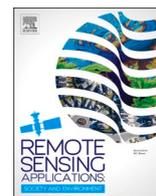


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NASA's Global Precipitation Measurement Mission: Leveraging Stakeholder Engagement & Applications Activities to Inform Decision-making

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ABSTRACT

The application of satellite precipitation estimates from NASA's Global Precipitation Measurement (GPM) Mission for decision-making has been a focus for the mission since launch. As a result, GPM data have enabled a range of applications that address societal needs, including water resource management, crop forecasting, ecological monitoring, disaster response, public health, aviation, weather forecasting, and climate modeling, among others. GPM applications activities have continued to focus on user engagement through in person trainings and interviews, workshops, webinars, and educational outreach activities. The goals of these efforts are to synthesize community data needs in order to effectively support and enable decision-making across agencies, academia and the global community. While these efforts have helped the GPM mission establish a large stakeholder community that encompasses federal and state partners, academic institutions, and private and nonprofit companies, there remains difficulties associated with accessing, processing, and applying the data to support or enable applications. In this article, we present GPM applications strategies and approaches used to enhance the applications value of GPM data, and most importantly, demonstrate how these efforts have and can inform different decision-making contexts. This work also provides a discussion on key lessons learned from the user community and how this information can be utilized to help better support and shape applications approaches for future NASA Earth Science missions.

1. Introduction

Space-borne precipitation estimates are invaluable for applications that support decision-making across environmental, economic and socioeconomic sectors (Kucera et al., 2013; Levizzani et al., 2018; Tapiador, 2018). Such applications include estimating tropical

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cyclone location and intensity, monitoring and forecasting potential floods and rainfall-triggered landslides, assessing water resources and agricultural yield, and tracking water- and vector-borne diseases (Kucera et al., 2013; Kansakar and Hossain, 2016; Kirschbaum et al., 2017). These examples are merely highlights of the breadth of applications that require precipitation estimates at a variety of spatial scales ranging from local to global and temporal scales from near real-time to long-term. While surface rain gauges and ground radar are more conventional methods for retrieving precipitation estimates, their overall distributions are relatively limited and often lack the adequate resolution to support applications (Kidd et al., 2017). Satellite observations, however, provide the coverage to support and monitor precipitation globally at various spatial and temporal resolutions, transforming the way that societal issues related to precipitation are addressed.

For over two decades, data from NASA's Precipitation Measurement Missions (PMM)¹ have helped serve societal needs through advanced precipitation measurements from space. The Tropical Rainfall Measuring Mission (TRMM), co-led by NASA and the Japan Aerospace Exploration Agency (JAXA), was a research satellite in operation from 1997 to 2015. TRMM has shown the value of precipitation data, focusing on heavy to moderate rainfall over Earth's tropical and subtropical regions, for fostering scientific investigation and operational applications (Simpson et al., 1996; Kummerow et al., 1998, 2000; Skofronick-Jackson et al., 2017, 2018). Since 2014, the Global Precipitation Measurement (GPM) Mission has expanded and continued efforts made by TRMM. The main goal of the GPM mission is to provide advanced precipitation measurements through understanding the physics and space-time variability of Earth's global precipitation as a key component to improve our understanding of Earth's water and energy cycles and provide timely precipitation information to directly benefit society.

The GPM mission centers around the GPM Core Observatory (CO), a spacecraft that carries two instruments with increased sensitivities in estimating precipitation ranging from light rain to heavy rain (0.2–110 mm/h) and snow, as well as generating information on particle drop size distribution over the latitude band 65°N–65°S. This includes the GPM Microwave Imager (GMI), which is a radiometer with 13 channels measuring microwave energy at frequencies ranging from 10 to 183 GHz that detects various precipitation at a swath of 885 km (550 miles), and the Dual-Frequency Precipitation Radar (DPR), a two-frequency precipitation radar with a Ku-band (13.6 GHz) and Ka-band (35.5 GHz) with swaths of 245 km (152 miles) that provide 3-dimensional observations of precipitation and estimates of rain and snowfall rate (Hou et al., 2014; Global Precipitation Measurement Mission, <https://gpm.nasa.gov/>). In addition, the GPM CO serves as a reference for microwave precipitation estimates from a constellation of satellites from partner agencies located in the United States, Japan, Europe and India. Together, these microwave retrievals improve the spatial and temporal sampling of precipitation to provide near global coverage, and better quantify the characteristics, amount and distribution of precipitation than before.

One of GPM's algorithms for using these microwave retrievals is the Integrated Multi-satellitE Retrievals for GPM (IMERG) (Huffman et al., 2015) and is NASA's gridded multi-satellite precipitation product. IMERG intercalibrates, merges, and time-interpolates satellite microwave precipitation estimates from the GPM constellation of domestic and international partner satellites. The product then incorporates microwave-calibrated infrared (IR) data and bias corrects with precipitation gauge climatologies (near real-time product) or monthly gauge data (research product) (Huffman et al., 2015, 2019a, 2020). The resulting products have a resolution of $0.1^\circ \times 0.1^\circ$, every 30 min covering latitudes of 60°N–60°S, and are available at different latencies (e.g., time that data are available to users): 4 h after observation time (IMERG Early), 12–14 h (IMERG Late), and 3.5 months (IMERG Final). The output map is an estimated instantaneous precipitation rate in mm/h every half hour, not an accumulation over the 30-min window. GPM-based algorithms and data products like IMERG continue to significantly increase our understanding of precipitation distribution and its impact on society and the environment (Kirschbaum et al., 2017; Skofronick-Jackson et al., 2018; Levizzani et al., 2020), enhancing scientific research and applications across the globe.

The application of GPM data for decision-making has been a focus for the GPM mission since launch (Skofronick-Jackson et al., 2017, 2018). As a result, GPM has established a large user community that has applied GPM data and derived products operationally to inform decisions and policies that directly benefit society (Kirschbaum et al., 2017). While these efforts have demonstrated the applicability and relevance of GPM precipitation measurements for a broad range of users, a fundamental component for GPM applications activities is to continue to facilitate, respond to and address the needs of current and potential user groups across the applications community. The GPM team has made significant strides to increase user engagement and improve data access and products; however, there often remains difficulties associated with accessing, processing, and applying the data to support or enable applications. In addition, expanding awareness of the applicability of GPM data for policy and decision-making for non-traditional user communities remains a challenge. The purpose of this paper is to highlight how GPM applications strategies and approaches are used to overcome some of these barriers and enhance applications to increase the societal benefit of GPM data, and most importantly, demonstrate how these efforts have and can inform different decision-making contexts. This work also serves as one model to demonstrate and shape applications approaches for future NASA Earth Science missions.

2. Strategies for enhancing societal benefit of GPM data

GPM applications efforts have been formulated using a multi-strategy approach, with a fundamental focus on guiding new and existing users to integrate GPM data into their systems and processes to drive actions that positively impact society. These efforts can be conceptualized as a two-way endeavor along a value chain composed of the *GPM leadership, science team and data systems, community*

¹ The NASA's Precipitation Measurement Missions (PMM) program supports scientific research, algorithm development, and ground-based validation activities for the Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM) mission.

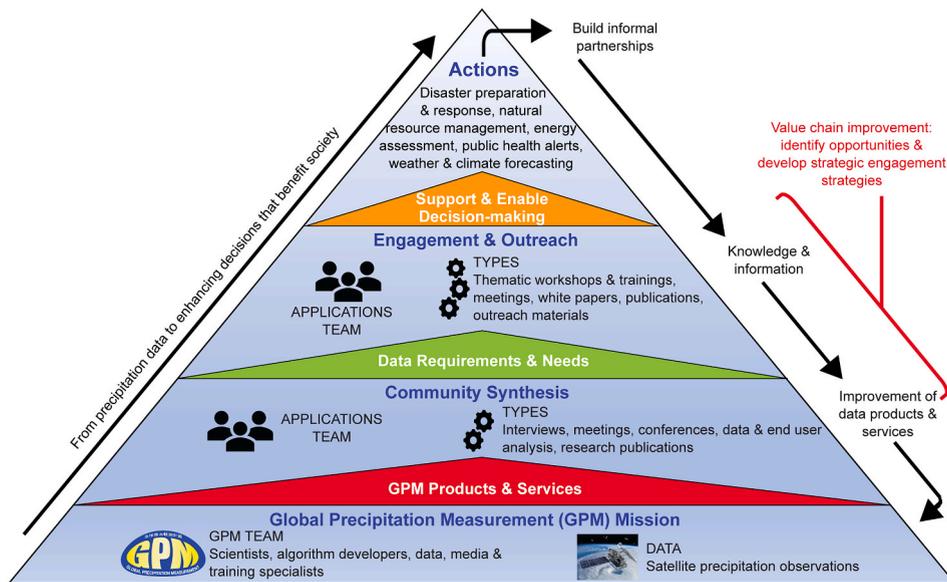


Fig. 1. GPM applications strategy and approaches used to enhance applications and increase the societal benefit of GPM precipitation data. GPM applications approaches can be represented as a virtuous triangle along a value chain consisting of the Global Precipitation Measurement mission, community synthesis, engagement and outreach, and actions (blue text). This is combined with teams (GPM logo and people icons) and processes (e.g., types) that transform these approaches into results (red, green, and orange triangles). Often resulting from this strategy is development of informal partnerships that results in knowledge sharing and information about the user community for effective ways to apply GPM data and inform decisions (text along right side of triangle). Information about user data needs, requirements and barriers provide insights to improve user engagement strategies and are communicated back to the GPM science team to help improve products and services to address the needs of the applications community (Figure adapted from Ackoff, 1989; Sharma, 2008; Virapongse et al., 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

synthesis, engagement and outreach, and actions (Fig. 1) (modified from Ackoff, 1989; Sharma, 2008; Virapongse et al., 2020). To increase the use of GPM data for decision-making, it is essential to foster out-of-the-box thinking and provide effective solutions to translate the data into initiatives as well as application development opportunities. The time and energy that is devoted to engagement with user communities helps amplify GPM applications efforts to improve data products and services and accelerate returns. For context, the terms “stakeholder”, “user”, “communities”, or a combination of these words are used interchangeably throughout and refer to any individual or organization that are directly or indirectly applying GPM data for decision-making activities.

