THE GLOBAL PRECIPITATION MEASUREMENT MISSION

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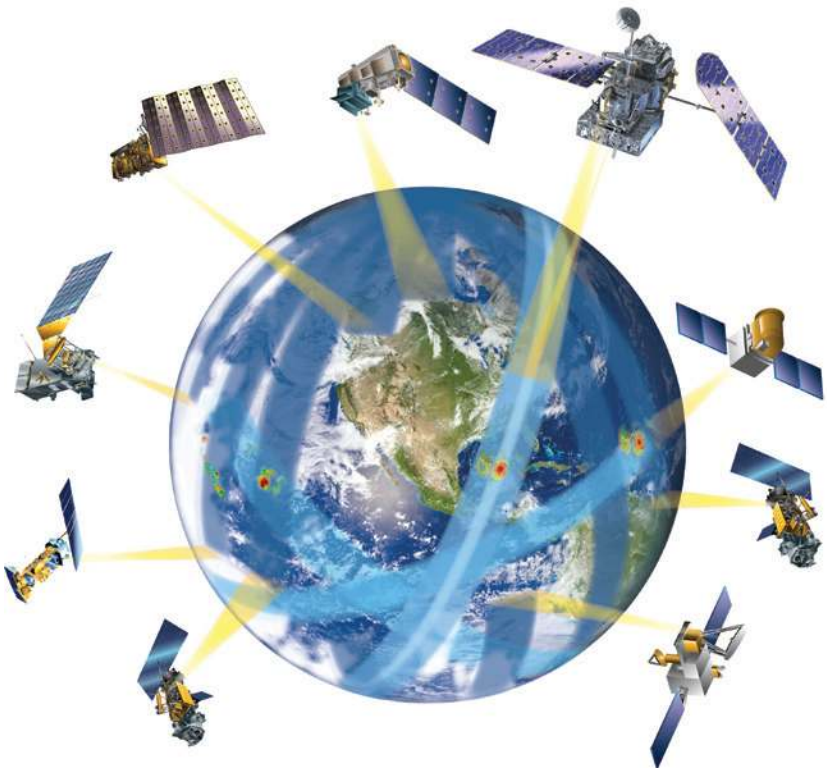
An international satellite mission to unify and advance precipitation measurements from space for scientific research and societal applications is described.



Precipitation affects our daily lives in many ways. The distribution of precipitation in space and time directly affects the availability of freshwater, vital for sustaining life (Montaigne 2002; NSTC 2004). Extreme precipitation events associated with hurricanes, blizzards, floods, droughts, and landslides have significant socioeconomic impacts on society (Futrel et al. 2005; NRC 2010). Historically, observations of precipitation have been an important focus of meteorology and engineering hydrology. Water resource management—be it irrigation for ▶

See Fig. 1 on p. 6 for more information about this satellite illustration.

agriculture, controlling floods, coping with droughts, or administering freshwater supplies—requires accurate and timely knowledge of when, where, and how much it rains or snows.

Not only is precipitation important for water resources, but also scientifically precipitation plays a key role in coupling Earth's water, energy, and biogeochemical cycles. Precipitation is linked to clouds, moisture, atmospheric and oceanic circulations (via latent heat release and salinity dilution, respectively), and surface albedo (through modulation of snow cover) (Trenberth et al. 2007). Accurate knowledge of precipitation intensity and accumulation is essential for understanding the cycling of global water fluxes and the energy balance of the Earth system.

While the measurement of precipitation at a given location using surface-based instruments is relatively straightforward, the large spatial and temporal variability of precipitation intensity, type, and occurrence make direct and uniformly calibrated measurements difficult over large regions, especially over the oceans. Over land, rain gauges suffer from representativeness issues when estimating precipitation over extended areas, particularly at fine temporal resolutions or over complex terrain. Radars, where available, must contend with beam blockage in mountainous regions, anomalous propagation errors, and imprecise backscatter to rain rate relationships. Globally, the limited networks of surface instrumentation over land and the impracticality of obtaining in situ measurements over oceans mean that a comprehensive description of global precipitation can only be achieved from the vantage point of space (Kidd and Levizzani 2011).

Global satellite-based rainfall products are currently based on microwave-only, calibrated infrared (IR), and microwave plus IR observations from various satellite missions using a variety of merging techniques (e.g., Sorooshian et al. 2000; Kuligowski 2002; Kidd et al. 2003; Turk and Miller 2005; Huffman et al. 2007; Kubota et al. 2007; Joyce et al. 2011). The range of available products reflects significant differences in the measurement accuracy, sampling frequency, and merging methodology. While IR sensors on geostationary satellites can provide precipitation estimates (inferred from cloud-top radiances) at high temporal resolutions (up to 15-min intervals on some platforms), microwave sensors remain the instrument of choice for measuring precipitation since the radiative signatures are more directly linked to the precipitating particles. Further advances in global precipitation product development require more accurate and more frequent microwave measurements within a unified observational framework.

The GPM (see the list of acronyms in the appendix for expansions) mission is specifically designed to unify and advance precipitation measurements from a constellation of research and operational microwave sensors (GPM 2013). Building upon the success of TRMM launched by NASA of the United States and JAXA of Japan in 1997, NASA and JAXA successfully deployed the GPM Core Observatory on February 28, 2014. The observatory carries the first spaceborne dual-frequency phased array precipitation radar, the DPR, operating at Ku and Ka bands (13 and 35 GHz, respectively) and a conical-scanning multichannel (10–183 GHz) microwave imager, the GMI. This sensor package is an extension of the TRMM instruments (Kummerow et al. 1998), which focused primarily on heavy to moderate rain over tropical and subtropical oceans. The GPM sensors will extend the measurement range attained by TRMM to include light-intensity precipitation (i.e., <0.5 mm h^{-1}) and falling snow, which accounts for a significant fraction of precipitation occurrence in the middle and high latitudes (Mugnai et al. 2007; Kulie and Bennartz 2009). In particular, the DPR and GMI measurements will refine retrieval algorithms through the construction of a unique observational database by quantifying the microphysical properties of precipitating particles. This database will set a new standard for spaceborne precipitation measurements through its use as common reference over a variety of environmental conditions to unify measurements from

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the many microwave radiometers before, during, and beyond the lifetime of the GPM Core Observatory.

GPM SCIENCE OBJECTIVES AND MISSION CONTEXT. GPM is a constellation-based satellite mission specifically designed to provide a new generation of observations of rainfall and snowfall from space to improve our understanding of Earth's water and energy cycle. As a science mission with integrated applications goals, it will make data available in near–real time (i.e., within 3 h of observation) for a host of societal applications that include the identification of storm locations, flood forecasting, freshwater monitoring, landslide warning, crop prediction, and tracking of waterborne diseases. A summary of the GPM mission science objectives is given in Table 1.

The current generation of multisatellite rainfall products is based largely upon algorithms and validation activities centered on TRMM, which focuses on medium to heavy rainfall over the tropical oceans. GPM will provide the next generation of global precipitation products characterized by 1) more accurate instantaneous precipitation estimates, particularly for light rainfall and cold-season solid precipitation, and 2) unified precipitation retrievals from a constellation of microwave radiometers through the use of intercalibrated brightness temperatures and a common observational hydrometeor database consistent with the combined radar/radiometer measurements obtained by the GPM Core Observatory. The greater global coverage of the GPM Core Observatory (68°N/S) compared to the TRMM coverage (37°N/S) will allow significantly better quantification of precipitation characteristics and more accurate precipitation products to be developed for the middle and high latitudes, especially over land and over a wider range of climate regimes (see the section titled "Constellation partnership and configuration" for Core Observatory coverage). The expected science contributions of the GPM mission and the ways in which society will directly benefit from the mission are described in the sidebars titled "GPM science contributions" and "GPM societal benefits," respectively.

Within the United States, the GPM mission is the Earth science community's response to the urgent need to decipher how the water cycle changes in a warming climate and the desire to enhance a broad range of societal applications (NRC 2007a). As a NASA foundation mission for systematic measurement in Earth sciences focusing on the global water and energy cycle (Asrar et al. 2001), GPM is an important contribution to the U.S. Climate Change Science Program and the U.S. Weather Research Program. In Japan, the GPM/DPR project of JAXA is a key element of Japan's Earth monitoring satellite program to

Table 1. GPM science objectives.

Science drivers	Mission objectives
Advancing precipitation measurements from space	Provide measurements of microphysical properties and vertical structure information of precipitating systems using active remote sensing techniques over a broad spectral range Combine active and passive remote sensing techniques to provide a calibration standard for unifying and improving global precipitation measurements by a constellation of research and operational microwave sensors
Improving knowledge of precipitation systems, water cycle variability, and freshwater availability	Provide four-dimensional (4D) measurements of space–time variability of global precipitation to better understand storm structures, water/energy budget, freshwater resources, and interactions between precipitation and other climate parameters
Improving climate modeling and prediction	Provide estimates of surface water fluxes, cloud/precipitation microphysics, and latent heat release in the atmosphere to improve Earth system modeling and analysis
Improving weather forecasting and 4D climate reanalysis	Provide accurate and frequent measurements of precipitation-affected microwave radiances and instantaneous precipitation rates together with quantitative error characterizations for assimilation into weather forecasting and data assimilation systems
Improving hydrological modeling and prediction	Provide high-resolution precipitation data through downscaling and innovative hydrological modeling to advance predictions of high-impact natural hazard events (e.g., floods/droughts, landslides, and hurricanes)

1) *Better understanding of global water cycle and its link to climate change.* Water and energy are inextricably linked in the Earth system. Changes in temperature as observed and predicted into the future by climate models are expected to alter global water vapor, clouds, and precipitation. Questions have been raised asking whether Earth will see more extreme precipitation events in the form of larger/wetter storms and/or more severe and frequent droughts as the global-mean temperature rises (NRC 2011). Current climate models predict increased heavy rain events in the next century but differ at moderate to light rain intensities. While present-day satellite data show more intense heavy rain events in certain regions such as the tropics (Gu et al. 2007), more accurate measurements of light rain, which contributes significant rain amounts in the extratropics, are required to assess climate model results. GPM will provide global precipitation measurements with improved accuracy, coverage, and dynamic range for studying changes in precipitation characteristics.

A key to understanding the coupling of the water and energy cycles is the release of latent heat, which redistributes the solar energy received at Earth's surface deep into the atmospheric interior to drive the large-scale circulation. Vertical rain profiles such as those from TRMM and GPM serve as a proxy for the latent heating in an atmospheric column above it, which cannot be directly observed. GPM will provide combined radar/radiometer estimates of the intensity and variability of 3D latent heating structures of precipitation systems beyond the tropics. GPM precipitation and latent heating data can also be assimilated to constrain 4D climate reanalyses (e.g., Hou and Zhang 2007) to improve our understanding of the interaction of atmospheric heating with large-scale dynamics and global teleconnection patterns. Indeed, TRMM has shown that detailed observations of the characteristic stages of the MJO (Morita et al. 2006) and their interaction with tropical waves (Masunaga et al. 2006) can help clarify the role of tropical convective systems in climate feedback processes (Back and Bretherton 2006; Del Genio et al. 2005).

