6.1 OPERATIONAL APPLICATIONS OF GLOBAL PRECIPITATION MEASUREMENTS OBSERVATIONS

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6.1.1 Introduction

The launch of next-generation satellites with advanced sensors, such as Global Precipitation Measurement (GPM) Core Observatory with the GPM Microwave Imager (GMI) and Dual-frequency Precipitation Radar (DPR) onboard, provide a unique opportunity to develop new products, tools, and capabilities to enhance operational weather forecasting. Many of the next-generation weather satellites boast of capabilities that have never been used in the operational environment. The operational environment is often fast-paced and requires forecasters to examine and make decisions based on analyzing many different types of data very quickly, particularly in rapidly evolving weather threat situations. This is a stark contrast to the research world, where researchers use a limited number of datasets to answer very specific scientific questions, taking months or years to perform analyses and arrive at conclusions. The National Aeronautics and Space Administration (NASA) Short-term Prediction Research and Transition (SPoRT) Center strives to bridge the gap between researchers and the operational community of end users to facilitate the transition of research products and capabilities to an operational environment.

NASA SPoRT was established in 2002 to transition NASA satellite observations and capabilities to end users to improve short-term, regional weather forecasts (Goodman et al. 2004, Jedlovec 2013). SPoRT began providing NASA Moderate Resolution Imaging Spectroradiometer (MODIS) imagery to National Weather Service (NWS) Weather Forecast Offices (WFOs) as a high-resolution complement to basic satellite imagery to improve situational awareness and short-term forecasts (Jedlovec 2013). Since 2002 SPoRT has used a research to operations / operations to research (R2O/O2R) paradigm to transition both NASA and National Oceanic and Atmospheric Administration (NOAA) satellite observations and research capabilities to operational end users throughout all NWS regions. Successful transition of research products and capabilities to operations can be facilitated through interactive partnerships between end users and product or algorithm developers through an iterative product development and assessment process. SPoRT conducted a series of assessments of GPM rain rate products with NWS weather forecasters and hydrologists, with the goal of determining the utility of GPM products in operations and providing feedback to product and algorithm developers. Herein, section 6.1.2 will describe the background and methods while section 6.1.3 will highlight operational applications of GPM data with a primary focus on rain rate, but other relevant applications related to supporting high impact weather events, snowfall, and hurricane forecasting are briefly highlighted.

6.1.2 Background and methods

6.1.2.1 GPM

The Global Precipitation Measurement (GPM) is a joint mission with NASA and the Japan Aerospace Exploration Agency (JAXA). GPM officially began with the launch of its Core Observatory platform in February 2014. The mission, however, includes data from an international constellation of 12 satellites all with similar passive microwave instruments. GPM's goal is to explore and build a better understanding of Earth's water and energy cycles (Hou et al. 2014). The Core Observatory's microwave imager, GPM Microwave Imager (GMI), and its Dual-frequency Precipitation Radar (DPR) are being used to intercalibrate GPM products using an algorithm called the Goddard Profiling algorithm (GPROF; Kummerow et al. 2001). GPROF compares the passive microwave retrievals to a database of profiles which contains radar estimates, environmental parameters, and in some cases gauge estimates, to create rain rate estimates.

6.1.2.2 Data

Passive microwave GPM Constellation data and products highlighted in this paper were obtained from NASA's Precipitation Processing System (PPS; GPM Science Team 2014a,b,c). GPM Constellation data are available from GMI, MHS (Microwave Humidity Sounder), AMSR2 (Advanced Microwave Scanning Radiometer-2), SSMIS (Special Sensor Microwave Imager/Sounder), and ATMS (Advanced Technology Microwave Sounder) and utilized in near-real time production and distribution of experimental, value-added products. SPoRT has introduced GPM Constellation brightness temperatures from the 36-37 GHz and 88-89 GHz channels (e.g., Level 1C intercalibrated brightness temperatures) as well as multispectral or Red, Green, Blue imagery (i.e., RGB imagery) derived from 37 and 89 GHz channel vertical and horizontal polarizations following Lee et al. (2002). SPoRT has also closely collaborated with the NOAA National Environmental Satellite, Data, and Information Service (NESDIS) on activities related to passive microwave swath snowfall rate products (Meng et al. 2017a,b; Ferraro et al. 2018). The snowfall rate product is directly obtained from NESDIS algorithm developers and SPoRT tailors the data for application in the operational environment. The NESDIS Snowfall Rate product is derived from polar-orbiting sensors onboard Suomi National Polar-orbiting Partnership (S-NPP), GPM, NOAA, MetOp, and Defense Meteorological Satellite Program (DMSP) satellites (Meng et al. 2017a,b; Kongoli et al. 2015, 2018). The product is useful for anticipating or validating snowfall in radar-deprived regions and tracking snowfall maxima.

The primary focus of this paper is application of the GPM Level 2 swath rain rate estimates that are available in near real time (NRT, < 1 h from satellite valid time) and the gridded Level 3 calibrated precipitation rain rate field (precipitationCal) IMERG (Integrated Multi-satellitE Retrievals for GPM; Huffman et al. 2015, 2018). The Level 2 rain rates utilize the GPM Constellation of satellites, as processed through the GPROF algorithm to estimate the rain rates that are available in the native resolution and swath width of the instrument. The Level 3 IMERG rain rate product is a 0.1° × 0.1° gridded precipitation estimate with nearly global coverage (from 60°N to 60°S latitude). IMERG rain rate estimates also utilize GPROF to produce precipitation estimates every 30 min. The Early run of IMERG is available several hours sooner than the Late run, and the Late run uses more advanced techniques to improve the accuracy of precipitation estimates such as both forward and backward morphing. IMERG produces an estimate for precipitation as well as a likelihood of precipitation phase.

SPoRT introduces "value-added" experimental products to NWS operational forecasters when features or functionality are added that does not exist in the initial dataset. For example, based on prior assessments of the satellite-based Quantitative Precipitation Estimate (QPE; Kuligowski 2002) products' utility in operations, SPoRT developed cumulative precipitation products from IMERG at synoptic times (1-, 3-, 6-, 12-, and 24-h; Smith et al. 2016). GPM datasets were obtained in near-real time from NASA's PPS and formatted to be compatible with the Advanced Weather Interactive Processing System (AWIPS) for integration in the operational environment with a latency of about 40 min for the swath rain rate, 6 h for the Early IMERG, and 14 h for the Late IMERG, with latency almost entirely upstream of SPoRT's initial acquisition of the data. Products are ultimately distributed to NWS end users by SPoRT via the Unidata Local Data Manager (LDM; Unidata 2018).

