reservoir for Applications Users. *Bull Am Meteorol Soc*. 2017;98(6):1169-1184. doi:10.1175/BAMS-D-15-00296.1
7. Portier A, Kirschbaum D, Gebremichael M, et al. NASA's Global Precipitation Measurement Mission: Leveraging Stakeholder Engagement & Applications Activities to Inform Decision-making. *Remote Sens Appl Soc Environ*. 2023;29:100853. doi:10.1016/j.rsase.2022.100853
8. Skofronick-Jackson G, Kirschbaum D, Petersen W, et al. The Global Precipitation Measurement (GPM) mission's scientific achievements and societal contributions: reviewing four years of advanced rain and snow observations. *Q J R Meteorol Soc*. 2018;144:27-48. doi:10.1002/qj.3313
9. Eylander J, Kumar S, Peters-Lidard C, Lewiston T, Franks C, Wegiel J. History and Development of the USAF Agriculture Meteorology Modeling System and Resulting USAF–NASA Strategic Partnership. *Weather Forecast*. 2022;37(12):2293-2312. doi:10.1175/WAF-D-22-0064.1
10. Tang G, Clark MP, Papalexiou SM, Ma Z, Hong Y. Have satellite precipitation products improved over last two decades? A comprehensive comparison of GPM IMERG with nine satellite and reanalysis datasets. *Remote Sens Environ*. 2020;240:111697. doi:10.1016/j.rse.2020.111697
11. Gao Z, Huang B, Ma Z, Chen X, Qiu J, Liu D. Comprehensive Comparisons of State-of-the-Art Gridded Precipitation Estimates for Hydrological Applications over Southern China. *Remote Sens*. 2020;12(23):3997. doi:10.3390/rs12233997
12. Satgé F, Pillot B, Roig H, Bonnet MP. Are gridded precipitation datasets a good option for streamflow simulation across the Juruá river basin, Amazon? *J Hydrol*. 2021;602:126773. doi:10.1016/j.jhydrol.2021.126773
13. Hayden LJM, Tan J, Bolvin DT, Huffman GJ. Variations in the Diurnal Cycle of Precipitation and Its Changes with Distance from Shore over Two Contrasting Regions as Observed by IMERG, ERA5, and Spaceborne Ku Radar. *J Hydrometeorol*. 2023;24(4):675-689. doi:10.1175/JHM-D-22-0154.1
14. Luitel S, Mukhopadhyay P, Singh M, Juneja S, Dhanuka S. GraphCast Skill and Systematic Biases in Indian Summer Monsoon Forecasts: Evaluation Against ERA5 and IMERG. *arXiv*. Preprint posted online July 27, 2026. doi:10.48550/ARXIV.2607.11905

