NASA Science Mission Directorate
Research Opportunities in Space and Earth Sciences
NNH15ZDA001N-PMM
A.23 Precipitation Measurement Missions Science Team

The Precipitation Measurement Missions (PMM) science team focuses on scientific investigations related to satellite observations of precipitation using measurements from, but not limited to, the Tropical Rainfall Measuring Mission (TRMM) 1997-2015, the Global Precipitation Measurement (GPM) Core Observatory launched February 2014, and GPM mission constellation partner spacecraft. This program supports scientific investigations in three research categories: (1) development, evaluation, and validation of TRMM and GPM retrieval algorithms; (2) development of methodologies for improved applications of satellite measurements; and (3) the use of satellite and ground measurements for physical process studies to gain a better understanding of the global water cycle, climate, and weather and concomitant improvements in numerical models on cloud resolving to climate scales.

These research activities will utilize satellite observations and products associated with a number of research missions and operational sensors. While the major focus of the expected research will be on the TRMM and GPM instruments, observations from other research sensors, such as the microwave humidity profiler (SAPHIR) on the Indo-French Megha-Tropiques satellite and the Advanced Microwave Scanning Radiometer-2 (AMSR-2) instrument on the Japanese Global Change Observation Mission – Water (GCOM-W1) satellite, as well as operational sensors, such as the Special Sensor Microwave Imager/Sounder (SSMIS), Advance Microwave Sounding Unit (AMSU), Microwave Humidity Sounder (MHS), Advanced Technology Microwave Sounder (ATMS), and others, such as CloudSat, may be used to provide information to complement scientific investigations and facilitate remote-sensing algorithm development.

NASA received a total of 135 proposals in response to this NRA element and selected 60 for support.

Robert Adler/University of Maryland, College Park
Climatology and Variations of Surface Precipitation: Use of GPM/TRMM in the Long-Term Record

This proposal focuses on the use of TRMM and GPM estimates to provide the best possible estimates of mean surface precipitation over the TRMM/GPM era in terms of monthly climatological means and variations. Estimates made from passive microwave, radar and combined radar/pmw techniques are used together (and separately) to make a "best" estimate of surface precipitation and to study the magnitude and spatial distribution of variations at seasonal, inter-annual and longer timescales.

One main avenue of activity will be the determination of the absolute magnitude of surface precipitation from TRMM and GPM data, i.e., an accurate climatology for use in water balance studies and in longer record climatologies (e.g., GPCP). This will involve

the improvement and extension of the TRMM Composite Climatology (TCC) described in Adler et al. (2009) and Wang et al. (2014), and will result in a TRMM/GPM Composite Climatology product for distribution via PPS and/or Goddard DISC. The current TCC provides a 15-year monthly climatology using PR information (adjusted after the TRMM boost), TMI-based estimates, and combined PR/TMI-based estimates to give a "best" estimate of mean surface precipitation over the tropics. The current version uses TRMM Version 7 data products, but will be updated, first to complete the TRMM era with Version 7, and then with the new GPM-based products. Evaluation of the GPM products in this regard, especially with respect to the Version 7 TRMM estimates, will be a critical, initial activity of this work.

A second, key area of research is to utilize all the TRMM and GPM products to investigate inter-annual and other variations of surface precipitation in relation to variations in surface temperature. This will involve ENSO, the global-warming hiatus (~ 1998-present) and other phenomena. One focus will be the current apparent limitation of the TRMM radar-based and combined products that do not show a significant increase total ocean precipitation during El Nino, unlike the PMW-based results, both from TRMM and from other sensors. This problem has been related to a lack of sufficient attenuation correction in PR algorithms at low levels (below 6 km) in convective rainfall, of which there is more during El Nino. We will work with members of the relevant algorithm science teams to examine the new GPM radar products to understand if the new GPM radar algorithms are better in this regard, or retain the problems of the TRMM V7 algorithms. Results of this work will produce a better understanding of the TRMM/GPM radar products and their role in understanding the climatology of surface rain and inter-annual variations thereof.

A third component of the work will be to link IMERG daily estimates of precipitation to the climatology and monthly estimates so that we can study the variations of intense precipitation during the TRMM and GPM era. This will include examining the variations in intense rain in relation to temperature variations and other factors.

Ana Barros/Duke University
4D Integration of Satellite and IPHEx GV Observations with Physical Models to Improve the Representation of Orographic Precipitation Processes and Enhance Precipitation Measurement and Simulation in Mountainous Regions

The objective of this proposal is to improve SQPE (Satellite Quantitative Precipitation Estimation) in mountainous regions by improving the representation of orographic precipitation processes in retrieval algorithms and physical models through research and analysis (R&A) of IPHEx (Integrated Precipitation and Hydrology Experiment) observations in the Southern Appalachians. Assessment of TRMM PR and initial GPM DPR SQPE products reveals robust spatial and temporal (seasonality and diurnal cycle) organization of False Alarms, Missed Detections and Underestimation errors. These errors are linked to uncertainty in the parameterization of precipitation microphysics, and in the interpretation of low level measurements in complex terrain, including ground-

clutter effects, and sub-grid scale vertical and horizontal heterogeneity of precipitation systems that result from interactions among fog and orographic clouds, and propagating storm systems.   In operational hydrologic modeling applications, these errors translate to high spatial and temporal uncertainty at the storm-event scale and poor predictive skill. The specific research objectives are: i) to elucidate the spatial and temporal variability of orographic precipitation microphysics in the lower troposphere; ii) to characterize the vertical signature of orographic precipitation regimes on multi-frequency radar reflectivity; and iii) to improve the accuracy and the spatial and temporal resolution of orographic SQPE at the storm-event scale. A three-pronged research strategy culminating in a synthesis study is proposed. 1-Characterization of Hydrometeor Life-Cycles and CCN-Cloud-Rainfall Interactions – The multi-sensor IPHEX IOP observations at the Maggie Valley (MV) supersite will be analyzed and integrated to study the microphysical processes that govern in-column hydrometeor evolution from CCN activation to fog and cloud formation and rainfall, and to characterize the signature of the vertical structure of low level rainfall on multi-frequency radar observations.   2 – Spatial Transferability Studies – The microphysics and radar models of rainfall structure at Maggie Valley will be tested against 4D merged radar products from the IPHEx IOP, and their transferability will be evaluated through leveraging the spatial network of disdrometer observations. High-resolution WRF (Weather Research and Forecasting) simulations will provide in-column atmospheric profiles of thermodynamic variables and water content. Next, R&A will be extended to the IPHEX EOP to characterize seasonality effects. Targeted short-duration microphysical and radar observations will be conducted to complement the existing EOP dataset and fill-in IPHEX gaps (i.e. observations of high elevation and mixed phase precipitation). 3- Hydrologic Corrections as Integral Estimates of Retrieval Errors â€" A framework for event-scale hydrologic correction (HC, i.e., bias correction and spatial uncertainty) of IPHEx GV QPE products (e.g. NWP, radar-only, merged radar-raingauge, IMERG) will be developed using hydrologic data-assimilation (HDA) of river discharge in gauged headwater basins. HC-QPE provides a georeferenced integral metric of event-scale precipitation that meets mass conservation constraints to test and evaluate rainfall structure and microphysics models developed in (1) and (2) to inform retrieval algorithms and improve SQPE. The findings of 1, 2 and 3 will be independently evaluated through an end-to-end interpretive synthesis study contrasting the "GPM-like" aircraft observations for the June 12 event over the Pigeon River basin against integrated GV observations and model simulations. Finally, HC-HDA framework will be applied to characterize the climatology of the spatial error structure of IMERG QPE in the IPHEx domain toward developing systematic orographic precipitation corrections for hydrological applications in mountainous regions globally.