The utility of current satellite rainfall products in determining spatially distributed runoff and renewable freshwater supplies is still limited (Fekete et al. 2004; Kucera et al. 2013). The enhanced measurement and sampling capabilities of GPM will help us better understand how changing precipitation patterns at multiple scales translate into changes in hydrologic fluxes and states (e.g., runoff, evapotranspiration, soil moisture, and groundwater recharge) both directly and through data assimilation into land process models (e.g., Rodell et al. 2004). By providing more accurate estimates of the rate of transfer of water from the atmosphere to the surface at local and global scales, GPM will reduce a major source of uncertainty in the global water/energy budget.

2) *New insights into storm structures and mesoscale dynamics.* The GPM radar will provide observations of the 3D structure of precipitation, succeeding TRMM in the tropics in detecting convective hot towers that often indicate rapid intensification of tropical storms (Simpson et al. 1998; Kelley et al. 2004; see Fig. S1). GPM will enable us to track, for the first time, 3D structural changes of tropical storms as they undergo the transition into midlatitude frontal systems to seek why some, but not all storms, intensify during this transition and what factors may affect the intensity change. Global precipitation products from satellites have enabled us to map changes in the precipitation structure over the life cycle of a storm over oceans, where conventional data are sparse, to gain insights into storm dynamics such as the eyewall replacement process in hurricanes. GPM observations will also extend the precipitation feature database (Nesbitt et al. 2000) to gain insights into the properties and regional variations of mesoscale convective systems (Lau and Zhou 2012; Wall et al. 2012). The enhanced instrument sensitivity will also help improve the understanding of precipitation characteristics in mountainous regions beyond what has been learned from TRMM (e.g., Bindlish and Barros 2000; Bhatt and Nakamura 2005).

3) *New insights into precipitation microphysics.* Satellite precipitation observations have been used in conjunction with other data to identify rainfall anomalies that may be associated with human impacts on the environment, which include the effects of aerosols from pollution or biomass burning (e.g., Rosenfeld et al. 2001; Andreae et al. 2004), land use (e.g., Cotton and Pielke 2007), deforestation (e.g., Wang et al. 2000; Negri et al. 2004; Avissar and Werth 2005), and urban environment on precipitation (e.g., Shepherd et al. 2002; Bell et al. 2008). By providing new microphysical measurements from the DPR to complement cloud and aerosol observations, GPM will provide further insights into how precipitation processes may be affected by human activities.

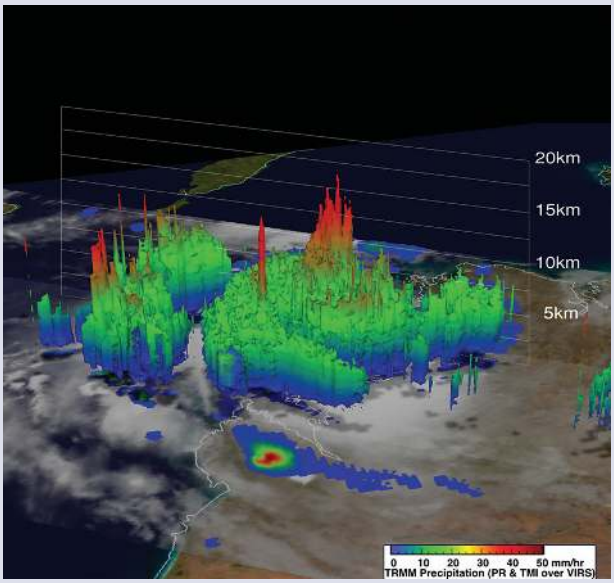

Fig. S1. Image of tropical cyclone MAGDA off the northern coast of Australia at 1927 UTC 21 Jan 2010 constructed from TRMM PR, TMI, and IR data showing the three-dimensional isosurface of the 15-dBZ radar reflectivity. The colors correspond to the vertical height (blue for the lowest altitude to red for tall thunderstorms indicative of future intensification). Also shown are surface rain rates in mm h^{-1} superimposed on IR cloud image.

provide advanced measurements for understanding the global water cycle. Within these contexts, GPM will provide key measurements that will be used synergistically with complementary observations to gain insights into the complex interactions among water and cloud, water vapor, aerosols, soil moisture, and ocean salinity provided by current and future satellite missions such as the Soil Mositure and Ocean Salinity (SMOS) mission of ESA, the Aquarius mission launched by NASA and Argentinean Space Agency, the Soil Moisture Active Passive (SMAP) mission of NASA, and the EarthCare mission of ESA and JAXA. Recognizing that the distribution of global precipitation provides a context within which to interpret the causes and consequences of local variations in water-related observations, the Earth Sciences Decadal Survey endorsed GPM as the first in a series of missions targeting Earth's water and energy cycle in the coming decade (NRC 2007b).

GPM data will help advance the objectives of a host of international scientific programs and activities that include GEWEX established under WCRP, to understand the global hydrological cycle and energy fluxes through observations and modeling, IGWCO directed by IGOS partners to inform the United Nations about the global environment and guide policymaking, GSICS initiated by WMO and CGMS to improve accuracy and consistency of space-based observations, and IPWG to improve spaceborne precipitation measurements and their utilization in research and applications. GPM has been identified as an outstanding example of peaceful uses of space by the United Nations Program on "Remote Sensing for Substantive Water Management in Arid and Semi-Arid Areas," and the GPM mission will be the first realization of the Precipitation Constellation developed by the CEOS for GEOSS to provide long-term, coordinated observations of Earth to contribute to the societal benefit areas as identified by GEO.

GPM CONSTELLATION PARTNERSHIP AND CONFIGURATION. The GPM constellation comprises both conical-scanning and cross-track-scanning microwave radiometers operating at

GPM SOCIETAL BENEFITS

1) *Extending current capabilities in monitoring and prediction of hurricanes and other extreme weather events.* The advantage of microwave instruments over infrared and visible sensors is their ability to see through clouds to reveal precipitation structures, including hurricane eyewalls and spiral rainbands within tropical cyclones. The capabilities are already being exploited by numerous operational agencies (NRC 2005). The GMI, with its 1.2-m antenna, is capable of providing measurements at the highest spatial resolution among all constellation radiometers (see Table 4), which will be crucial for obtaining accurate fixes of storm centers for track predictions. The improved consistency among rainfall products produced by the GPM constellation will further help improve the utility of these sensors.
2) *Enhanced numerical weather prediction skills.* Assimilation of precipitation information into global and regional forecast systems has been shown to improve atmospheric analyses and short-range forecasts in a variety of situations (Zupanski et al. 2002; Marécal and Mahfouf 2003; Hou et al. 2004; Aonashi et al. 2004). Rain-affected microwave radiances and precipitation retrievals are currently being used at NWP centers to improve operational forecasts (Bauer et al. 2006). By providing more accurate and frequent observations in near–real time, GPM will enable NWP centers to continue improving forecasts through the development of advanced assimilation techniques such as ensemble data assimilation and rainfall assimilation using the forecast model as a weak constraint. GPM GV activities are expected to provide better error characterizations of GPM measurements, which are crucial for making optimal use of precipitation information in NWP systems.
3) *Improved forecasting for floods, landslides, and freshwater resources.* GPM will provide frequent precipitation observations, of which 80% will be less than 3 h apart (see Fig. 4), exceeding the minimum deemed necessary for hydrometeorological applications (Nijssen and Lettenmaier 2004). GPM observations can be used operationally in land data assimilation to provide better soil moisture, temperature, snowpack, and vegetation initial conditions for coupled NWP forecasts (Mitchell et al. 2004), or integrated into Land Information Systems (Kumar et al. 2006) to improve operational land data assimilation systems (LDAS). The improved sampling over land in the GPM era will advance the detection and prediction capabilities for floods and landslides (Wu et al. 2012; Kirschbaum et al. 2012) as well as the assessment and forecasting of freshwater resources at medium to large basin scales, especially in developing nations, where in situ precipitation gauge networks are sparse (Hossain and Lettenmaier 2006; Kucera et al. 2013). GPM is currently working with the NOAA HMT program (Dabberdt et al. 2005; http://hmt.noaa.gov/) to improve the use of satellite precipitation data in operational hydrometeorological applications at small basin scales, and GPM data will be used in flood and famine warning systems such as the International Flood Network (IFNET; www.internationalfloodnetwork.org) in Japan, the USAID-NASA SERVIR program (www.servirglobal.net/), and the Famine Early Warning System (FEWS; www.fews.net/) in Africa, Asia, and Latin America.

Fig. 1. An illustration of the constellation of satellites contributing microwave sensor data to the GPM mission: Shown are the U.S.–Japan GPM Core Observatory (upper right), the Indo-French Megha-Tropiques, the GCOM-W1 of Japan, the European MetOp satellites, and the DMSP, POES, *Suomi-NPP*, and JPSS satellites of the United States.

frequencies between 6 and 183 GHz. These include the traditional channels used for rainfall estimation over oceans and land since the launch of the first SSM/I instrument in 1987, as well as high frequency microwave channels, originally designed for water vapor profiling, that provide useful information about precipitation in regions of uncertain land surface emissivities such as frozen and snow-covered areas.

The GPM mission achieves improved global coverage by building upon existing satellite programs and new mission opportunities from a consortium of partners via bilateral agreements with either NASA or JAXA. NASA and JAXA have a Memorandum of Understanding (MOU) to provide the GPM Core Observatory. NASA also has bilateral implementing agreements with Centre National d'Etudes Spatiales (CNES) of France and Indian Space Research Organisation (ISRO) of India, as well as a MOU with EUMETSAT and an interagency agreement with NOAA to contribute satellites as members of the GPM constellation (see Fig. 1). While each constellation member may have its unique scientific or operational objectives, they all contribute microwave sensor data to GPM for the generation and dissemination of unified global precipitation products to worldwide user communities. In addition to the DPR and GMI, the sensors that will provide data to GPM include 1) the SSMIS instruments on the U.S. DMSP satellites (Kunkee et al. 2008), 2) the Advanced Microwave Scanning Radiometer 2 (AMSR-2) on JAXA's GCOM-W1 satellite (Shimoda 2005), 3) the MADRAS and Sondeur Atmospherique du Profil d'Humidite Intertropicale par Radiometrie (SAPHIR) instruments on the French-Indian Megha-Tropiques satellite (Desbois et al. 2003), 4) the MHS instruments on the NOAA Polar Orbiting Environmental Satellites (POES) satellites, 5) the MHS instruments on the EUMETSAT MetOp satellites (Edward and Pawlak 2000), 6) the ATMS instrument on the NPOESS NPP satellite, and 7) the ATMS instruments on the NOAA–NASA JPSS satellites (Bunin et al. 2004).

