The NASA-GPM and DOE-ARM Midlatitude Continental Convective Clouds Experiment (MC3E)

Walter Petersen, NASA's Wallops Flight Facility, walt.petersen@nasa.gov
Michael Jensen, Department of Energy Brookhaven National Laboratory, mjensen@bnl.gov

The MC3E field experiment took place in central Oklahoma from April 22–June 6, 2011, focused on and around the ARM Southern Great Plains (SGP) Central Facility (CF), where an extensive array of both airborne and ground-based instrumentation was deployed.

Introduction

The development and validation of physically-based, over-land precipitation retrieval algorithms for satellite-based remote sensing requires the collection of detailed cloud and precipitation observations. Similarly, improving the representation of convective clouds in numerical weather prediction and climate models requires detailed observations and analysis of convective cloud processes. These synergistic needs underpin a collaborative effort led by NASA's Global Precipitation Measurement (GPM) and the U.S. Department of Energy (DOE)'s Atmospheric Radiation Measurement (ARM) programs to conduct the Midlatitude Continental Convective Clouds Experiment (MC3E).

The MC3E field experiment took place in central Oklahoma from April 22–June 6, 2011, focused on and around the ARM Southern Great Plains (SGP) Central Facility (CF), where an extensive array of both airborne and ground-based instrumentation was deployed—see **Figure 1**. The overarching goals of the field effort were to provide a complete three-dimensional characterization of precipitation microphysics in the context of improving the reliability of GPM precipitation retrievals over land, and to advance understanding of the primary physical components that form the basis for models that simulate convection and clouds.

The GPM mission, currently scheduled for launch in February 2014, was initiated by NASA and the Japanese Aerospace Exploration Agency (JAXA). GPM is a global successor to the Tropical Rainfall Measuring Mission (TRMM) that will provide the next generation of observations of rain and snow over the entire Earth every three hours. The GPM concept centers on deploying a "core" satellite carrying two instruments, the multichannel GPM Microwave Imager (GMI) and the K_u/K_a-band Dual-frequency Precipitation Radar (DPR), to set a new reference standard for precipitation measurements from space. Precipitation retrievals from these instruments require algorithms to transform the radar reflectivities (Z) and brightness temperatures (T_B) into precipitation information. Observations from aircraft and ground-based instruments, such as those taken during the MC3E field campaign (described below) are required both to improve and validate the science of the instrument retrieval algorithms for the radar and radiometer. The data from the GPM Core Observatory will then serve as a transfer standard to unify precipitation measurements made by an international network of partner satellites to provide near-real-time observations of rain and snow worldwide.