Achieving GPM applications goals means starting from the bottom of the triangle and moving upward (Fig. 1). GPM applications leverages current GPM mission data, products and resources to quantify and understand how and what types of GPM data are used across communities. This information promotes the characterization of community satellite precipitation data requirements and needs. Articulating community data requirements and needs enables effective engagement and outreach strategies to increase awareness of GPM data products and services as well as expand opportunities for communities to apply GPM data to new situations. By pursuing these strategies, it strengthens incentives for users to integrate GPM data into their systems and inform decisions that lead to actions that improve societal outcomes. In turn, these efforts not only help formulate informal partnerships and collaborations across private companies, nonprofit organizations, government agencies, and others, but help establish GPM use cases that can lead to new understandings of how GPM data supports various applications. GPM use cases enhance opportunities for knowledge sharing and information about user requirements, needs, and challenges with satellite data that can be directly communicated to the GPM science team to improve data products and services. This information and knowledge can ultimately feed back into the value chain to improve user accessibility and increase data usage among the application community.

As part of these efforts, it is essential to recognize that there is a strong emphasis on the user-driven approach, where user information and their needs frame and help design impactful and meaningful solutions for GPM applications activities. Various organizations and individuals across the value chain benefit in different ways from GPM data. As such, identifying and understanding where organizations or individuals fall across the GPM user value chain is important (Fig. 2). This value chain in its most simplistic form includes the following:

- (1) Intermediaries that synthesize, integrate, manage and translate information that is meaningful to support downstream users’ decisions;
- (2) Direct end users that are similar to intermediaries, however, they integrate GPM data to transform data directly into decisions and actions; and,
- (3) End users that receive much of the information from intermediaries so that they can make decisions and provide recommendations and alerts that directly impact society.

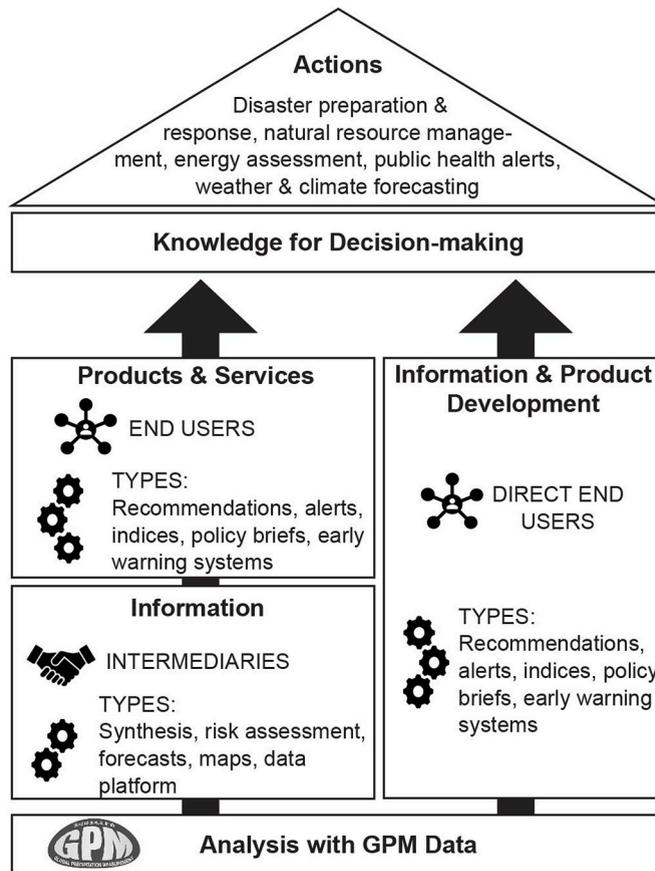


Fig. 2. GPM user value chain. A simplistic overview of tracing the flow of GPM data to actions and the relationship among organizations or individuals directly or indirectly using GPM data for decisions.

Details about an organization’s characteristics, preferences, and perceptions towards directly or indirectly using GPM data helps us target creative solutions and prioritize methods to maximize the benefit of GPM data for society. As one example, addressing solutions for organizations that develop and manage weather risk management platforms (e.g., combination of intermediaries and direct end users), can indirectly benefit downstream users such as the insurance and logistics sectors (e.g., end users) as well as directly support disaster alerts systems geared to the public (e.g., actions). As such, working directly with organizations that design these platforms and address their needs can have significant benefits for communities down the value chain. While an organization’s EO value chain can be actually quite complex, a simplistic view can help focus on specific strategies that are digestible and can be implemented efficiently from the GPM applications side, such as thematically-focused application trainings, and have a positive impact for applications.

This multi-strategy approach has helped GPM applications formulate an extensive list of over 9900 unique users across 130 countries who have accessed or routinely access GPM data from NASA data archives alone.² Of these unique users, approximately 5000 users were analyzed to determine the sector, organization, and application characteristics with regards to using GPM data. This information was documented and organized into a database that was used to establish a comprehensive and unique GPM data portfolio of users to understand and quantify the use of GPM data for decision-making. These efforts have contributed to identifying six GPM application thematic areas: water resources and agriculture, ecology, energy, disasters, public health and development, and extreme weather and climate modeling. In addition, these efforts have helped quantify organizational aspects about the GPM user community, with 78% coming from the research and academic community, 11% from the federal sector, 6% from nonprofit organizations, and the remainder from a range of public and private companies (Fig. 3). Sector statistics can help identify gaps and opportunities for communities that may benefit from GPM data to support decisions.

² GPM data can be accessed through two primary NASA archives, the [Precipitation Processing System \(PPS\)](#) and the [NASA Goddard Earth Sciences \(GES\) Data and Information Services Center \(DISC\)](#).

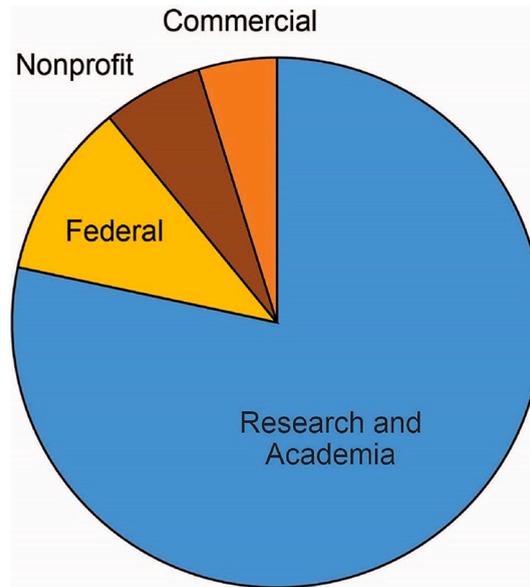


Fig. 3. Breakdown of the GPM user community by sector: research and academia (78%), federal (11%), nonprofit (6%) and commercial (5%).

2.1. Synthesizing the stakeholder community

Through synthesis of the stakeholder databases, we explore the core of the GPM applications value chain, describing how GPM applications activities helped culminate this unique and large user community. In this approach, we seek to understand more about who is using GPM data and how GPM data is being used to inform decisions. We consider different ways to synthesize user applications and glean information on their needs and existing decision-making structures that incorporate satellite data. These approaches include: 1) convening focus groups and informational interviews with users where we bring similar users together to encourage dialogue and find common themes and share their practices and lessons learned, or meet with them individually; 2) attending conferences and workshops to both hear about current activities or share our awareness of precipitation applications and new opportunities (e.g., new data products); 3) gathering published research to qualitatively assess the current use of GPM data for science and applications; and 4) analyzing the user databases to determine what GPM products are of highest value and utility to different sectors. A common limitation to this approach is that much of this information requires time and willingness for users to share information that can be used in this community synthesis. For example, private companies may not be willing to share information publicly so individual interviews may be more appropriate to understand their use of GPM data for applications. Although timely, these actions add value to the GPM mission and bring in context for defining user needs and requirements for using satellite precipitation data for applications. As such, we can gain an understanding on user needs by asking questions such as:

- To what extent does data continuity, data latency, resolution, uncertainty estimates, or data accessibility rank within your organization from high to low in terms of importance? Could you provide some examples or explanations as to why?
- What types of decisions are being made with GPM data?
- What information do you need to aid decisions?