As a reference satellite for the GPM constellation, the Core Observatory will fly in a non-sun-synchronous orbit at 65° inclination to obtain coincident measurements with constellation sensors facilitating intersensor calibration over 90% of the globe (note that in a 65° inclined orbit, the actual coverage of the GMI swath extends from 68°N to 68°S). The 65° orbit inclination was selected to offer a broad latitudinal coverage without locking into a sun-synchronous polar orbit, while still maintaining a sufficiently short precession period to sample diurnal variability within a season. TRMM has shown the importance of observations from a non-sun-synchronous orbit for reducing the temporal gaps between the overpasses of polar orbiting sensors at fixed local times. Additional sampling by the GPM Core Observatory from an inclined orbit will benefit near-real-time monitoring of rapidly intensifying storms, quantifying the diurnal variation of precipitation, and obtaining more accurate estimates of precipitation accumulation. The GPM Core Observatory, which has a prime design life of 3 years with sufficient fuel for a minimum of 5 years of operation.

CORE OBSERVATORY MEASUREMENT CAPABILITIES. The DPR and GMI instruments aboard the GPM Core Observatory together will

characterize the physical properties of precipitating particles through their microwave emission/scattering signatures. Over the region where the radar and radiometer swaths overlap, precipitation retrievals constrained by both DPR reflectivities and GMI radiances are expected to be of the highest quality and accuracy. The global observational hydrometeor database, derived from the combined DPR and GMI measurements over a wide range of environmental conditions and climate regimes, will constitute a major advance over the model-simulated database used in current retrievals. The technical capabilities of the DPR and GMI instruments are described below.

Radar. The DPR instrument, developed by JAXA and NICT (also of Japan), measures the three-dimensional structure of precipitation, consisting of a Ka-band precipitation radar (KaPR) operating at 35.5 GHz and a Ku-band precipitation radar (KuPR) at 13.6 GHz. The KuPR and KaPR will provide coaligned 5-km-resolution footprints on Earth's surface, with cross-track swath widths of 245 and 120 km, respectively, as shown in Fig. 2. Within the inner swath of 120 km, data from both frequencies will be acquired nearly simultaneously. While the Ku-band radar acquires data in the outer portion of the full swath of 245 km, the Ka-band radar will operate in the high-sensitivity mode to acquire data from the interlaced fields of view as illustrated in Fig. 2. Both radars have a nominal vertical range resolution of 250 m, sampled every 125 m, with a minimum detectable signal of better than 18 dB*Z*. The KaPR high-sensitivity mode, used during the period of interleaved sampling, has a minimum detectable signal of approximately 12 dB*Z* with a vertical resolution of 500 m.

Although nearly identical to the TRMM PR, the Ku-band channel of the DPR will have higher precision resulting from a greater number of independent samples (used to form the average return power) and greater sensitivity owing to the higher transmitted peak power to achieve a minimum detection threshold of 0.5 mm h^{-1} (or 18 dB*Z*). The Ka band, when operated in the high sensitivity mode, will further extend the DPR sensitivity range to detect precipitation rates down to about 0.2 mm h^{-1} (12 dB*Z*). Table 2 provides a detailed comparison of the instrument characteristics of the GPM DPR with those of the TRMM PR.

In addition to offering higher sensitivity at light rain rates, a key advance of the DPR over the TRMM PR is its ability to provide quantitative estimates of the precipitation particle size distribution (PSD) from the overlapping portion of the Ku and Ka swath over a nominal range of precipitation intensities from a few to ~15 mm h^{-1}. The characterization of the size parameter and number concentration of the PSD can be used to refine a priori assumptions in retrieval algorithms (see the section "Precipitation algorithms"). Overall, DPR measurements will offer new physical insights into microphysical processes (evaporation, collision/coalescence, aggregation) and improved capabilities in distinguishing regions of liquid, frozen, and mixed-phase precipitation, in addition to providing bulk precipitation properties such as water flux and column water content.

Radiometer. The GMI instrument, developed and built by the Ball Aerospace and Technology Corporation under contract with NASA's Goddard Space Flight Center (GSFC), is a conical-scanning passive microwave radiometer with 13 channels ranging from 10 to 183 GHz. These frequencies have been optimized over the past decades to detect heavy, moderate, and light precipitation: specifically,

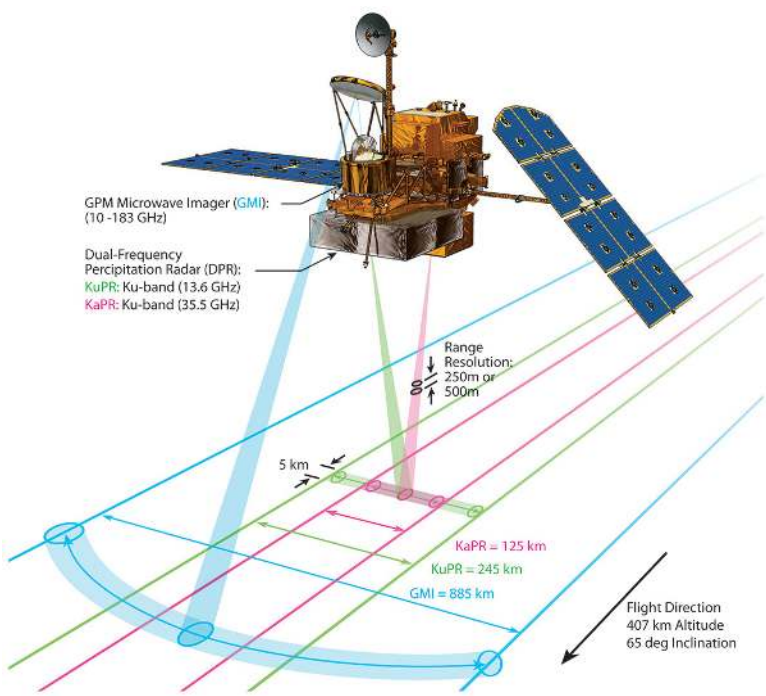

Fig. 2. A schematic of the scanning patterns and swaths of the DPR and GMI instruments on board the GPM Core Observatory.

Table 2. Comparison of GPM DPR instrument characteristics with TRMM PR.			
Instrument	GPM KaPR at 407 km	GPM KuPR at 407 km	TRMM KuPR at 350 km
Antenna type	Active phased array (128)	Active phased array (128)	Active phased array (128)
Frequency (GHz)	35.547 and 35.553	13.597 and 13.603	13.796 and 13.802
Swath width (km)	120	245	215
Horizontal resolution at nadir (km)	5	5	4.3
Transmitter pulse width (μs)	1.6/3.2 (×2)	1.6 (×2)	1.6 (×2)
Range resolution (m)	250/500	250	250
Observation range (km) (mirror image at nadir)	18 to −3	18 to −5	15 to −5
Pulse repetition frequency (Hz)	Variable (4275 ± 100)	Variable (4206 ± 170)	Fixed (2776)
Sampling number	108 ~ 112	104 ~ 112	64
Transmitter peak power (W)	>146	>1013	>500
Minimum detectable Z_e and rain rate*	12 dBZ (500 m res.) (0.2 mm h^{-1})	18 dBZ (0.5 mm h^{-1})	18 dBZ (0.7 mm h^{-1})
Measurement accuracy (dBZ)	<±1	<±1	<±1
Data rate (Kbps)	<78	<112	<93.5
Mass (kg)	<300	<365	<465
Power consumption (W)	<297	<383	<250
Physical dimensions (m)	1.44 × 1.07 × 0.7	2.4 × 2.4 × 0.6	2.2 × 2.2 × 0.6

* Minimum detectable rain rate defined as $Z_e = 200\ R^{1.6}$ for DPR and $Z_e = 372.4\ R^{1.54}$ for TRMM PR.

- 10-GHz channel, optimal for the sensing of liquid precipitation;
- 19- and 37-GHz channels for sensing moderate to light precipitation over ocean;
- 21-GHz channel for correction of the emission by water vapor;
- 89-GHz channel for the detection of ice particles for precipitation over ocean and land;
- 166-GHz channel for sensing light precipitation, typical outside the tropics; and
- 183-GHz channel for detecting scattering signals due to small ice particles and estimating light rainfall and snowfall over snow-covered land.

By combining channels that are normally flown on imagers (i.e., 10–89 GHz) with high-frequency (166 and 183 GHz) channels, the GMI will be capable of retrieving the wide spectrum of precipitation intensities found across the globe and to serve as a common radiometric reference for intersatellite calibration over the range of frequencies present on GPM constellation radiometers. For improved calibration accuracy and stability, the GMI uses noise diodes to perform a four-point calibration to allow linear and nonlinear calibration fittings. In doing so, the stability of the noise diodes is assessed during operations, and the effects of solar intrusion on the warm load can be identified and eliminated, resulting in more accurate calibration both for short-term constellation sensor comparisons and for producing climate quality datasets over the mission lifetime. As a result, the GMI will be well calibrated in an absolute sense. The quality of the calibration will be evaluated after launch by comparison with other sensors and through internal self-consistency checks (Wilheit 2013).

The GMI main reflector rotates at 32 rpm to collect microwave radiometric measurements over a 140° sector centered on the spacecraft ground track, giving a cross-track swath of 885 km on Earth's surface (Fig. 2). The central portion of the GMI swath will overlap the DPR Ka-Ku swaths (with an approximately 67-s lag between the GMI and radar observation times due to geometry and spacecraft motion). The GMI has a 1.2-m diameter antenna, which at the altitude of 407 km will achieve higher spatial resolution than the TMI and all other radiometers in the GPM constellation. Detailed characteristics of the GMI instrument are given in Table 3.

GPM CONSTELLATION COVERAGE AND SAMPLING. The spatial coverage and temporal sampling of the baseline GPM constellation will vary with

Table 3. GMI instrument characteristics.								
	10.65 V & H	18.7 V & H	23.8 V	36.5 V & H	89.0 V & H	166 V & H	183.31 ± 3 V	183.31 ± 7 V
Resolution (km)	19.4 × 32.2	11.2 × 18.3	9.2 × 15.0	8.6 × 15.0	4.4 × 7.3	4.4 × 7.3	4.4 × 7.3	4.4 × 7.3
Sample NEDT* (K)	0.96	0.84	1.05	0.65	0.57	1.5	1.5	1.5
Sample NEDT** (K)	0.93	0.76	0.73	0.52	0.41	0.92	0.76	0.67
Beam NEDT* (K)	0.53	0.61	0.82	0.52	0.65	1.72	1.72	1.72
Beam NEDT** (K)	0.51	0.55	0.40	0.42	0.47	1.05	0.87	0.77
Beam efficiency** (%)	91.1	91.2	93.0	97.8	96.8	96.5	95.2	95.2
Uncertainty** (K)	0.99	1.05	0.71	0.53	0.69	0.69	0.66	0.66
Pass-band Bandwidth (MHz)	100	200	400	1000	6000	4000	3500	4500
Antenna 3-dB beamwidth (Max)	1.75°	1.0°	0.9°	0.9°	0.4°	0.4°	0.4°	0.4°
Sampling interval (ms)	3.6							
Incidence angles	Nominal Earth incidence = 52.8° Off-nadir angle = 48.5°					Earth incidence = 49.19° Off-nadir angle = 45.36°		
Data rate, power, mass	30 kbps, 162 W, 166 kg, deployed size = 1.4 m × 1.5 m × 3.5 m							
Antenna size, swath width	1.2 m, 885 km							

* Instrument requirements.

