How's the Weather up There? The IPHEx GPM Ground Validation Campaign

Mitchell K. Hobish, Sciential Consulting, LLC, mkh@sciential.com
Ana Barros, Duke University, barros@duke.edu
Walter Petersen, NASA's Wallops Flight Facility, walt.petersen@nasa.gov
Ellen Gray, NASA's Goddard Space Flight Center, Wyle Information Systems, ellen.t.gray@nasa.gov

As with all satellite-based remote-sensing activities, data gleaned from instruments on orbital platforms must be validated by comparison with in situ data—that is, data retrieved directly in and around the area of interest.

There's a very old social gambit, usually spoken to a very tall person by one much shorter: "How's the weather up there?"—the inference being that there is a difference between what is being experienced by the individuals of disparate heights.

That inference is being put to the test in the real world—as regards precipitation, anyway—with the Integrated Precipitation and Hydrology Experiment (IPHEx) field campaign, held between October 2013 and October 2014 to validate data from the Global Precipitation Measurement (GPM[1]) mission. The GPM mission is an international network of satellites that together provide next-generation global observations of precipitation from space led by NASA and the Japan Aerospace Exploration Agency (JAXA). GPM builds upon and significantly extends the Tropical Rainfall Measuring Mission (TRMM). In addition to NASA and JAXA, who partnered in TRMM, participants in GPM include the French Centre National d'Études Spatiales (CNES), the Indian Space Research Organization (ISRO), the U.S. National Oceanic and Atmospheric Administration (NOAA), and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT).

Rationale for IPHEx

As with all satellite-based remote-sensing activities, data gleaned from instruments on orbital platforms must be validated by comparison with *in situ* data—that is, data retrieved directly in and around the area of interest. The satellite-based aspects of the GPM mission began with the launch of the GPM Core Observatory[2] in February 2014; ground validation activities were taking place even before the satellite reached orbit. One such prelaunch field campaign was *IFloodS,* or the Iowa Flood Studies, which took place in northeast Iowa from May 1 to June 15, 2013[3]. The campaign was designed to explore the hydrologic and weather conditions that could lead to flooding—studies that provided both applications support for agriculture in the area and a means to assess algorithms and future GPM product application for the then-planned GPM mission.

Collectively, the IPHEx field campaign involved well over 100 government and university investigators, and included approximately 40 undergraduate and graduate students in science, technology, engineering, and mathematics (STEM) disciplines who participated either directly or indirectly in the IPHEx field effort. Aside from NASA and NOAA scientists, IPHEx investigators included representatives from local and national universities, and faculty and staff from Duke University, the University of North Carolina (UNC)-Asheville, the University of North Carolina, North Carolina Central University, North Carolina State University, Georgia Institute

[1] To learn more about GPM, please refer to "GPM Core Observatory: Advancing Precipitation Measurements and Expanding Coverage" in the November–December 2013 issue of *The Earth Observer* [**Volume 25**, **Issue 6**, pp. 4-11] or visit pmm.nasa.gov. *pmm.nasa.gov.*
[2] The GPM mission centers on the deployment of the GPM Core Observatory and consists of a network, or *constellation*, of additional satellites that together will provide next-generation global observations of precipitation from space.
[3] For more information on IFloodS, see "A Flood—of Information—Is Needed" in the January–February 2014 issue of *The Earth Observer* [**Volume 26, Issue 1,** pp. 12-18].

of Technology, the University of Connecticut, the University of Utah, Colorado State University, the University of Georgia, and Smith College, among others. Key observing sites were developed in cooperation with the U.S. National Park Service, the U.S. Geological Survey, and local colleges and universities, including Western Carolina University, Asheville-Buncombe Technical Community College, Wilson College, Haywood Community College, the Pisgah Astronomical Research Institute, and the Maggie Valley Sanitary District.

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Ground validation activities continue now that the GPM Core Observatory is in orbit. IPHEx was a postlaunch field campaign, designed to support the continued development, evaluation, and improvement of GPM's precipitation algorithms across the missions' constellation of satellites. Ground-based and airborne activities all combined to take appropriate measurements of precipitation patterns and the effects of mountainous terrain on such phenomena, in an effort to validate GPM's relevant algorithms and data products.

IPHEx Location

As shown in **Figure 1**, the IPHEx campaign took place in the Southern Appalachian Mountains, specifically western North Carolina and the adjacent Coastal Plain along the Atlantic Ocean and the Piedmont Region, which comprises the central portion of NC between the Coastal Plain and the Mountain regions to the west. Several precipitating cloud systems were also sampled over the Atlantic Ocean off the coast of NC.