6.1.2.3 Motivation

Accurately measuring precipitation rate and accumulation is an integral part of the operational forecasting process and assessing potential hazards such as drought, flash flooding, and landslides/mudslides. Although rain is the most common weather event and has been recorded, along with temperature, in the most basic of climate records, precipitation is actually fiendishly difficult to measure accurately. Forecasters rely on ground-based radars, using different mathematical relationships and algorithms, to estimate rain rates or amounts. Leaving aside all arguments for or against the various methods of calculating a precipitation estimate from radar reflectivity, radars must be able to observe the precipitation in question; the rain must be falling near a ground-based radar that is not beam-blocked, which largely excludes mountainous areas, large bodies of water, and any global location with limited weather observing infrastructure. Therefore, estimating precipitation with ground-based radar is a challenge for NWS forecasters in the mountainous regions of the western United States and Alaska. A rain gauge offers a straight-forward measurement of rainfall, but precipitation is highly spatially variable. Even in dense rain gauge networks, statistically significant differences in rainfall can be recorded. It would be impractical to have a rain gauge network dense enough to confidently measure global rain rates, and again mountainous terrain would be difficult to cover. And as already alluded to, these methods are relevant to precipitation falling on land surfaces. Precipitation from atmospheric rivers originating in tropical oceans accounts for a large proportion of terrestrial rainfall and high impact events at a large range of latitudes. These types of events pose a unique challenge since the precipitation may develop over oceanic regions that lack radar and gauge observations and move inland, creating high impact events due to heavy rainfall.

Space-based sensors can be utilized to address the challenges and limitations with observing precipitation rate and accumulation with ground-based radars and gauges. The best space-based estimates of rain rate come from radar and passive microwave instruments on satellites with Low Earth Orbits, providing global observations and filling in the observational gaps where ground-based observations are missing (i.e., mountainous and oceanic regions). As with any dataset, limitations exist. The swath width of the satellite observations is narrow (100s to 1000s of km) and the orbital dynamics limit these observations to a few overpasses a day over any given location on earth, making it difficult to continuously track a single storm. Methods for getting from a brightness temperature to a rain rate vary significantly, from incorporating infrared and passive microwave together with empirical relationships (e.g., Self-Calibrating Multivariate Precipitation Retrieval, SCaMPR; Kuligowski et al. 2002), to integrating multiple instruments as close to near-real time as possible (e.g., Microwave Integrated Retrieval System, MiRS; Boukabara et al. 2011), to utilizing an a priori database of precipitation profiles to statistically estimate rainfall (GPROF; Kummerow et al. 2001). The nominal performance requirements for these methods and algorithms, including their latency, are targeted to satisfy research requirements rather than operational requirements. Methods vary over land and oceans, and the resolution of these instruments (5 km to 10s of km) would negate the possibility for point observations.

While considering all these different strengths and weaknesses, an interactive collaboration between research scientists, NWS forecasters, and SPoRT was used to determine whether the GPROF satellite-based measurements of precipitation rate are an effective tool for operational weather forecasters and hydrologists. Feedback from operational end users led to the development of value-added data products from next-generation sensors to address forecasting challenges unique to the operational environment. Within the context of its R2O/O2R paradigm and testbed environment, SPoRT conducted a series of assessments of experimental GPM rain rate products with NWS weather forecasters and hydrologists, with the goal of determining the utility of GPM products in operations and providing feedback to product and algorithm developers.

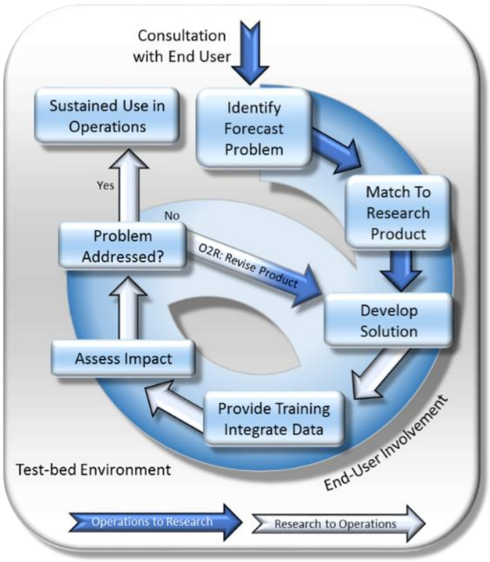


Figure 6.1.1: SPoRT research-to-operations / operations-to-research paradigm, adapted from Jedlovec (2013).

6.1.2.4 End user interaction

SPoRT adheres to an R2O/O2R paradigm (Figure 6.1.1) to introduce experimental products to end users though an iterative process. Note that throughout the iterative process, the specific operational environment and forecasters' needs were the driving force behind product adjustments and changes; successful R2O/O2R transitions have kept the end user at the forefront of the activity. An integral part of the paradigm is integrating the new product or capability into the analysis tools in the end users' operational environment such as AWIPS, the processing, display, and telecommunications system for the NWS. The ability to use the new product within and alongside existing tools and datasets makes it easier for end users to adopt a new product in the fast-paced operational environment. Forecasters can also integrate new datasets more easily if they receive adequate applications-focused training on the new product. SPoRT-developed training materials demonstrate how the new product addresses an existing forecast challenge within a focused case example. The training materials also show other products that a forecaster would routinely utilize to address that challenge. This link from the familiar products to the unfamiliar product improves forecaster confidence and understanding of the new product, helping them integrate it into their existing process. In order to further facilitate the successful implementation of new data products into NWS operations, including those for precipitation, focused operational assessments are conducted. Product assessment activities provide the opportunity to assess the utility and impact of the product in the operational environment where the end user provides actionable feedback to the developers to improve the product to better address their needs. To garner feedback, end users are asked to respond to Likert-type questions (Likert 1932) to rate the impact of the new product on the forecasting and decision process. As SPoRT facilitates feedback between end users and product and/or algorithm developers, a new product can undergo several iterations through the development and assessment cycles of the R2O/O2R paradigm until it is successfully transitioned into operations.

Since 2015 SPoRT has conducted three assessments of GPM Level 2 swath rain rate and the IMERG Early and Late products with NWS forecasters and hydrologists to determine the utility of satellite derived rain rate products in the operational weather forecasting environment. SPoRT selected rain rate products from the GPM datasets for experimental demonstration of GPM observations based on the unique needs and scopes of NWS WFOs and River Forecast Centers (RFCs). In addition to issuing short- and long-term weather forecasts, WFOs are responsible for issuing forecast products regarding areal flooding, flash flooding, and other highly localized, quickly evolving (often minutes to hours) precipitation events. RFCs have regional areas of responsibility and focus on modeling streamflow through river basins and making gridded products of observed and modeled precipitation, typically at scales of hours to days. As a GPM Early Adopter SPoRT was able to obtain initial access to the swath rain rate and IMERG datasets in April 2015.