Wesley Berg/Colorado State University
Improving Consistency in Precipitation Estimates from the GPM Radiometer Constellation Through Intercalibration, Sensitivity Analysis, and Bias Characterization

According to Hou et al. 2014 "The GPM mission is specifically designed to unify and advance precipitation measurements from a constellation of research and operational

microwave sensors". This approach takes advantage of existing satellite sensors from many different space agencies, but presents a number of challenges in producing consistent precipitation estimates from radiometers with widely varying capabilities and calibrations. Understanding and addressing the issues leading to differences in precipitation estimates between sensors is critical to accomplish many of the stated GPM science goals. Consistency in the precipitation estimates from the constellation sensors requires physically consistent input brightness temperatures (Tb) between sensors as well as properly accounting for and understanding how differences in sensor characteristics and calibration impact the retrieval apriori database, the retrieval algorithm, and the level 3 merged precipitation products. The objectives of the proposed work consist of two parts that will focus on 1) improving consistency in the observed Tb and precipitation estimates from the constellation sensors, and 2) quantifying the impact of differences in information content between sensors on the resulting distribution of precipitation estimates. This proposal seeks to expand upon previously funded PMM efforts related to sensor calibration, algorithm sensitivity to instrument characteristics, and regime-dependent biases in precipitation estimates. These efforts will involve working closely with the XCAL intercalibration team as well as the radiometer and merged algorithm development teams.

Since the launch of the GPM core satellite in February of 2014, the focus of XCAL team has been on the calibration of GMI and the current GPM radiometer constellation. Now that the GMI calibration has been finalized and deliveries are under way for version 2 reprocessing of the GPM products, the focus of calibration activities will evolve. Specific tasks related to the first part of this project will include monitoring and maintenance of the current radiometer constellation, incorporating new sensors, addressing problem issues that impact the precipitation retrievals, extending and/or updating corrections and calibration offsets to pre-GPM radiometers for planned TRMM reprocessing, and improving current calibration methods by addressing deficiencies in simulated Tb over clear-sky oceans. The impact of calibration changes on the retrieval algorithm will also be evaluated and uncertainties in the precipitation estimates due to residual calibration errors will be quantified. The objectives related to the second part of the proposed effort will focus on quantifying the impact of differences in information content between sensors on the precipitation estimates over different regions and surface types. This will involve performing sensitivity studies with the operational radiometer retrieval algorithm as well as comparisons with the GPM DPR retrievals and GV data to identify problems and to characterize differences between radiometers and with respect to DPR and validation datasets.

Rafael Bras/Georgia Tech Research Corporation
Data Assimilation and Downscaling of Remotely-Sensed Satellite Precipitation and Soil Moisture Data for Hydrologic Applications

This proposal is built on the on-going effort of developing modern data assimilation techniques for downscaling of satellite precipitation and soil moisture measurements to improve hydrological modeling and prediction at high spatiotemporal resolutions. The

goal of this proposal is to develop a joint data assimilation system to effectively incorporate the merged products of the Global Precipitation Measurement (GPM) and the Soil Moisture Active and Passive (SMAP) missions into a coupled land surface and atmosphere model to better understand catchment-scale hydrologic dynamics such as flash floods.

In the past, as part of the PMM Science Team, we have developed an algorithm that uses the Weather Research and Forecasting (WRF) model with a four-dimensional variational (4D-Var) data assimilation scheme to directly assimilate and downscale the Tropical Rainfall Measuring Mission (TRMM) 3B42 precipitation product. Good results were obtained. Furthermore, we developed a one-dimensional variational (1D-Var) data assimilation scheme and linked it with the coupled WRF-Noah model to directly assimilate soil moisture retrieval provided by the Soil Moisture and Ocean Salinity (SMOS) mission. With this effort demonstrated that such soil moisture assimilation significantly improves the soil moisture prediction and thus related hydrologic predictions. Both independent activities are a proof of concept of the potential of joint data assimilation in the current real GPM-SMAP era.

This new proposal seeks to make the most of products from the GPM and SMAP missions. The proposed project will focus on the following new research tasks. First, we will develop a new joint data assimilation system to simultaneously assimilate the precipitation data from the Integrated Multi-satellite Retrievals for GPM (IMERG) and soil moisture data from the SMAP level II radar/radiometer products. Second, using the developed system, we will produce high space-time resolution fields, including precipitation, soil moisture, radiation, humidity, wind, and pressure, and temperature that will serve as inputs to stream flow prediction models. We will use complementary advantages of distributed hydrological models including WRF-Hydro and the Triangulated Irregular Network (TIN)-based Real-time Integrated Basin Simulator (tRIBS) developed in our group. The outcome of this research will improve knowledge and hydrologically useful products to the basket of efforts of the PMM Science Team including: (1) a joint data assimilation system that quantifies the relative impact of the GPM and SMAP on precipitation and soil moisture predictions and (2) a further understanding of the relative importance of the GPM and SMAP on the parameterization and hydrologic/streamflow predictions of the WRF-Hydro and tRIBS models. The direct deliverables of this project are downscaled rainfall and soil moisture data products from joint data assimilation of satellite precipitation and soil moisture.

Daniel Cecil/NASA Marshall Space Flight Center
Better Understanding GPM Radiometer Measurements Using Ground-Based Radar

The Global Precipitation Mission (GPM), Tropical Rainfall Measuring Mission (TRMM), and related satellites have observed a huge number of precipitating systems around the globe. Pairing high-quality ground-based radar data with coincident satellite observations can help us learn to better interpret the satellite data, and to apply that understanding to satellite observations from otherwise data-sparse regions. The relatively recent upgrade of the United States Weather Surveillance Radar - 1988 Doppler (WSR-88D) network to dual-polarization capabilities enables an independent assessment of

hydrometeor types that can be paired with the satellite measurements. We propose to use data from the GPM, TRMM, and WSR-88D databases to improve understanding of how different hydrometeor types (and their vertical profiles and amounts) relate to observed satellite measurements. We propose to use that new understanding to investigate precipitation retrieval quality (error characteristics and biases) associated with particular hydrometeor types or profiles. We further propose to use this improved understanding of how to interpret the satellite measurements to investigate characteristics of precipitation systems (and their related weather and climate patterns) around the globe.

With the focus on improving our interpretations of GPM and related satellite measurements, our efforts will also include a theoretical component using radiative transfer modeling, and analysis of other ground-based radar products and detailed ground-based and airborne data collected during GPM field programs. The radiative transfer modeling will be grounded in observations, applying existing models (not new model development) to realistic vertical profiles of precipitation from the radar database and comparing model output to the actual satellite data.