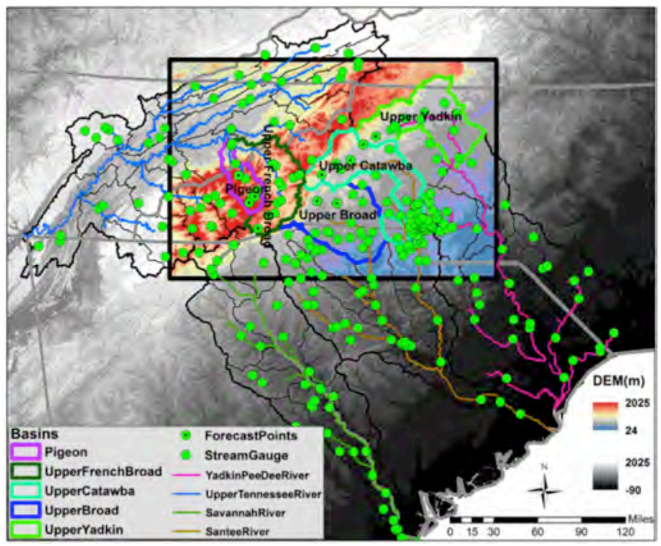

Figure 1. *Southern Appalachian Mountain location for IPHEx activities.* The study region during the 2013-2014 field campaign is outlined. Several of the rivers and river basins named here are discussed in the text. **Image credit:** Ana Barros

This region provided the science team with mountainous terrain during warm seasons that they could use to examine the nature and distribution of precipitation over complex terrain that varies over a relatively small area and over many different elevations. The region was chosen to allow IPHEx's teams to see how mountain precipitation affects and is affected by relevant processes at lower elevations. It was, if you will, the perfect place to study, "How's the weather *up there*… and *down here*."

The irregular and complex terrain provided locations for the ground-based-instrumentation (see *IPHEx Instrumentation* on page 6) that allowed IPHEx scientists and staff to collect data on mesoscale convective systems and fronts (usually driven by westerly winds), convective systems and tropical storms (usually driven by southeasterly and southerly winds), and phenomena that cause convection to begin and subsequently to be suppressed. In addition, observing interactions between fog and several layers of clouds in the inner-mountain region allowed the science team to examine the effects of mountains and mountain ranges on the microphysical properties of precipitation—information needed to validate GPM-based measurements of such properties from low-Earth orbit.

IPHEx Science Objectives

The science objectives for IPHEx were to:

- Collect datasets appropriate to physical validation of GPM data algorithms for observations over complex terrain;
- provide measurements that improve our understanding of precipitation processes over complex terrain; and
- better understand the impact of GPM products with their uncertainties in hydrologic application.

Science topics were quite comprehensive. Only a few are listed here, to give the flavor of the study's breadth and depth. These topics determined which measurements were to be taken. These included:

- Coupling of precipitation ice processes to dominant rainfall production and the nature of radar and radiometer signatures in these processes;
- characteristic drop size distributions (DSD) and microphysical mechanisms including spatiotemporal variability;
- roles of fog and other mechanisms in the vertical structure of reflectivity profiles;
- effects of landform and land cover on storms; and
- error characteristics of GPM instrumentation and their relationship(s) with local and regional hydrometeorological regimes.

IPHEx Implementation

Two suites of activities were planned and implemented during IPHEx. The first was an *extended observing period* (EOP) from October 2013 through October 2014; the second was an *intensive observing period* (IOP) from May through July 2014, which included aircraft observations, as discussed later in this article. Each had its own set of requirements and success criteria, as will be discussed later.

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In addition to the aircraft measurements, a real-time, hydrologic forecasting testbed became operational during the IOP, which built upon a successful benchmark project that ran from 2007 to 2012. The Integrated Precipitation and Hydrology Experiment - Hydrologic Applications for the Southeast U.S. (IPHEx-H4SE) was designed to compare results between hydrological models for four major river basins in the U.S. Southeast.

Concurrent with—but not formally part of—IPHEx, three additional monitoring activities took place: (1) examination of aerosol-cloud-rainfall interactions; (2) measurements of soil moisture over several land use and land cover types using the airborne the airborne Scanning L-band Active Passive (SLAP) instrument; and (3) performing trace gas analysis of streamflows to assess groundwater transit times.

The GPM-led IPHEx campaign also had important collaborations with partners that included the National Oceanic and Atmospheric Administration (NOAA) Hydrometeorological Testbed Southeast Pilot Studies (HMT-SEPS) program and the NASA Aerosol Cloud Ecosystem (ACE[4])/Radar Experiment (RADEX) study teams. The HMT-SEPS activity was focused on collecting precipitation and related meteorological measurements to support activities related to improved flood and weather prediction from "summit to sea" in the Southeastern U.S. The NASA ACE/RADEX team collaborated with GPM scientists to collect complementary measurements of clouds and weakly-precipitating cloud systems. The goals of the RADEX Team were to examine the physics of cloud-to-precipitation water-content transitions, determine the characteristics of cloud ice, and assess radar technology needs in relation to potential future aerosol, cloud, and precipitation satellite missions.

IPHEx Instrumentation

A wide variety of instrumentation was used for IPHEx activities. A representative subset of these instruments is summarized in **Table 1**, next page, which gives an overview of their nature and breadth. For full details, visit *gpm.nsstc.nasa.gov/iphex/instruments.html.* Please note that while the requirements for the EOP and IOP differed, EOP instruments were also used during the IOP. Technologies ranged from the relatively simple, such as rain gauges, to the highly sophisticated, such as dual-polarization radar.

[4] The 2007 National Research Council (NRC) Decadal Survey report, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* identified ACE as a *Tier 2* priority mission; it is now under NASA pre-formulation study.