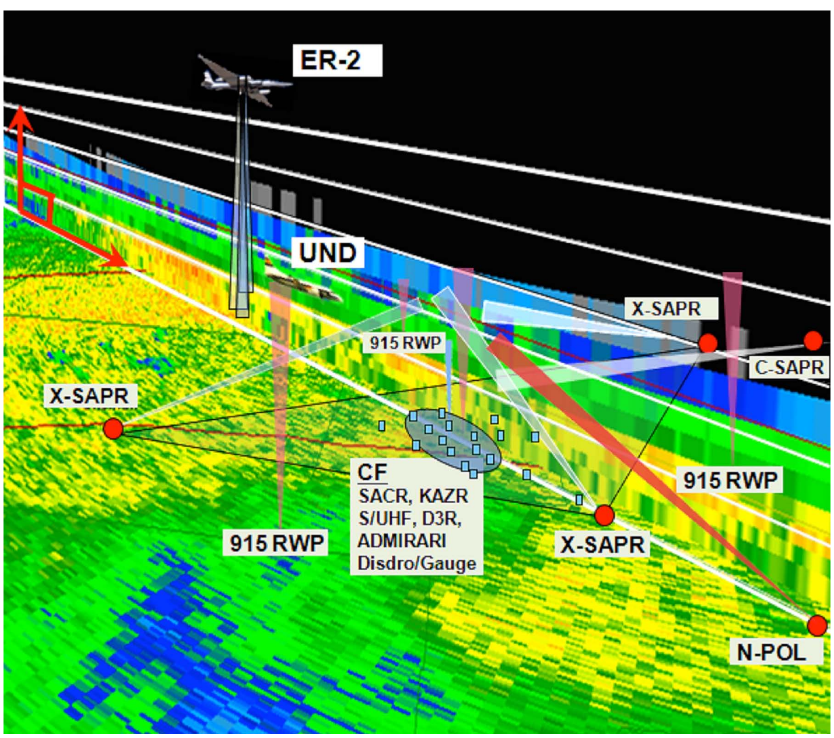


Figure 1. *Conceptual 3-D "top-down" sampling strategy for MC3E.* Sampling from aircraft [ER-2 and University of North Dakota (UND) Citation aircraft] occurred over a nested multifrequency ground-based network of radars (see full article for more details) and 915 MHz Radar Wind Profilers (RWP), covering a dense array of disdrometers and rain gauges. **Note:** Acronyms used in figure are defined in text.

MC3E Science Objectives

The MC3E science objectives were driven by the NASA GPM and DOE ARM programs' need to acquire a more complete understanding of the complex and interconnected physical processes driving mid-latitude convection, clouds, and precipitation production. GPM science objectives were crafted to validate precipitation retrieval algorithm physics, and coupled cloud-resolving model (CRM) and land-surface model (LSM) databases to advance passive microwave (PMW) and DPR over-land precipitation retrieval algorithm development, and to test those algorithms (i.e., to act as satellite simulators). Specific GPM objectives for MC3E included:

- *Collection of cloud physical properties that vary in space and time.* Such properties include cloud liquid and ice water contents, rain drop and ice particle size distributions, particle size distributions, melting layer structure, and precipitation rates in a midlatitude continental environment during the varying "regimes" of transition from spring to summer in the Northern Hemisphere.

- *Collection of coincident high altitude, dual-frequency radar, and microwave radiometer measurements with concomitant (nearly simultaneous) ground and airborne microphysical measurements.* These measurements would be used to support algorithm cloud database development and retrieval testing.

- *Construction of accurate large-scale forcing environments for CRM/LSM simulations*. These environments—with observed cloud properties—would be used to evaluate the fidelity and improve the physics of coupled model simulations—e.g., satellite simulator models (SSM).

- *Evaluation of the core complement of GPM Ground-Validation (GV) instrumentation.* This instrumentation (e.g., aircraft, radars, profilers, disdrometers, etc.), would be evaluated to assess sampling methodologies and associated measurement error characteristics.

- *Further establishment of CRM space-time integration capability.* This capability would be used for quantitative precipitation estimation.

- *Observation of land-surface properties.* Such properties—including microwave radiative fluxes, temperature, and soil moisture—would be used to better understand land-surface emission properties.

Observations from aircraft and ground-based instruments, such as those taken during the MC3E field campaign are required both to improve and validate the science of the instrument retrieval algorithms for the radar and radiometer.

DOE science objectives addressed three fundamental components of convective simulation and microphysical parameterization in numerical models:

- *Definition of the pre-convective environment in relation to convective initiation*. Prior to and during convective initiation, activities would define the vertical and horizontal structure of the atmospheric thermodynamic state and its evolution, with emphasis on boundary layer structure.

- *Identification of updraft and downdraft dynamics.* Available radar networks and multiple analysis techniques would be used to estimate three-dimensional (3-D) air motions within convective cloud systems, and to relate draft statistics to lower tropospheric instability and thermodynamic properties.

- *Characterization of precipitation and cloud microphysics*. Multi-frequency radar observations, combined with polarization capabilities, would be used to to quantify cloud and precipitation particle size distributions, total water contents, and cloud/precipitation particle phase.