15. NASA. Hydrosphere - NASA Science. Accessed August 22, 2026. <https://science.nasa.gov/earth-science/research/hydrosphere/>
16. Wright DB, Derin Y, Peng K, Maggioni V. Ensemble-Based Uncertainty Quantification Can Improve Large-Scale Precipitation Data for Hydrologic Prediction. *Hydrol Process*. 2026;40(7):e70635. doi:10.1002/hyp.70635
17. Milani L, Kulie MS, Casella D, et al. Extreme Lake-Effect Snow from a GPM Microwave Imager Perspective: Observational Analysis and Precipitation Retrieval Evaluation. *J Atmos Ocean Technol*. 2021;38(2):293-311. doi:10.1175/JTECH-D-20-0064.1
18. Milani L, Kidd C. The State of Precipitation Measurements at Mid-to-High Latitudes. *Atmosphere*. 2023;14(11):1677. doi:10.3390/atmos14111677
19. Skofronick-Jackson G, Kulie M, Milani L, Munchak SJ, Wood NB, Levizzani V. Satellite Estimation of Falling Snow: A Global Precipitation Measurement (GPM) Core Observatory Perspective. *J Appl Meteorol Climatol*. 2019;58(7):1429-1448. doi:10.1175/JAMC-D-18-0124.1
20. Derin Y, Anagnostou E, Berne A, et al. Evaluation of GPM-era Global Satellite Precipitation Products over Multiple Complex Terrain Regions. *Remote Sens*. 2019;11(24):2936. doi:10.3390/rs11242936
21. Navarro A, García-Ortega E, Merino A, Sánchez JL, Kummerow C, Tapiador FJ. Assessment of IMERG Precipitation Estimates over Europe. *Remote Sens*. 2019;11(21):2470. doi:10.3390/rs11212470
22. Navarro A, García-Ortega E, Merino A, Sánchez JL, Tapiador FJ. Orographic biases in IMERG precipitation estimates in the Ebro River basin (Spain): The effects of rain gauge density and altitude. *Atmos Res*. 2020;244:105068. doi:10.1016/j.atmosres.2020.105068
23. Tapiador FJ, Navarro A, García-Ortega E, et al. The Contribution of Rain Gauges in the Calibration of the IMERG Product: Results from the First Validation over Spain. *J Hydrometeorol*. 2020;21(2):161-182. doi:10.1175/JHM-D-19-0116.1
24. Derin Y, Kirstetter PE, Gourley JJ. Evaluation of IMERG satellite precipitation over the land-coast-ocean continuum – Part I: Detection. *J Hydrometeorol*. 2021;22(11):2843-2859. doi:10.1175/JHM-D-21-0058.1
25. Pradhan RK, Markonis Y, Vargas Godoy MR, et al. Review of GPM IMERG performance: A global perspective. *Remote Sens Environ*. 2022;268:112754. doi:10.1016/j.rse.2021.112754
26. Duan Y, Barros A. Understanding How Low-Level Clouds and Fog Modify the Diurnal Cycle of Orographic Precipitation Using In Situ and Satellite Observations. *Remote Sens*. 2017;9(9):920. doi:10.3390/rs9090920
27. Yamamoto MK, Shige S, Yu CK, Cheng LW. Further Improvement of the Heavy Orographic Rainfall Retrievals in the GSMaP Algorithm for Microwave Radiometers. *J Appl Meteorol Climatol*. 2017;56(9):2607-2619. doi:10.1175/JAMC-D-16-0332.1
28. Pfreundschuh S, Guilloteau C, Brown PJ, Kummerow CD, Eriksson P. GPROF V7 and beyond: assessment of current and potential future versions of the GPROF passive microwave precipitation retrievals against ground radar measurements over the continental US and the Pacific Ocean. *Atmos Meas Tech*. 2024;17(2):515-538. doi:10.5194/amt-17-515-2024
29. Nepal B, Shrestha D, Sharma S, Shrestha MS, Aryal D, Shrestha N. Assessment of GPM-Era Satellite Products' (IMERG and GSMaP) Ability to Detect Precipitation Extremes over Mountainous Country Nepal. *Atmosphere*. 2021;12(2):254. doi:10.3390/atmos12020254

30. Chen H, Sun L, Cifelli R, Xie P. Deep Learning for Bias Correction of Satellite Retrievals of Orographic Precipitation. *IEEE Trans Geosci Remote Sens.* 2022;60:1-11. doi:10.1109/TGRS.2021.3105438
31. Wright DB, Kirschbaum DB, Yatheendradas S. Satellite Precipitation Characterization, Error Modeling, and Error Correction Using Censored Shifted Gamma Distributions. *J Hydrometeorol.* 2017;18(10):2801-2815. doi:10.1175/JHM-D-17-0060.1
32. Wang J, Wolff DB, Tan J, Huffman GJ. Understanding Overland Satellite-Based Precipitation Errors in IMERG Products as a Function of Input Sources. *J Hydrometeorol.* 2025;26(8):1219-1235. doi:10.1175/JHM-D-25-0047.1
33. Watters DC, Huffman GJ, Gatlin PN, et al. A Diagnosis of Oceanic Precipitation in IMERG-GMI. *J Hydrometeorol.* 2025;26(4):459-480. doi:10.1175/JHM-D-24-0137.1
34. Peng K, Wright DB, Derin Y, et al. Advancing Ensemble Streamflow Prediction Through Satellite-Based Precipitation Product and Model Parameter Uncertainty Quantification. *J Adv Model Earth Syst.* 2025;17(10):e2025MS004953. doi:10.1029/2025MS004953
35. Peng K, Wright DB, Derin Y, Hartke SH, Li Z, Tan J. STREAM-Sat: A Novel Near-Realtime Quasi-Global Satellite-Only Ensemble Precipitation Dataset. *Water Resour Res.* 2025;61(3):e2023WR036756. doi:10.1029/2023WR036756
36. Kofidou M, Stathopoulos S, Gemitzi A. Review on spatial downscaling of satellite derived precipitation estimates. *Environ Earth Sci.* 2023;82(18):424. doi:10.1007/s12665-023-11115-7
37. Sanò P, Casella D, Camplani A, D'Adderio LP, Panegrossi G. A Machine Learning Snowfall Retrieval Algorithm for ATMS. *Remote Sens.* 2022;14(6):1467. doi:10.3390/rs14061467
38. Petković V, Orescanin M, Kirstetter P, Kummerow C, Ferraro R. Enhancing PMW Satellite Precipitation Estimation: Detecting Convective Class. *J Atmos Ocean Technol.* 2019;36(12):2349-2363. doi:10.1175/JTECH-D-19-0008.1
39. Wang C, Tang G, Gentine P. PrecipGAN: Merging Microwave and Infrared Data for Satellite Precipitation Estimation Using Generative Adversarial Network. *Geophys Res Lett.* 2021;48(5). doi:10.1029/2020GL092032
40. Garshasbi M, Subedi B, Ebtehaj A, Milani L, Turk FJ, Huffman GJ. Incremental Learning for Passive Microwave Precipitation Retrievals Using Advanced Technology Microwave Sounder. *IEEE J Sel Top Appl Earth Obs Remote Sens.* 2026;19:16912-16934. doi:10.1109/JSTARS.2026.3691675
41. Jennings KS, Arienzo MM, Collins M, Hatchett BJ, Nolin AW, Aggett G. Crowdsourced Data Highlight Precipitation Phase Partitioning Variability in Rain-Snow Transition Zone. *Earth Space Sci.* 2023;10(3). doi:10.1029/2022EA002714
42. Heidinger A, Stephens G, Schulz J, et al. A GEO-Ring of Spectral Radiances: Toward a Next Generation of the International Satellite Cloud Climatology Project (ISCCP-NG). *Bull Am Meteorol Soc.* 2026;107(2):E291-E308. doi:10.1175/BAMS-D-24-0161.1
43. Reed PM, Chaney NW, Herman JD, Ferringer MP, Wood EF. Internationally coordinated multi-mission planning is now critical to sustain the space-based rainfall observations needed for managing floods globally. *Environ Res Lett.* 2015;10(2):024010. doi:10.1088/1748-9326/10/2/024010