The key objectives for this research are:
1.1 Build empirical relationships between GPM (and related) satellite measurements and hydrometeor types derived from ground-based dual-polarization radar.
1.2 Build physical understanding of relationships between satellite measurements and hydrometeor types.
1.3 Analyze GPM precipitation retrieval characteristics relative to the retrieved hydrometeor classifications; assess if certain hydrometeor types are associated with consistent biases or error characteristics in the GPM retrievals.
1.4 Associate GPM precipitation features in the U.S. with derived characteristics from the WSR-88D radar network, including information on hydrometeor types and signatures of severe weather.
1.5 Apply relationships from objectives 1.1-1.4 to interpret characteristics of precipitation systems throughout the GPM (and related satellites') domain.

Chandra V. Chandrasekar/Colorado State University
GPM Observations and Precipitation Microphysics: Satellite Algorithm Support, Product Validation, Enhancement, Interpretation, Precipitation Estimation and Applications

The objective of the proposed research is to develop analytical techniques and to study precipitation microphysical parameters such as drop size distribution parameters at global and regional scales to derive microphysical inferences of precipitation variations at these scales with the main goal of algorithm product validation and enhancement for the profile classification module for DPR. The studies will be conducted using space-borne observations from the GPM platform as well as ground polrimetric radars and in-situ observations. The specific topics to be addressed are a) Validation and enhancement of Development of profile classification algorithms that will classify the dual-frequency (Ka/Ku- band) data profiles on a global scale to regions of microphysical significance, as part of the DPR algorithm module; b) development of global maps of raindrop size

distribution parameters such as the median drop diameter and the normalized concentration for microphysical studies; c) analysis of dual-frequency (Ka/Ku-band) based classification of precipitation profiles and precipitation estimation; d) develop a strategy to transfer microphysics knowledge and precipitation estimates from ground radar to GPM dual-frequency precipitation radar (DPR); and e) collect and analyze the coordinated data sets between GPM DPR and ground polarimetric radars that are part of the ground validation program to ensure transfer of quantitative and qualitative microphysical interpretations to TRMM and GPM observations.

In order to make an impact on the use of GPM observations and retrievals, the microphysical information must be correlated to the space-borne observations. The specific activities in that direction include: a) simulation of GPM precipitation radar profiles for categories of microphysical significance, b) the development of techniques to generate global maps of drop size distribution parameters and compare them against ground based DSD retrievals, and c) making use of the advances in the previous two steps to improve GPM microphysical retrieval algorithms.

Currently the PI plays a significant role in the DPR algorithm development group, and is responsible for the profile classification module, that has been released and operational on the GPM DPR. The main task of this proposal is validation and enhancement of that module that the PI is responsible for. The PI proposes to continue to play that role and be a part of the international DPR algorithm team, and in addition, play a significant role in the analysis of ground radar and other in-situ sampling infrastructure for the GPM ground validation program, including cross-validation of hydrometeor classification as well as mixed-phase precipitation studies with space-borne measurements.

GPM precipitation radar observations, combined with the knowledge of precipitation microphysics observed on the ground worldwide, provide a sound basis for modeling the precipitation observations for space-borne systems. We propose the use of observations-based simulations as well as ground-based dual-frequency radar observations to develop data-based models to evaluate the space-borne dual-frequency radar observations.

Continuous educational outreach associated with the research will be an integral feature of this proposal.

Shuyi Chen/University of Miami, Key Biscayne
TRMM-GPM Precipitation Tracking and Water Cycle of the MJO

The Madden-Julian Oscillation (MJO) is the most dominant mode of tropical intraseasonal variability that affects the global weather patterns, including high-impact weather like drought, heat waves, flooding, and tropical cyclone developments. The most challenging aspect in observing and predicting the MJO is the convective initiation of the MJO over the Indian Ocean, which is characterized by development of large-scale equatorial precipitation, and its eastward propagation through the Maritime Continent to the West Pacific. Current operational MJO forecasting uses the RMM (Real-time Multivariate MJO) index to identify, track, and predict the MJO. However, the RMM cannot capture the MJO convective initiation accurately. Complex interactions among the convective cloud systems, air-sea fluxes, and environmental water vapor are the key for the accurate prediction of extreme weather events. Satellite observations of

precipitation using measurements from the Tropical Rainfall Measuring Mission (TRMM) 1997-2015 and the Global Precipitation Measurement (GPM) core observatory launched in February 2014 will provide an unprecedented long record of global precipitation data for consistently studying MJO events over two decades and beyond. This will help better understand and predict the MJO and high-impact tropical weather systems over longer time scales that can bridge the gap between the weather and climate.

The proposed research aims to 1) develop a new precipitation-based index for the MJO convective initiation over the Indian Ocean and subsequent eastward propagation across the Maritime Continent using TRMM-GPM data from 1998-present, 2) develop a water cycle dataset combining precipitation, water vapor, and air-sea fluxes using observations from NASA satellites (e.g., TRMM-GPM, AIRS and others) and the DYNAMO (Dynamics of MJO) field campaigns, 3) better understand the convective organization over the Maritime Continent, especially the contrasting diurnal cycles of precipitation over the large islands and adjacent seas, and their impact on the eastward propagation of the MJO, and 4) improve model prediction of the MJO by better representation of the water cycle in a cloud-resolving, fully coupled atmosphere-ocean-land model. Observations obtained during the DYNAMO field campaign including the ground/ship based and airborne radar, rain gauges, GPS dropwindsondes and AXBTs, and air-sea fluxes will be used together with the multi-year satellite data to evaluate the high-resolution coupled model results. The focus is on process-oriented relationships between precipitation, air-sea fluxes, and the environmental water vapor. The outcome of this study is expected to improve prediction of MJO convective initiation through a better understanding of the physical processes affecting convective organization as well as their feedback on the MJO evolution over the Indian Ocean and its eastward propagation through the Maritime Continent.

This proposed study will primarily address the following NASA PMM objective: through the use of satellite and ground measurements for physical process studies to gain a better understanding of the global water cycle, climate, and weather and concomitant improvements in numerical models on cloud resolving to climate scales. It will be under the Research Category 2.2–Utilization of satellite/GV products for process studies and model development. This project will build on the PI team's prior experience working with the NASA satellite data including TRMM, CloudSat, AIRS, GPSRO, QuikSCAT, and airborne data from the NASA DC-8, ER-2, AF C-130s, and NOAA P-3's as well as high-resolution cloud-resolving, fully coupled atmosphere-wave-ocean models. It will greatly enhance the science application of TRMM-GPM and other NASA products and contribute to improved understanding and prediction of high impact weather such as the MJO.

Brian Colle/State University of New York, Stony Brook
Using OLYMPEX Field Data, Satellite Simulators, and Unique Surface
Instrumentation to Improve Cloud Microphysical Parameterizations

This proposal addresses section 2.2 of the solicitation, focusing on the Utilization of Satellite/GV Products for Process Studies and Model Development. Field campaign, satellite, and in situ data will be used to study precipitation and microphysical processes, particularly for mixed phase and frozen precipitation, and their improved representation in cloud resolving models. Our recent efforts using Global Precipitation Mission (GPM) and other field data have advanced our understanding of snow and riming processes in winter storms and led to bulk microphysical parameterization (BMP) development. We have also used the NASA Goddard Satellite Data Simulator Unit (G-SDSU) to perform simulations of remotely-sensed quantities for comparison to model-simulated outputs. Previous GPM field programs (C3VP and GCPEx) provided some opportunities to examine BMP performance in dry to lightly rimed environments, however, upcoming field data sets (e.g., OLYMPEX over the Pacific Northwest) combined with our previous experience with other field microphysical experiments in this same region (e.g., IMPROVE) are needed to advance our ability to simulate mixed phase microphysics, which is important for precipitation forecasts and satellite retrievals.