From the perspective of application users, we identified that ease of data access, data formats, and data access demonstrations (e.g., hands on trainings) are critical to aid in the development and enhancement of applications. One example is the PMM Publisher API (<https://gpm.nasa.gov/data/visualizations/precip-apps>) tool that allows users to directly pull precipitation data into their systems in various formats. Additionally, trainings that provide step-by-step processes to access and use GPM data in open access tools such as Google Earth Engine have helped support many users. Users have also emphasized the importance that data continuity plays in supporting their analyses, where long and consistent precipitation data records can help to identify anomalies or calibrate and evaluate models. This includes accurate characterization of errors within these data sets where precision and bias are known. Data continuity and knowledge of uncertainty estimates can support the climate research, disaster insurance and water management sectors, among others.

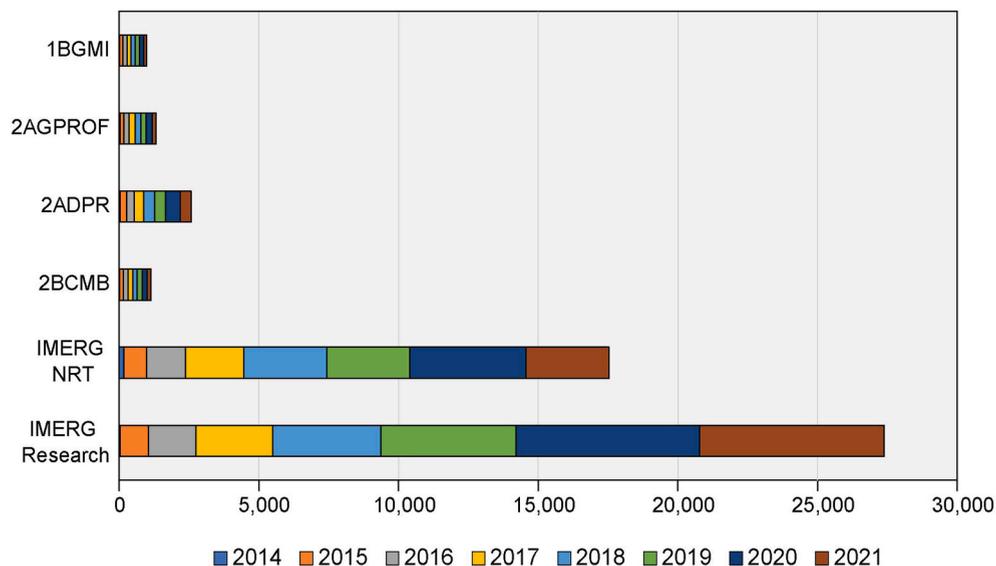


Fig. 4. Most used GPM data products per year since the launch of the GPM mission in 2014. The IMERG research and near-real-time (nrt) products are used 7–17 times more for research and applications than the Level 2 GPM Combined Radar-Radiometer (2BCMB), Radar (2ADPR) and Radiometer (2AGPROF) products, and the Level 1 GMI product (1BGMI). Full a full list of data processing level definitions and GPM data products descriptions see [NASA Data Processing levels](#) and the [GPM Data Directory](#).

Through assessing user access statistics, we have learned that GPM's Level 3³ gridded precipitation products are used nearly 17 times more for research and applications compared to other most-commonly used GPM data products (Fig. 4) and are among the top ten NASA Earth data products downloaded from NASA data archives since 2014. This analysis shows that GPM satellite products that are swath-based (Level 1 and 2) rather than gridded (Level 3) are found to be used less frequently by most stakeholder communities, as they require some remote sensing and geoscientific data expertise to effectively apply the products. While GPM Level 1 and 2 products have significant value to some communities, particularly for research, the GPM multi-satellite global product IMERG plays a key role in enabling applications.

2.2. Engagement and outreach

Engagement and outreach to the community are a critical part of increasing awareness of the products that are available and improving skills and capabilities to access and apply GPM data within their systems and processes. This is achieved by expanding on efforts made from community synthesis activities and identifying opportunities and gaps to create effective engagement and outreach resources. This includes but is not limited to:

- **Targeted trainings:** several IMERG-focused trainings for the public enabled broader use of GPM's most-commonly used product for science and applications in many of the applications communities with whom we engaged. Trainings include the [International Precipitation Working Group \(IPWG\)](#) and [Global Precipitation Measurement \(GPM\) Applications Training](#), the NASA's Applied Remote Sensing Training (ARSET)⁴ program's [Applications of GPM IMERG Reanalysis for Assessing Extreme Dry and Wet Periods](#), and the [Introductory Webinar: Overview and Applications of Integrated Multi-Satellite Retrievals for GPM \(IMERG\) Long-term Precipitation Data Products](#), which also catered to user needs for data access demonstrations and example IMERG use cases for applications.
- **Workshops:** GPM applications team has participated in or led workshops to increase engagement across different thematic application areas and facilitate the use of GPM data. Recent workshops include the [2021 AGU Workshop Applying Earth Observation to Extreme Weather Events in Support of Humanitarian Aid and Sustainable Development](#), [2020 Transportation and Logistics Workshop](#), and the [2019 GPM Weather and Air Quality Forecasting Applications Workshop](#). Community feedback and engagement efforts through GPM user workshops even pre-dates GPM launch including the [2013 GPM Applications Workshop](#)

³ NASA's Earth Observing System Data and Information System (EOSDIS; <https://earthdata.nasa.gov/eosdis>) data products are processed at levels ranging from Level 0 to Level 4. For a full list of data processing level definitions and GPM data product level descriptions, see [NASA Data Processing levels](#) and the [GPM Data Directory](#).

⁴ NASA's Applied Remote Sensing Training (ARSET) program helps to promote and facilitate the use of satellite data for decision-making through online webinars and in-person workshops intended for policymakers, NGOs, and other applied science professionals seeking to incorporate NASA remote sensing into their daily activities (<https://arset.gsfc.nasa.gov/>).

(Ward and Kirschbaum, 2014). For a full list of GPM-held workshops and supporting information can be found at <https://gpm.nasa.gov/science/meetings>; and,

- **White papers:** workshops have been essential to articulate and identify user needs and data requirements across communities. This work has been summarized through white papers (e.g., [Transportation and Logistics Workshop Summary](#), [GPM Weather and Air Quality Workshop](#), and [2015 GPM Applications Workshop](#)).

In addition to user engagement through trainings and workshops, there have been several improvements for how users can access or interact with GPM data. For nonexpert users (and even those who are more experienced), deciding which product to use, where to access these products and understand the product uncertainties can be a daunting task. Such activities can be even more difficult as changes and updates are implemented to GPM datasets such as changes in data format, structure and new algorithm developments. To help improve GPM data use within the applications community, the GPM team has streamlined efforts over the past few years to redesign and restructure the GPM webpage (<https://gpm.nasa.gov/>), and the GPM Applications (<https://gpm.nasa.gov/applications>) and Data Access (<https://gpm.nasa.gov/data>) sections. The GPM Applications section features over 80 examples highlighting the use of GPM data for applications (GPM Applications Highlights, <https://gpm.nasa.gov/applications/highlights>) as well as opportunities for users to learn more about the use of GPM data for thematic application areas through “GPM Applications Packages” (<https://gpm.nasa.gov/applications/whos-using-gpm-data>). The Data Access section provides a landing page to different types of GPM data and products, the sources to download the data, and helpful tips for utilizing precipitation data for research and applications. This includes clear labeling of precipitation fields (e.g., precipitation rate (mm/hr)), easy-to-interpret quality-control flags, product improvement updates, as well as direct links to access GPM data through the two primary NASA archives, the Precipitation Processing System (PPS) and the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC).

The GPM science team also undertook a major effort to reprocess all TRMM precipitation era data using the IMERG algorithm for the Early, Late and Final products (Stocker et al., 2018). This approach ensures a longer, continuous precipitation data record with consistent retrievals and the IMERG data is now available from June 2000 to present. The longer precipitation record helps compare and contrast past and present data that helps users develop more accurate climate and weather models, understand normal and anomalous extreme precipitation events, and strengthen the baseline information and situational awareness for applications such as for disasters, agriculture and food security, water resources, and energy production, among others. For more guidance on Google data products, data access, and resources see the supporting information document.