Table 1. Sample of primary IPHEx ground-based instrumentation characteristics

Campaign Phase	Instrument (Type)	Number Implemented	Measurement
EOP	Rain gauge	60	Precipitation amount
	Disdrometer	20	Precipitation amount, type, fall speeds, and drop size distribution (DSD)
	Micro Rain Radar (MRR)*	1	Rain rates, DSD, radar reflectivity, fall speeds
	Rawindsonde	1	Profiles of pressure, temperature, humidity, and wind collected for targeted tropical cyclones and large storm events
IOP	NASA's S-band Dual Polarimetric Radar (NPOL)*	1	Spatial structure of precipitation, hydrometeor classification, DSD, and rain mapping
	Dual-Frequency, Dual-Polarized, Doppler Radar (D3R)*	1	Same as NPOL but at higher frequencies and expansion to light rain mapping.
	MRR*	4	Same as during the EOP but increased number of units
	NOAA X-band Dual Polarimetric Radar (NOXP)**	1	Same as NPOL but with intra-mountain coverage
	Rawinsonde	1 site	IOP sounding profiles of pressure, temperature, humidity and wind collected at 3-hour intervals during intensive operations
	Aerosol-Cloud-Humidity Interactions, Exploring and Validating Enterprise (ACHIEVE) Facility***	1	Cloud radar reflectivity, water vapor profiling, and aerosol contents
	Wind Profiler**	4	Vertical profiles of precipitation rate, DSD, and wind

* Some instrumentation details: MRR is a 24-GHz, vertically pointing Doppler radar; NPOL is an S-band (10-cm) scanning dual-polarization radar; and D3R, also a dual-polarization radar, operates at nominal frequencies of 13.91 GHz and 35.56 GHz (K_a and K_u bands, respectively, similar to the GPM Core satellite's Dual-frequency Precipitation Radar (DPR).
** NOXP is a scanning X-band (3-cm) dual-polarimetric mobile radar provided by NOAA.
*** Deployed by NASA's ACE/RADEX Team

In addition to ground-based instrumentation, NASA's ER-2—a high altitude aircraft typically operating at 60,000 ft (18 km) or higher—provided much of the airborne satellite-simulator remote sensing capability. The high-altitude vantage point acted as a proxy for the GPM Core satellite's own observations. Of note is that the IPHEx field campaign is the first time four different radar frequencies made simultaneous measurements from a single NASA aircraft. Some of the ER-2 airborne instrumentation is presented in **Table 2.**

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Table 2. ER-2 instrumentation and measurements for IPHEx

Instrument	Measurement
Advanced Microwave Precipitation Radiometer (AMPR)	Multi-frequency (10-85 GHz) dual-polarized measurements of precipitation-sized ice, liquid water, and water vapor
Conical Scanning Millimeter Imaging Radiometer (CoSMIR)	Multi-frequency (50-183 GHz) dual-polarized measurements of precipitation rates, water vapor, and temperature profiles
Cloud Radar System (CRS)	94-GHz (W-band) measurements of reflectivity and Doppler velocity in clouds
ER-2 X-band Radar (EXRAD)	Radar measurements at 9.6 GHz of cloud, wind, and precipitation structure

Table 2. ER-2 instrumentation and measurements for IPHEx (continued)

Instrument	Measurement
High-altitude Imaging Wind and Rain Airborne Profiler (HIWRAP)	K_a/K_u-band, dual-beam Doppler radar system for cloud and precipitation observation

A second aircraft, the Cessna *Citation* based at the University of North Dakota (UND), provided *in situ* measurements within clouds. The Citation carried cloud physics probes to sample cloud and precipitation particles and water contents for hydrometeor diameters ranging from approximately 1 µm to 2 cm (see **Table 3**). The cloud physics measurements made from the Citation were collected at the same time as the ER-2 measurements by flying below the ER-2. The coordinated Cessna flights serve to bridge satellite observations of precipitation-making cloud processes with measurements of the precipitation falling from the clouds to the ground—as observed by ground-based radars and supporting gauge networks.

Table 3. Cessna *Citation*-based instrumentation and measurements

Instrument	Measurement
King Liquid Water Probe	Cloud liquid water content (LWC)
2D-C (Cloud) and 2D-S (Stereo) probes	Cloud and precipitation particle spectra
High-volume Precipitation Spectrometer (HVPS)-3	Precipitation particle-size spectra (50 µm-1.92 cm)
Cloud Particle Imager (CPI)	High-resolution ice crystal and cloud-droplet imaging
Cloud Spectrometer and Impacter (CSI)	Total condensed atmospheric water content measurement and droplet size spectrum (2-50 µm)
Cloud Droplet Probe (CDP)	Droplets in the range of 2-50 µm, in concentrations as high as 2000 cm^{-3}
Nevzorov Airborne Hot-Wire Probe	LWC and total water content (TWC)
Rosemount Icing Detector	Rate of ice formation via supercooled water for LWC measurements
Condensation Nuclei (CN) counter	Aerosols [e.g., condensation nuclei, cloud condensation nuclei (CCN)]

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IPHEx Logistics and Operations

IPHEx Operations during the IOP were coordinated from a central location at the Asheville, NC, airport. Each day began with a weather forecast to support coordinated ER-2 and UND Citation flights and ground operations planning. The IPHEx team members that were in Ashville coordinated operations with GPM overpasses when

[5] For a description of the A-Train please read "Taking the A-Train to New Orleans" in the January-February 2011 issue *of The Earth Observer* [**Volume 23, Issue 1**, pp. 12-23].

possible. They also managed the ground instruments and received instrument status updates, conducted daily status briefings for scientists, and wrote daily mission summaries for archiving with the collected datasets.