The goal of the initial assessment activity, during July and August 2015, was to determine whether the GPM Level 2 swath rain rates and Level 3 IMERG calibrated rain rate products have utility in NWS forecasting operations. Select partner WFOs and RFCs from Alaska, the Southwestern US, and the Southeastern US were asked to compare the GPM products to gauges and other satellite products available operationally. The Level 2 swath rain rates were found to have utility primarily at Alaska WFOs where there are gaps in radar coverage due to the complex terrain (Smith et al. 2016). The product was deemed most useful for identifying rainfall location and intensity used in near-real time operations. Forecasters recommended that improved detection efficiency of low rain rates and improved accuracy of higher rain rates would improve the operational utility of the GPM products. The utility of near-real time operations of IMERG were considerably lower; in about 66% of evaluated events, respondents stated that IMERG had a “very small” impact on their operations, typically citing long latency as the main limitation, meaning that the IMERG data were not suitable for NRT operations in WFOs (Smith et al. 2016). Despite these limitations, forecasters found value in applying the IMERG data to post-event analysis of high impact landslide and flooding events, which are described in Section 3.

The second assessment, during August and September 2016, focused on the use of Version 4a GPM Level 2 swath rain rates and Version 3b IMERG datasets (LeRoy et al. 2017a). The primary participants were again from Alaska and the Southwestern U.S. and the focus was to examine events related to precipitation from the Southwest monsoon, atmospheric rivers, and more commonplace precipitation activity commensurate with summer season instability. Because the participating WFOs are in areas largely not well-represented by rain gauges or are in radar-void regions with beam-blockage due to complex terrain, forecasters also used this dataset to validate other satellite data, such as single channel infrared imagery. In 53% of events evaluated, the GPM data were used to provide information where ground-based precipitation products did not provide detailed information (LeRoy et al. 2017a). This assessment uncovered a data error that resulted in clear air returns and marine layer returns of very low rain rates that can more accurately be described as statistical noise (LeRoy et al. 2017a). The noise is a side effect of the GPROF algorithm assigning a probability of precipitation to each pixel, along with a rain rate estimate in versions 4 and earlier (G. Huffman 2016, personal communication). As an example of O2R interactions, forecasters and SPoRT personnel were able to alert developers of the frequency of data artifacts in higher latitudes. As a result, the end users, SPoRT, and the GPM team were able to develop a solution to filter the raw rain rate data to eliminate or substantially decrease the clear air returns so that the product better suited the operational forecasting needs and developers choose to prioritize corrections to the data in subsequent algorithm versions. Despite the clear air returns, forecasters stated that the Level 2 swath rain rates had a "high" impact on the analysis of 57% of events evaluated during the assessment (LeRoy et al. 2017a). Related to IMERG, forecasters at WFOs requested post-event data after high-impact events, for similar applications as the previous assessment, to help supplement rain rate information in otherwise data-sparse locations and as an additional observational tool to be included in reports. For post-event analysis and for incoming events, IMERG provided reliable qualitative information about the location and relative intensity of rain in otherwise data-void locations, particularly in mountainous and offshore locations. IMERG was used for post-event analysis in approximately 67% of events evaluated during this assessment (LeRoy et al. 2017a). Another limitation of IMERG noted by the forecasters was the coverage area. The latency of the product makes it much more viable in RFCs, in which the hydrologic forecasting is longer-term and basin response can be delayed, and the RFC hydrologists considered incorporating the gridded dataset into hydrologic models; however, because IMERG did not extend beyond 60°N, hydrologists did not incorporate the dataset in their models for operational activities.

Once the next version of GPROF was available, SPoRT conducted the third assessment with Alaska region forecasters and hydrologists during late summer 2017 (LeRoy et al. 2017b). Version 5 of the swath rain rates showed improved accuracy and detection efficiency in both stratiform and convective rain events in field studies, and also featured a correction to the spurious clear air returns observed in the prior assessment. IMERG Version 4b showed improved accuracy near coastlines and incorporated other algorithm changes that were expected to improve the accuracy of rain rates in general. GPM algorithm developers also indicated that some processing activities were streamlined, reducing Early IMERG latencies to about 4 h. To address limited latitudinal extent of IMERG that limited its operational utility in the previous assessment with Alaska forecasters and hydrologists, SPoRT collaborated with the GPM Science Team on a solution and identified the Level 3 High Quality Precipitation (HQPrecipitation, hereafter referred to as HQPrecip) field to potentially meet the operational need (LeRoy et al. 2017b). The HQPrecip combined swath rain rate information with the gridded and morphed rain rates in IMERG (Huffman et al. 2015, 2018). SPoRT began providing the HQPrecip product in AWIPS format to NWS partners, primarily the Alaska Pacific RFC, which increased GPM product utility for Alaska

Region forecasters by giving insight into precipitation north of IMERG's normal data extent (60°N). Forecasters stated that it provided some additional continuity particularly when precipitation systems like atmospheric rivers would transition from the Gulf of Alaska to the mainland, impacting the interior of the state well beyond 60°N. This product mainly provided a gap-fill solution while anticipating a "global" IMERG product in the future. To summarize the assessment results, the accuracy of the swath rain rate product was viewed favorably when compared to most other precipitation data sources by the forecasters (Figure 6.1.2) and the GPM data had "some" or "high" impact to operations in 64% of evaluated cases (LeRoy et al. 2017b). With the slight improvement of latency of the IMERG product to 4 h, forecasters began to use the product not only for post-event analysis but to also increase situational awareness of incoming high-impact precipitation events and especially for the assessment of precipitation moving onshore from the data-void oceanic regions and radar-beam blocked mountainous regions (LeRoy et al. 2017b).

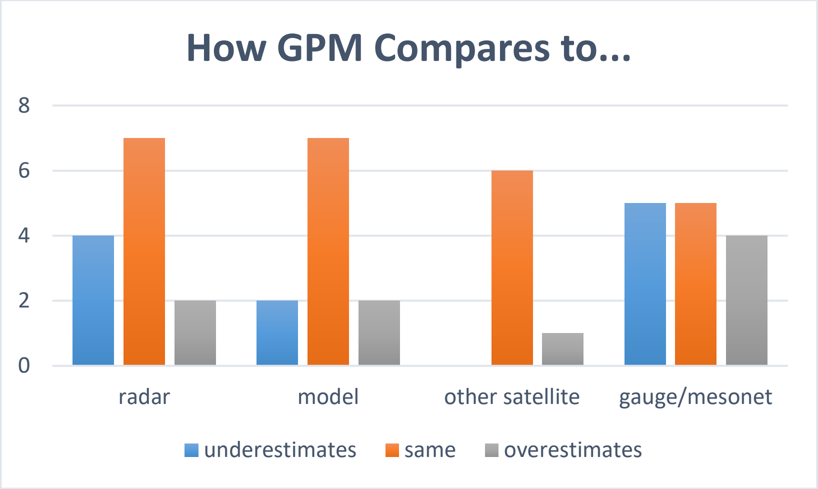


Figure 6.1.2: GPM Level 2 swath rain rates were typically estimated by forecasters to be the same as radar, model estimated rain, other satellite products, and gauge data for the events they evaluated (adapted from LeRoy et al. 2017b). Number of events in which comparisons were performed is shown on the y-axis.