** Preflight performance values. Sample NEDT is for a fixed integration time of 3.6 μs for all channels. Beam NEDT is the noise integrated over a footprint for each channel.

the available on-orbit partner assets, as can be seen from the expected operating periods of the constellation members shown in Fig. 3. For comparison, in 2012 there were seven satellites providing microwave measurements of precipitation: namely, TRMM, three DMSP satellites (F16, F17, and F18), two POES satellites (*NOAA-18* and *-19*), and *MetOp-A*.

Figure 4 shows that the GPM constellation will provide marked improvements in coverage and sampling relative to present-day capabilities by reducing the annual-mean revisit times of the microwave radiometers over much of the globe (Fig. 4a) and by providing more frequent observations as well as greater number of observations (Fig. 4b). In particular, Fig. 4b shows that by 2015 more than 60% of constellation sampling will be less than 1 h apart, and over 80% will be less than 3 h apart at all latitudes, compared with 45% and 70%, respectively, for their counterparts in 2012. As more nations share Earth observations from space, the sampling of global precipitation could be further enhanced with microwave data from the Chinese FY-3 radiometers (NSMC 2013) and the Russian Combined Microwave-Optical Imaging/Sounding Radiometer (MTVZA) sounder/imagers (Cherny et al. 2002).

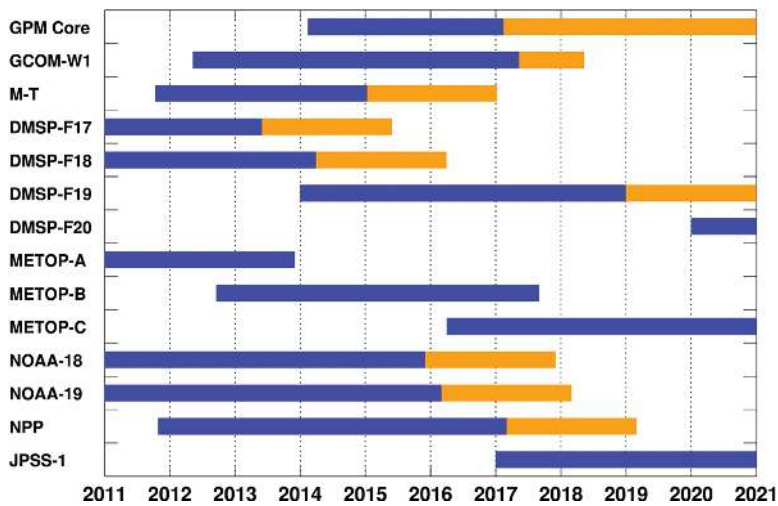

Fig. 3. Estimated launch schedules and life spans of GPM constellation satellites, with blue denoting the primary mission phase and yellow the extended mission phase. GPM Core Observatory operations beyond the primary mission phase are subject to science and satellite performance evaluation after launch.

INTERSATELLITE CALIBRATION OF RADIOMETRIC MEASUREMENTS. A major goal of the GPM mission is to provide uniform global precipitation products from a heterogeneous constellation of microwave sensors within a consistent framework. The GPM mission will provide four levels of data products: 1) level 1 data consisting of geolocated, calibrated DPR radar power, GMI brightness temperatures, and intercalibrated brightness temperatures from partner radiometers at the instantaneous field of view (IFOV); 2) level 2 products consisting of geolocated, geophysical data (e.g., precipitation rates) and DPR reflectivities at the IFOV; 3) level 3 products consisting of gridded time–space sampled geophysical data (including latent heating estimates) from the GPM Core sensors and partner radiometers; and 4) level 4 products consisting of merged remotely sensed and model information.

Since the GPM constellation consists of a network of microwave radiometers that have similar but not identical characteristics (Table 4), an important first step in developing a uniform precipitation dataset is the removal of relative biases in brightness temperatures across the sensors to provide a self-consistent input dataset for precipitation retrieval. This requires that brightness temperatures of the constellation radiometers be intercalibrated to a common standard by accounting for the differences in central frequency, viewing geometry, spatial resolution, etc. The NASA GPM program has established an international working group to develop a community consensus for intersatellite calibration of microwave radiances observed under all weather conditions (Wilheit 2013). For precipitation retrievals from GPM constellation sensors, GPM will produce a bias-corrected self-consistent radiometric dataset as a "level 1C" product while maintaining the official level 1B products of the sensor providers.

For conically scanning radiometer imagers (with channels up to 90 GHz), the strategy is to convert

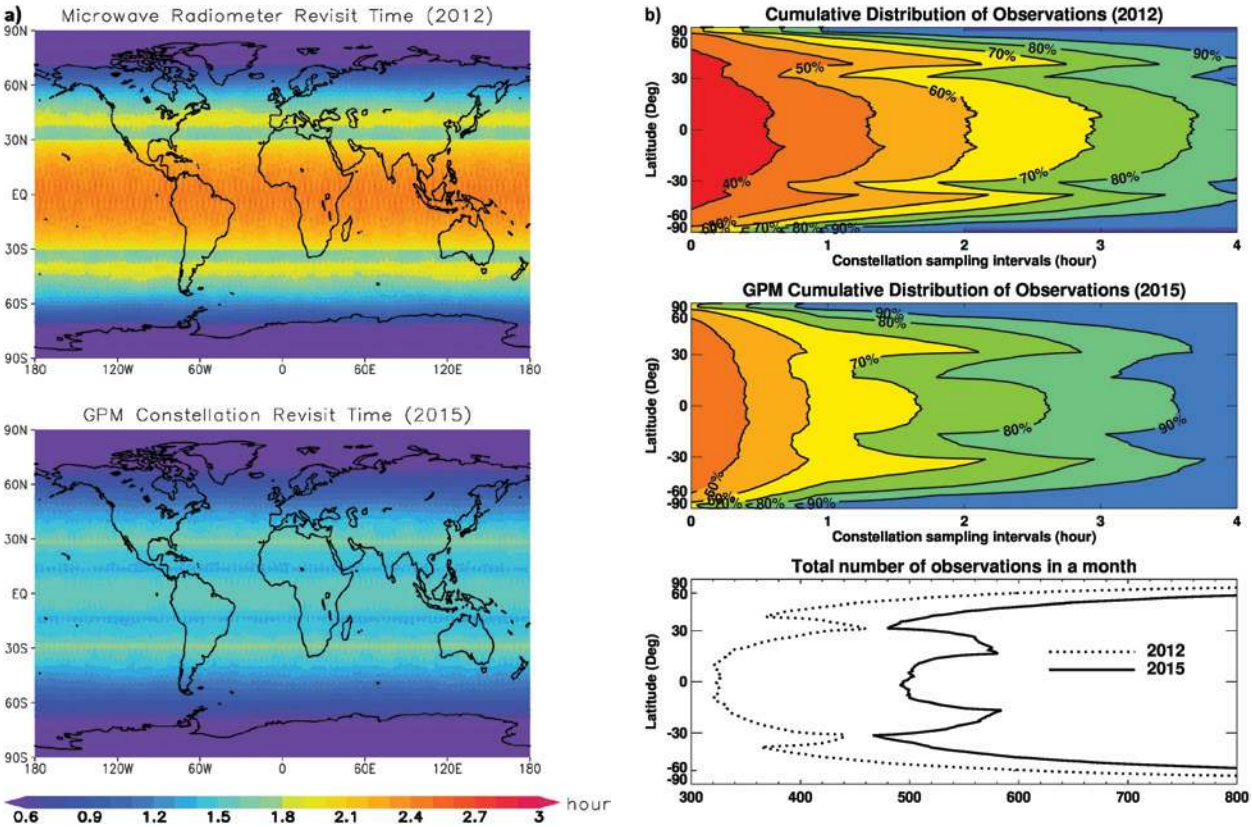

Fig. 4. (a) (top) Mean revisit times of seven microwave radiometers (TRMM, three DMSP satellites, two POES satellites, and *MetOp-A*) that provide precipitation measurements in 2012. (bottom) Mean revisit times of the GPM constellation of satellites in 2015 (GPM Core, GCOM-W1, Megha-Tropiques, three DMSP satellites, two PEOS satellites, *Suomi-NPP*, and *MetOp-B*; see Fig. 3). (b) (top) Cumulative distribution of observations by constellation radiometers in 2012 as a function of sampling intervals and latitudes in 2012. (middle) Corresponding results for the GPM constellation in 2015. (bottom) Comparison of the numbers of observations in a month by constellation radiometers at different latitudes in 2012 with those by the GPM constellation in 2015.

observations of one satellite to virtual observations of another using a non-sun-synchronous sensor (e.g., TMI or GMI) as a transfer standard. Prior to the GPM launch, the prototype intercalibrated level 1C brightness temperature product developed using the TMI as reference provides an example of how constellation radiometric measurements can be reconciled within a consistent framework (GPM ATBD 2013). An important by-product of this cross-calibration effort is the ability to monitor each instrument in the GPM constellation for abrupt and/or gradual calibration changes as well as other degradations.

Intercalibration of the cross-track-scanning water vapor microwave sounders on the operational sun-synchronous satellites has, until recently, relied on very high-latitude orbital crossings for near-simultaneous, collocated observations or the use of high-quality ground truth sites for limited intercalibration. The recent launch of the Megha-Tropiques satellite with the SAPHIR water vapor sounder into a low inclination (20°) orbit has provided a wide swath of near-simultaneous collocated observations with the operational water vapor sounders, which can be analyzed in ways analogous to those used for the microwave imagers. This will enable the cross-calibration across large range of incidence angles prior to the launch of the GMI. In a complementary activity, GPM is coordinating efforts with the GSICS program sponsored by the WMO to employ bias removal diagnostics used in operational forecasting as an alternative approach to intercalibrate microwave sounders.

PRECIPITATION ALGORITHMS. Precipitation retrievals from GPM Core Observatory and constellation satellite measurements at the instantaneous field of view will consist of GPM level-2 DPR-only algorithms, combined DPR+GMI algorithms, and radar-enhanced radiometer algorithms using an a priori hydrometeor database constrained by Core sensor measurements. In addition, there are separate algorithms to merge the multiple satellite products and to obtain latent heating estimates. These algorithm methodologies are outlined below.

DPR retrievals. As the first spaceborne dual-frequency radar, the DPR offers several advances in precipitation retrieval relative to its single-frequency counterparts on TRMM and ground radars (Iguchi et al. 2000). These include improvements in hydrometeor identification (particularly in convective storms), greater accuracy in the estimation of rain rate and water content, and information on the PSD in both rain

Table 4. Characteristics of passive microwave radiometers in the GPM era.