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## 7 List of Abbreviations

|                     |                                                                         |
|---------------------|-------------------------------------------------------------------------|
| <b>EUMETSET</b>     | European Organisation for the Exploitation of Meteorological Satellites |
| <b>GEO</b>          | geostationary                                                           |
| <b>GMI</b>          | GPM Microwave Imager                                                    |
| <b>GPM</b>          | Global Precipitation Measurement [mission]                              |
| <b>IMERG</b>        | Integrated Multi-satellitE Retrievals for GPM                           |
| <b>IR</b>           | infrared                                                                |
| <b>JAXA</b>         | Japanese Aerospace Exploration Agency                                   |
| <b>LEO</b>          | low-Earth orbit                                                         |
| <b>MIO</b>          | Multi-source Integrated Observatory                                     |
| <b>ML</b>           | machine learning                                                        |
| <b>NASA</b>         | National Aeronautics and Space Administration                           |
| <b>NOAA</b>         | National Oceanic and Atmospheric Administration                         |
| <b>NOAA/NCEI</b>    | NOAA/National Centers for Environmental Information                     |
| <b>NOAA/NWS/CPC</b> | NOAA/National Weather Service/Climate Prediction Center                 |
| <b>PMM</b>          | Precipitation Measuring Mission                                         |
| <b>PMW</b>          | passive microwave                                                       |
| <b>TMPA</b>         | TRMM Multi-satellite Precipitation Analysis                             |
| <b>TRMM</b>         | Tropical Rainfall Measuring Mission                                     |

## 8 Tables

*Table 1: Key on-going users of GPM data for applications.*

|                                                       |                                                                                                                                                                                                                                                                                                                                                     |
|-------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Weather assimilation/ forecasting</b>              | Australia Bureau of Met., ECMWF, Environ. and Climate Change Canada, Korea Met Agency, Météo France, NASA GEOS model, NOAA eTRaP, UK Met Office, USAF global analysis                                                                                                                                                                               |
| <b>Tropical cyclone analysis</b>                      | FNMO, NHC, NRL                                                                                                                                                                                                                                                                                                                                      |
| <b>Flooding/landslides</b>                            | Fathom Science, Floodmapp, CIMA Foundation FloodPROOFS, Google Flood Hub, ITHACA, NASA LHASA, Univ. of Maryland GFMS, U.S. Army ERDC                                                                                                                                                                                                                |
| <b>Disaster recovery</b>                              | European Emergency Response Coordination Centre, JBA Risk Management Ltd., Monarch Weather Consulting, Netherlands Red Cross, Pacific Disaster Center, UN Off. for the Coord. of Humanitarian Affairs                                                                                                                                               |
| <b>Insurance and finance</b>                          | Balyasny, Asset Management, BTG Pactual, CelciusPro, Cystellar, Floodbase, Howden (MiCRO), Munich Re, Raincoat, Swiss Re, ZonaGeo                                                                                                                                                                                                                   |
| <b>Water resources, agricultural and supply chain</b> | aWhere, Inc., Cargill Inc., CEMADEN, Ecoclimasol, Embrapa, FEWSNET, hydro & meteo GmbH, NASA's Western Water Appl. Off. (WWAO)/Navajo Nation Drought Severity Eval. Tool, PrecisionAg®, Univ. of Washington Smart Agricultural Water Management, U.S. Army Engineer Research and Development Center, USDA Foreign Ag. Service, U.S. Drought Monitor |
| <b>Renewable energy</b>                               | Hydropower reservoir operations, Indonesia Hydro Consult, NASA Prediction Of Worldwide Energy Resources (POWER), Stima Energia, Targus Energia, Wood Mackenzie                                                                                                                                                                                      |