This is the purpose of the SPoRT paradigm: a NASA research product(s) underwent iterative improvements and value-added adjustments based on feedback from end users who were able to use the product(s) seamlessly within their operations environment. Forecaster feedback was communicated to algorithm and product developers and each iterative cycle of the R2O/O2R paradigm unveiled increased utility and impact on decision making in the operational environment. As SPoRT engaged with end users to assess GPM data in operations, limitations (e.g., detection efficiency, noise, spatial coverage, and latency) were identified and brought to the attention of the GPM Science Team. As a result, the GPM Science Team was able to prioritize addressing these limitations in subsequent algorithm versions earlier than planned. For example, including high-latitude data was prioritized 1.5 versions before the notional plan called for it (G. J. Huffman 2018, personal communication). This R2O/O2R interaction helped accelerate the usability of GPM data in NWS operations and SPoRT plays a key role in providing data and end user support beyond the scope of the GPM Science Team's priorities (G. J. Huffman 2018, personal communication).

These assessments have been an avenue to discover novel applications of GPM data as a direct result of forecasters utilizing the data in the operational environment. This paper will highlight novel application examples of GPM products related to anticipating hazards due to heavy precipitation such as landslides and flooding, atmospheric river events, and rain gauge verification, as well as briefly highlight other applications related activities including supporting high impact events, anticipating snowfall, and assessing hurricane structure and intensity.

6.1.3 Applications

6.1.3.1 Landslides/mudslides

Alaska is highly susceptible to landslides and mudslides due to a variety of factors related to its steep slopes, silty soils (Dai et al. 2002), and retreating glaciers (Kääb et al. 2003), and exposure to triggers such as high winds (Buma and Johnson, 2015) and heavy rains in its temperate rainforest climate (Hong et al. 2007). Because of this and the NWS mission to protect life and property, forecasters in Alaska Region routinely assess precipitation to ascertain landslide risk and issue public products to alert the public of such landslide potential. The introduction of GPM datasets to Alaska Region forecasters provided a value-added dataset to assess the impact of precipitation on landslide risk allowing for the ability to assess heavy precipitation potential where observations and radar coverage lack. During our interaction with Alaska Region forecasters, two events occurred where GPM data provided the forecasters with more information for post and pre-event analysis.

For example, the trial assessment which occurred in 2015 was the first time forecasters in Alaska used the precipitation estimates from GPM. Because these products are derived from a NASA research mission and are considered experimental to NWS, forecasters were evaluating the impact these products could have in operations, and whether there were specific benefits and limitations to their use. A major benefit of these products was that they provide information in data-sparse locations. One limitation identified was the latency, particularly in IMERG; recall that the early versions of these products (V03 in 2015) included processing latencies of about 6 h for the early run of IMERG. The trial assessment partly aimed to determine if forecasters would find value in IMERG despite its latency, and whether they had confidence in these products. A tragic landslide, occurred in Southeast Alaska on 18 August 2015, would shed light on these questions.

At about 10 AM Alaska Daylight Time (AKDT) on 18 August, a landslide of mud, trees, and other entrained debris swept down a hillside on Harbor Mountain and tore through a housing development in Sitka, Alaska, destroying a home and killing three people. In the aftermath, forecasters at the NWS WFO Juneau (AJK) documented the weather events leading up to the landslide and requested some additional imagery from IMERG and GPM swath rain rate estimates to help supplement their post-event analysis. Imagery like Figure 6.1.3, a 6-h precipitation accumulation from IMERG, helped forecasters determine where the heaviest rain fell just prior to the landslide event, supplementing the radar information from the Baranof Island Weather Surveillance Radar, 1988, Doppler (WSR-88D) radar, which is partially beam-blocked by the terrain. Forecasters also requested imagery from the DPR on GPM. Despite the experimental nature of these data products, they were able to effectively utilize them for the post-event analysis and official report.

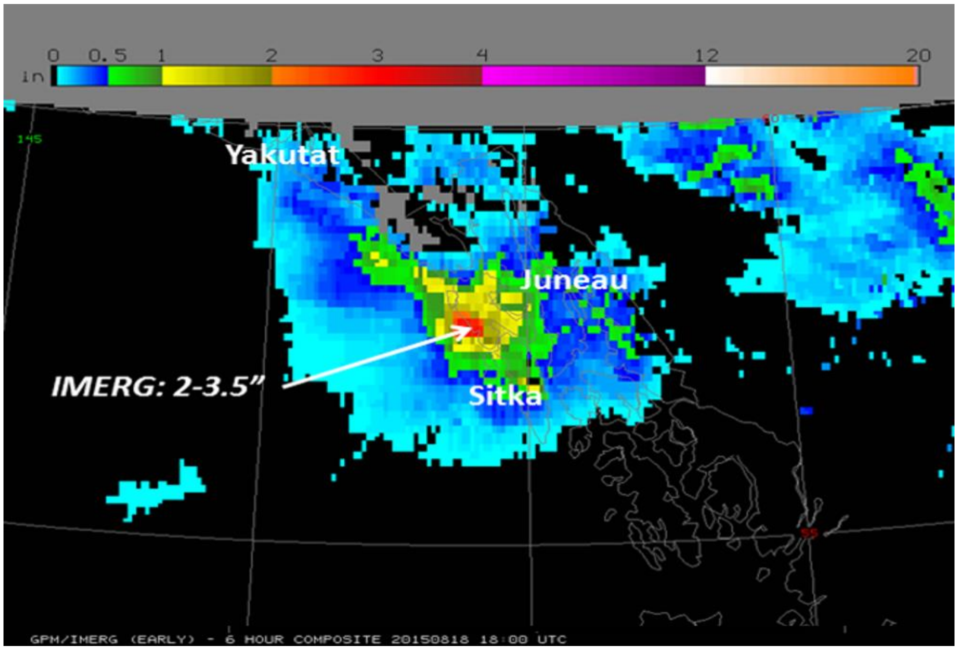


Figure 6.1.3: IMERG 6 h precipitation accumulation (inches) 1200–1800 UTC 18 August 2015. IMERG imagery gave forecasters insight into the heaviest rain rates outside of radar coverage. IMERG was used by forecasters to analyze an event that resulted in a mudslide in the Juneau WFO's area of responsibility on 18 August 2015 (annotations by Aaron Jacobs, NWS WFO AJK).