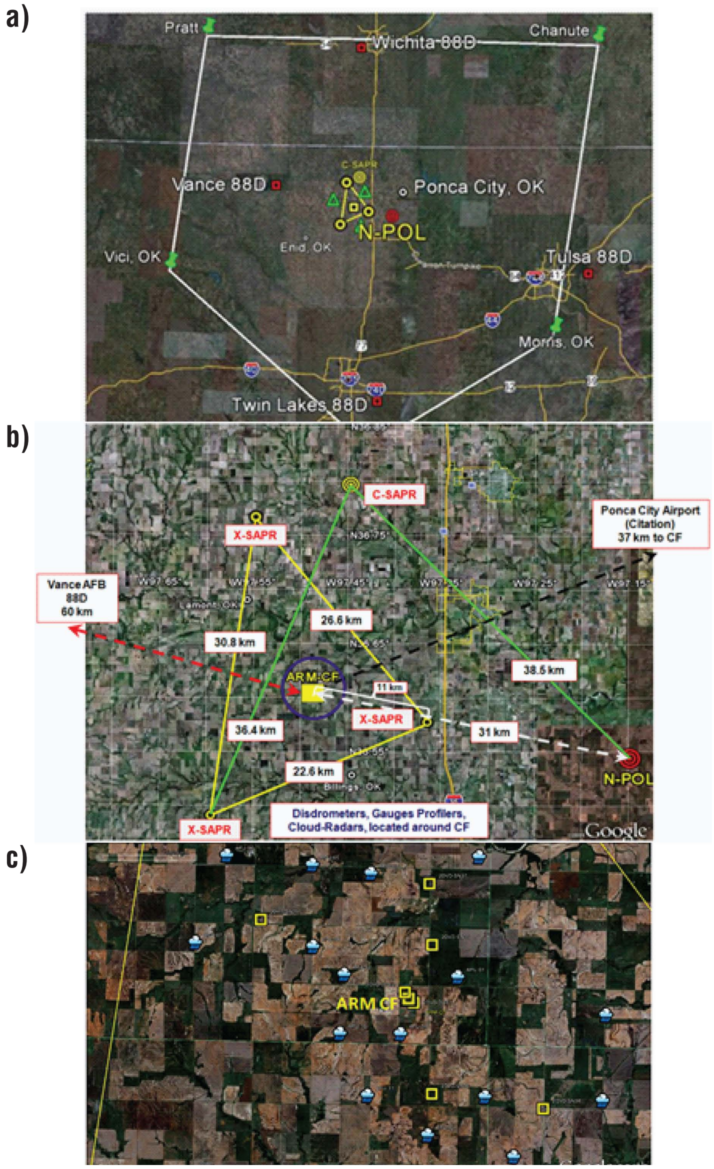
The complementary nature of these science objectives provided DOE and NASA researchers a common framework around which they could design a field experiment that provided maximum benefit to both agencies but with only minor accommodation of sampling approaches to achieve the objectives.

Figure 2. *MC3E Experiment design.* These images show: (a) The sounding network that encircled the central radar array (NPOL, C-SAPR, triangular array of X-band radars in yellow; 915-MHz profilers, green triangles) and the SGP CF; (b) a close-up of the central scanning-radar network showing the relative positions and distances between the NPOL radar, the DOE X and C-SAPR radars, and the Vance Air Force WSR-88D radar; and (c) the spatial distribution of APU and collocated rain gauges shown as green rain clouds, and 2DVD, indicated by white squares, within the X-SAPR radar array and surrounding the CF, shown as a purple circle in (b). For additional details please see the text.

Field Experiment Strategy, Instruments, and Operations

MC3E employed a "top-down" multiscale observing strategy—see **Figure 1**—that was implemented via the deployment of nested instrument networks and airborne platforms centered on the ARM SGP CF site in northern Oklahoma—see **Figure 2**. At the top of the sampling domain (i.e., ~12 mi (20 km) altitude), the NASA ER-2 aircraft carried the High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP), the Advanced Microwave Precipitation Radiometer (AMPR), and the Conically Scanning Microwave Imaging Radiometer (CoSMIR)—compare to **Table 1**. From their high-altitude vantage point, these instruments provided a dataset more consistent with the viewing angles and radar and radiometer measurements that will be characteristic of the GPM Core satellite.