The NASA Global Hydrology Resource Center Distributed Active Archive Center provided an operations web portal for logging daily mission, program, and instrument science status reports; weather briefing materials; and to monitor real-time weather information relevant to operations. The IPHEx portal also served as a means to archive both real-time, quick-look products and raw data products from the instruments deployed in the field. The NASA Airborne Science Mission Tools Suite served as the primary platform for conducting aircraft operations and guidance during the IPHEx campaign, which included communications between aircraft scientists and the ground, and mission scientists and remote ground instrument locations (e.g., NPOL, D3R, and NOXP radars) via chat-based services.

IPHEx Early Findings

With the last of the field campaign activities having finished just a few months ago as of this writing, results are only beginning to become available. A few examples of already noteworthy findings are presented here that clearly show the utility of the combined, integrated, synergistic approach built into the IPHEx structure. More will follow as time goes on.

Rainfall Variability as a Function of Locale

Figure 2 illustrates the unique microphysical processes governing the spatial and temporal variability of rainfall in the inner region of the Southern Appalachians. Unlike previous GPM ground validation field campaigns, the IPHEx campaign emphasized *orographic modification*—i.e., how mountainous terrain impacts precipitation. In addition, this was the first ground validation campaign to "follow" water once it was on the ground. To accomplish this, the researchers relied upon *Quantitative Precipitation Estimates* (QPE), which estimate the amount of precipitation that has fallen across a given region, and *Quantitative Precipitation Forecasts* (QPF), which output the expected amount of melted precipitation accumulated over a specified time period over a specified area, to help them track the water once it reached the ground. They used this information for a number of hydrological applications, including operational streamflow forecasting—as will be described later.

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One important result that IPHEx observations have confirmed is that the contrasting amount of rainfall that occurs on ridges as opposed to valleys can be traced directly to how drop size distributions (DSD[6]) of precipitation vary over an area of land through the course of a day-night cycle. These observations are statistically significant and have a robust physical basis, which means they can be used to guide precipitation retrievals in complex terrain—as long as the algorithm takes the terrain into account.

During the IPHEX IOP, streamflow forecasts were generated daily for 12 headwater catchments (or basins), initialized by NASA-Unified Weather Research and Forecasting (NU-WRF)

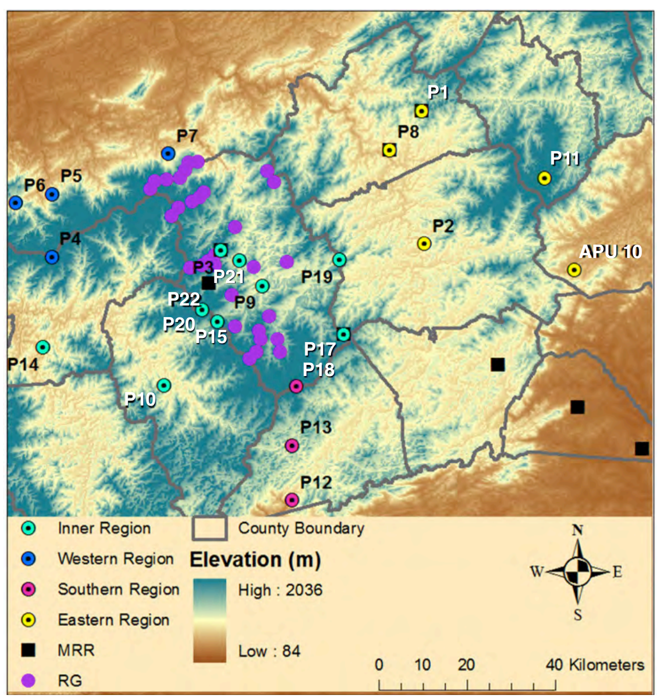

Figure 2. This map indicates the unique microphysical processes governing the spatial and temporal variability of rainfall in the inner region of the Southern Appalachians. In particular, note the range of elevations. The nocturnal rainfall peak was to the west of a line from just east of Parsivel 7 (P7) to just north of P18; the daytime rainfall peak was east of that line. MRR stands for Micro Rain Radar; RG stands for rain gauge; and APU stands for Autonomous Parsivel Unit. **Image credit:** Anna Wilson [Duke University]

[6] A *drop size distribution* is a statistical method to "count raindrops;" they are placed into "bins" based upon their size.

forecasts as well as forecasts and *hindcasts*[7], using one of two different NOAA QPE products that blend rain gauge and ground-based radar observations, which are abbreviated SW and MW in Figure 3[8].