## 9 Figures

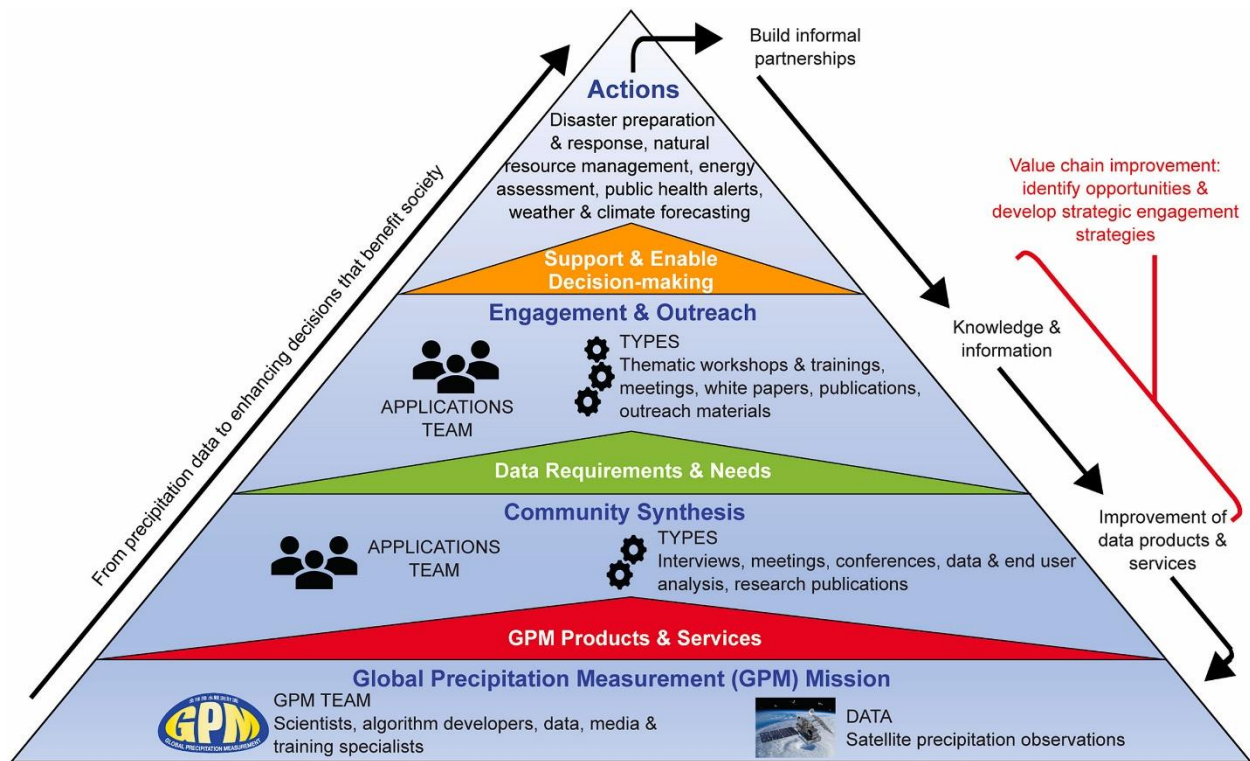


Figure 1: GPM applications strategy and approaches represented as a virtuous triangle along a value chain, consisting of the GPM mission, community synthesis, engagement and outreach, and actions, with informal partnerships that result in knowledge sharing from users to developers. **The GPM mission has been engaging with application users well before NASA formally adopted the Earth Science to Action strategy.** From Figure 1 of Portier et al.<sup>7</sup>.