Within and under the coverage of the ER-2 aircraft instrumentation, the University of North Dakota Citation aircraft sampled coincident cloud microphysical properties through the atmospheric column with special attention paid to sampling ice and mixed-phase particle characteristics—see **Table 2**.



The airborne measurements that have been described were conducted within the broad coverage of a nested ground-based instrumentation network—see **Figures 2a-c**. At the largest scale (186 mi; 300 km)—**Figure 2a**—a network of radiosondes were deployed to quantify regional temperature, wind, and humidity properties of the environment surrounding the ARM SGP CF. Over 1200 coordinated radiosonde launches from six sites took place at a nominal frequency of four per day to resolve the diurnal cycle, and eight per day during periods of intensive aircraft and ground-based operations. These data will form the basis of CRM and column model forcing datasets.

Nested within the radiosonde network was a smaller array—separations < 37 mi (60 km)—of seven multiparameter radar platforms. Anchoring the network were the recently upgraded NASA S-band scanning dual-polarimetric radar (NPOL) and the new DOE ARM X and C-band scanning dual-polarimetric radars (X-SAPR and C-SAPR, respectively). The C-SAPR radar provided customized but steady volumetric sampling of precipitation systems over the broader radar observation domain—nominal 50-mi (80-km) range. In turn, the NPOL radar was used as a reference to provide targeted, detailed, and relatively unattenuated sampling of precipitation processes over length scales ranging from approximately 0.16–62 mi (0.25–100 km). NPOL operations emphasized high temporal and vertical resolution dual-polarimetric sampling of precipitation rates and particle size distributions in coincident volumes of atmosphere sampled by the aircraft and other higher-frequency radar, disdrometer, and gauge instrumentation located in the immediate vicinity of the ARM SGP CF. The three X-SAPR radars provided convective scale multi-Doppler velocity observations for retrieval of 3-D wind fields and a higher-frequency dual-polarimetric measurement within the coverage domain of the aircraft, NPOL, and C-SAPR radars. Surrounding the SGP CF, was a dense network of 18 Autonomous Parsivel disdrometers (APU), 16 rain gauge pairs, and seven two-dimensional (2D) Video Disdrometers [2DVD]. These instruments sat within a radius of approximately 3.7 mi (6 km) of the CF. The APUs and rain gauges measured rainfall and drop size distribution (DSD) correlation properties at kilometer scales. The 2DVDs provided a DSD reference measurement to the APU network and were used to calibrate dual-polarimetric radar measurements and DSD retrievals. At finer scales and within the SGP CF, the full suite of ARM cloud, radiation, and atmospheric state instrumentation is available including the Scanning ARM Cloud Radar (SACR), Ka-band vertically pointing radar (KAZR), and micropulse lidar enhanced by the NASA Micro Rain Radar (MRR) and Advanced Microwave Radiometer for Rain Identification (ADMIRARI). The National Oceanic and Atmospheric Administration (NOAA) S-band/UHF profiler provided continuous vertically pointing measurements of precipitation and clear air velocity within the SGP CF. As operated, the S-band/UHF profiler provided a well-calibrated measurement of precipitation rate and DSDs that serve as a comparison to similar quantities estimated using dual-polarimetric radar platforms like the NPOL.

Table 1. NASA ER-2 Instrumentation

Instrument	Characteristics
AMPR	Passive microwave radiometer
Frequencies	10.7, 19.35, 37.1, 85.5 GHz; all channels H/V
Resolution at 12.4-mi (20-km) range	0.37 mi (0.6 km) (85.5 GHz),0.93 mi (1.5 km) (37.1 GHz), 1.74 mi (2.8 km) (10.7-19.35 GHz)
CoSMIR (Radiometer)	Passive microwave radiometer
Frequencies	52, 89 (H/V), 165.5 (H/V), 183.3+/-1, 183.3+/-3, 183.3+/-8 GHz
Resolution at 12.4-mi (20-km) range	0.87-mi (1.4-km) footprint at nadir
HIWRAP Radar	Profiler radar
Frequencies	13.91/13.35 GHz, 35.56/33.72 GHz
Transmit peak power	30 W (K_u), 10 W (K_a)
3-dB beamwidth	2.9° K_u, 1.2° K_a
Minimum reflectivity at 0.04-mi (60-m) resolution, 3.3-ms chirp pulse, 6.2 mi (10 km)	0.0, -5.0 dB_{Ze}