These efforts have helped reach into communities of novice satellite data users and increase awareness of Google data capabilities while also supporting more advanced stakeholder communities to ensure they are able to retrieve the most relevant precipitation information for their applications. These engagement efforts began well before GPM’s launch and have increased significantly through GPM’s launch and operations; however, there is still room to expand our reach into non-traditional communities that may benefit from GPM data to inform decisions. As such, Google applications efforts will continue to identify opportunities among communities to support practical applications, bridging the gap between data scientists and practitioners alike.

3. From data to decision-making

The unique capabilities of the Google mission and development of its data products, from product levels 1–3, continue to support and enable new data applications across a diverse range of users from government agencies, research institutions and the international community; many of which have evolved from their initial use of TRMM data (Skofronick-Jackson et al., 2017, 2018). Next, we present an overview of applications examples, tracing the flow of GPM data used for situational awareness and decision-making.

Level 1 (L1) datasets consist of reconstructed and unprocessed instrument data at the sensor’s resolution (e.g., brightness temperatures (Tb) derived from radiance data) and are commonly used by experts for algorithm development and ingestion into numerical weather prediction systems. As one example, GPM L1 Tb products continue to be operationally assimilated into NWP models across the globe to improve short-to long-term weather forecasts and inform track forecasts for tropical cyclones. Agencies and organizations such as the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center (NHC), Naval Research Laboratory (NRL), European Centre for Medium-Range Weather Forecasts (ECMWF), among others, ingest GMI Tb data to support their operational systems.

These users are highly proficient at using lower-level data products and are familiar at integrating these datasets into their systems. Near-real time access to these GPM observations (e.g., less than 20 min) are critical for the parametrization of and improving initial conditions of forecast models. Data needs that are often communicated by these user groups include low latency (<1 h, 3–6 h, and 12 h’ time span), high spatial (5–20 km) and temporal (sub-hourly to hourly) resolutions, and access to compatible formats such as HDF5 and NetCDF. With a minimum latency of 20 min, a spatial coverage down to 5 km and a repeat time of 1.5 h, GPM’s L1 data products have proven to be more than adequate to support and improve forecasts for operational agencies.

Level 2 (L2) data are processed from L1 using algorithms to compute a geophysical parameter, which includes rain rate and latent heating products. L2 datasets are typically viewed to be more easily digestible and have wider usage for science and applications compared to L1 products because of the derived geophysical parameters. For example, GPM L2 swath rain rate products are being assessed for weather forecasting and hydrological operations, and studies have shown that L2 swath rain rates have been useful for

identifying rainfall location and intensity in near-real time for weather forecast operations (LeRoy et al., 2020). In addition, GPM L2 latent heating products are being used for climate model parametrization development, where changes in latent heating help to capture changes in atmospheric circulation and better predict storm tracks (Portier, 2021).

Depending on the use case, these end users often have data requirements similar to users that access L1 datasets. However, many organizations that work within hydrological and climate modeling applications fields have also expressed the need for data continuity and uncertainty quantification estimates. For these specific applications that require longer records of satellite precipitation estimates at a high spatial and temporal resolutions, GPM L2 products have proven to meet end users' technical data requirements to continue to support and enable these various applications.

Although more experienced users use L1 and L2 products, the majority of the GPM user community relies on Level 3 (L3) gridded products (Fig. 4), which includes the IMERG Early, Late and Final products at various latencies with a resolution of $0.1^\circ \times 0.1^\circ$, every 30 min covering latitudes of 60°N - 60°S , that has helped support several applications activities (e.g., Famine Early Warning Systems Network (FEWS NET), <https://www.fews.net/>; Neumann et al., 2015; Kirschbaum et al., 2015a, 2015b; 2017; Hossain et al., 2017; Khan et al., 2017; Field, 2020; Portier, 2021). Many end users have communicated that L3 data products help facilitate the ease-of-access and use to satellite precipitation products as they require less technical expertise, time, and financial resources that are often required by using lower-level satellite products within systems.

As such, the "Early" product has been best suitable for end users that require immediate precipitation data for situational awareness (e.g., precipitation rate and precipitation accumulation) to support disaster response and weather forecasting activities. With a low latency of 4 h, IMERG Early provides timely precipitation data at a spatial coverage that is suitable for detecting extreme events at medium to large basin scales, especially where in situ precipitation gauge networks are sparse. The IMERG Late product has been routinely used by drought monitoring, public health modeling and parametric insurance communities, among others, to assess and analyze situations in real time. The IMERG Late has a latency of about 12 h and employs both a forward and backward morphing scheme that enables more robust precipitation estimates compared to IMERG Early. Because IMERG Late incorporates more ancillary data than early, the timeliness and better precipitation estimates have continued to meet end users' data requirements needs to make informed and timely decisions. Lastly, the IMERG Final product that uses monthly gauge data to correct the IMERG estimates and is

Table 1

Examples of user communities by organizational sectors, highlighting how satellite precipitation estimates are being used for situational awareness and decision-making.

Organizations	User Communities	Topic	Application
Meteorological agencies and organizations	NOAA; NRL; U.S. Navy Fleet Numerical Meteorology and Oceanography Center; European Centre for Medium-Range Weather Forecasts; United Kingdom Met Office; Météo France; Australia Bureau of Meteorology; Environment and Climate Change Canada; Indonesia Meteorology, Climatology, and Geophysical Agency; Meteorological Connections, LLC	Numerical weather prediction	Assimilation of Level 1 brightness temperatures within NWP modeling for initializing model runs
		Tropical cyclones	Improved characterization of tropical cyclone track and intensity using GPM Level 1 and Level 2 products
		Subseasonal to seasonal and climate modeling	Verification and validation of seasonal and climate modeling using Level 2 Latent Heating product and IMERG
Reinsurance companies	Swiss Re; Munich Re; Microinsurance Catastrophe Risk Organisation; CelsiusPro; Agvesto; Syngenta®; Pacific Catastrophe Risk Insurance Company	Parametric insurance and reinsurance modeling	Define extreme precipitation thresholds using IMERG for development of multi-peril index-based insurance products and improve situational awareness of rainfall to trigger policy payouts
Data-driven agriculture organizations	U.S. Department of Agriculture; Cargill, Inc.; Nutrien™; aWhere, Inc.; PrecisionAg®; Ecoclimasol; BASF Corporation; Embrapa	Agricultural forecasting and food security	Integration of IMERG precipitation estimates within agricultural models to estimate growing season onset, crop productivity and other variables
Disaster risk management organizations	CyStellar; JBA Risk Management, Ltd; Pacific Disaster Center; Monarch Weather Consulting; Information Technology for Humanitarian Assistance (ITHACA); ZonaGeo; United Nations Office for the Coordination of Humanitarian Affairs (UN OCHA)	Flooding	Incorporation of IMERG in hydrologic routing models for flood estimation
		Disaster response and recovery	Situational awareness of extreme precipitation using IMERG in potentially affected areas
		Data risk management platforms	Integration of IMERG within models to deliver real-time weather insights to customers

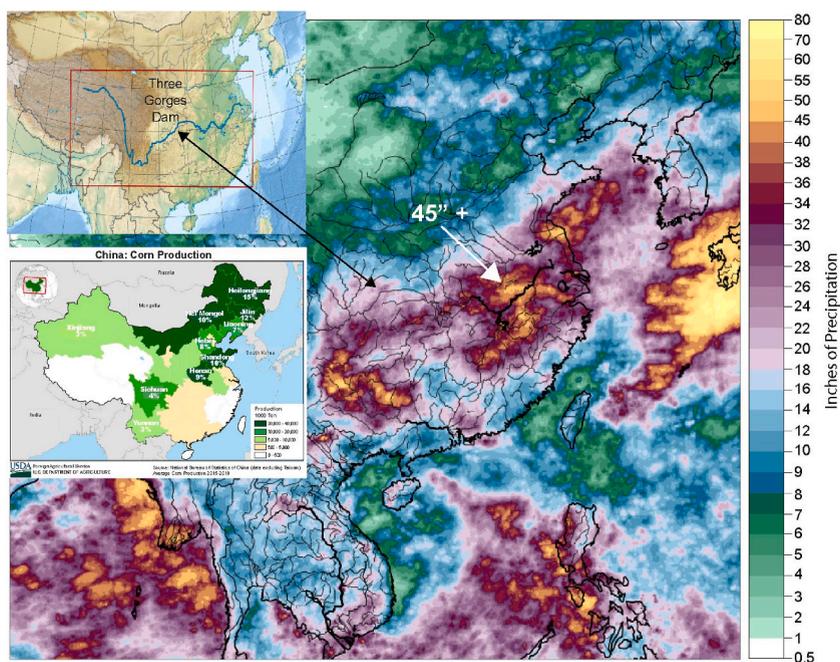


Fig. 5. Total accumulated precipitation using IMERG from June 1 to August 3, 2020 over China, with the highest precipitation estimates in yellow. Top inset image indicates location of precipitation event in China (Yangtze River Route, 2015) and bottom inset features corn production in China from 2015 to 2019 with areas in dark green with highest production amounts (USDA Foreign Agricultural Service). Image credit: Eric Snodgrass, Nutrien Ag Solutions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

available 3.5 months after observation has catered to a range of applications including the water resource management, agriculture, ecology, and energy sectors who are more interested in precipitation research and that do not require low latency data. The reprocessing of GPM IMERG back to 2000 has been especially crucial for applications that need to evaluate trends such as for water resource management and climate studies. In addition to the 30-min IMERG products, there are IMERG precipitation accumulation products that are available at 3 h, 1, 3, and 7 days, and monthly temporal resolution which have been useful for a variety of organizations including weather risk management and data driven agriculture companies. A list of more examples highlighting the applicability of GPM for decision-making by various organizations are summarized in Table 1.