In subsequent assessments, forecasters had more confidence and familiarity with the GPM rain rate estimates and integrated them into their workflow with the ability to quickly synthesize the new dataset with existing observations and tools. For example, as a forecaster stated, "Comparisons between the sparse rain gauge network over SE [Southeast] Alaska and the GPM product revealed generally good agreement. This gave better confidence in using this product to estimate rainfall in data sparse areas." As a result, forecasters utilized the GPM rain rate estimates for another landslide event, this time during the assessment that took place late summer 2017. On 4 September 2017, forecasters observed moderately heavy rains offshore in the GPM swath rain rate estimates prior to a landslide near Sitka, which fortunately caused no fatalities or major damage. With experience from the previous assessments, forecasters were able to utilize the GPM data to assess the landslide risk rather than utilizing the GPM data solely for post-event analysis.

6.1.3.2 Flooding

Another post-event application of the product was the assessment of a flash flood event at Superman Canyon near Gallup, NM. GPM IMERG was used for a post-event report of a local canyon flash flood fatality by the NWS WFO Albuquerque, NM (ABQ). Operational forecasters augmented the official National Climate Data Center (now known as National Center for Environmental Information, NCEI) Storm Events Database with IMERG 3-h and 6-h accumulated precipitation products. Forecasters gave positive feedback: "This data helped me supplement the info provided by Navajo Police along with the AHPS [Advanced Hydrologic Prediction Service] data to determine that the event occurred on 13 July." The gridded IMERG Early and Late products helped to supplement existing information, like the WSR-88D radar near Albuquerque, which has compromised low-level radar coverage toward northwestern NM, and the accumulation products developed from IMERG, shown in Figure 6.1.4, helped forecasters better understand the timing of this event. The daily precipitation from IMERG (Figure 6.1.4) provided additional information about how much rain had fallen near Gallop, NM, where the complex terrain blocks the radar and limits surface precipitation estimates. The forecasters already had some experience and confidence in the IMERG dataset and were able to use it as an additional reliable data source to write the post-event analysis and determine the time the event occurred.

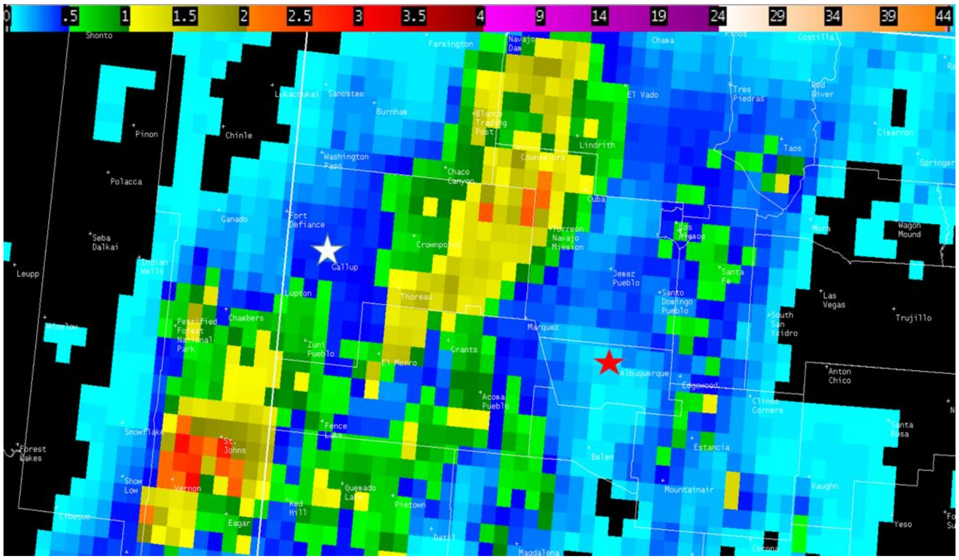


Figure 6.1.4: Daily precipitation (inches) from Early IMERG for precipitation ending 1200 UTC 13 July 2015. Gallup, NM, is labeled with a white star, and the ABQ radar is labeled with a red star.

In later assessments, forecasters used the GPM swath rain rate estimates to forecast flooding events. In a case from 2016 from NWS WFO AJK, the forecasters had observed several swath rain rate overpasses over the system offshore. The forecasters eventually issued flood advisories and a Special Weather Statement (SPS) discussing the observations from the swath rain rates and the expected impact of the heavy rain in downstream locations. As the event moved onshore, GPM swath rain rate data were very comparable to the available gauge estimates. Seeing the agreement between the satellite estimates and the available gauge data gave the forecasters confidence in the swath rain rates as the event progressed, helping forecasters go from using the datasets in post-event analysis, as shown above in the landslide application, to integrating the GPM data in the real-time forecasting process to assess timing and intensity of rainfall and associated hazards to influence public forecasts and text products as shown here and in the following examples.

6.1.3.3 Atmospheric rivers

The GPM precipitation estimate products were also used by forecasters to assess the potential rain rate of incoming systems called atmospheric rivers. Atmospheric Rivers are plumes of water vapor transport that originate in the tropics and are often responsible for flooding events when they reach land, especially in mountainous terrain (Zhu and Newell 1998, Ralph and Dettinger 2011). One challenge of forecasting the effects of an AR is that they are well beyond the reach of ground-based radar, leaving forecasters to observe them using satellite products like the GPM rain rate estimates or use model data to estimate the extent and intensity of the moisture. In fact, AR events are among the cases in which forecasters stated that GPM had the most impact on their operational decisions.

For example, on 20 August 2017, forecasters were tracking the development of an atmospheric river in the North Pacific Ocean, specifically working to target when and where the most intense rainfall was likely to occur. Through an anonymous survey, forecasters stated before the event reached their area of responsibility that, “the [GPM Level 2 swath] rain rates showed a [maximum] about where the second plume / or impulse would be based on satellite vapor imagery and IR [infrared] shots. This [plume] is due into SEAK [Southeast Alaska] Monday night and added confidence to the forecast that the second wave was going to a significant feature.” Additional feedback submitted during this event supported the utility and accuracy of the swath rain rates, which they examined alongside other products within their AWIPS system. The need for accurate datasets for atmospheric rivers is so great that, in another atmospheric river event, forecasters stated that even the higher latency IMERG product had a high impact on operations. In a case example from 9 September 2016 (Figure 6.1.5), forecasters used the GPM products to issue a flood advisory - anticipating the impact of the precipitation associated with the AR. Despite the 4-h latency of IMERG, forecasters found value in the GPM product as a tool to increase situational awareness of the location, movement, and intensity of offshore precipitation; a forecaster indicated that, “[…]we can look at what rain rates the system was producing over the Gulf and then take those values and move them over the panhandle.” Once the systems reach land, forecasters continue to use the satellite data to assess rainfall and flood potential and modify public messaging, particularly in that these datasets help supplement gauge information and the relatively sparse radar available in Southeast Alaska.