Table 2. UND Citation Instruments

Instrument	Measurement
Particle Measuring Systems Inc. (PMS) King Liquid Water Sensor	Cloud liquid water
PMS Two-dimensional (2D)-Cloud Imaging Probe (CIP)	Cloud and precipitation particle spectra
High-volume Precipitation Spectrometer (HVPS)	Precipitation particle spectra
Cloud Particle Imager (CPI)	Cloud particle images
Cloud Droplet Probe (CDP)	Cloud droplet spectra
Nevzorov Water Content Probe	Total water content
Rosemount icing probe	Supercooled liquid water
Condensation Nuclei (CN)/Ultra-high-sensitivity Aerosol Spectrometer (UHSAS)	Aerosol characterization

The MC3E *Dream Scenario*

Early in the morning of May 20, an intense north-to-south oriented convective line called a *mesoscale convective system* (MCS) moved over the CF and was extensively sampled by the ground-based instruments. Shortly thereafter, carefully orchestrated flights of the ER-2 and Citation sampled the MCS stratiform region over and near the CF. Finally, several long ER-2 transects were flown normal (perpendicular) to the direction of the MCS convective line and over stratiform precipitation as it moved eastward out of the sampling domain. These observations—shown in **Figure 3**—represent one of the best examples of the coordinated sampling strategy obtained throughout the entire MC3E campaign.