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Figure 3 shows precipitation and streamflow observations and predictions for two of the 12 basins for an event that took place on May 15, 2014. This is an excellent example of the kind of event and subsequent analysis that IPHEx was organized to explore. The left panel of Figure 3 shows results obtained for the Yadkin River, located in the Upper Yadkin River, in the Yadkin/PeeDee basin, which is situated in the inner region of the Southern Appalachians (see Figure 1). The results show that the forecast for the May 15 event using NU-WRF rainfall is more accurate than the forecast using the same model forced by either of the two observational products (i.e., SW and MW). Note the difference in the timing, and especially the intensity of rainfall between the NU-WRF forecasts, Stage IV and MRMS averaged over the basin. As is the case for most small-to-medium size [400 mi^2 (1036 km^2)] basins in complex terrain across the continental U.S., there are no ground observations of rainfall in the Upper Yadkin, and consequently radar estimates alone are inadequate.

The right panel of Figure 3 shows results obtained for the West Fork of the Pigeon River in the upper Tennessee River, located in the Upper Tennessee basin on the eastern slopes of the Southern Appalachians—at a higher elevation than the Upper Yadkin River (see Figure 1 for comparison). In this case, the streamflow forecast is

[7] In a *hindcast,* observed data from a previous time period are used as input to see how accurately the model produces the conditions that were actually observed. In this particular case, data from the previous 24 hours were used as initial conditions for the model.

[8] SW stands for the National Centers for Environmental Prediction (NCEP) "Stage IV" analysis; MW stands for multiradar/multisensor (MRMS) system, an operational precipitation product system intended to enhance decision making and improve forecasts. The distinction is that SW involves a human in the quality control and merger process, while MW is produced as a merged product in a completely automated fashion.

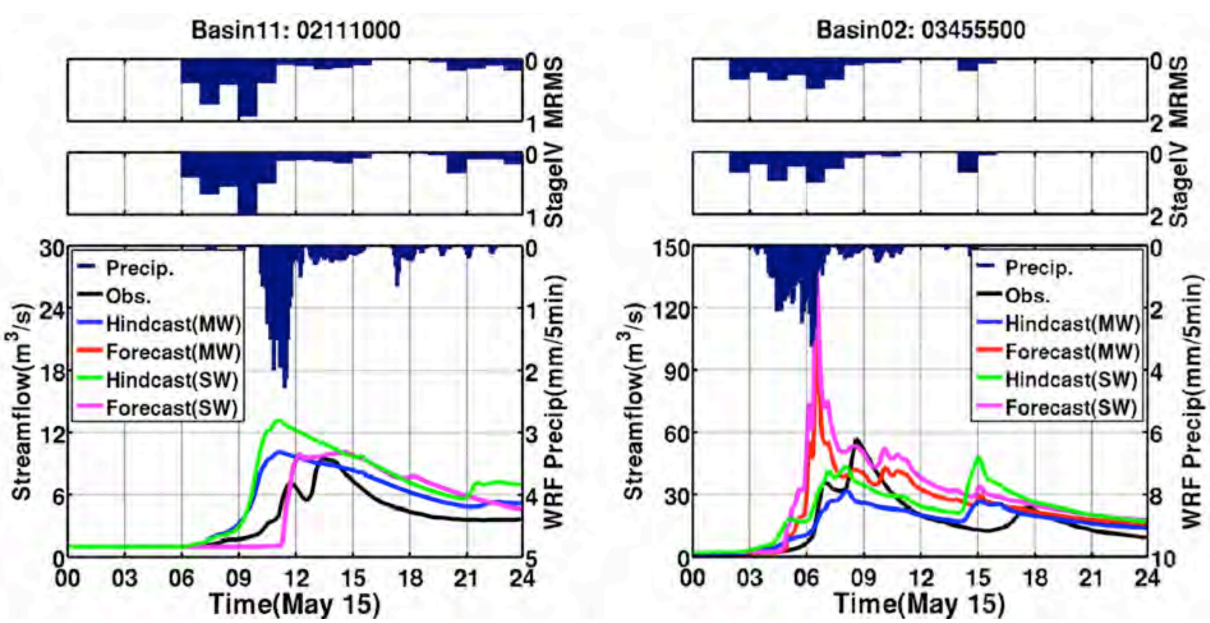

Figure 3. These two sets of plots show results from 24-hour streamflow forecasts and hindcasts during IPHEx using the new (uncalibrated) Duke Coupled Hydrology Model (DCHM)) at 250-m (820-ft) resolution for the Upper Yakin River [*left panel*] and the West Fork of the Pigeon River [*right panel*]. The two top plots in each panel represent the observed rainfall rate averaged over the catchment for each of the observational products, as indicated by the "y-axis label" on the right-hand side. In the bottom plot of each panel, the NU-WRF precipitation forecast averaged over the catchment is plotted along the top, with the amount of precipitation plotted down the right hand side. The streamflow forecasts and hindcasts are plotted along the bottom, with the flowrates plotted up the left-hand side. The pink lines are forecasts using NU-WRF precipitation and initial conditions from the hindcast for the previous day using Stage IV rainfall. The red lines are the same as the pink lines, but where the previous day hindcast was obtained using MRMS rainfall. The blue line is the hindcast for the present day, using MRMS rainfall at the end of the day. The green line is the same as the blue line, but using Stage IV rainfall. Please see text for definitions of acronyms used in graphs. **Image credit:** Jing Tao [Duke University]

excessively high, whereas the hindcast hydrographs are closer to the observations. The hindcast produced after blending the SW product with observations from additional rain gauges installed for IPHEx shows further improved streamflow simulations, thus indicating that the QPE has improved. Nevertheless, these results give a clear indication that the "true" rainfall is not known.