Channel	6–7 GHz	10 GHz	19 GHz	23 GHz	31–37 GHz	50–60 GHz	89–91 GHz	150–167 GHz	183–190 GHz
Channel center frequency (GHz): V–vertical polarization, H–horizontal polarization									
GMI		10.65 V/H	18.70 V/H	23.80 V	36.50 V/H		89.0 V/H	165.6 V/H	183.31 V
AMSR-2	6.925/ 7.3 V/H	10.65 V/H	18.70 V/H	23.80 V/H	36.5 V/H		89.0 V/H		
SSMIS			19.35 V/H	22.235 V	37.0 V/H	50.3–63.28 V/H	91.65 V/H	150 H	183.31 H
MADRAS			18.7 V/H	23.80 V	36.5 V/H		89.0 V/H	157 V/H	
MHS							89 V	157 V	183.311 H 190.311 V
ATMS				23.8	31.4	50.3–57.29	87–91	164–167	183.31
SAPHIR									183.31 H
Mean (or nadir; marked with *) spatial resolution (km)									
GMI		26	15	12	11		6	6	6
AMSR-2	62/58	42	22	26	12		5		
SSMIS			59	59	36	22	14	14	14
MADRAS			40	40	40		10	6	
MHS*							17	17	17
ATMS*				74	74	32	16	16	16
SAPHIR*									10

and snow. For a reasonable range of assumed gamma distribution shape parameters or snow mass densities, the overlapping Ku- and Ka-band measurements can be used to determine two parameters of the PSD (e.g., the median mass diameter and characteristic number concentration) at each range bin in the vertically sampled profile (Liao et al. 2005). In addition, attenuation correction, which is key to the success of any radar algorithm at these frequencies, can be accomplished either through the use of the surface as reference target or by an iteration where the PSD itself is used in a stepwise correction procedure (e.g., Meneghini et al. 1997; Mardiana et al. 2004; Rose and Chandrasekar 2006). The DPR algorithms being developed provide instantaneous surface rainfall and vertical hydrometeor profiles at the pixel (~5 km horizontal, 125 m vertical) level as well as gridded space–time accumulations (GPM ATBD 2013; also see Table 5).

Combined DPR and GMI retrievals. While the DPR profiling algorithms are a major improvement over the TRMM PR algorithms, ambiguities still exist as a result of a number of assumptions such as the "shape" parameter of the size distribution, the mass densities of snow aggregates and graupel, and the vertical profiles of water vapor and cloud liquid water. The goal of the combined DPR+GMI retrieval is to use the multichannel GMI radiometric measurements as additional integral constraints on DPR algorithms to produce a set of geophysical parameters that are physically consistent with both DPR reflectivity profiles and GMI radiances over the radar swath. Specifically, some of the abovementioned assumptions can be constrained by using variational procedures that minimize departures between simulated and observed brightness temperatures, or by using ensemble Kalman filtering approaches that determine an ensemble of radar solutions that are consistent with the brightness temperatures and their uncertainties. The combined retrieval methodology builds upon the rich heritage of algorithms developed for TRMM (e.g., Haddad et al. 1997; Grecu et al. 2004; Masunaga and Kummerow 2005). The combined DPR+GMI retrievals, which will provide the highest-quality precipitation estimates, will also facilitate the construction of an a priori database that relates hydrometeor profiles to microwave radiances over the range of brightness temperatures observed over nearly the entire globe. The advantage of such a database derived from combined observations over one provided by cloud-model simulations has been already demonstrated (e.g., Grecu and Olson 2006). The combined DPR+GMI algorithms will provide pixel-level surface precipitation together with its vertical structure as well as accumulations over selected space–time domains (GPM ATBD 2013; also see Table 5).

Table 5. Description of GPM data products.

Product level	Description	Coverage
Level 1B GMI Level 1C GMI Latency ~1 h	Geolocated brightness temperature and intercalibrated brightness temperature	Swath, IFOV (produced at NASA)
Level 1B DPR	Geolocated, calibrated radar powers	Swath, IFOV (produced at JAXA)
Level 1C, partner radiometers	Intercalibrated brightness temperatures	Swath, IFOV (produced at NASA)
Level 2 GMI Latency ~1 h	Radar enhanced (RE) precipitation retrievals	Swath, IFOV
Level 2 partner radiometers	RE precipitation retrievals from 1C	Swath, IFOV
Level 2 DPR Latency ~3 h	Reflectivities, sigma zero, characterization, PSD, precipitation with vertical structure	Swath, IFOV (Ku, Ka, combined Ku/Ka)
Level 2 combined GMI/DPR Latency ~3 h	Precipitation	Swath, IFOV (initially at DPR Ku swath and then at GMI swath)
Level 3 latent heating (GMI, DPR, Combined)	Latent heating and associated related parameters	0.25° × 0.25° monthly grid
Level 3 instrument accumulations	GMI, partner radiometers, combined and DPR	0.25° × 0.25° monthly grid
Level 3 merged product	Merger of GMI, partner radiometer, and IR	0.1° × 0.1°30-min grid
Level 4 products	Model-assimilated precipitation forecast and analysis	Model temporal and spatial scales

"Radar-enhanced" radiometer retrievals. Building upon the TRMM heritage (e.g., Evans et al. 1995; Kummerow and Giglio 1994; Kummerow et al. 1996; Marzano et al. 1999), GPM will implement the 2014 version of the Goddard Profiling Bayesian approach (GPROF2014) for precipitation retrievals from all passive microwave radiometers in the GPM constellation. But unlike TRMM algorithms that used model-generated hydrometeor databases, GPROF2014 will take advantage of the Core Observatory measurements to build a priori databases from DPR retrieved precipitation profiles and their associated microwave radiometric signals. These observation-constrained databases are then used in conjunction with Bayesian inversion techniques to build consistent retrieval algorithms for GMI on the Core and for each of the GPM constellation satellites. Since these retrievals employ a priori databases that contain information from the DPR, they are effectively radar enhanced. A prototype GPM radiometer retrieval using a tropical cloud database constrained by TRMM PR reflectivities and TMI radiances has been developed to demonstrate the effectiveness of this technique (Kummerow et al. 2011). Since the construction of an observation-constrained database requires on-orbit DPR and GMI data, the GPM radar-enhanced radiometer products are expected to be available 6 months after the completion of on-orbit calibration of the Core instruments. GPM radiometer algorithms will provide surface precipitation and some vertical structure at the pixel level as well as selected space–time accumulations (GPM ATBD 2013; also see Table 5). The advances in intersatellite radiometric calibration and level 2 sensor retrievals for the GPM constellation of satellites should significantly improve the accuracy and consistency of precipitation estimates produced by the individual microwave instruments.

Multisatellite merging algorithms. While the frequent coverage afforded by GPM constellation radiometers will be unprecedented, there will always be applications such as hydrology that require even greater temporal and spatial resolution. The purpose of the level 3 multisatellite precipitation algorithm (I-MERG) is to combine the intermittent precipitation estimates from all constellation microwave sensors with the more frequent, albeit less accurate, IR-based observations from geosynchronous satellites and monthly surface precipitation gauge data to create a consistently calibrated, uniformly gridded, global precipitation data product with appropriate error and metadata information. This general concept has been developed over the last 15 years, with a proliferation of alternative approaches in the last five, and is the basis for the most requested dataset in the TRMM suite of products (i.e., the TRMM plus other satellites products 3B42 and 3B43). The merged microwave–infrared approach will directly benefit from the constellation radiometer algorithms being developed for GPM in that GPM will ensure that the microwave products being used for bias correction are consistent with one another—an essential ingredient to make these algorithms perform optimally.

GPM multisatellite algorithms will build upon the algorithms developed over the past 15 years that include GPCP (Huffman et al. 2001), PERSIANN (Sorooshian et al. 2000), NRL-Blend (Turk and Miller 2005), SCaMPR (Kuligowski 2002), TMPA (Huffman et al. 2007), CMORPH (Joyce et al. 2011), and GSMaP (Kubota et al. 2007; Ushio et al. 2009). The GPM multisatellite global precipitation data will be complemented by national precipitation products generated by GPM partners. The near-term U.S. GPM multisatellite algorithm, I-MERG, will incorporate the salient components of PERSIANN, CMORPH, and TMPA to produce a hierarchy of merged global precipitation products ranging from MW-only to MW-plus-IR data products (GPM ATBD 2013). Efforts are also underway in the United States to develop global precipitation datasets that combine satellite and ground-based precipitation measurements at their native spatial resolution in order to preserve precipitation extremes at the local scales. In the near term, the Japanese multisatellite algorithm team is focusing on the continued development of merged GSMaP products but ultimately plans to directly assimilate level 1 satellite precipitation measurements into numerical models to generate level 4 global precipitation products.

Latent heating algorithms. Atmospheric latent heating (LH) associated with the production of clouds, rain, and snow as a result of phase conversion of water vapor into liquid and/or frozen particles can strongly influence the large-scale circulation patterns in the tropics, excite and modulate tropical waves, maintain the intensity of tropical cyclones, and supply the energy to cyclones and other mobile weather systems in the midlatitudes. The determination of the intensity and three-dimensional structure of tropical latent heating has been a major objective of TRMM. The PR and TMI can provide estimates of the convective and stratiform components of rain rates that are key to retrieving the vertical LH structure. Currently, TRMM has two standard LH products—the convective–stratiform heating derived from the

PR and TMI (Tao et al. 2010) and the spectral latent heating derived from the PR (Shige et al. 2007). GPM will extend these algorithm development efforts while taking advantage of the more advanced measurement capabilities of the DPR and GMI to create 3-hourly gridded LH estimates as level 3 data products.

GROUND VALIDATION. The traditional approach to validating satellite precipitation data is to use ground-based observations (e.g., radars and rain gauges) as a reference or *truth* to directly assess the quality of satellite products. Among the lessons learned from TRMM is that while such comparisons are useful and necessary, ground measurements do not necessarily represent the "truth" but rather have their own set of uncertainties that must be carefully monitored and quality controlled. Moreover, in order to improve physically based satellite precipitation profile algorithms, ground validation must go beyond surface rainfall comparisons to provide ancillary information within a precipitating column to identify sources of errors in retrieval algorithms under a variety of environmental conditions. Hydrological measurements (e.g., streamflow data, snowpack depths, etc.) and water budget analyses with proper error characterizations could also be potentially useful as area/time-integrated constraints to assess the quality and utility of multisatellite precipitation products.