The OLYMPEX field campaign is scheduled from November 2015-February 2016 over the Olympic Mountains of Washington State and coastal Pacific Ocean. We will use this field dataset to evaluate and improve the snow and riming processes within BMPs. We plan to validate newer and more sophisticated BMP schemes in WRF: Goddard 4ICE, revised Stony Brook University (SBU-YLIN), and the predicted particle properties (P3) scheme (new scheme developed by Hugh Morrison), as well as the WRF Spectral Bin Microphysics (WRF-SBM). The results from OLYMPEX and previous microphysical field experiments (CV3P, GCPEx, and IMPROVE) will be put in context with different ambient conditions, such as height of freezing level and -15 oC level, presence of turbulence, and cross barrier flow, all of which can modify the depth of the cloud and riming processes. We will evaluate the particle size distribution, density, and riming through comparisons with aircraft measurements. We also have access to other unique datasets that will allow further testing and development of the schemes for winter storms. A surface Multi-Angle Snowflake Camera (MASC) provides unique three-dimensional imagery to obtain more accurate snow sizes, shape, and riming, and a Single Hydrometeor hot plate (for melted mass), both of which together can yield high temporal frequencies of snow density, which is very important for BMP development.

We will also use the G-SDSU to translate forecast model output to simulated observations from the following satellite sensors: Moderate Resolution Imaging Spectroradiometer (MODIS) onboard NASA Terra and Aqua, Suomi-National Polar-orbiting Partnership (S-NPP) Advanced Technology Microwave Sounder (ATMS), Advanced Microwave Sounding Unit (AMSU) and Microwave Humidity Sounder (MHS) onboard NASA Aqua along with NOAA and MetOp satellites, Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager/Sounder (SSMIS), GPM frequencies for comparison to aircraft-mounted GPM simulators and Global Precipitation Measurement Microwave Imager (GMI)/Dual-frequency Precipitation Radar (DPR) instruments, and CloudSat data where observations are available. The agreement between the observed and simulated satellite products will be

used to determine which assumptions/parameterizations in the BMPs offer the best representations of riming and aggregation processes. The spectral bin scheme (WRF-SBM) will also be used to modify and improve these processes in the bulk schemes. Using the above datasets, we will modify a scheme to include variable riming and snow variations within each grid box and better habit determination, both of which will improve the parameterizations of riming efficiency and aggregation.

Anthony Del Genio/NASA Goddard Space Flight Center
Analysis of Organized Convection and Synoptic Storms in TRMM-GPM Data and a General Circulation Model

The plausibility of projections of future changes in the global water cycle depends on the representation of processes that couple clouds, precipitation, and dynamics in different climate regimes. These include phenomena such as tropical and summer midlatitude mesoscale convective systems (MCSs) that are unresolved at current global climate model resolutions but will be marginally resolved in the next generation of models, and phenomena such as midlatitude baroclinic storms that are ostensibly resolved at current climate model resolutions but contain important cloud-precipitation-dynamics interactions at unresolved frontal scales. Simulations of both types of storms are further compromised by uncertainty in mixed-phase microphysics parameterizations.

We will use satellite IR data to identify and track MCSs through their lifecycle. GPM Microwave Imager (GMI) high-frequency channels ($\geq$ 85 GHz) and Dual-Frequency Precipitation Radar (DPR) reflectivity fields will then be mapped into the resulting IR lifecycle phase to document the 3D spatial extent of organized convective systems spanning both the tropics and mid-latitudes at different times in the evolution of the MCSs. DPR ice/liquid hydrometeor and diabatic heating profile products will be investigated as a function of system convective and stratiform areal coverage. Temperature and humidity profiles from nearby GPM-constellation microwave sounders and coincident radiosonde launches will be used to understand the composite relationship between temperature, moisture and diabatic heating profiles as a function of stratiform area (which is related to system lifecycle stage). Commonalities and differences in organized systems in the tropics versus the mid-latitudes will serve as important benchmarks for the development of the organized-stratiform component of a mesoscale convective parameterization in the NASA GISS GCM. Analysis will focus both on differentiating pre-development environments that are favorable and unfavorable for organization, and post-development environments that affect the lifetimes of the clusters that develop.

We will also examine the structure and evolution of clouds and precipitation in warm and cold season midlatitude synoptic storm systems in two ways. First, we will compare statistics of GPM DPR dual-frequency surface snowfall vs. rainfall frequency and amount to similar statistics from the GISS GCM for several winters and test the sensitivity of these statistics to assumptions about mixed-phase processes made in the GCM microphysics parameterization. Second, we will perform and analyze GCM hindcasts

initialized by analysis products to evaluate sources of GCM shortcomings in the simulations of precipitation in these storms. We will first analyze existing global Fall 2009 hindcasts performed previously as part of the Year of Tropical Convection MJO intercomparison. Midlatitude synoptic storms will be identified using an existing midlatitude storm identification and tracking algorithm and the hindcasts analyzed to see whether their dynamics intensifies as it does in the analysis, and if so, whether the precipitation that develops is consistent with the TRMM Multi-Satellite Precipitation Analysis rain product. We will then perform similar hindcasts for the GPM era initialized by MERRA-2 and compare modeled and DPR-observed precipitation amounts and phase for the cold and warm front regions, for the cold conveyor belt region north and west of the low, and for cold air outbreak clouds in lake-effect snow situations.

Stephen Durden/Jet Propulsion Laboratory
GPM DPR Algorithm and Product Validation Using APR-2 Field Campaign Data

The Airborne 2nd Generation Precipitation Radar has participated in numerous NASA field campaigns, most recently GCPEx and SEAC4RS. Data from these campaigns have been used by a variety of investigators to develop and test algorithms for GPM DPR and combined algorithms, as well as for studies of various atmospheric processes, including microphysics and hurricane structure and intensification. APR-2 will also collect data during the OLYMPEX GPM-sponsored field campaign planned for fall of 2015. This proposal will address both relative and absolute calibration of GPM by direct and statistical comparison of GPM sigma0 and reflectivity with measurements from APR-2 and satellite scatterometers and altimeters. The validation of the GPM precipitation products uses a two-fold strategy. Where possible, we plan to do a direct/statistical comparison of GPM products with APR2 retrievals. We also plan to carry out a physical validation strategy, whereby the assumptions in GPM DPR retrieval algorithms are evaluated.

James Famiglietti/Jet Propulsion Laboratory
Precipitation Measurement Mission for Improved Forcing in Hyper-Resolution Land Surface Models

Here we propose to explore the impact of precipitation forcing accuracy and resolution on land surface model simulations. The relevance of hydrology simulations for water resources and disaster management is entirely dependent upon the scale at which reliable information can be produced. This scale in turn depends on the quality and resolution of the hydrometeorological forcing used to drive the simulations. In this research, we aim to supplement the next generation of land surface models, at 'hyper-resolution', by creating and demonstrating the next generation high-resolution precipitation forcing based on Precipitation Measurement Mission observations.