These examples, which were produced operationally during IPHEx proper, illustrate well the grand challenge of precipitation uncertainty for hydrological applications, and underscore the importance of GPM's contribution to the national observing system—which will be to fill current observational gaps in mountainous regions and complex terrain, broadly.

Severe Storm Precipitation Properties

Another example of the data collected during IPHEx—from May 23, 2014, illustrated in **Figures 4 – 8**—includes a small line of severe storms that formed and passed over the Piedmont. This dataset demonstrates the utility of synchronous ground-based observations and aircraft flights during a GPM Core Observatory overpass (2316 UTC). While severe storms are comparatively rare events when considered in the broader spectrum of precipitating cloud systems, they often produce rains that contribute significantly to local rainfall climatologies. Moreover, the deep columns of ice and liquid water found in these storms can pose special problems to GPM retrieval algorithms. For both these reasons, scientists are eager to learn more about the properties of precipitation produced by severe storms, and the opportunity to observe a line of storms as the GPM satellite passed over while simultaneously taking aircraft and ground-based observations was fortuitous.

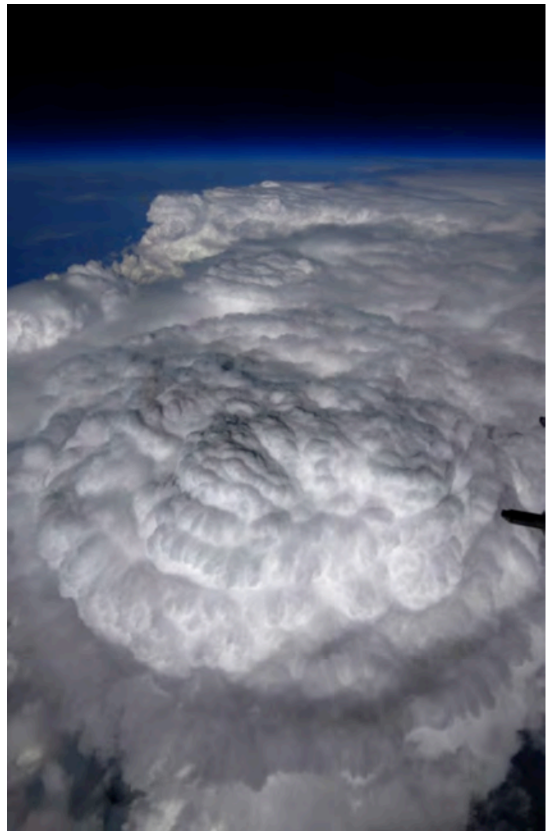

Figure 4. *The severe convective storm as seen from above.* The pilot of the ER-2 captured this photo of severe convection over the Piedmont of North Carolina on May 23, 2014—just prior to the GPM Core satellite overpass at 2316 UTC. **Image credit:** Donald "Stew" Broce [NASA's Armstrong Flight Research Center]

The storms sampled were located on the Piedmont approximately 80 to 150 km (50 to 190 mi) southeast of the NPOL radar, and even closer to the Greenville-Spartanburg, NC and Columbia, SC WSR-88D radars. **Figure 4** shows an example of what the event looked like when viewed from the cockpit of the high-flying ER-2.

The May 23 storm produced cloud tops greater than 50,000 ft (15 km), tennis ball-sized hail, and robust ice scattering signatures at even the lowest AMPR frequencies—see **Figure 5**. These measurements are consistent with the NPOL

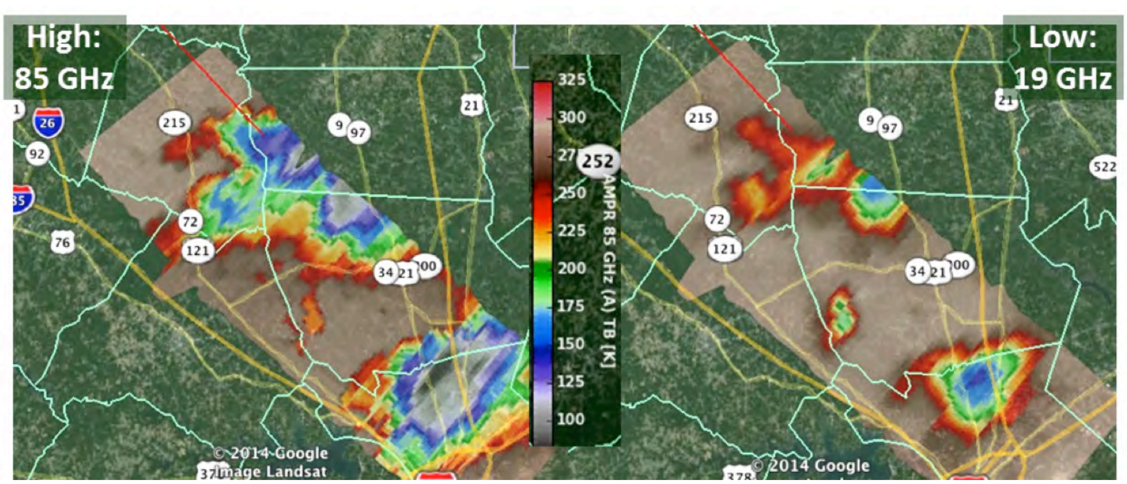

Figure 5. *Microwave brightness temperatures during severe storm convection.* These data—at high frequency [*left*] and low frequency [*right*]—in severe convection were observed by the AMPR radiometer aboard the ER-2 during a GPM Core satellite overpass at approximately 2316 UTC on May 23, 2014. Regions of increasing intensity are shown as nominally concentric color changes. **Image credit:** NASA

measurements—see **Figure 6**—and associated deep reflectivity structures in the airborne radar data—see **Figure 7**—with significant attenuation noted at the highest frequencies, which is to be expected in the presence of heavy precipitation.