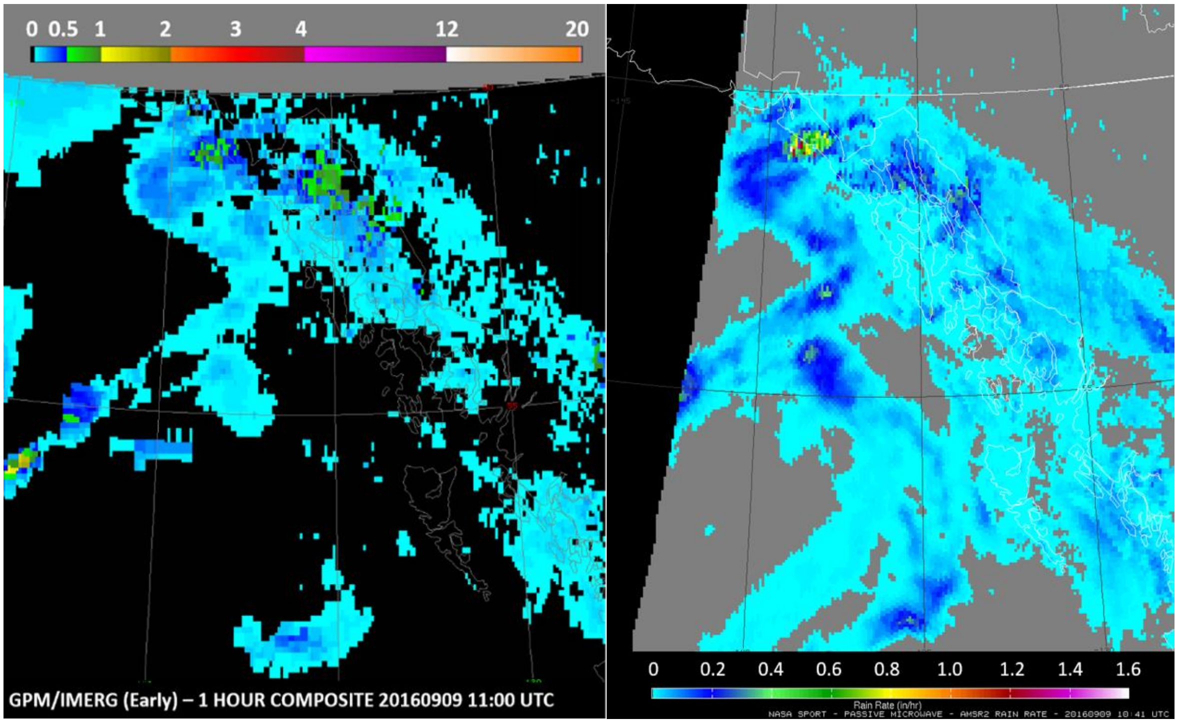


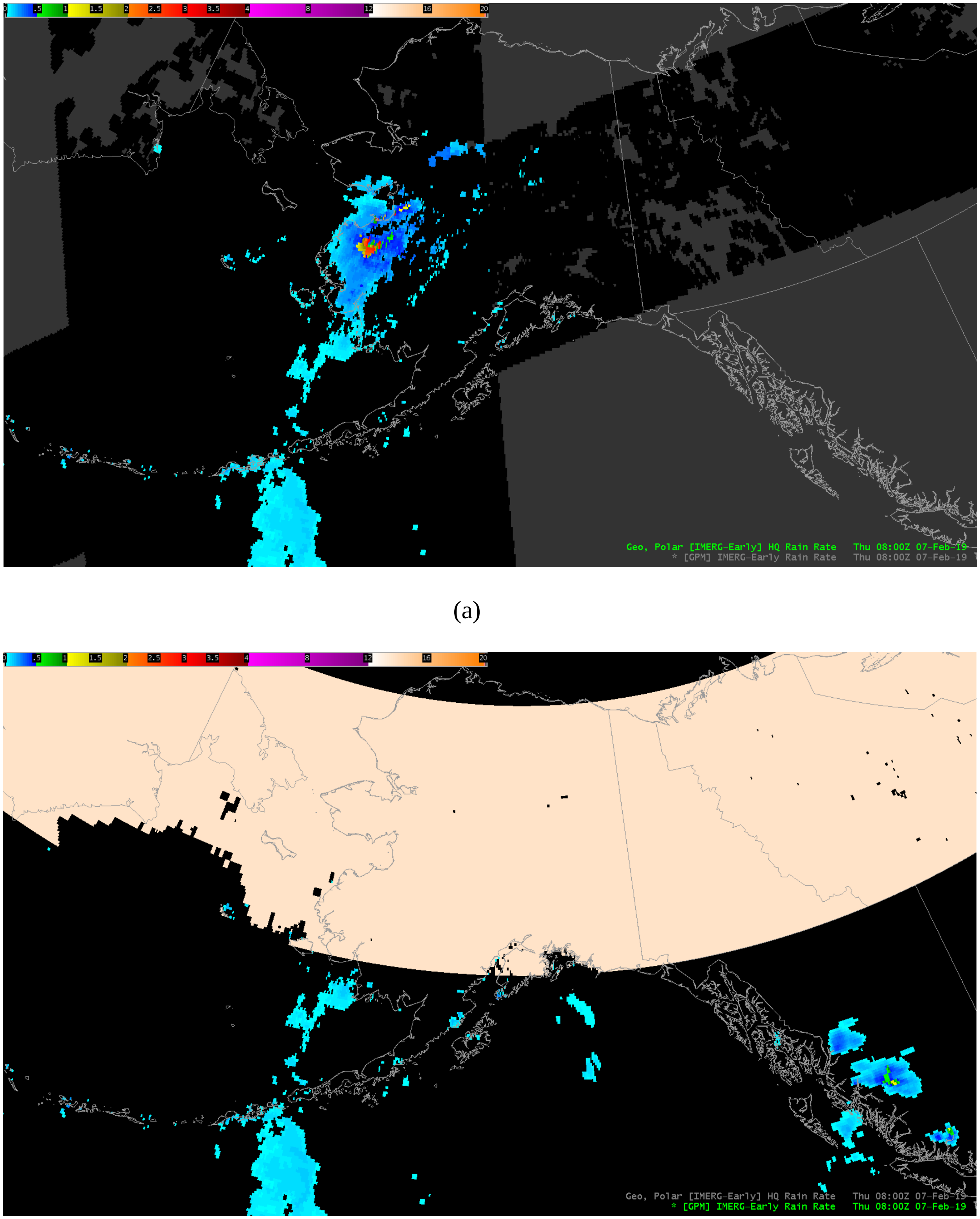
Figure 6.1.5: (a) IMERG 1-hour precipitation accumulation (inches) 1100 UTC 9 September 2016, and (b) swath rain rate estimates (in h^{-1}) 1041 UTC 9 September 2016 offshore of southeast Alaska helped a forecaster issue a flood advisory by showing rain rate intensity produced by the system prior to landfall.