The proposed research is in direct response to research category 2.3 of the PMM NRA - specifically, we target the "development and implementation of downscaling of satellite

precipitation information for hydrological modeling and prediction", and the "development of metrics and methodologies for assessing satellite precipitation products in hydrological applications".

First, we will develop a new approach to blend the PMM observations into an existing dynamical downscaling methodology. The results of this blending approach will be used to quantify the improvements in precipitation generated by the addition of PMM products. Then, we will use the downscaled precipitation estimates to support work towards a new frontier in the hydrological sciences, namely the development of 'hyper-resolution' (~1-km or higher) land surface models over large study domains. The impact of improved precipitation forcing will be tested through a sequence of 1-km model simulations over two study regions: the Southwestern United States and Japan. Model outputs will be compared to in-situ observations for validation and determination of simulation improvement due to the inclusion of PMM products, for variables such as soil moisture, latent heat flux, snow formation and runoff generation.

This research addresses several key Earth Science Research needs: (1) It enables better assessment and management of water quantity to accurately predict how the global water cycle evolves in response to climate change. Specifically, this is addressed by creating a framework for the improvement of land-surface model simulations by improved meteorological forcing in order to better represent hydrologic processes in climate models. (2) It improves the capability to predict weather and extreme weather events using land surface models, namely the hydrologic extremes associated with flood generation, which require high-resolution model simulations and appropriate atmospheric forcing to simulate accurate precipitation partitioning and runoff generation. (3) It furthers the use of Earth system science research to inform decisions and provide benefits to society, specifically by making land surface model simulations more relevant and accurate at the scales of water management.

Ralph Ferraro/National Oceanic and Atmospheric Administration, NESDIS/ORA NOAA's Continued Contributions to the Development and Utilization of NASA's GPM Products

The successful launch of the GPM core satellite and commencement of routine production of GPM Day-1 products provide a great opportunity for NOAA to improve a wide array of its operational products and services, ranging from severe weather / flood warning, weather forecasting, climate monitoring and water resources management. The NOAA GPM team intends to continue their contributions to the NASA GPM in the next several years in the development, enhancement, and utilization of the GPM products in support of NASA objectives whiles also fulfilling NOAA's mission to understand and predict changes in climate, weather, oceans and coasts. Specifically, we propose to:
• Collaborate with GPM GV activities to improve our understanding of precipitation processes and develop better QPE products using the IPHEX field observations and improve NOAA radar-based snowfall rate estimates for GPM product validation;

• Participate in GPM Level 1, 2, 3 algorithm development, emphasizing the development of snowfall rate retrieval algorithms, exploration of the direct broadcasting capability of the Level 2 products, and improving the Level 3 IMERG product;
• Enhance the GPM Level 3 merged satellite precipitation products through multi-sensor fusion with gauge observations, radar estimates and numerical model forecasts; and
• Improve NOAA operational weather forecast models (data assimilation), hydrometeorological nowcasts and forecasts, and climate data record (CDR) products with GPM radiance and precipitation products.

The proposed activities will be no cost to NASA. NOAA will contribute over $1.7 million per year in resources (to support scientific support staff and new infrastructure) and in-kind support (FTE time of its scientists, infrastructure already in place or planned through current and emerging NOAA programs) to the effort.

Robert Field/Columbia University
Applying NASA Satellite Precipitation Products to Global Fire Prediction: Assimilating GPCP, TRMM and GPM into the Global Fire Weather Database

Fire prediction involves estimating 1) moisture content of different classes of fuels in response to changing weather conditions, and 2) potential fire behavior if a fire were to start. In that regard, the Fire Weather Index (FWI) System is the most commonly used fire prediction system in the world. The FWI System has proven flexible enough for adoption in all of the world's fire environments. Because of its wide application and modest input requirements, it forms the basis for the GOFC-GOLD Global Early Warning System for Wildland Fires and the JRC's Global Wildfire Information System.

To support FWI-based research and management, we have developed the Global Fire WEather Database (GFWED, http://data.giss.nasa.gov/impacts/gfwed/). It uses measurements of daily precipitation, and surface temperature, relative humidity and wind speed. It currently uses only global gauge-based estimates of precipitation and MERRA estimates of the other input parameters.

Incorporation of GPM and TRMM precipitation estimates would represent a significant advance to the development of GFWED. The objectives of this proposal are to:
- Assimilate GPCP, TRMM and GPM precipitation estimates into the calculation of the Fire Weather Index and its sub-components.
- Compare the satellite precipitation-based FWI calculations to those based on conventional calculations from gauge estimates.
- Determine the extent to which these approaches can separate areas and periods of low and high fire activity.

We will add the functionality to calculate FWI System components from satellite precipitation estimates in the GFWED development framework. We will compare the different FWI calculations over representative fire-prone regions where fire is known to be fuel-moisture limited and where TRMM and GPM estimates exist. Candidate regions

are the Brazilian Mato Grosso, east-central Africa, the Upper Mekong, western Indonesia, southeast Australia, southern Europe, and the western US. Finally, we will compare the relationships between regional fire activity and FWI System components computed conventionally and from satellite precipitation estimates. For fire activity, MODIS active fires and Global Fire Emissions Database (GFED) estimates will be our starting point, supplemented by data from VIIRS, SEVERI and the anticipated SLSTR.

GFWED is the first community dataset of its kind and the response has been very positive. The data is available through the NASA Center for Climate Simulation Dataportal, the Columbia University International Research Institute for Climate and Society (IRI) Data Library. Different groups worldwide are now using it to understand fire weather controls on fire occurrence, large-scale atmosphere-ocean controls on fire weather, for calibration of prognostic fire prediction models, and for interpretation of the GOFC-GOLD and JRC global fire prediction systems. As an important application of NASA's satellite-based precipitation estimates, fire prediction lies at the intersection of the water and carbon cycles.

NASA Earth Observations of fire activity, land cover change, and atmospheric composition are central to understanding the role of fire in the Earth System. Continuing with that heritage, the perceived significance of our proposed work is that the community will benefit from any improvement in GFWED that results from assimilating NASA satellite precipitation data.

This is a companion proposal to one recently submitted to NASA ROSES NNH15ZDA001N-SUSMAP called "Global Fire Prediction: Assimilating SMAP soil moisture retrievals into the MERRA-based Global Fire Weather Database". The proposed work is separate, but much of the background material is taken from that proposal. Both proposals are part of an effort to continue GFWED development and application, making use of the cutting edge in satellite data.

Efi Foufoula-Georgiou/University of Minnesota
Advanced Inversion Algorithms for GPM Passive Microwave Retrievals and Multi-Sensor Merging

Accurate precipitation retrieval over land is of paramount importance in the GPM era for better understanding the water cycle, climate, weather, and improving hydrologic modeling and prediction, including extremes and hazards. It is also one of the main challenges in transitioning the success of TRMM to GPM.