3.1. GPM applications case studies

Below, we highlight four unique case studies to demonstrate the utility of GPM data being applied within processes and data assimilation and modeling systems across different thematic areas. These case studies were selected by reviewing our stakeholder projects and were designed to highlight the breadth, scope and diversity of applications using GPM data.

3.1.1. Assessing agricultural impacts

Weather risk is ubiquitous in production agriculture. Monitoring weather's impact on global food and feed production during a growing season is critical to understanding global supply and demand. In the past, accurately monitoring the spatial distribution of rainfall in places where government weather data collection is inadequate or not made publicly available created problems for companies working within the global food supply chain. As an example, rapid drought development combined with extreme heat in 2010 near the Black Sea and throughout the Russian grain belt forced Russia to halt grain exports sending shockwaves through the grain markets (Welton, 2011). Grain prices skyrocketed around the world as a result of these actions.

Maintaining a steady and sustainable supply of food and feed is a core mission of Nutrien Ag Solutions. Eric Snodgrass is currently a Science Fellow and Principal Atmospheric Scientist at Nutrien Ag Solutions, where he is responsible for delivering daily weather content to the company and clients. Access to near-real-time precipitation estimates on a global scale is valuable for regional assessments of extreme precipitation events for the company. "NASA's GPM mission is an integral part of my global weather analysis toolset. Without NASA's global precipitation products, like IMERG, I wouldn't be able to observe weather events in near-real time that are impacting global ag productivity" (Eric Snodgrass, personal communication).

As one example, Nutrien Ag Solutions used IMERG precipitation estimates to capture and assess the widespread flooding event across China's Yangtze River watershed during summer 2020 (Fig. 5). Heavy and persistent rains fell during June and July along the Meiyu front, which is a seasonal stationary front that often forms over the Yangtze River. Flooding across this agriculturally rich region stressed China's Three Gorges Dam and put nearly half a billion people at risk. The spatial and temporal resolution of IMERG provided the capability to monitor regional flooding and its impact on the local crops. Results from these efforts helped the company prepare for potential disruptions across their supply chain. Fig. 5 is a map created using Python for a Nutrien Ag Solutions' weather briefing in

early August and shows the total accumulated precipitation from June 1 to August 3, 2020. The IMERG Early Daily product was used and accessed through GES DISC, https://gpm1.gesdisc.eosdis.nasa.gov/data/GPM_L3/GPM_3IMERGDE.05/ (Huffman et al., 2019b), to produce the maps. To support company operations, GPM data products have been used for several other applications. Such as the use of IMERG to monitor drought development in eastern Ukraine and the southern Russian wheatbelt during the late Summer and early Fall of 2020, where few public weather stations exist. This drought event led to disruptions across the global wheat supply/demand chain. Additionally, IMERG was used to monitor the late arrival of the South American monsoon in October 2020, which delayed planting in Brazil's northern growing regions and helped send soybean prices higher during harvest in the U.S.

In remote agricultural areas with limited infrastructure, the ingestion of IMERG within analysis tools to assess extreme precipitation events will continue to support company operations like Nutrien Ag Solutions, providing professional meteorologists in the private industry the high-quality, high-resolution rainfall data needed to inform decisions across the agricultural and supply management chains.

3.1.2. Development of parametric indices for extreme rainfall and drought

The impacts of precipitation variability, such as extreme precipitation or drought, disproportionately affect low to middle income countries where individuals often are not insured and live and work in conditions that leave them vulnerable to natural disasters. This can lead to significant economic and environmental challenges if preventive measures or mitigating measures are not taken in time. An increasingly viable option for helping organizations and small business owners build climate resilience and strengthen disaster response and recovery is parametric insurance covers. The term parametric insurance, also known as index-based cover, describes a type of insurance that pays out benefits on the basis of a predetermined index (e.g., precipitation amount) for material and/or financial losses resulting from weather and catastrophic events. The concept of parametric insurance plays a significant role in the market of disaster response and recovery and agriculture as this type of insurance provides faster and more flexible funds as well as coverage for difficult-to-model losses to support recovery after extreme weather events. The IMERG spatial and temporal resolution as well as the availability back to 2000 has been critical for examining precipitation trends that have been used to support parametric insurance and reinsurance modeling. First, analysis of measurable and historical data (i.e., amount of precipitation, duration) are used to set thresholds and develop a credible index on which to trigger a policy. Next, the trigger that determines the payout on a parametric policy can take a number of forms including extreme precipitation and drought. Near-real time monitoring and measurements of these parameters indicate when these extreme weather events exceed threshold conditions and claim payments are warranted.

Numerous organizations have recognized the applicability of satellite precipitation, such as GPM, for the development of multi-peril index-based insurance products to help cover loss of income and/or increases in expenditures as a result of excess rainfall and drought. This includes but is not limited to Pacific Catastrophe Risk Insurance Company (PCIRC), Munich Re, Swiss Re, ZonaGeo, and Agvesto. One successful application using GPM data to inform parametric insurance products is from the Microinsurance Catastrophe Risk Organisation (MiCRO; <http://www.microrisk.org/>). The company has the support of various organizations such as the Swiss Development Agency, KfW Bank, Mercy Corps, and Swiss Re. Using this support, MiCRO has developed comprehensive insurance programs to increase climate resilience and support disaster response for vulnerable and low-income customers throughout Central and South America. Local partners also play a fundamental role in the design and implementations of the solutions, including Seguros Futuro and Banco de Fomento Agropecuario (BFA) in El Salvador; Banrural and Aseguradora Rural, Banco de Antigua, Finca and Seguros Universales in Guatemala; SBS, Finamiga, the United Nations Development Programme and Bancamia in Colombia.

MiCRO's approach is based on a technology platform that provides risk management solutions to deliver tailor-made insurance policies. These policies are designed to protect vulnerable individuals (e.g., subsistence farmers) and small and micro-entrepreneurs against various natural perils such as excessive rainfall, severe drought, and earthquakes using indexes that are highly correlated to losses in the field. The drought and rainfall indices are derived using IMERG Late precipitation from 2000 to present to analyze the frequency and extent of excess rainfall and drought. The drought index identifies drought events based on a number of 'dry' days occurring, while the excess rainfall index identifies events based on three-day rainfall accumulations.

One of the many success stories from MiCRO is that of a maize grower from the department of La Union in El Salvador. Three extreme precipitation events in 2019 were measured in his area using real-time IMERG data, which triggered payouts for each event. In this application, the IMERG product added value to MiCRO's platform by monitoring changes in precipitation to quantify the number of people affected and to provide the specific location of an extreme weather trigger. The ability of measuring extreme events using real-time satellite data enabled MiCRO, Seguros Futuro and BFA to provide fast relief and communication of payments to their clients more efficiently. In most cases this can be accomplished via mobile phones. Index-based insurance can significantly benefit customers as it helps reduce the need to use their savings and sell personal assets when disasters occur. With the incorporation of GPM precipitation data into data risk management platforms, MiCRO and its partners have protected over 80,000 individuals throughout Guatemala, San Salvador, and Colombia against disasters and have continued to support these low-income entrepreneurs to be more climate resilient, competitive and improve their standard of living.