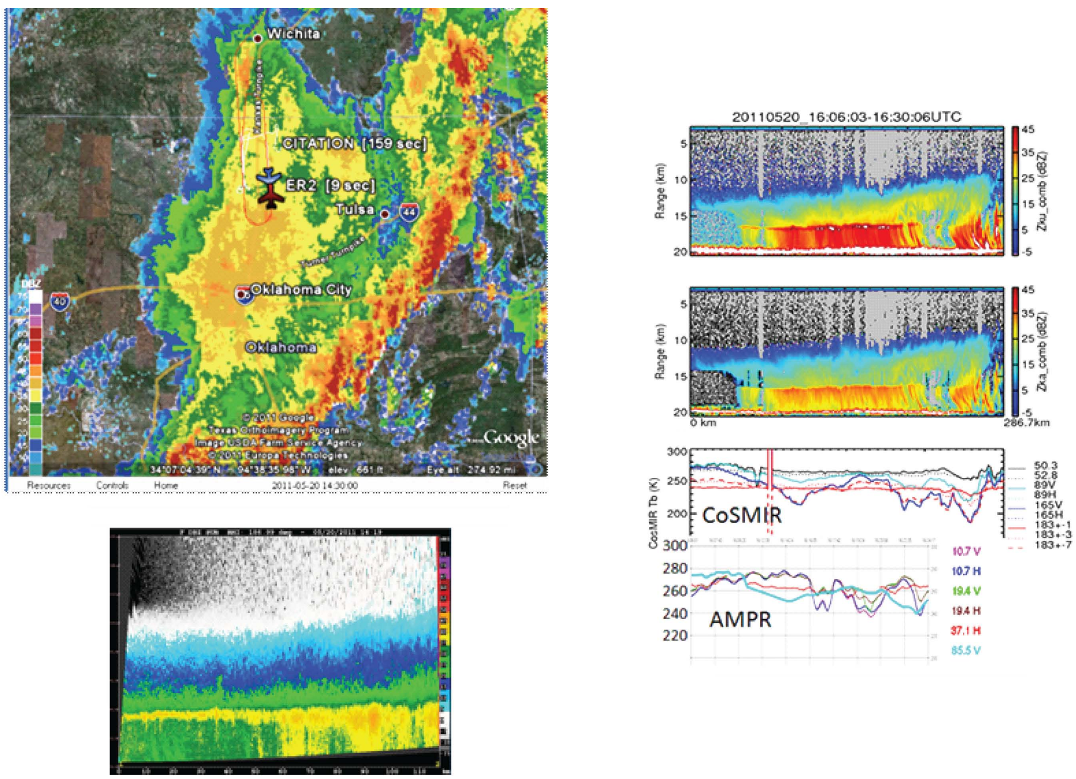


Figure 3. *The MC3E "Dream scenario" for coordinated airborne sampling.* The image shown at top-left is an example of ER-2 (red) and Citation (white) flight leg coordination overlaid on radar reflectivity from 1430 UTC on May 20, 2011. A vertical cross section (RHI; 1419 UTC) of radar reflectivity from the C-SAPR oriented approximately along the Citation/ER-2 flight tracks is shown bottom-left. The right panels show, from top to bottom, the 1606-1630 UTC ER-2 transect of coincident HIWRAP Ku-band, Ka-band reflectivity, and CoSMIR and AMPR radiometer brightness temperatures. This sample was collected in a line-normal flight leg over MCS stratiform precipitation and across the intense leading convective line. *HIWRAP and CoSMIR figure on right courtesy Gerry Heymsfield [NASA's Goddard Space Flight Center].*

Data Collection Summary and Example Observations

Airborne and ground-based precipitation instruments took a wide variety of coordinated measurements during MC3E. Several ER-2 and UND Citation missions with "stacked" sampling flew within 62 mi (100 km) of the SGP CF. These flights were of considerable importance to GPM—see **Table 3**—because they provided the best opportunity to fully describe column cloud and precipitation characteristics within the observational domain of a high-altitude GPM Core satellite simulator (i.e., the ER-2). In addition to these cases, numerous other airborne missions occurred that: a) provided coincident, and much needed, K_a-K_u band radar and 10–183-GHz radiometer datasets in view of other ground radars (including one mission conducted in concert with the Colorado State University CHILL radar in northeastern Colorado); b) allowed for detailed microphysical profiling; c) conducted cloud sampling; and d) facilitated HIWRAP, AMPR and CoSMIR sampling of the land surface with the goal of testing new approaches for unmasking precipitation signals from a background signal of strongly varying land-surface emission.

Table 3. Summary of Aircraft Flights During MC3E

Airborne Case Type	Dates
Coordinated ER-2, Citation within 62 mi (100 km) of CF	April 25, May 11, May 18, May 20, and May 23
ER-2/Citation outside CF coverage (i.e., NE Kansas)	June 1
Citation-only microphysics missions	April 27, May 1, May 10, May 24
Citation cloud missions	May 27, June 2
ER-2 Land Surface	April 25, May 8, May 29
University of Tennessee Space Institute (UTSI) Piper-mounted Marshall Airborne Polarimetric Imaging Radiometer (MAPIR)	Nine missions between May 21–June 2 (including a coordinated flight with ER-2 on May 29)

These flights were of considerable importance to GPM because they provided the best opportunity to fully describe column cloud and precipitation characteristics within the observational domain of a high-altitude GPM Core satellite simulator (i.e., the ER-2).

In addition to the coordinated operations with aircraft flights during MC3E, ground-based radar and disdrometer operations also focused on targeted high-resolution sampling of 3-D microphysical processes. For example, the NPOL radar was placed into a special 45-second scanning cycle on several occasions that consisted of range-height vertical cross-sections and low-level, plan-view elevation scans. When combined with the disdrometer data, these scans provide a means to map the full 3-D evolution and variability of DSD characteristics, which are fundamental to GPM radar and combined radar/radiometer algorithm retrievals. In particular, the polarimetric properties of the NPOL and DOE radars provided a means to discriminate liquid from ice-phase precipitation, and to examine how different liquid and ice processes impacted DSD properties in terms of the drop size and number concentration. **Figure 4** demonstrates this principal for an event observed on May 11. During this event the NPOL, 2DVD, and MRR observed momentary broadening of the DSD associated with occasional large raindrop production. High-temporal-resolution range-height indicator (RHI) scans collected by the NPOL suggest that at least some population of the observed larger drops were produced as a result of descending regions of melting hail and graupel.