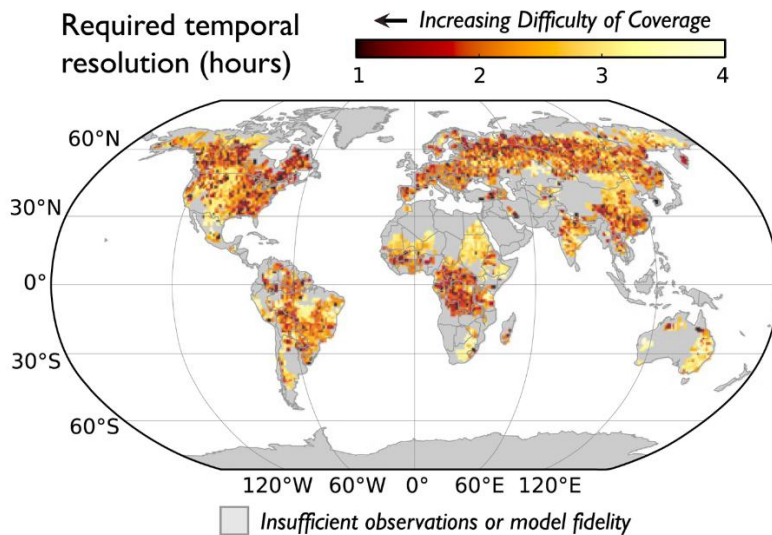


Figure 2: Estimate of the temporal resolution (in hours) required of satellite-based precipitation observations to maintain acceptable flood predictions. Gray indicates locations where either the hydrologic model lacked acceptable performance relative to historical streamflow observations or sufficient historical streamflow data are lacking. **Hydrology users typically require a short sampling interval of precipitation to capture important events.** From Figure 1 in Reed et al. <sup>43</sup>.

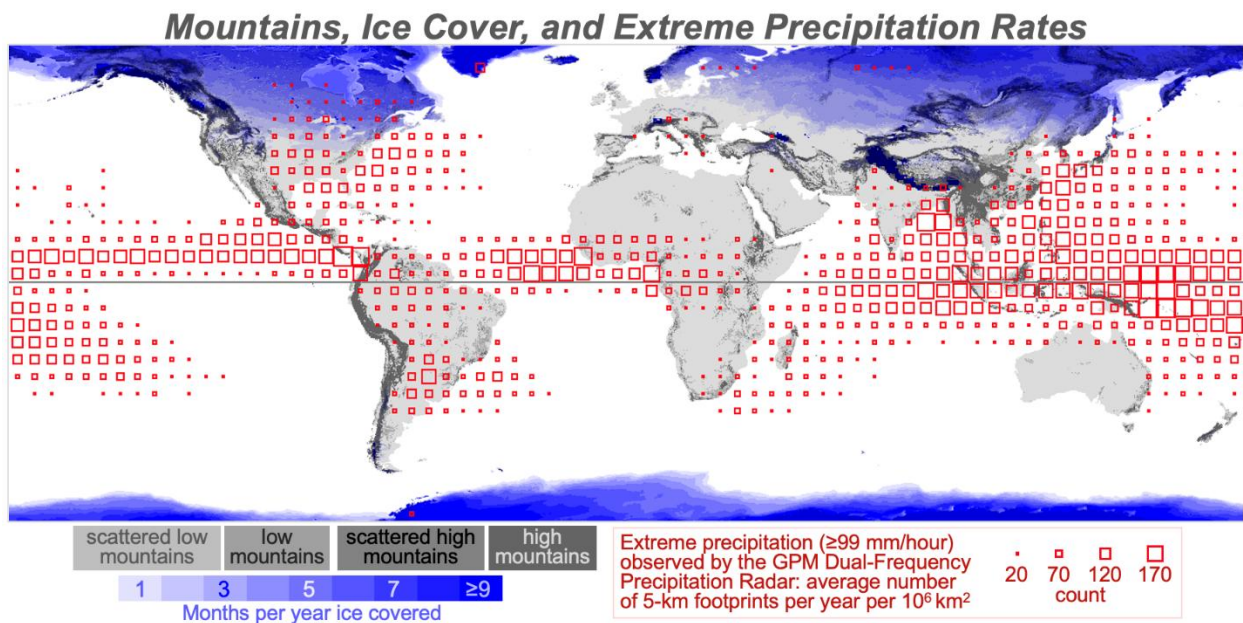


Figure 3: Locations where precipitation is challenging to estimate from satellites: mountainous regions (based on the GPM PMW surface classification), snow-covered regions (from NOAA NCEI's Global Multi-sensor Automated Snow and Ice), and regions with frequent intense precipitation. **Precipitation estimates over these locations will benefit should recommendations from this white paper be adopted.**