The aircraft and ground-based data matched well with the satellite data—see **Figure 8**—although the more spatially coarse reflectivity data from GPM's Dual-frequency Precipitation Radar (DPR) exhibited relatively lower values than the ground-radar (see Figures 6 and 7). As in the case of the ER-2 AMPR data, the GPM Microwave Imager also observed cold brightness temperatures at 89 GHz that were indicative of ice scattering (cf., Figure 4). Relative to the importance of the ice scattering signature, note that the enhanced ice process aloft in this storm (and storms like it) is likely responsible for the production of a significant fraction of the heavy rainfall observed at the surface, with indications that large rain drops produced in heavy rainfall are associated with the melting of large ice particles such as hail (cf., Figure 5). (Indeed, this matches what was observed

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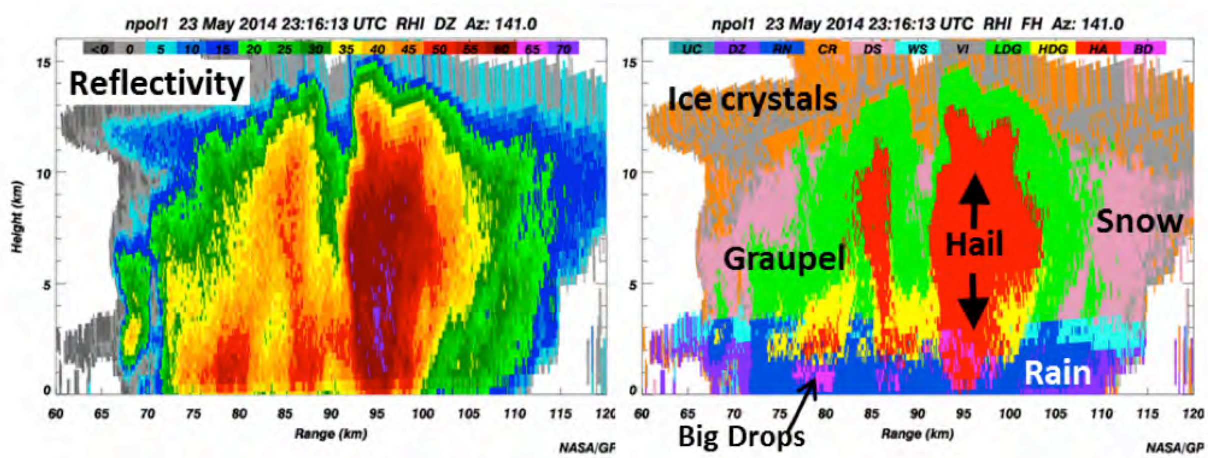

Figure 6. Cross-sections of radar scans obtained during a severe storm. NASA NPOL Radar range-height scan cross-sections cut through the severe storm sampled by the ER-2 and observed by the AMPR on May 23, 2014. The image on the left shows radar reflectivity, while the image on the right shows the derived precipitation types in the storm as estimated from polarimetric radar variables. Note the production of "big drops" underneath melting hail and large graupel. Increasing reflectivity is indicated by the gradations of color, with the highest reflectivity shown as purple. **Image credit:** David Wolff and Walt Petersen [both from NASA's Wallops Flight Facility]