The overarching goal of the proposed research is to develop state-of-the-art algorithms for accurate and robust multi-sensor retrieval and merging of precipitation over radiometrically complex land surfaces using the GPM constellation of satellites. The specific objectives are: (1) Improve passive retrievals of precipitation, especially over coastal zones, shallow orographic effects, and snow-covered land surfaces; (2) Develop a new combined variational formalism for simultaneous retrieval and optimal merging of

multi-platform active-passive precipitation measurements; (3) Explore new approximation methodologies to construct compact but representative a-priori databases for improved retrievals, especially over land; and (4) Validate and calibrate the results of the developed algorithms using a suite of GPM ground validation data and other reference precipitation products.

Our methodologies rely on new fundamental theories of sparse and low-rank approximations for Bayesian inverse problems, which have already been demonstrated to yield unprecedented accuracy in recovering natural signals from multiple noisy and under-sampled observations. We will devote special effort in better understanding the background signals of radiometrically complex land surfaces on all GPM channels and properly discriminate them from precipitation signatures. Given the dynamic nature of the land surface cover, we will explore new objective land surface classification methodologies which depend minimally on external ancillary data to stratify the a-priori database for making the retrievals consistent with the geophysical states of the underlying land surfaces. The multi-sensor combined algorithm will explicitly accommodate multiple physical/observational a-priori databases and account for correlated errors not only among multiple radiometers/databases but also across different channels--by adopting variational principles and advanced regularization techniques. Finally, we aim to jointly estimate a compact set of "basis elements" of rainfall spectral signatures and their associated rainfall profiles over different earth surface conditions, which can form the elementary building blocks of improved physically-based databases.

The proposed research contributes to the GPM research category "algorithm/product validation and enhancement". Its major scientific and operational significance is summarized as follows. 1) Our modern Bayesian inversion and regularization techniques, warranty that the accuracy of our retrievals can go beyond what is possible with currently used standard inversion techniques and allow more accurate retrievals of both low and extreme precipitation values from either observational or physically-based databases. 2) The incorporation of non-diagonal geophysical error covariance matrices of the GPM constellation of radiometers can provide instrumental feedback to the GPM radiometer team for improvement of the operational retrieval skills. 3) Our research on characterizing and discriminating microwave background surface contamination from the precipitation signal promises improved retrievals over coastal and snow-covered mountainous areas for extended hydrologic forecast skills. 4) Construction of compact and representative physically-based a-priori databases by narrowing down to only a few fundamental precipitation profiles and their spectral signatures, promises increased accuracy and computational efficiency of retrievals.

Mircea Grecu/Morgan State University
Improved Radar Models and Parameterizations for the GPM Combined Algorithm

The operational GPM Combined Algorithm (CMB) has been designed to reduce uncertainties in precipitation retrievals by effectively incorporating complementary information from the GPM radar and radiometer observations. Its application to the first

16 months of GPM data and the analysis of results revealed that, although the algorithm performs satisfactorily, improvements can be achieved through more accurate physical and statistical modeling. Among the areas of improvements, the quantification of Multiple Scattering (MS) effects and the parameterization of Non-Uniform Beam Filling (NUBF) in radar observations is of paramount importance in reducing uncertainties in the retrieval of convective precipitation (especially overland). A one-dimensionl multiple scattering model and a crude NUBF parameterization have already been implemented in the combined algorithm by the PI. However, the joint impact of MS and NUBF effects have not been thoroughly investigated and mitigated yet. Moreover, MS effects have been found to be occasionally significant even at Ku-band.

We propose the enhancement of the current GPM combined algorithm through the implementation of Ku-band radar profiling procedure that accounts for potential multiple scattering effects at Ku-band and the implementation of improved parameterizations to account for non-uniform beam filling and 3D effects in both Ku- and Ka-band radar observations.

Primary objectives of our proposed research are to implement an improved Ku-band radar profiling algorithm and more accurate non-uniform beam filling and multiple scattering parameterizations accounting for 3D effects in the GPM combined algorithm. These objectives will be achieved through:
1. The development of an optimal estimation methodology to account for potential MS effects in Ku-band observations. That is, explicit MS calculations will be carried out at Ku-band and an iterative procedure will be developed to incorporate the Ku-band MS calculations in initial ensemble of Ku-band retrievals used in the combined algorithm;
2. The quantification and parameterization of 3D effects in multiple scattering calculations by evaluation of the 1D MS model used in the operational combined algorithm against a more accurate 3D (but operationally impractical) MS model;
3. The use of GV and field campaign radar data to quantify NUBF effects in GPM combined retrievals and the extension of the current (empirical) Monte Carlo methodology to mitigate such effects.
4. The evaluation of entire set of proposed models and parameterizations through sensitivity analysis and direct comparison of combined retrievals to GV products.

The proposed work falls with the "Algorithm/Product Validation and Enhancement" category of the research call.

Ziad Haddad/Jet Propulsion Laboratory
Parametrizing the Non-Linear Beam-Filling and the Multiple-Scattering for the GPM Radar, and Assimilating Sounder Observations into WRF

The "non-uniform beam filling" (NUBF) problem has received much attention in the context of retrieving instantaneous rain amounts from radar measurements because of the non-linearity of the relation between the amount of rain and the signature it leaves in the received echo signals. The non-linearities convert additive white uncertainty into biases

in the measured quantities, and the accuracy of any estimate of the biases depends on how detailed a description one can use of the underlying non-uniformity. The first portion of this proposal is to characterize this non-uniformity in a very similar way to the treatment of Hydrometeor-Size-Distribution variability, by parametrizing it. This will allow one to retrieve a pair of non-uniform-beam-filling parameters along with the precipitation variables, from DPR reflectivity profiles and integrated attenuation estimates, with or without coincident GMI brightness temperatures. It would also give the option of not retrieving the NUBF parameters, but at least averaging over their a-priori values (from ancillary or archival data), in order to avoid the NUBF-induced bias.

Another major source of uncertainty in interpreting simultaneous Ku- and Ka-band radar reflectivities is multiple scattering. The second portion of this proposal is to parametrize the dependence of successive orders of scattering on the underlying single-scatter reflectivity factors. We propose to do this from a data set of forward simulations with resource-intensive but correspondingly realistic representations of the multiple scattering. The parametrization will allow an iterative estimation of the underlying single-scatter reflectivity factors, which can subsequently be treated as is done in existing current algorithms to retrieve the precipitation variables.

The first two portions of the proposal, parametrizing the beam-filling and the multiple-scattering, address retrieval algorithm problems in a way that improves the retrievals. The third portion of the proposal is to extend our approach to assimilate TMI radiances over precipitation to the case of the mm-wave radiometers of the GPM constellation, whose frequent observations hold much promise if one were able to interpret them sufficiently accurately over precipitation (where the scattering signatures at these high frequencies vary a great deal with the unknown hydrometeor properties) -- and yet the observations themselves are readily recognizable to the naked eye with regards to the presence, localization, depth and intensity of convection. Our assimilation appraoch in the case of TMI would be very well suited to this case, and we propose to adapt it and specifically account for the competing effects of water vapor and condensed water, with the help of a background ensemble forecast from a cloud-resolving model.