3.1.3. Data assimilation enhancements for U.S. Air Force

The U.S. Air Force (USAF) 557th Weather Wing has continuously maintained the U.S. Department of Defense's (DoD) authoritative source and only operational land data assimilation system since January 1958. In this role, they provide routine geospatial intelligence information to decision-makers across the military, agricultural and research sectors. A strategic partnership between USAF and NASA Goddard Space Flight Center that began in 2005 led to the use of the NASA Land Information System (LIS; Kumar et al., 2006; Peters-Lidard et al., 2007), allowing rapid transition of state-of-the-science terrestrial hydrological modeling research into USAF operations. The LIS-based environment provides global land surface characterization at 10 km grid-space resolution and includes the

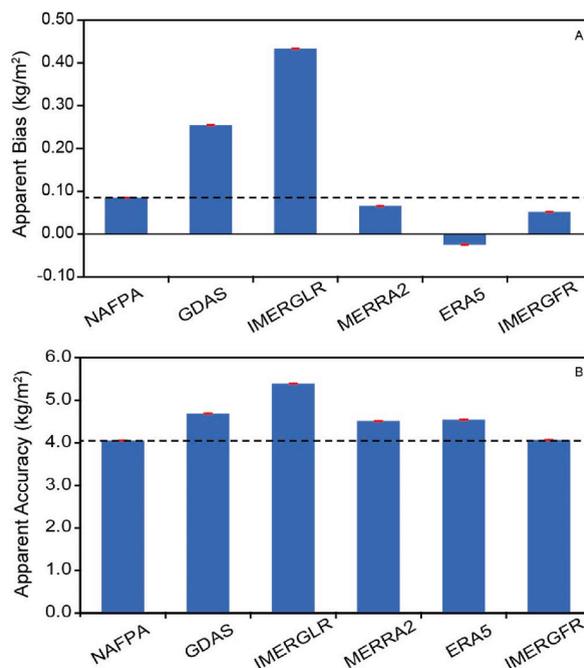


Fig. 6. Arithmetic means of 24-hr precipitation metrics calculated at each CHIRPSv2-Final analysis land point in and near Africa for 2012–2019. (A) Mean Error (apparent bias) in kg m^{-2} ; (B) RMSE (departure from apparent accuracy) in kg m^{-2} . Dashed line indicates metric score from NAFPA. Alternatives to NAFPA are listed left-to-right in order of latency. Red lines at top of bars indicate 95% confidence intervals of domain means. After Kemp et al. (2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

assimilation of remotely sensed soil moisture from the Advanced SCATterometer (ASCAT) and Soil Moisture Active Passive (SMAP) instruments. It also assimilates an in-house snow analysis using microwave data from the Special Sensor Microwave Imager/Sounder (SSMIS) instruments (Kunkee et al., 2008) and in-situ measurements. An additional key input is the NASA Air Force Precipitation Analysis (NAFPA; Kemp et al., 2022) produced within LIS by blending multiple sources of data:

- 17-km forecasts from the Air Force Global Air-Land Weather Exploitation Model (GALWEM; Stoffler, 2017);
- 0.5-deg forecasts from the NOAA Global Forecast System, as an emergency backup to GALWEM;
- rain gauge reports from multiple sources, including national meteorological services;
- retrievals from SSMIS microwave radiometers, flown on-board Defense Meteorological Satellite Program (DMSP) platform;
- Infrared-based rainfall retrievals from the Air Force GEOPRECIP product, based on Vicente et al. (1998); and
- estimates from an Air Force implementation of CMORPH (Xia et al., 2012), combining passive microwave and infrared retrievals from multiple satellites and interpolating through time to fill spatial gaps.

In the latest LIS version 7.4 system, support has been added for ingesting the NASA GPM IMERG Early precipitation product as observations (Wegiel et al., 2020). The assimilation of the IMERG Early product (with a latency of 4 h) satisfies USAF needs, allowing the Air Force to leverage state-of-the-art precipitation retrieval algorithms in near-real-time, and retire the older SSMIS, GEOPRECIP, and CMORPH products. Analyses reflect 3-h accumulations. Operational implementation of LIS 7.4 is fall 2022.

Before performing the analysis, the observations are subjected to multiple tests to screen out erroneous or suspicious reports. Since the analysis is intended to drive a land surface model, all observations over water are automatically rejected. Checks for duplicate gauge reports are made, with reports either merged or rejected depending on how many duplicates exist and how well they agree. Reports coinciding with low surface temperatures (less than 2°C) are rejected; the philosophy is that gauge reports of snow often suffer from a low bias (undercatch), while satellite retrievals of snowfall are likely of poor quality. Satellite retrievals where snowpack exists in LIS are also rejected. A basic sanity check is made by comparing observations with the numerical forecast, with observations rejected if they differ “too much” (that is, several times the summed error covariances of the observation and forecast). Finally, observations of the same type in the same LIS grid box are averaged together.

The different quality-controlled data sources are blended together using a Bratseth (1986) analysis, which is similar to the classic Optimal Interpolation approach but has smaller computer memory requirements (Daley, 1991). This is an important benefit, as the precipitation analysis often works with several million observations over land across the globe and requires careful use of computer resources to run in near-real-time. The numerical forecasts serve as the global first guess, and are adjusted to a closer fit to nearby observations. Relative weights are assigned to different data sources based on user-specified expected error ranges, with higher accuracy data given more weight. In addition, observation spatial density is considered, with clustered observations given less weight than more isolated observations; this accounts for redundant information when observations are close together or co-located. Finally,

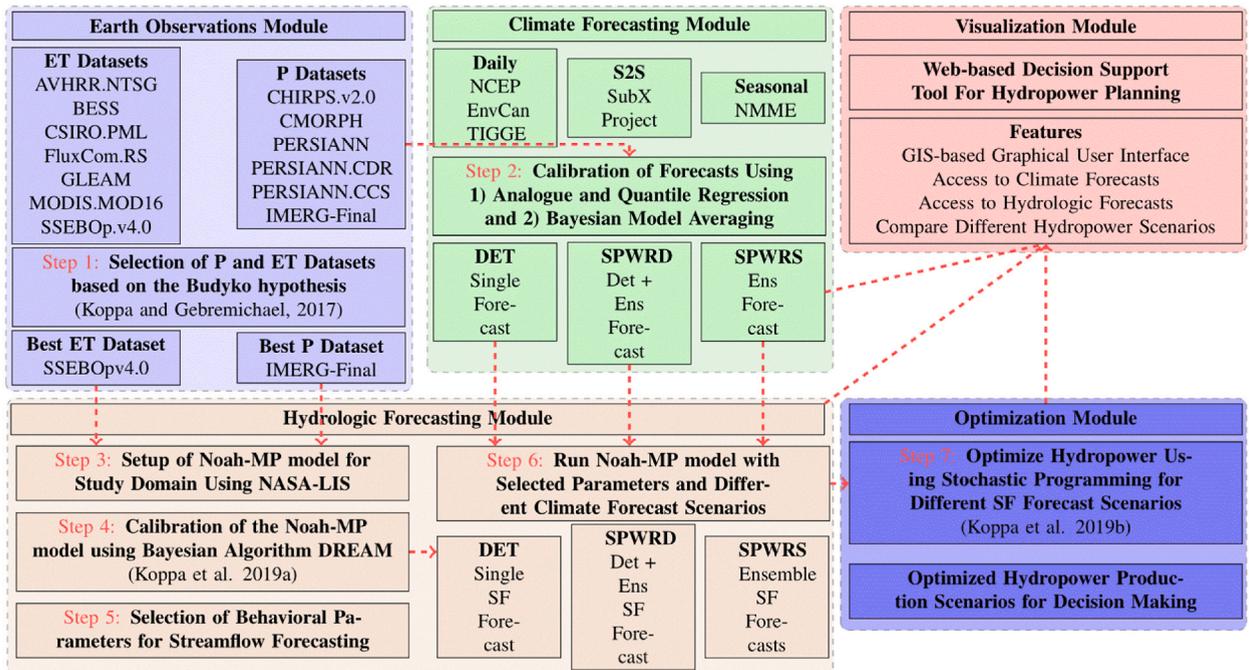


Fig. 7. Block diagram of the hydropower Decision Support System (DSS). ET, evapotranspiration; P, precipitation; for a full list of terms see Koppa et al. (2021).

correlated errors in satellite data are also accounted for in the weights.

A reanalysis was generated by NASA to test the quality of NAFPA with the IMERG Early product (Kemp et al., 2022). In this configuration, gauges and “Early” IMERG were assimilated as observations, while SSMIS, GEOPRECIP, and CMORPH were withheld. Physical precipitation was selected as the analysis variable. This reanalysis, plus other precipitation products, were compared with three reference analyses:

- > NLDAS-2 (Xia et al., 2012; <https://ldas.gsfc.nasa.gov/nldas/v2/forcing>) in CONUS;
- > CHIRPSv2 (Funk et al., 2015) in Africa; and
- > version 1901 of the APHRODITE-2 (Yatagai et al., 2012, 2020) in parts of Asia.

The CONUS and Africa evaluations were performed from 2012 to 2019, while for Asia the evaluation is restricted to 2012–2015 due to data availability. Fig. 6A shows apparent biases in Africa, and indicates NAFPA with IMERG Early product has better bias scores than the NOAA GDAS and the IMERG Late product, but is too wet compared to the NASA MERRA-2 (Reichle et al., 2017), ERA5 (Hersbach et al., 2020), and the IMERG Final product. Fig. 6B shows RMS differences in Africa, and indicates superior accuracy from NAFPA compared to GDAS, IMERG Late product, MERRA-2, and ERA5. Similar results for other regions, as well as results for Pearson correlation, are presented in Kemp et al. (2022), and draw the conclusion of generally superior results for NAFPA compared to alternative low-latency products.