To support prelaunch algorithm development and postlaunch product evaluation, NASA has established a broad range of joint projects with domestic and international partners to use ground-based observations (including aircraft measurements) to conduct the following three categories of ground validation (GV) activities:

1) *Direct statistical validation at the surface using national networks*: These activities provide direct statistical comparisons of satellite precipitation products with measurements provided by national networks of radars and gauges around the world. The goal is to identify first-order discrepancies between remotely sensed and ground-based estimates that require in-depth examination. Direct validation also seeks to characterize uncertainties in satellite retrievals and ground-based measurements to estimate the *true* precipitation rate through the convergence of these two types of estimates. Such comparisons serve to enhance the credibility of both satellite and ground estimates at locations where they agree.
2) *Physical validation of precipitation properties in a vertical column through field experiments:* This validation approach focuses on collecting field campaign measurements of cloud microphysical properties, radar reflectivity, microwave radiances, and precipitation rates to improve the understanding of the physical relationships between cloud/precipitating particles and microwave radiances at different frequencies. A high-priority goal of these activities is to establish, wherever feasible, relationships between microphysical properties of precipitating particles that can be used to reduce the number of independent physical parameters and assumptions in satellite retrieval algorithms. Given the challenge of estimating precipitation using scattering-based techniques over land, another important goal is to observationally categorize and simulate dependencies of cloud microphysics on meteorological regimes (i.e., identification of the background surface environment associated with a given precipitation characteristic) and to better characterize ice scattering and the impact of mixed phase microphysics at the higher GMI frequencies, which are critical for estimation of liquid/frozen precipitation over land.
3) *Integrated validation over space and time via hydrometeorological applications:* These validation activities use stream gauges and other hydrological measurements as time-area integrated measurements to assess the quality of satellite precipitation products used in coupled hydrological and land surface modeling and prediction systems for watersheds maintained by U.S. agencies and international partners. The overall objective is to identify the optimal space and time scales at which satellite precipitation products will be useful for water budget studies and hydrological applications. Since neither the satellite data nor the coupled models are expected to be perfect, these assessment activities will necessarily include efforts to characterize uncertainties in satellite and ground estimates over a broad range of space–time scales, as well as uncertainties in hydrological models and how errors propagate from model inputs to model forecasts. Given that hydrologic characteristics such as soil moisture and snow cover, etc., directly affect passive microwave radiances through surface emission, these efforts can also provide useful information for improving precipitation retrieval algorithms over land.

GV science collaboration. The NASA Precipitation Science Program has established collaborations

with domestic and international research organizations and operational agencies to conduct a broad range of GV activity in different geographic and climate regimes, while JAXA's GV activities focus on validating DPR algorithms using ground-based assets in Japan and Asia. For direct validation within the continental United States, NASA is collaborating with NOAA on the development and use of the National Mosaic and QPE (NMQ; http://nmq.ou.edu/) high-resolution surface radar dataset for GPM in partnership with other federal agencies and universities (Vasiloff et al. 2007). For direct validation worldwide, international partnership will be key in evaluating the quality of GPM data products. To date, NASA has established joint GV research projects with 14 nations to assess current satellite rainfall products to guide GPM algorithm development (Table 6), and is working with international programs such as the EUMETSAT–Operational Hydrology and Water Management Satellite Application Facility (H-SAF) to collaborate on satellite precipitation product assessments in Europe and elsewhere.

For physical and hydrological validation, NASA has been conducting a series of field experiments that include both intensive observation periods, each of 4–6 weeks' duration, and longer-term extended observation periods leveraging off existing research and/or operational networks of instruments. The first of the physical validation efforts was the Mid-latitude Continental Convective Clouds Experiment (MC3E) conducted jointly with the U.S. Department of Energy (DOE) Atmospheric System Research (ASR) Program in April–June 2011 at the ASR Southern Great Plains Central Facility Cloud and Radiation Testbed (CART) in north-central Oklahoma. The campaign collected coincident high-altitude airborne Ka-Ku band radar and multifrequency (10–183 GHz) radiometer data, airborne in situ microphysical observations, and accompanying ground-based polarimetric radar and disdrometer datasets in a wide variety of continental precipitation types to refine the physical basis of precipitation retrievals from the DPR and passive microwave radiometers over land. The second physical validation campaign was the GPM Cold-season

Table 6. International collaboration on GPM ground validation.

Country	Science theme
Argentina	Impact of deep moist convection on rainfall, development of techniques to calibrate and check rainfall estimates
Australia	Australian calibration and validation activities in support of GPM
Brazil	Convective systems life cycle, physical processes in warm clouds, direct validation, hydrologic validation over the Iguacu river basin
Canada	Winter precipitation studies in the Great Lakes area, the high Arctic, and in mountainous terrain
Ethiopia	The Blue Nile River basin in Ethiopia as the regional GPM GV site in Africa
European Union	EUMETSAT Satellite Application Facility (SAF) to support operational hydrology and water management (H-SAF) activities.
Finland	Winter precipitation—Calibration and validation activities in Finland for GPM mission
France	Contribution of the French component of the Megha-Tropiques Mission to the Precipitation Measurement Missions Science Team
Germany/United Kingdom	Ancillary active and passive polarimetric studies and observations providing a better insight into rain and precipitation processes
Israel	Statistical and integrated hydrometeorological validation
Italy	Mediterranean precipitation—Calibration and validation activities in Italy for the GPM mission
South Korea	Seasonal direct and physical validation activities using South Korean national network and research radar, disdrometer, and rain gauge resources
Spain	High-density mobile disdrometer measurements in Spain and GPM GV field campaigns in order to analyze the PSD variability
Switzerland	Precipitation processes and size distributions in complex terrain (liquid and frozen); dense mobile disdrometer measurement datasets

Precipitation Experiment (GCPEx) carried out jointly with Environment Canada in Ontario, Canada, during the winter of 2012 (17 January–29 February). The campaign provided snowfall algorithm developers and satellite simulator models with a set of airborne and ground-based observations as well as model simulations to test the ability of active and passive microwave sensors to detect and estimate falling snow (GPM 2013).

The first integrated hydrologic validation campaign, the Iowa Flood Studies (IFloodS) experiment, took place in April–July 2013 in northeastern Iowa, using intensive multifrequency polarimetric radar and dense rain gauge/disdrometer measurements with coupled land surface and hydrologic models to assess uncertainties in satellite precipitation products and their impact on flood forecasting as a function of scale and basin morphology. In addition, two post-launch campaigns now in planning stages will target precipitation and hydrologic processes over complex terrains—the Integrated Precipitation and Hydrology Experiment (IPHEx) in 2014 to be held jointly with the NOAA Hydrometeorological Testbed (HMT)–Southeast Program and the Olympic Peninsula Experiment (OLYMPEX) in 2015/16.

In addition to NASA-sponsored campaigns, NASA has also participated in a number of leveraged field campaigns of opportunity: the *CloudSat/Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (*CALIPSO*) Ground Validation Program (C3VP) field campaign in the winter of 2006/07 to collect data for snowfall algorithm development (Hudak et al. 2006); the "Pre-CHUVA" field experiment hosted by the GPM-Brazil Program in March 2010 targeting tropical warm rain processes over land; the Light Precipitation and Validation Experiment (LPVEx) held jointly with *CloudSat*, the Finnish Meteorological Institute, and Environment Canada in the fall of 2010 over the Helsinki Testbed and the Gulf of Finland to study cool-season, high-latitude light rain characterized by a shallow melting layer; and the 2012 Hydrological Cycle in the Mediterranean Experiment (HyMEX) special observation periods in France and Italy to study precipitation processes over complex terrains.

DATA PROCESSING AND PRODUCT DISSEMINATION. Observational data collected by the GPM Core Observatory will be transmitted via the NASA Tracking and Data Relay Satellite System (TDRSS) to the GPM Mission Operations Center at the NASA GSFC by way of the ground station at White Sands, New Mexico. These level 0 data will be immediately processed by NASA's Precipitation Processing System (PPS) and JAXA's data distribution system into higher-level products in near–real time (i.e., within 3 h of observation), followed by more complete and higher-quality research products within 48 h.

The NASA PPS is a measurement-based, multisatellite data processing and science information system that has the processing and communications capacity to handle data from the GPM Observatory and partner assets to create GPM products through level 3. The PPS will process and make available for delivery GMI precipitation products (Table 5) from the GPM Core Observatory at the instrument field of view within 1 h of observation time, as well as radar and combined radar/radiometer swath data within 3 h of the observation time. In addition to the GPM sensor products, other key products produced by the PPS include 1) intercalibrated (level 1C) brightness temperatures from all partner constellation radiometers and 2) radar-enhanced precipitation estimates from all partner radiometers obtained using the common a priori cloud database constructed from combined DPR/GMI measurements, including $0.1° \times 0.1°$ gridded global analyses of instantaneous precipitation rates, 3-h precipitation rates, and daily and monthly precipitation accumulation. As algorithms continue to mature and refine, GPM datasets will be updated and reprocessed by the PPS throughout the GPM mission life.

GPM data produced by the PPS will be available to GPM partners and the wider international user community from a dedicated server as soon as they are generated. In addition, in cooperation with operational numerical weather prediction centers and data assimilation research organizations, NASA plans to provide the scientific research community level 4 precipitation data products from global forecast models (Bauer et al. 2006) and precipitation assimilation systems (e.g., Hou and Zhang 2007). For certain hydrological applications that require multisatellite precipitation estimates at very high spatial and temporal resolutions, NASA has been developing techniques to assimilate satellite precipitation information into cloud-resolving models to produce dynamically downscaled precipitation analyses at 1–2-km resolution for regional hydrological applications (e.g., Zupanski et al. 2010; Zhang et al. 2013) and to combine satellite and ground-based measurements into variable-resolution precipitation analyses that preserve precipitation extremes at native measurement scales within the framework of probabilistic data fusion.

SUMMARY. GPM is an international satellite mission that will unify and advance precipitation measurements by a constellation of research and operational microwave sensors to set a new standard for global precipitation estimation from space. The GPM concept centers upon the use of coordinated measurements from a network of microwave radiometers to provide the best possible global coverage and sampling, and the use of combined observations from active and passive sensors from a common reference satellite—the GPM Core Observatory provided by NASA and JAXA—to improve the accuracy and consistency of precipitation estimates from all constellation radiometers.

Building upon the success of TRMM, the GPM mission will provide a new generation of rain and snow data products in all parts of the world within 3 h characterized by 1) more accurate instantaneous precipitation measurement, especially for light rain and cold-season solid precipitation; 2) intercalibrated microwave brightness temperatures from constellation radiometers within a consistent framework; and 3) unified precipitation retrievals from all constellation radiometers using a common observationally constrained global hydrometeor database derived from GPM Core sensor measurements instead of model-generated hydrometeor databases used in current retrievals.

GPM is a science mission with integrated applications goals. GPM observations will quantify the space–time variability of global precipitation with improved accuracy, coverage, and spatiotemporal resolution for studying the cycling of global water fluxes and their interactions with other climate components such as atmospheric transport, soil moisture, ocean salinity, and Earth's radiation budget. By providing measurements of 3D structures of precipitation systems, GPM will offer insights into the development and intensification of storms and hurricanes, as well as the properties and regional variations of mesoscale convective systems. GPM will provide estimates of 3D latent heat release associated with precipitation processes for understanding their coupling with large-scale circulation features such as the Madden–Julian oscillation (MJO), El Niño–Southern Oscillation, and Hadley cells. The expanded dynamic range of GPM measurements relative to current capabilities will improve detection of subtle changes in precipitation characteristics such as the rain intensity spectra in a changing climate.

For societal applications, GPM will provide high-resolution microwave imagery in near–real time for accurate geolocation fixes of storm centers to improve track prediction, as well as rain-affected radiances and precipitation retrievals for assimilation into numerical prediction systems to improve operational weather forecasts. With the improved retrieval accuracy, especially over land in the mid- and high latitudes, and frequent sampling with 80% of observations less than 3 h apart over all latitudes, GPM will provide more accurate estimates of rainfall totals over continents to improve the monitoring and prediction of floods, droughts, and landslides by hydrological models, as well as forecasting freshwater resources at basin scales, especially in many regions around the world where in situ precipitation gauge and radar networks are sparse.