Gerald Heymsfield/NASA Goddard Space Flight Center
DPR Algorithm Improvement Using Airborne Radar Measurements

This proposal primarily focuses on algorithm/product validation and enhancement (Topic 2.1) and in the broader context the utilization of satellite/GV products for process studies and model development (Topic 2.2). The MC3E and IPHEx GPM Ground Validation campaigns have provided high-altitude ER-2 radar and radiometer data sets to address DPR algorithms. During MC3E, The HIWRAP Ku- and Ka-band radar flew along with the AMPR and CoSMIR radiometers. During IPHEx, the Cloud Radar System (CRS) at W-band, and the ER-2 X-band Doppler radar flew in addition to the MC3E payload. The proposed effort will use the HIWRAP multiple-wavelength (Ka/Ku-band from MC3E, W/Ka/Ku/X for IPHEx and upcoming OLYMPEX) measurements for improving the GPM DPR, GMI, and combined radar/radiometer algorithms for convection, stratiform,

and light rain. This effort will also include use of in situ aircraft microphysical data and ground-based polarimetric measurements to help support some of the physical interpretations on mixed phase precipitation. Previous work on examination of multiple scattering from hail in deep convection using Ka and Ku-band will be extended to more moderate convection and stratiform to determine what extent multiple scattering plays a role in less severe precipitation systems. The observational analysis will be augmented by a multi-frequency retrieval that includes multiple scattering. We plan to continue this close collaboration with the DPR and GMI algorithm developers on utilizing our results and data sets to improve the DPR, GMI, and combined algorithms.

Robert Houze/University of Washington, Seattle
Precipitation Processes over the Globe

TRMM and GPM have aimed to measure Earth's precipitation and provide physical understanding of the processes producing the precipitation. Great progress has been made on the first goal. However, much remains to be done in using the datasets to advance physical understanding. This proposal focuses on achieving physical understanding of the most important of Earth's precipitation processes. We will use a comprehensive resource of NASA data: the TRMM archive, the accumulating GPM dataset, ground validation field program data collected in OLYMPEX, and airborne data from GRIP to gain insight into the precipitation processes of Earth's major types of precipitation systems: convective systems, frontal systems, and tropical cyclones. These analyses will not only improve basic understanding of the precipitation mechanisms in these storm types but provide a basis for improving algorithms for TRMM and laying the groundwork for advanced numerical modeling of cloud systems in all latitudes. For all three storm types, emphasis will be on how precipitation processes are affected by passage over mountains and coastlines. The convective studies will build on previous work on the global distribution of the nature of convection. The methodology will use the TRMM and GPM radar data to identify shallow isolated convection, deep intense convective cores, wide intense convective cores, and broad stratiform areas. These features represent convection in different stages of development, and the global distribution of these entities will indicate how convection in different forms is distributed over land, ocean, coasts, mountains, arid regions, rain forests, etc. The analysis will extend examination of convection in the TRMM latitude domain to determine if and how the forms of convection manifest differently at higher latitudes. The analysis of convection will be global, but with special focus on mountain regions, monsoonal coastal zones, the Amazon, the Maritime Continent, China, and the U.S. Great Plains. Special effort will be on distinguishing different types and forms of stratiform precipitation and how identifying them more precisely will impact latent heating algorithms. The frontal studies will concentrate on atmospheric river systems over the oceans and mountainous coastal regions. Analysis of OLYMPEX will be done as basic physical validation for Pacific frontal systems approaching and passing over the Olympic Mountains. Prefrontal, frontal and postfrontal precipitation processes will be examined upstream over the ocean, on the windward side of the mountains, and on the leeside. The entire GPM radar dataset will be used to analyze the effect of atmospheric rivers on the global water budget. To round out

the examination of all storm types, a small part of this study will be directed at tropical cyclones. Airborne radar data from the GRIP field program will be used as a validation study to determine how down-looking radars similar to those on the TRMM and GPM satellites sense the precipitation in a rapidly intensifying tropical cyclone and how the eyewall and rainband precipitation is modified over mountains during landfall. Thus, the proposed research will be a holistic examination using NASA data to advance knowledge of the precipitation processes and how they are distributed on Earth. Thus, GPM will be providing not only precipitation amounts but also insight into the nature of how precipitation is produced, so that models can eventually calculate precipitation amounts for the correct physical reasons over the whole globe. As such, this research addresses central PMM objectives, which include: using both satellite and ground validation measurements to better understand the global water cycle, weather, and climate; integrating information from multiple types of instruments and platforms; and conducting studies in a way that will help to improve satellite algorithms and lead to better model representations of precipitation processes.

George Huffman/NASA Goddard Space Flight Center
Extending the IMERG Multi-Sensor Level 3 Precipitation Product Across the TRMM-GPM Era

We propose to continue to support PMM with comprehensive science algorithm development, implementation, maintenance, and validation, including user support, for the current and legacy quasi-global combined-satellite precipitation estimates at fine time/space scales, both in near-real and post-real time. This work continues the key product concept in PMM of combining all available precipitation estimates to provide a "best" estimate, for which the current algorithm is the Integrated Multi-satellitE Retrievals for GPM (IMERG), and the legacy algorithm is the TRMM Multi-Satellite Precipitation Analysis (TMPA). The investigator's research team in the GSFC Mesoscale Atmospheric Processes Laboratory has had comprehensive responsibility for this line of products since their inception well over a decade ago and the PI currently leads the PMM Multi-Satellite Algorithm Team. These data sets fill critical needs in the broader scientific and user communities by providing straightforward access to a long archive of state-of-the-art estimates at a variety of latencies.
Specifics include:
1. Support for the legacy Version 7 TMPA systems until IMERG is retrospectively processed into the TRMM era to provide continuity for data users (currently planned for mid-2017).
2. Comprehensive development and support for the U.S. GPM multi-satellite algorithm, IMERG, starting with close involvement in the retrospective processing into the TRMM era, analysis of this new long record, and continued development for a Day-2 algorithm that builds on lessons learned and implements features that were not sufficiently mature for use in the Day-1 algorithm. We plan to continue close interaction with the CMORPH and PERSIANN developers, who are key contributors to IMERG as a unified U.S. algorithm.

3. Leadership for the PMM Multi-Satellite Algorithm Team to coordinate and focus expertise that is spread across the PMM Science Team.

4. Continued exemplary contributions to the Science Team, PPS, GV, Applications, and other meetings, advisory panels, and other groups needed to make TRMM and GPM successful, as well as continued outstanding user support for our products.

5. Analysis with the TMPA and IMERG data sets to provide scientific insight into: a) statistical descriptions of precipitation at sub-daily and longer time scales as a function of season, region, ENSO status, etc., including the analysis of extreme rainfall and diurnal variations; b) the synoptic-scale modulation of precipitation events by the dominant synoptic scale variations in atmospheric flow; and c) data homogeneity and model-observation differences that impinge on our understanding of global climate variations.

W. Linwood Jones/University of Central Florida
Inter-Satellite Radiometric Calibration (XCAL) for GPM Constellation

This proposal from the University of Central Florida, Central Florida Remote Sensing Laboratory (CFRSL), in collaboration with Data and Image Processing Consultants (DIPCON), is to conduct analytical cross-calibration techniques for cooperative satellites within the multi-satellite Global Precipitation Mission (GPM) constellation. The objective is the refinement of methodologies for the inter-calibration of brightness temperature radiance measurements from passive microwave radiometer sensors, which supports the PMM science team NRA call for scientific investigations related to development, evaluation, and validation of TRMM and GPM retrieval algorithms: 2.1 Algorithm/Product Validation and Enhancement - Development of methodologies for the intercalibration of measurements from microwave sensors.