3.1.4. Hydropower production in Africa

The lack of optimal hydropower reservoir operation causes more frequent power outages and associated economic losses, and incurs substantial opportunity costs (Conway et al., 2017; Sridharan et al., 2019). These reasons necessitate the use of decision support systems (DSSs), which can provide reliable and effective information to decision-makers at relevant time scales. A DSS consists of two main parts: (1) an inflow forecasting system to generate possible realizations of future inflow into the reservoir at required timescales, and (2) an optimization system, based on the nature of the inflow forecasts, to optimize reservoir outflows. The emergence of ensemble climate and hydrologic forecasting in the last decade has shown potential for improving the quality of the inflow forecasts, and hence forecast-informed decision-making (Alfieri et al., 2013; Benninga et al., 2017). However, the value of forecasts is limited by the large uncertainty in ensemble members and questions about which ensemble forecast products are reliable. Researchers from the University of California of Los Angeles, led by principal investigator, Mekonnen Gebremichael, have developed a DSS that uses the IMERG Final precipitation dataset to quantify the uncertainty in the climate ensemble forecast products and reduce the uncertainty to a level that is useful for decision-making. They applied the DSS for hydropower systems in Ethiopia, specifically for the Gilgel Gibe I hydropower dam within the Omo-Gibe River Basin, and results from this study are presented here.

This hydropower DSS consists of the following components (Fig. 7): (a) an Earth observations module (EOM), (b) a Climate forecasting module (CFM), (c) a Hydrologic forecasting module (HFM), (d) an Optimization module (OM), and (e) a Visualization module (VM). The first step in implementing the DSS is the selection of appropriate satellite-based precipitation (P) and evapotranspiration (ET) datasets required for the calibration of weather and climate forecasts and the calibration of the hydrologic model.

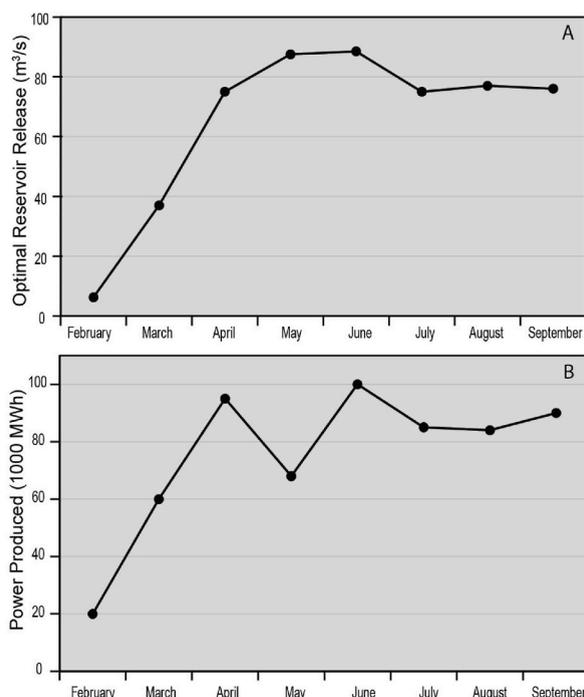


Fig. 8. (A) Optimal release decisions and (B) optimal power produced in the Gibe I reservoir in Ethiopia when IMERG Final is used, along with climate forecasts and optimization tool, as input into a DSS.

These satellite-based datasets were selected using the Budyko-based framework (Budyko and Mikhail, 1974; Koppa and Gebremichael, 2017), which includes the selection of the IMERG Final precipitation (P) product, and the operational version 4 Simplified Surface Energy Balance (SSEBOPv4.0) model for the ET product (Step 1).

Next, the accuracy of short-range and seasonal precipitation forecasts in hindcast mode were evaluated in the CFM. The National Centers for Environmental Prediction (NCEP) Global Ensemble Forecast System (GEFS), NCEP Coupled Forecast System model version 2 (CFSv2), and the THORPEX Interactive Grand Global Ensemble (TIGGE) were used for short-range forecasts, and the North American Multi-Model Ensemble (NMME) was used for seasonal forecast precipitation. Large uncertainties and variabilities among the models and ensemble members were observed, indicating the need for reliable precipitation observations to identify realistic model ensemble members and remove the bias. The IMERG Final product was one of six precipitation datasets used for calibration and bias correction of the ensemble weather and climate forecasts using combined analogue and quantile regression and Bayesian averaging approaches (Hopson, 2014; Hopson and Webster, 2010; Knivel et al., 2017; Koenker and Bassett, 1978) at the daily to seasonal timescales (Step 2).

To translate the calibrated weather and climate forecasts into reservoir inflow forecasts, the DSS uses the Noah-MP (Multi-Parameterization) Land Surface Model (LSM) (Niu et al., 2011), driven through NASA's Land Information System (LIS) (Kumar et al., 2006) (Step 3). The DSS then uses satellite-based estimates of ET (SSEBOPv4.0) as a proxy for streamflow and P (IMERG) to calibrate the hydrologic model using the Differential Evolution Adaptive Metropolis (DREAM) algorithm (Vrugt et al., 2008, 2009) (Step 4). This then helps develop a set of behavioral parameters for the calibrated Noah-MP model (Step 5). These parameters along with the calibrated weather and climate forecasts from the CFM are run with the calibrated Noah-MP to determine a hydrologic forecast (Step 6). The simulated flows are then used as input into a stochastic programming with recourse model to generate optimized power releases and the associated hydropower production (Step 7).

As an example, the optimized reservoir releases and hydropower results in Gibe I for the months of February 2005 to September 2005 are shown (Fig. 8). The optimal reservoir release varies from month to month. The actual power produced in Gibe I for the eight-month study period was 0.53 million MWh (Fig. 8A). In comparison, the optimized hydropower is 0.76 million MWh, which is 43% higher than the actual power generated (Fig. 8B). The use of IMERG Final precipitation dataset, along with weather/climate forecasts and the optimization model, can lead to a significant increase in efficiency in power production from hydropower systems.

In the development of the DSS, Gebremichael and others worked closely with the end-users and key stakeholders in Ethiopia, namely, the Ethiopian Water Works Corporation, the Ethiopian Ministry of Water, Irrigation, and Energy, and the Ethiopian Electric Power. They have also conducted a series of hands-on training workshops to transfer the DSS to these stakeholders. In addition, a web-based graphical user interface (GUI) was developed for the dissemination of real-time and automated IMERG precipitation, and weather and climate forecasts. The DSS demonstrates how Earth Observation data, such as data from GPM, can be leveraged to create a valuable tool for decisions to improve water resource management issues. For more information on these efforts, see Koppa et al. (2021).

4. Lessons learned and the view forward

Since launch, GPM precipitation data have provided valuable information for a diverse range of applications, supporting decision-makers for disaster response and situational awareness, weather forecasting, data assimilation, water resource management, energy, agricultural monitoring, and animal migration, along with many others. While the successes of GPM data are shown through the applications examples in Section 3, GPM applications efforts are continuing to expand as the user communities increase. Outreach strategies provide new and existing users new opportunities to ingest GPM data into their systems and processes through trainings, interactive data access tools and workshops that can directly inform decisions for societal benefit. Collecting information about the make-up, cultures and experience of user communities is essential to enhance applications activities.

Several themes have emerged from these engagement efforts and dialogues across the applications community that we have identified as being fundamental to enable and enhance applications as well as to support strategies for continued satellite product improvement and development of new services. Many users have articulated the importance of continuity. A long, consistent precipitation record is critical for users who rely on assessing anomalies, distribution, determining rainfall intensity thresholds, or evaluating precipitation extremes for applications and research. Users have also expressed interests to have easy access to data uncertainty estimates to carry out analysis of these longer records as well as communicated the need for increased data coverage and spatial resolution at or less than 10 km (i.e., similar to the IMERG product). These findings have helped lead to new understandings of the value of near global, L3 gridded precipitation products, such as IMERG, that provide needed data fields including precipitation estimates and intensities, quality index and a long data record to support a range of applications in near real-time and research. Another theme arising from this work as a future path is the importance of assimilating GPM data into global models to develop additional products or variables, resolutions and spatiotemporal coverage (e.g., Level 4 data) that could be used to address stakeholder needs.

Within the areas of stakeholder analysis and engagement, we identified that amassing a database of users is both very time consuming but also very important and helpful to understand the community more broadly. These efforts have helped in the selection and development of hands-on trainings (e.g., GPM- and NASA ARSET-led IMERG trainings) and workshops (e.g., GPM NWP and Transportation workshops), with both activities proving to be very useful in providing opportunities to connect to stakeholders directly and for creating awareness of GPM data. As result, direct communication with the user community has supported the creation of several applications highlights and case studies. These materials have been essential to demonstrate how the availability of satellite precipitation data can influence and support societal issues, as well as articulate who is working in this field. Lastly, communicating this stakeholder feedback and information directly to the GPM science team is important. Working closely with the science team of the mission and leadership not only helps ensure that there are clear and open communication pathways across the GPM mission on engagement activities, but also helps accelerate stakeholder feedback to GPM algorithm developers to aid in the improvement of GPM data products and services for the public.