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APPENDIX: LIST OF ACRONYMS

ATMS	Advanced Technology Microwave Sounder
CEOS	Committee on Earth Observation Satellites
CGMS	Coordination Group for Meteorological Satellites
CMORPH	Climate Prediction Center (CPC) morphing technique
DMSP	Defense Meteorological Satellite Program

DPR	Dual-frequency precipitation radar
ECMWF	European Centre for Medium-Range Forecasts
ESA	European Space Agency
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FEWS	Famine Early Warning System
GCOM-W1	Global Change Observation Mission–Water 1
GEO	Group on Earth Observations
GEOSS	Global Earth Observing System of Systems
GEWEX	Global Energy and Water Cycle Experiment
GMI	GPM Microwave Imager
GPCP 1DD	Global Precipitation Climatology Project One-Degree Daily (GPCP 1DD)
GPM	Global Precipitation Measurement
GSICS	Global Space-Based Inter-Calibration System
GSMaP	Global Satellite Mapping of Precipitation
GV	Ground validation
HMT	Hydrometeorology Testbed
IFNET	International Flood Network
IFOV	Instantaneous field of view
IGOS	Integrated Global Observation Strategy
IGWCO	Integrated Global Water Cycle Observations
IPWG	International Precipitation Working Group
IR	Infrared
JAXA	Japan Aerospace Exploration Agency
JPSS	Joint Polar Satellite System
LDAS	Land Data Assimilation Systems
MADRAS	Multi-Frequency Microwave Scanning Radiometer
MHS	Microwave Humidity Sounder
MJO	Madden–Julian oscillation
NASA	National Aeronautics and Space Administration
NICT	National Institute of Information and Communications Technology (of Japan)
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NMQ	National Mosaic and QPE (Quantitative Precipitation Estimate)
NRC	National Research Council
NRL	Naval Research Laboratory
NSF	National Science Foundation
NSTC	National Science and Technology Council
NWP	Numerical weather prediction
PERSIANN	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks
PMM	Precipitation Measurement Missions
PPS	Precipitation Processing System
PR	Precipitation Radar
SCaMPR	Self-Calibrating Multivariate Precipitation Retrieval
SERVIR	The Regional Visualization and Monitoring System
SSM/I	Special Sensor Microwave Imager
SSMIS	Special Sensor Microwave Imager/Sounder
TDRSS	Tracking and Data Relay Satellite System
TMI	TRMM Microwave Imager
TMPA	TRMM Multi-satellite Precipitation Analysis
TRMM	Tropical Rainfall Measuring Mission
USAID	United States Agency for International Development
WCRP	World Climate Research Program
WMO	World Meteorological Organization

REFERENCES

Andreae, M. O., D. Rosenfeld, P. Artaxo, A. A. Costa, G. P. Frank, K. M. Longo, and M. A. F. Silva-Dias, 2004: Smoking rain clouds over the Amazon. *Science,* **303,** 1337–1341.

Aonashi, K., N. Yamazaki, H. Kamahori, and K. Takahashi, 2004: Variational assimilation of TMI rain type and precipitation retrievals into global numerical weather prediction. *J. Meteor. Soc. Japan,* **82,** 671–693.

Asrar, G., J. Kaye, and P. Morel, 2001: NASA research strategy for Earth system science: Climate component. *Bull. Amer. Meteor. Soc.,* **82,** 1309–1329.

Avissar, R., and D. Werth, 2005: Global hydroclimatological teleconnections resulting from tropical deforestation. *J. Hydrometeor.,* **6,** 134–145.

Back, L. E., and C. S. Bretherton, 2006: Geographic variability in the export of moist static energy and vertical motion profiles in the tropical Pacific. *Geophys. Res. Lett.,* **33,** L17810, doi:10.1029/2006GL026672.

Bauer, P., P. Lopez, D. Salmond, A. Benedetti, S. Saarinen, and M. Bonazzola, 2006: Implementation of 1D+4D-var assimilation of precipitation-affected microwave radiances at ECMWF. II: 4D-Var. *Quart. J. Roy. Meteor. Soc.,* **132A,** 2307–2332.

Bell, T. L., D. Rosenfeld, K.-M. Kim, J.-M. Yoo, M.-I. Lee, and M. Hahnenberger, 2008: Midweek increase in U.S. summer rain and storm heights suggests air pollution invigorates rainstorms. *J. Geophys. Res.,* **113,** D02209, doi:10.1029/2007JD008623.

Bhatt, C. B., and K. Nakamura, 2005: Characteristics of monsoon rainfall around the Himalayas revealed by TRMM precipitation radar. *Mon. Wea. Rev.,* **133,** 149–165.

Bindlish, R., and A. Barros, 2000: Disaggregation of rainfall for one-way coupling of atmospheric and hydrological models in regions of complex terrain. *Global Planet. Change,* **25,** 111–132.

Bunin, S. L., D. Holmes, T. Schott, and H. J. Silva, 2004: NOAA/NESDIS preparation for the NPOESS era. Preprints, *20th Int. Conf. on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology,* Seattle, WA, Amer. Meteor. Soc., 16.5. [Available online at https://ams.confex.com/ams/84Annual/techprogram/paper_73182.htm.]

Cherny, I. V., G. Chernyavsky, V. Nakonechny, and S. Pantsov, 2002: Spacecraft "Meteor-3M" Microwave Imager/Sounder MTVZA: First results. *Proc. IGARSS'02,* Vol. 5, Toronto, ON, Canada, IEEE, 2660–2662.

Cotton, W. R., and R. A. Pielke, 2007: *Human Impacts on Weather and Climate.* 2nd ed. Cambridge University Press, 308 pp.

Dabberdt, W., and Coauthors, 2005: Multifunctional mesoscale observing networks. *Bull. Amer. Meteor. Soc.,* **86,** 961–982.

Del Genio, A. D., W. Kovari, M.-S. Yao, and J. Jonas, 2005: Cumulus microphysics and climate sensitivity. *J. Climate,* **18,** 2376–2387.

Desbois, M., R. Roca, L. Eymard, N. Viltard, M. Viollier, J. Srinivasan, and S. Narayanan, 2003: The Megha-Tropiques mission. *Atmospheric and Oceanic Processes, Dynamics, and Climate Change,* Z. Sun, F.-F. Jin, and T. Iwasaki, Eds., International Society for Optical Engineering (SPIE Proceedings, Vol. 4899), 172–183, doi:10.1117/12.466703.

Edward, P., and D. Pawlak, 2000: MetOp: The space segment for EUMETSAT's polar system. *ESA Bull.,* **102,** 6–18.

Evans, K. F., J. Turk, T. Wong, and G. Stephens, 1995: A Bayesian approach to microwave precipitation profile retrieval. *J. Appl. Meteor.,* **34,** 260–279.

Fekete, B., C. Vörösmarty, J. Roads, and C. Willmott, 2004: Uncertainties in precipitation and their impacts on runoff estimates. *J. Climate,* **17,** 294–304.

Futrel, J. H., and Coauthors 2005: Water: Challenges at the intersection of human and natural systems. NSF/DOE Tech. Rep. PNWD-3597, 50 pp, doi:10.2172/1046481.

GPM, cited 2013: Precipitation measurement missions. Global Precipitation Measurement Program, NASA. [Available online at http://gpm.nasa.gov/.]

GPM ATBD, cited 2013: Global Precipitation Measurement algorithm theoretical basis documents. [Available online at http://pps.gsfc.nasa.gov/atbd.html.]

Grecu, M., and W. S. Olson, 2006: Bayesian estimation of precipitation from satellite passive microwave observations using combined radar–radiometer retrievals. *J. Appl. Meteor. Climatol,* **45,** 416–433.

——, ——, and E. Anagnostou, 2004: Retrieval of precipitation profiles from multiresolution, multifrequency active and passive microwave observations. *J. Appl. Meteor.,* **43,** 562–575.

Gu, G., R. Adler, G. Huffman, and S. Curtis, 2007: Tropical rainfall variability on interannual to interdecadal and longer time scales derived from the GPCP monthly product. *J. Climate,* **20,** 4033–4046.

Haddad, Z., E. Smith, C. Kummerow, T. Iguchi, M. Farrar, S. Durden, M. Alves, and W. Olson, 1997: The TRMM 'day-1' radar/radiometer combined rain-profiling algorithm. *J. Meteor. Soc. Japan,* **75,** 799–809.

Hossain, F., and D. Lettenmaier, 2006: Flood prediction in the future: Recognizing hydrologic issues in anticipation of the Global Precipitation Measurement mission. *Water Resour. Res.,* **42,** W11301, doi:10.1029/2006WR005202.

Hou, A. Y., and S. Q. Zhang, 2007: Assimilation of precipitation information using column model physics as a weak constraint. *J. Atmos. Sci.,* **64,** 3865–3879.

——, ——, and O. Reale, 2004: Variational continuous assimilation of TMI and SSM/I rain rates: Impact on GEOS-3 hurricane analyses and forecasts. *Mon. Wea. Rev.,* **132,** 2094–2109.

Hudak, D., H. Barker, P. Rodruguez, and D. Donovan, 2006: The Canadian CloudSat/CALIPSO Validation Project. *Proc. Fourth European Conf. on Radar in Hydrology and Meteorology,* Barcelona, Spain, ERAD, 609–612.

Huffman, G. J., R. F. Adler, M. Morrissey, D. T. Bolvin, S. Curtis, R. Joyce, B. McGavock, and J. Susskind, 2001: Global precipitation at one-degree daily resolution from multisatellite observations. *J. Hydrometeor.,* **2,** 36–50.

——, and Coauthors, 2007: The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *J. Hydrometeor.,* **8,** 38–55.

Iguchi, T., T. Kozu, R. Meneghini, J. Awaka, and K. Okamoto, 2000: Rain-profiling algorithm from the TRMM precipitation radar. *J. Appl. Meteor.,* **39,** 2038–2052.

Joyce, R. J., P. Xie, and J. E. Janowiak, 2011: Kalman filter–based CMORPH. *J. Hydrometeor.,* 12, 1547–1563.

Kelley, O., J. Stout, and J. Halverson, 2004: Tall precipitation cells in tropical cyclones eyewalls are associated with tropical cyclone intensification. *Geophys. Res. Lett.,* **31,** L24112, doi:10.1029/2004GL021616.

Kidd, C., and V. Levizzani, 2011: Status of satellite precipitation retrievals. *Hydrol. Earth Syst. Sci.,* **7,** 8157–8177, doi:10.5194/hessd-8-8157-2010.

——, D. R. Kniveton, M. C. Todd, and T. J. Bellerby, 2003: Satellite rainfall estimation using combined passive microwave and infrared algorithms. *J. Hydrometeor.,* **4,** 1088–1104.

Kirschbaum, D., R. Adler, D. Adler, C. Peters-Lidard, G. Huffman, 2012: Global distribution of extreme precipitation and high-impact landslides in 2010 relative to previous years. *J. Hydrometeor.,* **13,** 1536–1551.