6.1.3.4 Rain gauge verification

During the 2016 summer assessment, a forecaster at the APRFC demonstrated a specific use of the GPM precipitation products in their environment. RFCs use precipitation and river gauge data along with other available rainfall estimates to model streamflow in river basins, and in Alaska, gauges are sparse and occasionally faulty. Gauge data is also used in hydrologic models and must be "quality controlled" to prevent faulty data from being passed to the model framework. Therefore, additional datasets are desired to verify the gauge data and supplement spatial gaps where no gauges are present.

In a case submitted by an APRFC hydrologist, the focus of the forecast challenge was the Taiya river basin. The Taiya basin is in steep terrain and is not well represented by the few gauges in the area. A weak atmospheric river reached Southeast Alaska and produced some locally heavy rainfall, resulting in the Taiya River reaching moderate flood stage. The anonymous feedback provided for this flooding event included the forecaster showing IMERG data over this challenging location, stating that the rainfall amounts in IMERG appeared to match the known rainfall. Indeed, the IMERG gridded datasets provided value in this and similar cases in which there were data challenges in Southeast Alaska. But recall that IMERG coverage does not go beyond 60°N latitude, covering very little of the Alaskan mainland.

Through collaboration with the GPM Science Team, SPoRT was able to introduce another experimental GPM product to the forecasters, this one from the HQPrecip field which incorporates the high-quality calibrated swath data with the gridded, half-hourly IMERG data. The GPM Science Team was able to prioritize including high-latitude data 1.5 algorithm versions before planned inclusion (G. J. Huffman 2018, personal communication). The resulting product showed Level 3 precipitation estimates wherever there was Level 2 swath data, giving forecasters a gridded dataset that could be incorporated into their existing decision support system highlighting precipitation over portions of the Alaskan interior. Figure 6.1.6 is an example of the additional coverage of HQPrecip (Figure 6.1.6a) compared to standard IMERG (Figure 6.1.6b). The product was launched in time for an assessment activity planned for the summer of 2017, less than a year from the prior assessment in which end users articulated the need for additional IMERG coverage. By providing actionable feedback, forecasters helped spur the development of a new experimental product, demonstrating an example of the R2O/O2R paradigm used by SPoRT.



(a)

(b)

Figure 6.1.6: (a) HQPrecip precipitation (inches) and (b) IMERG-Early precipitation (inches) for 0800 UTC on 07 February 2019 over Alaska.

This new product was put to use in the 2017 assessment series. In one example, hydrologists at the APRFC used HQPrecip to examine the impact of a system that reached landfall on the far western coast of Alaska. In this particular case, the forecaster used the product to observe a system coming in off the ocean, and was able to follow up with the impact it was having on land in a region with a sparse gauge network, providing an estimate of rainfall there. In another event, the forecaster used the HQPrecip to compare to gauge data, specifically because two gauges were showing much higher rain rates than the other gauges in the vicininty. These applications further highlight the use of this product to improve the continuity of observations available and to help verify or supplement gauge observations.

6.1.3.5 Additional applications

6.1.3.5.1 Supporting high impact events

The hurricane season of 2017 brought several significant storms to the Atlantic basin including three major hurricanes with significant impacts to the United States: Hurricanes Harvey, Irma, and Maria. Hurricane Harvey produced record-setting rainfall and flooding within the Houston metro area. NASA remote sensing including observations from GPM and Soil Moisture Active Passive (SMAP) captured torrential rains and lingering, high soil moisture content with regions prone to flooding well after the event. SPoRT operates the NASA Land Information System in collaboration with NASA Goddard, and the integration of NOAA radar-estimated rainfall and atmospheric forcing captured the signature of Harvey’s rainfall in southeastern Texas as saturated soils persisted in the weeks and months following the storm. Hurricane Irma’s faster movement brought different impacts to Florida, and scientists within NASA’s Earth Science programs provided flood mapping, damage mapping, and tracking of the loss or restoration of lights and power through various optical and synthetic aperture radar remote sensing techniques. Many of these same techniques were applied to monitoring the impacts from Hurricane Maria in Puerto Rico and the US Virgin Islands, which experienced the brunt of the storm, and helped to document and monitor the long-lasting and continuing impacts of Maria on Puerto Rico’s infrastructure. Prior to Hurricane Maria’s landfall, SPoRT responded to a request from the NWS Southeast RFC for satellite-based QPE over Puerto Rico due to fears that the island’s two Doppler radars would be damaged by the storm. SPoRT quickly provided GPM IMERG data to both the RFC and the Puerto Rico WFO who were then able to access the GPM observations online and within AWIPS. In fact, During Maria, both radars sustained significant damage leaving hydrologic forecasters without a way to determine rainfall amounts for flood forecasting. Therefore, GPM played a critical role in helping NWS forecasters map heavy rainfall and other impacts following damage to and loss of the WSR-88D weather radar. Data products generated by GPM and delivered to NWS partners in Puerto Rico by SPoRT were commented on by NWS staff for providing crucial information on rainfall amounts during the radar outage, supplemented with other agency information including United States Geological Survey (USGS) stream gauges and other satellite products from the GOES series.

6.1.3.5.2 Precipitation – Applications related to snowfall

SPoRT has closely collaborated with NESDIS since 2014 to engage with NWS forecasters to assess the application of the passive-microwave derived NESDIS Snowfall Rate product (Meng et al. 2017a) in NWS operations (Meng et al. 2017b, Ferraro et al. 2018). The first assessment was conducted during the 2014 winter season to determine the operational utility of the product as it relates to radar gaps, beam blockage, and tracking of snowfall rate maxima. In 2014, the initial snowfall rate product was derived from the Advanced Microwave Sounding Unit (AMSU) and MHS sensors onboard NOAA-18, -19 and MetOp-A, -B. The product was produced by the Satellite Climate Studies Branch at NOAA NESDIS Center for Satellite Applications and Research (STAR) and SPoRT converted it to an AWIPS and N-AWIPS (i.e., National Center for Environmental Prediction AWIPS) format for distribution to NWS WFOs and National Centers, developed applications-based training, and assessed the product with end users. At that time, up to 8 land-only snowfall rate retrievals were available per day, limited to regions with a surface temperature greater than -6°C (22°F) and maximum detectable snowfall rates of 50.8 mm h^{-1} (2 in h^{-1}) (for snow to liquid ratio of 10 to 1). Forecaster feedback from the first assessment was positive in that the product was useful for improving data coverage where radar was lacking and valuable for tracking snowfall maxima in combination with other satellite observations (Meng et al. 2017b). During the first assessment, forecasters discovered a novel application of the data as a short-term forecasting tool to increase confidence and situational awareness of snowfall development aloft and cloud seeding before snow is detected by ground based radar (Meng et al. 2017b).