As we look toward future community engagement, user inputs will help facilitate GPM applications efforts and will be used to formulate a framework for applications related to future mission planning, such as NASA's Earth System Observatory missions. GPM applications are already being used to identify communities of potential for new satellite observations and opportunities for thematic areas of engagement. This knowledge is also being used to help articulate satellite data products that are of highest value and use, all with the goal of maximizing the benefit of NASA satellite data for operational applications. By continuing engagement activities and soliciting feedback among communities, GPM applications efforts will help guide NASA product development and the next generation of NASA Earth observation satellites that can enable decision-making and actions that benefit society on a global scale.

Ethical statement

I, Andrea Portier (and on behalf of the co-authors), am declaring that all ethical practices have been followed in relation to the development, writing, and publication of the article.

Author statement

Andrea Portier: conceptualization, methodology, visualization, Writing- original draft, Writing-review and editing, formal analysis, investigation.

Dalia Kirschbaum: conceptualization, Writing-review and editing.

Mekonnen Gebremichael: conceptualization, methodology, visualization, Writing- original draft, Writing-review and editing of *Hydropower Case Study*.

Eric Kemp, Sujay Kumar, and Jerry Wegiel: conceptualization, methodology, visualization, Writing- original draft, Writing-review and editing of *USAF Case Study*.

Iker Llabres: conceptualization, methodology, visualization, Writing- original draft, Writing-review and editing of *USAF Case Study*.

Eric Snodgrass: conceptualization, methodology, visualization, Writing- original draft, Writing-review and editing of *Agricultural Case Study*.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rsase.2022.100853>.

References

- Ackoff, R.L., 1989. From data to wisdom. *J. Appl. Syst. Anal.* 16 (1), 3–9.
- Alfieri, L., Burek, P., Dutra, E., Krzeminski, B., Muraro, D., Thielen, J., Pappenberger, F., 2013. GloFAS - global ensemble streamflow forecasting and flood early warning. *Hydrol. Earth Syst. Sci.* 17, 1161–1175.
- Benninga, H.-J.F., Booij, M.J., Romanowicz, R.J., Rientjes, T.H.M., 2017. Performance of ensemble streamflow forecasts under varied hydrometeorological conditions. *Hydrol. Earth Syst. Sci.* 21, 5273–5291.
- Bratseth, A.M., 1986. Statistical interpolation by means of successive corrections. *Tellus* 38A, 439–447. <https://doi.org/10.1111/j.1600-0870.1986.tb00476.x>.
- Budyko, M.I., Mikhail, I., 1974. *Climate and Life*. Academic Press. https://books.google.co.in/books/about/Climate_and_Life.html?id=Ln89Y-6KwZYC&redir_esc=y.
- Conway, D., Dalin, C., Landman, W.A., Osborn, T.J., 2017. Hydropower plans in eastern and southern Africa increase risk of concurrent climate-related electricity supply disruption. *Nat. Energy* 2, 946–953.
- Daley, R., 1991. *Atmospheric Data Analysis*. Cambridge University Press, p. 457.
- Famine Early Warning Systems Network. <https://www.fews.net/>. (Accessed 6 December 2021).
- Field, R.D., 2020. Using satellite estimates of precipitation for fire danger rating. In: *Satellite Precipitation Measurement*. Springer, Cham, pp. 1131–1154.
- Funk, C., Peterson, P., Landsfeld, M., et al., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Sci. Data* 2, 150066. <https://doi.org/10.1038/sdata.2015.66>.
- Global Precipitation Measurement. <https://gpm.nasa.gov/>. (Accessed 15 April 2022).
- Hersbach, H., Bell, B., Berrisford, P., et al., 2020. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* 146, 1999–2049. <https://doi.org/10.1002/qj.3803>, 2020.
- Hopson, T.M., 2014. Assessing the ensemble spread-error relationship. *Mon. Weather Rev.* 142, 1125–1142.
- Hopson, T.M., Webster, P.J., 2010. A 1–10-day ensemble forecasting scheme for the major river basins of Bangladesh: forecasting severe floods of 2003–07. *J. Hydrometeorol.* 11, 618–641.
- Hossain, F., Biswas, N., Ashraf, M., Zeeshan, B.A., 2017. Growing more with less in the Indus valley using cellphones and satellite data. *Eos* 98, 1–12. <https://doi.org/10.1029/2017EO075143>.
- Hou, A.Y., Kakar, R.K., Neeck, S., Azarbarzin, A.A., Kummerow, C.D., Kojima, M., Oki, R., Nakamura, K., Iguchi, T., 2014. The global precipitation measurement mission. *Bull. Am. Meteorol. Soc.* 95 (5), 701–722. <https://doi.org/10.1175/BAMS-D-13-00164.1>.
- Huffman, G.J., Bolvin, D.T., Braithwaite, D., Hsu, K., Joyce, R., Xie, P., Yoo, S.H., 2015. NASA global precipitation measurement (GPM) integrated multi-satellite retrievals for GPM (IMERG). Algorithm Theoretical Basis Document (ATBD) Version 4, 26.
- Huffman, G., Bolvin, D., Braithwaite, D., Hsu, K., Joyce, R., Kidd, C., Nelkin, E., Sorooshian, S., Stocker, E., Tan, J., Wolff, D., Xie, P., 2020. Integrated multi-satellite retrievals for the global precipitation measurement (GPM) mission (IMERG). In: *Satellite Precipitation Measurement*. Springer, Cham, pp. 343–353.
- Huffman, G.J., Bolvin, D.T., Nelkin, E.J., Stocker, E.F., Tan, J., 2019a. V06 IMERG Release Notes. NASA/GSFC, Greenbelt, MD, USA.
- Huffman, G.J., Stocker, E.F., Bolvin, D.T., Nelkin, E.J., Tan, J., 2019b. GPM IMERG early precipitation L3 1 day 0.1 degree x 0.1 degree V06. In: Savtchenko, Andrey, Greenbelt, M.D. (Eds.), *Goddard Earth Sciences Data and Information Services Center (GES DISC), 10.5067/GPM/IMERGDE/DAY/05*. (Accessed 15 August 2020).
- Kansakar, P., Hossain, F., 2016. A review of applications of satellite earth observation data for global societal benefit and stewardship of planet earth. *Space Pol.* 36, 46–54.
- Kemp, E.M., Wegiel, J.W., Kumar, S.V., Geiger, J.V., Mocko, D.M., Jacob, J.P., Peters-Lidard, C.D., 2022. A NASA-air Force precipitation analysis for near-real-time operations. *J. Hydrometeorol.* 23 (6), 965–989. <https://doi.org/10.1175/JHM-D-21-0228.1>.
- Khan, R., Anwar, R., Akanda, A., McDonald, M.D., Huq, A., Jutla, A., Colwell, R., 2017. Assessment of risk of cholera in Haiti following Hurricane Matthew. *Am. J. Trop. Med. Hyg.* 97, 896–903. <https://doi.org/10.4269/ajtmh.17-0048>.
- 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? *Bull. Am. Meteorol. Soc.* 98 (1), 69–78. <https://doi.org/10.1175/BAMS-D-14-00283.1>.
- Kirschbaum, D., Stanley, T., Zhou, Y., 2015a. Spatial and temporal analysis of a global landslide catalog. *Geomorphology* 249, 4–15. <https://doi.org/10.1016/j.geomorph.2015.03.016>.
- Kirschbaum, D.B., Stanley, T., Simmons, J., 2015b. A dynamic landslide hazard assessment system for central America and Hispaniola. *Nat. Hazards Earth Syst. Sci.* 15 (10), 2257–2272. <https://doi.org/10.5194/nhess-15-2257-2015/>.
- Kirschbaum, D.B., Huffman, G.J., Adler, R.F., Braun, S., Garrett, K., Jones, E., McNally, A., Skofronick-Jackson, G., Stocker, E., Wu, H., Zaitchik, B.F., 2017. NASA's remotely sensed precipitation: a reservoir for applications users. *Bull. Am. Meteorol. Soc.* 98 (6), 1169–1184. <https://doi.org/10.1175/BAMS-D-15-00296.1>.
- Kniviel, J.C., Liu, Y., Hopson, T.M., Shaw, J.S., Halvorson, S.F., Fisher, H.H., Roux, G., Sheu, R.S., Pan, L., Wu, W., Hacker, J.P., Vernon, E., Gallagher, F.W., Pace, J. C., 2017. Mesoscale ensemble weather prediction at U.S. Army dugway proving ground, Utah. *Weather Forecast.* 32, 2195–2216.
- Koenker, R., Bassett, G., 1978. Regression quantiles. *Econometrica* 46, 33.
- Koppa, A., Gebremichael, M., 2017. A framework for validation of remotely sensed precipitation and evapotranspiration based on the Budyko hypothesis. *Water Resour. Res.* 53 <https://doi.org/10.1002/2017WR020593>.