Kubota, T., and Coauthors, 2007: Global precipitation map using satelliteborne microwave radiometers by the GSMaP project: Production and validation. *IEEE Trans. Geosci. Remote Sens.,* **45,** 2259–2275.

Kucera, P. A., E. E. Ebert, F. J. Turk, V. Levizzani, D. Kirschbaum, F. J. Tapiador, A. Loew, and M. Borsche, 2013: Precipitation from space advancing Earth system science. *Bull. Amer. Meteor. Soc.,* **94,** 365–375.

Kulie, M. S., and R. Bennartz, 2009: Utilizing spaceborne radars to retrieve dry snowfall. *J. Appl. Meteor. Climatol.,* **48,** 2564–2580.

Kuligowski, R. J., 2002: A self-calibrating real-time GOES rainfall algorithm for short-term rainfall estimates. *J. Hydrometeor.,* **3,** 112–130.

Kumar, S., and Coauthors, 2006: Land Information System—An interoperable framework for high resolution land surface modeling. *Environ. Modell. Software,* **21,** 1402–1415.

Kummerow, C., and L. Giglio, 1994: A passive microwave technique for estimating rainfall and vertical structure information from space. Part I: Algorithm description. *J. Appl. Meteor.,* **33,** 3–18.

——, W. Olson, and L. Giglio, 1996: A simplified scheme for obtaining precipitation and vertical hydrometeor profiles from passive microwave sensors. *IEEE Trans. Geosci. Remote Sens.,* **34,** 1213–1232.

——, W. Barnes, T. Kozu, J. Shiue, and J. Simpson, 1998: The Tropical Rainfall Measuring Mission (TRMM) sensor package. *J. Atmos. Oceanic Technol.,* **15,** 809–817.

——, S. Ringerud, J. Crook, D. Randel, and W. Berg, 2011: An observationally based a priori database for microwave rainfall retrievals. *J. Atmos. Oceanic Technol.,* **28,** 113–130.

Kunkee, D. B., G. Poe, D. Boucher, S. Swadley, Y. Hong, J. Wessl, and E. Uliana, 2008: Design and evaluation of the first Special Sensor Microwave Imager/Sounder. *IEEE Trans. Geosci. Remote Sens.,* **46,** 863–883.

Lau, W. K. M., and Y. P. Zhou, 2012: Observed recent trends in tropical cyclone rainfall over the North Atlantic and the North Pacific. *J. Geophys. Res.,* **117,** D03104, doi:10.1029/2011JD016510.

Liao, L., R. Meneghini, T. Iguchi, and A. Detwiler, 2005: Use of dual-wavelength radar for snow parameter estimates. *J. Atmos. Oceanic Technol.,* **22,** 1494–1506.

Mardiana, R., T. Iguchi, and N. Takahashi, 2004: A dual-frequency rain profiling method without the use of a surface reference technique. *IEEE Trans. Geosci. Remote Sens.,* **42,** 2214–2225.

Marécal, V., and J.-F. Mahfouf, 2003: Experiments on 4D-Var assimilation of rainfall data using an incremental formulation. *Quart. J. Roy. Meteor. Soc.,* **129,** 3137–3160.

Marzano, F., A. Mugnai, G. Panegrossi, N. Pierdicca, E. Smith, and J. Turk, 1999: Bayesian estimation of precipitating cloud parameters from combined measurements of spaceborne microwave radiometer and radar. *IEEE Trans. Geosci. Remote Sens.,* **37,** 596–613.

Masunaga, H., and C. Kummerow, 2005: Combined radar and radiometer analysis of precipitation profiles for a parametric retrieval algorithm. *J. Atmos. Oceanic Technol.,* **22,** 909–929.

——, T. S. L'Ecuyer, and C. D. Kummerow, 2006: The Madden–Julian Oscillation recorded in early

observations from the Tropical Rainfall Measuring Mission (TRMM). *J. Atmos. Sci.,* **63,** 2777–2794.

Meneghini, R., H. Kumagai, J. R. Wang, T. Iguchi, and T. Kozu, 1997: Microphysical retrievals over stratiform rain using measurements from an airborne dual-wavelength radar-radiometer. *IEEE Trans. Geosci. Remote Sens.,* **35,** 487–506.

Mitchell, K., and Coauthors, 2004: The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. *J. Geophys. Res.,* **109,** D07S90, doi:10.1029/2003JD003823.

Montaigne, F., 2002: *National Geographic Magazine,* Vol. 202 (3), International Publishing, 2–33.

Morita, J., Y. N. Takayabu, S. Shige, and Y. Kodama, 2006: Analysis of rainfall characteristics of the Madden-Julian oscillation using TRMM satellite data. *Dyn. Atmos. Oceans,* **42,** 107–126.

Mugnai, A., and Coauthors, 2007: Snowfall measurements by proposed European GPM Mission. *Measuring Precipitation from Space: EURAINSAT and the Future,* V. Levizzani, P. Bauer, and J. Turk, Eds., Springer-Verlag, 655–674.

Negri, A. J., R. F. Adler, L. Xu, and J. Surratt, 2004: The impact of Amazonian deforestation on dry season rainfall. *J. Climate,* **17,** 1306–1319.

Nesbitt, S. W., E. J. Zipser, and D. J. Cecil, 2000: A census of precipitation features in the tropics using TRMM: Radar, ice scattering, and lightning observations. *J. Climate,* **13,** 4087–4106.

Nijssen, B., and D. P. Lettenmaier, 2004: Effect of precipitation sampling error on simulated hydrological fluxes and states: Anticipating the Global Precipitation Measurement satellites. *J. Geophys. Res.,* **109,** D02103, doi:10.1029/2003JD003497.

NRC, 2005: *Assessment of the Benefits of Extending the Tropical Rainfall Measuring Mission*. National Academies Press, 103 pp.

——, 2007a: *NOAA's Role in Space-Based Global Precipitation Estimation and Application*. National Academies Press, 131 pp.

——, 2007b: *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. National Academies Press, 428 pp.

——, 2010: *When Weather Matters: Science and Service to Meet Critical Societal Needs*. National Academies Press, 198 pp.

——, 2011: *Global Change and Extreme Hydrology: Testing Conventional Wisdom*. National Academies Press, 60 pp.

NSMC, cited 2013: The Storm III (FY-3) Program. National Satellite Meteorological Center, China Meteorological Administration. [Available online at www.nsmc.cma.gov.cn/newsite/NSMC_EN/Home/Index.html.]

NSTC, 2004: Science and technology to support fresh water availability in the United States. National Science and Technology Council, 19 pp.

Rodell, M., and Coauthors, 2004: The global land data assimilation system. *Bull. Amer. Meteor. Soc.,* **85,** 381–394.

Rose, C., and V. Chandrasekar, 2006: A GPM dual-frequency retrieval algorithm: DSD profile-optimization method. *J. Atmos. Oceanic Technol.,* **23,** 1372–1383.

Rosenfeld, D., Y. Rudich, and R. Lahav, 2001: Desert dust suppressing precipitation: A possible desertification feedback loop. *Proc. Natl. Acad. Sci. USA,* **98,** 5975–5980.

Shepherd, J. M., H. Pierce, and A. Negri, 2002: Rainfall modification by major urban areas: Observations from spaceborne rain radar on the TRMM satellite. *J. Appl. Meteor.,* **41,** 689–701.

Shige, S., Y. N. Takayabu, W.-K. Tao, and C.-L. Shie, 2007: Spectral retrieval of latent heating profiles from TRMM PR data. Part II: Algorithm improvement and heating estimates over tropical ocean regions. *J. Appl. Meteor. Climatol.,* **46,** 1098–1124.

Shimoda, H., 2005: GCOM missions. *Proc. IGARSS '05,* Vol. 6, IEEE, Seoul, South Korea, 4201–4204.

Simpson, J., J. Halverson, B. Ferrier, W. Petersen, R. Simpson, R. Blakeslee, and S. Durden, 1998: On the role of "hot towers" in tropical cyclone formation. *Meteor. Atmos. Phys.,* **67,** 15–35.

Sorooshian, S., K.-L. Hsu, X. Gao, H. V. Gupta, B. Imam, and D. Braithwaite, 2000: Evaluation of PERSIANN system satellite-based estimates of tropical rainfall. *Bull. Amer. Meteor. Soc.,* **81,** 2035–2046.

Tao, W.-K., S. Lang, X. Zeng, S. Shige, and Y. Takayabu, 2010: Relating convective and stratiform rain to latent heating. *J. Climate,* **23,** 1874–1893.

Trenberth, K., L. Smith, T. Qian, A. Dai, and J. Fasullo, 2007: Estimates of the global water budget and its annual cycle using observational and model data. *J. Hydrometeor.,* **8,** 758–769.

Turk, F. J., and S. D. Miller, 2005: Toward improved characterization of remotely sensed precipitation Regimes with MODIS/AMSR-E blended data techniques. geoscience and remote sensing. *IEEE Trans. Geosci. Remote Sens.,* **43,** 1059–1069, doi:10.1109/TGRS.2004.841627.

Ushio, T., and Coauthors, 2009: A Kalman filter approach to the Global Satellite Mapping of Precipitation (GSMaP) from combined passive microwave and infrared radiometric data. *J. Meteor. Soc. Japan,* **87A,** 137–151.

Vasiloff, S. V., and Coauthors, 2007: Improving QPE and very short term QPF: An initiative for a community-wide integrated approach. *Bull. Amer. Meteor. Soc.,* **88,** 1899–1911.

Wall, C. L., E. J. Zipser, and C. T. Liu, 2012: A regional climatology of monsoonal precipitation in the southwestern United States using TRMM. *J. Hydrometeor.,* **13,** 310–323.

Wang, J., R. Bras, and E. Eltahir, 2000: The impact of observed deforestation on the mesoscale distribution of rainfall and clouds in Amazonia. *J. Hydrometeor.,* **1,** 267–286.

Wilheit, T., 2013: Comparing calibrations of similar conically scanning window-channel microwave radiometers. *IEEE Trans. Geosci. Remote Sens.,* **51,** 1454–1464, doi:10.1109/TGRS.2012.2207122.

Wu, H., R. F. Adler, Y. Hong, Y. D. Tian, and F. Policelli, 2012: Evaluation of global flood detection using satellite-based rainfall and a hydrologic model. *J. Hydrometeor.,* **13,** 1268–1284.

Zhang, S., M. Zupanski, A. Hou, X. Lin, and S. Cheung, 2013: Assimilation of precipitation-affected radiances in cloud-resolving WRF ensemble data assimilation system. *Mon. Wea. Rev.,* **141,** 754–772.

Zupanski, D., S. Zhang, M. Zupanski, A. Hou, and S. Cheung, 2010: A prototype WRF-based ensemble data assimilation system for dynamically downscaling satellite precipitation observations. *J. Hydrometeor.,* **12,** 118–134.

Zupanski, M., D. Zupanski, D. Parrish, E. Rogers, and G. DiMego, 2002: Four-dimensional variational data assimilation for the blizzard of 2000. *Mon. Wea. Rev.,* **130,** 1967–1988.