Future Analysis Directions

After completion of data quality control and archiving (targeted for completion in December 2011), the MC3E dataset will yield a rich data source from which to conduct detailed precipitation and cloud physical process studies, test GPM algorithm

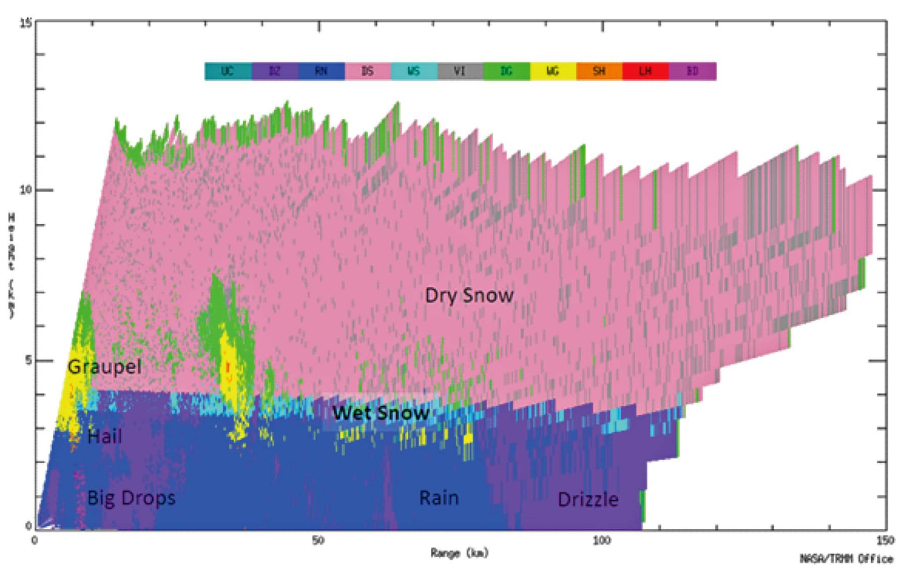


Figure 4. *Production of large rain drops by the melting of hail and graupel.* Color shading represents different hydrometeor (precipitation) types as identified using NPOL polarimetric radar variables observed in a range-height indicator scan taken at 1806 UTC on May 11, 2011. Of particular interest is the transition zone in the far left of the figure, where graupel (yellow) transitions to small hail (orange) and then to rain and large drops (blue and light purple respectively). **Image credit:** Brenda Dolan [Colorado State University].

physics and assumptions regarding those physics, and create CRM and SSM validation datasets. A focused effort to synthesize campaign measurements will be made in order to provide:

a) Model forcing datasets derived from the radiosonde array.

b) Precipitation microphysical characteristics (e.g., hydrometeor types, DSD parameters and rain rate covariance properties) concomitantly diagnosed from the array of W- through S-band polarimetric radars, disdrometer, and profiler observations.

c) Unified airborne radar, radiometer, and aforementioned ground-based microphysical measurements.

d) Two-dimensional and three-dimensional wind retrievals from multi-Doppler radar observations.

For more information about the GPM mission and Ground Validation activities please consult the GPM website: *gpm.nasa.gov*. For information regarding datasets please visit the GPM Ground Validation Data Portal: *gpm.nsstc.nasa.gov.* ■

In Memoriam

It is with deep sorrow that we report the death of Greg Leptoukh. He passed away unexpectedly on January 12 of cardiac arrest.

Greg joined NASA's Goddard Earth Sciences Data and Information Services Center in 1997 and quickly became known for his leadership in linking science and technology. He was passionate about making Earth science data more readily accessible to the end-user and later, was a pioneer of *Giovanni*—a Web-based application tool that provides a simple and intuitive way to visualize, analyze, and access vast amounts of Earth science remote sensing data (e.g., data from instruments aboard the A-Train satellites). Greg's work brought together data from several Earth Observing System satellite missions and provided a means for easy distribution of NASA Earth science data to policy makers, teachers, students, modelers, researchers, and the like.

Greg will be greatly missed by the NASA community and by his many collaborators and colleagues around the world. *The Earth Observer* staff wishes to express our condolences.