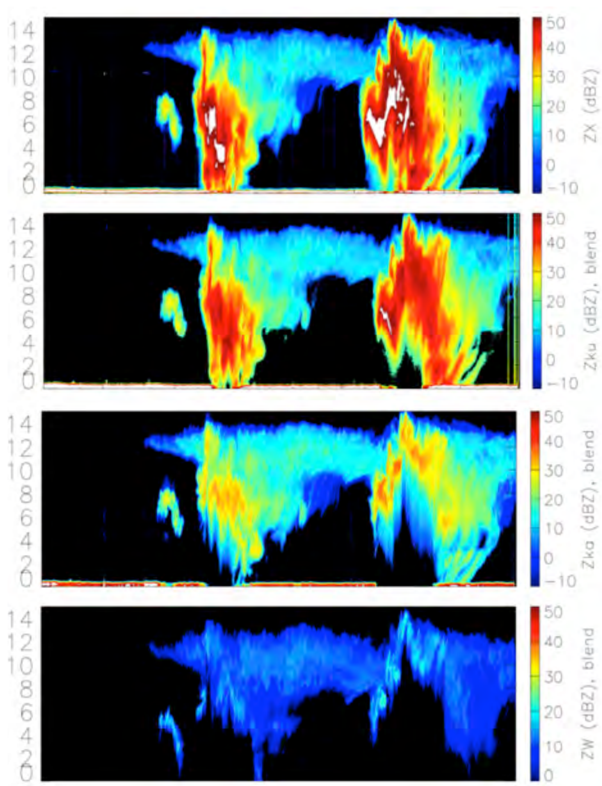

Figure 7. *Radar sampling of a severe storm from the ER-2.* Shown are radar reflectivity profiles from ER-2-based quad-frequency radar sampling of a severe convective storm, sampled on May 23, 2014. The data are a function of altitude along the ER-2 track at X, K_u, K_a, and W-bands [*top to bottom panel*], respectively. Increasing intensities are indicated by red and orange as the signals move toward the center of the cell. Note the progressively stronger attenuation and loss of signal in the higher K_u, K_a, and W-band frequencies as the radar beams propagate through the large hail and heavy rain at the storm's core. Also note the "notch" structure and weak radar echo region of the strong storm updraft near 2320 UTC. Radar reflectivity data as presented here are still preliminary and require final calibration. **Image credit:** Gerry Heymsfield [NASA's Goddard Space Flight Center]

For more detail to aid in interpreting the figures in this article, visit the full-color version at *eospso.nasa.gov/earth-observer-archive.*

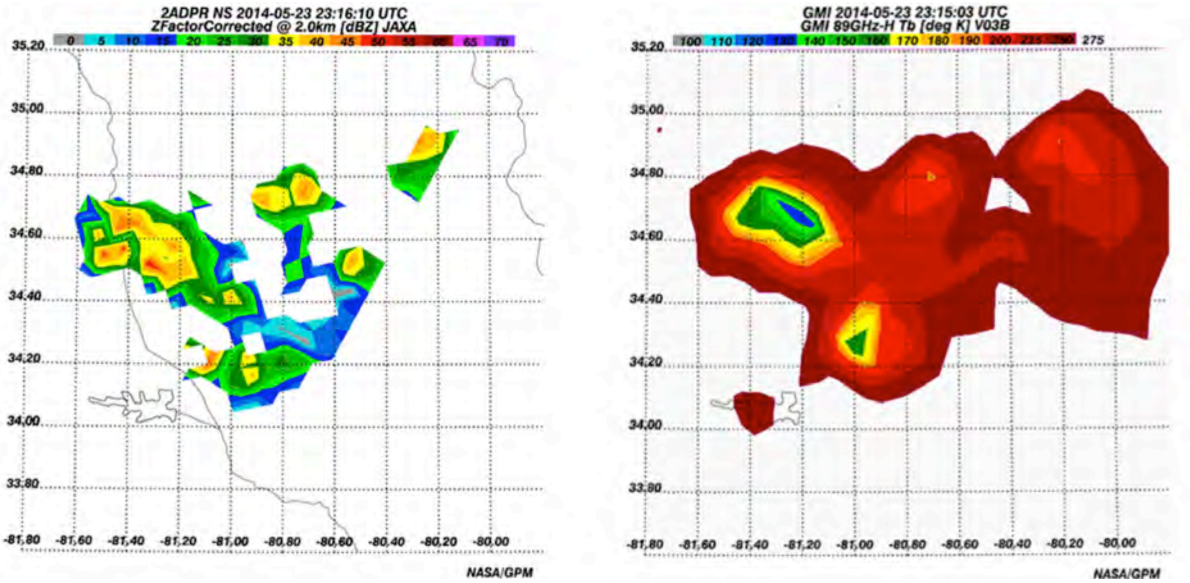

Figure 8. *GPM Core Satellite overpass image of severe storm convection*. These data were obtained over the Piedmont at 2316 UTC, May 23, 2014. Shown here are the dual-polarization radar reflectivities observed by the K_u-band channel at the 2-km (1.2 mi) height level [*left*] and GMI radiometer brightness temperatures (K) observed by the 89 GHz, horizontal polarization channel [*right*]. Note that the footprint for both GMI and the dual-polarization radar are approximately 5 km (3.1 mi), while the ER-2 and ground-based radar instruments collect at resolutions of 1-km (0.6-mi) to less than 1-km. Increasing intensities are indicated by brighter colors as the signals move toward the center of the cell. **Image credit:** David Marks [NASA's Wallops Flight Facility]

directly by ground-based disdrometers in another similar event during IPHEx.) The presence of even a few very large rain and/or hail particles can substantially impact signals observed at the higher GPM radar frequencies in a disproportionate fashion; hence understanding their formation and occurrence within individual storms is important.

Conclusion

As the examples in this article show, the early IPHEx results have already led to some exciting discoveries. With the comprehensive suite of results and datasets still to analyze, these preliminary results are expected to be just the first indicators of new information that scientists will use to address a wide and deep set of specific questions related to precipitation patterns over variable terrain. The results from IPHEx will not only have benefits to support GPM validation, but could also lead to longer-lasting studies of the effects of orography on precipitation phenomena. As with other such campaigns, the opportunities for science collaboration and participation amongst a wide range of interested organizations are manifold.

For more on IPHEx, visit *gpm.nsstc.nasa.gov/iphex* and *iphex.pratt.duke.edu*. ■

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