At times the product was limited by the latency and temporal gaps between overpasses, so the product developers addressed forecaster concerns by utilizing Direct Broadcast data where it is possible to reduce latency to 30 to 60 min and developed a radar-merged snowfall rate product with a temporal frequency of 10 min. This means that the passive microwave swath is complemented by National Severe Storm Laboratory's Multi-Radar/Multi-Sensor (MRMS; Zhang et al. 2016) data to increase situational awareness of snowfall rate and fill in the gaps between polar-orbiter overpasses. As part of the R2O/O2R paradigm, the developers at STAR added S-NPP ATMS snowfall rate retrievals to the product and improved the algorithm for use in colder regimes in order to expand to an Alaska domain (Meng et al. 2017b). After these changes, the product was assessed again during the 2016 winter season during which forecasters found the swaths and merged snowfall rate products valuable for identifying snowfall in data-deprived regions. One forecaster example highlights use of the product to increase situational awareness of a rain to snow transition event. A forecaster from the NWS WFO Charleston, WV, indicated the utility of the product for a rain to snow transition event with this anonymous feedback: "Much of the precipitation across West Virginia was still in the form of rain…with an area of snow extending from northwest PA across Ohio into southwest portions of the state. There appears to be several observations of rain across Ohio with surface temperatures of 32 - 35°F where the [SFR] Snowfall Rate product indicated snow in the clouds". Another example highlights use of the product during a widespread heavy snow event on 23 January 2016. A forecaster at the NWS WFO Sterling, VA, noted in a forecast discussion that the product was observing 1-2 inches of snow an hour, and warned of whiteout conditions in the impacted areas. In this event, the snowfall rate product compared well with ground observations of snowfall in both amounts and areal extent.

Prior to the 2018 winter assessment, additional observations were added from the SSMIS instruments onboard DMSP -F16, -F17, and -F18 as well as GMI onboard the NASA GPM Core Observatory and there were also improvements to the snowfall detection algorithm (Meng et al. 2017b). During the 2018 assessment, forecasters continued to provide feedback that the NESDIS Snowfall Rate product is valuable for use in radar-deprived regions, depicting where the heaviest snow is falling, and verifying model performance, anticipating rain to snow transitions, and identifying snowfall aloft before detection by WSR-88D radar. SPoRT and NESDIS have continued to collaborate on R2O/O2R activities since 2014 to transition and assess the NESDIS Snowfall Rate product in the operational environment. Targeted training, assessments, and deliberate interaction with forecasters and algorithm developers has led to product improvements and increased usability and applicability of the NESDIS Snowfall Rate product in operations (Meng et al. 2017b, Ferraro et al. 2018).

6.1.3.5.3 Hurricane structure and intensity

Shortly after the launch of the GPM Core Observatory in 2014, SPoRT began providing experimental passive microwave products to the National Hurricane Center (NHC) to supplement existing observations in the N-AWIPS display system. SPoRT provided GPM's intercalibrated brightness temperatures from the 37 and 89 GHz channels from GMI and the suite of GPM Constellation Satellites. In addition to providing the 37 and 89 GHz brightness temperatures from GPM, SPoRT developed a technique to provide passive microwave RGB imagery (Lee et al. 2002) to forecasters in N-AWIPS format. RGB imagery combines radiometer channels into the red, green, and blue color components of the data display to leverage the advantages of each channel to allow for quick identification of features without analyzing the single channels independently. The resulting RGB image provides a qualitative means to observe an emphatic view of extent and intensity of precipitation and locations of deep, ice-laden convection, both of which are beneficial for identifying hurricane eye location and eyewall structure. Passive microwave RGB imagery and single channel brightness temperatures are used by the NHC to identify the tropical storm or hurricane center ("center fix"), used in intensity measurements, to readily identify vigorous convective activity in tropical storms, and to infer locations of heavy precipitation. For example, during Hurricane Irma GMI data helped NHC forecasters recognize that the storm was undergoing an eyewall replacement during the overpass. The forecasters modified their intensity estimates accordingly and noted the eyewall changes, citing GMI in the publically issued text product. NHC continues to extensively utilize and cite these passive microwave products in operations leveraging the ability for observations in cloudy regions to detect features of interest to determine hurricane structure and intensity.

6.1.4 Conclusions

Since the launch of GPM in 2014, NASA SPoRT has collaborated with NWS forecasters to experimentally transition the research-quality datasets developed from the GPROF algorithm to the operational environment to assess their utility for a variety of applications. With a main focus on forecasting precipitation and related hazards as discussed in this paper, SPoRT has also collaborated with forecasters to provide GPM data to supplement the NWS Puerto Rico weather radar outage during the 2017 hurricane season, applications related to passive microwave-derived snowfall rate, and forecasting hurricane structure and intensity. SPoRT uses an interactive R2O/O2R paradigm that involves the end-user in the entire process to match research products to forecasting challenges, develop a solution, provide data in appropriate formats, and develop applications-based training to demonstrate how the data can be analyzed in tandem with familiar products. These activities occur in a focused testbed environment in which forecasters have the opportunity to integrate and use the datasets in the operational environment and provide actionable feedback on how the dataset can be improved to meet their needs. This process results in incremental improvements to the dataset to benefit operational end users, tailoring the products to their environment and applications.

This paper highlights applications of GPM products that were a direct result of experimentally transitioning value-added GPM products to NWS forecasters and hydrologists. The novel applications highlighted in this paper related to GPM rain rate estimates include understanding and forecasting landslide threat, observing and responding to flooding incidents, forecasting the location and intensity of precipitation associated with atmospheric rivers, and supplementing and verifying rain gauge data. These activities highlighted are a testament to the interactive R2O/O2R process whereby SPoRT has bridged the gap between operational end users and mission scientists to expand the utility of research products in the operational environment for integration into weather forecasting applications. For example, by engaging with the end users and the GPM science team, it was determined that the Level 2 swath rain rates were most useful for identifying rainfall location and intensity in near-real time WFO operations while the higher latency IMERG data were more applicable in RFCs, in WFOs for post-event analysis, and in some cases, during offshore events to provide areal extent and intensity information in data-sparse regions. Forecasters also provided information on limitations such as detection efficiency, noise, spatial coverage, and latency and SPoRT collaborated with the GPM Science Team to either improve the products on the user side or prioritize solutions in the next algorithm update. This R2O/O2R interaction helped accelerate the usability of GPM data in NWS operations. As of this writing, passive microwave single channel imagery and IMERG precipitation type and rate are soon to be delivered to forecasters via the operational NOAA data stream (e.g., Satellite Broadcast Network). SPoRT continues to provide experimental data to operational end users and look toward the next-generation of NASA's precipitation missions in development now that have the potential to improve short-term forecasts on a regional scale.

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