Our research objective is simple: GPM will reduce errors in global rainfall estimates associated with temporal/spatial sampling by using a constellation of satellites. In order for the merged product to be satisfactory, the rainfall retrievals from each instrument must be consistent with the others; and this begins with the basic sensor radiance measurements (brightness temperature, Tb). Fundamental to this concept is the existence of the GPM observatory (with GMI) in non-sun-synchronous orbit, which serves as a radiometric transfer standard for the other passive microwave sensors on cooperative constellation satellites.

This proposal builds upon our previous PMM science team experience with the Inter-satellite Calibration Working Group (X-CAL). We will continue to provide an on-orbit assessment of systematic calibration errors (to an accuracy of order 0.1 K) as a function of instrument and satellite parameters e.g. critical instrument temperatures, solar beta angle, and spacecraft attitude. The calibration error sources and their root causes will be identified, and appropriate radiometric calibration correction algorithms will be developed. This activity provides critical radiometric bias tables for the constellation radiometers in support the GPM sensor algorithms maintenance for the Precipitation Processing System.

The primary objective of this proposal is to extend previous X-CAL results by conducting comprehensive pair-wise inter-satellite radiometric comparisons between the GPM Microwave Imager (GMI) and constellation member radiometers (both imagers and sounders). A significant part of this research is the XCAL between the previous radiometric standard (TRMM Microwave Imager, TMI) and the new standard, GMI. Since the launch of GPM (Feb 2014) and the on-orbit checkout of the GMI (~60 days thereafter), CFRSL has been an active participant in this activity, and we now have preliminary analysis of one-year of inter-comparison with TMI. However, evaluation of GMI is an on-going process to assess its on-orbit radiometric stability continuously with other satellite radiometers. While the TRMM mission has now ended, we are fortunate to have the WindSat, with which CFRSL has established over one-decade of XCAL with TMI. Results have shown the relative calibration stability between these two sensors has been of order < 0.1 K for over one-decade. This implies that both sensors are radiometrically stable within this uncertainty bound. Therefore, we propose to continue WindSat/GMI XCAL to link the future radiometric calibration of the GMI constellation to the past 18 years of the TRMM precipitation data products. Moreover, we plan to incorporate lessons learned from recent TMI Deep Space Calibration Maneuvers (May 2015) to refine the TMI brightness temperature product 1B11 version-8 for the TRMM archival dataset.

Eugenia Kalnay/University of Maryland, College Park
Further Advances on Effective Assimilation of Precipitation with GPM and TRMM

Abstract:
In our previous proposal we introduced a method to address the problem that has plagued the assimilation of precipitation: the model rains as observed until the assimilation ends, and then it "forgets" the precipitation assimilation and after a few hours, returns to the original forecast. Our proposed approach is based on 1) Use of an Ensemble Kalman Filter (the LETKF) which modifies all the model variables (including potential vorticity), not just the moisture and temperature in the vertical column, as done in current systems. This update of dynamic variables should make the model "remember" the assimilation of precipitation during the forecast. 2) The LETKF, like all data assimilation methods, assumes that the observation errors are Gaussian, which is false for precipitation. To address this we proposed to use a Gaussian Transform on both the rain observations and the model precipitation. We showed in Lien et al (2013, Tellus) with a perfect model OSSE that the new approach of assimilating precipitation was very successful, achieving for the first time a significant improvement in the 5-day forecast. We then assimilated TMPA real precipitation with a low resolution NCEP/GFS model, and found that the model and the observations have very different statistics, but that assimilating precipitation also improved the 5-day forecast for all variables and all regions of the world (Lien et al., 2015a, 2015b, MWR, under revision).

After these successful results we applied Ensemble Forecast Sensitivity to Observations (EFSO, Kalnay et al, 2012, Hotta et al. 2015, to be submitted in July 2015 to MWR) to determine whether each TMPA observation improves the analysis or makes it worse. The

first experiment showed that 1) The Gaussian Transform works much better than all the alternative methods of No Transform, No Assimilation of rain, and Assimilation with the widely used Logarithmic Transform; b) The TMPA observations were more useful reducing forecast errors over the ocean and less useful over land, especially over regions of low precipitation.

We propose to extend our initial successful results in several ways so that at the end of three years the system for effective assimilation of IMERG precipitation will be ready for operational testing for implementation. The tests we will perform include: a) Use IMERG and compare with TMPA. b) Use a higher resolution GFS model with assimilation of current observing systems. c) Test using a Gaussian Transform for the model precipitation based purely on the ensemble. d) Assimilate precipitation in hurricanes, using GPM radar observations, to test whether the track and intensity forecasts are improved. e) Implement EFSO and Proactive QC to assimilate the optimal set of IMERG observations. f) Compare the impact of assimilating early IMERG with final IMERG estimates. g) Understand why the TMPA observations are found (using EFSO) to be more useful over ocean than over land, and whether this is related to convective precipitation. h) Explore whether using lightning information can improve the assimilation of convective precipitation. i) Use EFSO to estimate IMERG/TMPA observation errors.

We will also collaborate with the team at RIKEN, Japan, led by Prof. Takemasa Miyoshi, which will perform similar data assimilation of the Global Satellite Mapping of Precipitation (GSMaP), a product analogous to TMPA. This team will use the Nonhydrostatic Icosahedral Atmospheric Model (NICAM). This should provide useful comparisons of TMPA and GSMaP and the methodologies used.

Christopher Kidd/University of Maryland, College Park
A Physically-Based Scheme for the Retrieval of Precipitation from Cross-Track Sensors in the GPM Constellation

The retrieval of precipitation from all available Earth observations sensors is critical to achieve the spatial and temporal sampling required to capture and represent the precipitation across the Earth's surface. The Global Precipitation Measurement mission Core Observatory provides a keystone in the cross-calibration of observations and precipitation retrievals for a host of constellation satellites. The current GPM constellation includes not only 6 conically-scanning (CS) passive microwave (PM) radiometers, but also 6 cross-track (XT) PM radiometers, therefore the inclusion of precipitation estimates from the latter play a crucial role in providing comprehensive observations.
An initial version of a physically-based retrieval scheme for the XT sensors has been developed and is currently implemented for the operational production of precipitation products at the Precipitation Processing System at NASA's Goddard Space Flight Center. The scheme is built upon the Goddard Profiling scheme that is used for retrievals from CS observations, but with modifications to account for the XT characteristics of the

instrumentation. At the heart of the GPROF scheme is the database that is used as a reference to select comparable atmospheric profiles to those being observed by the sensors; the CS database is built upon a set of actual observations matched against surface/satellite reference data together with profiles from NASA's Multi-scale Modeling Framework (MMF). Initial testing of the XT scheme implementing a similar database structure revealed problems with the representativeness of the database that resulted in significant regions of 'missing' retrievals. Consequently, the current version of the database for the XT retrievals rely solely the MMF model to generate the database entries, although the final database is bias-corrected against the CS database to ensure consistency across the different instruments.

Initial comparisons of retrievals from both the CS and XT sensors has been carried out over the US and Western Europe. These results show that the XT results are comparable with the results from the CS results. Indeed, in many cases the XT retrievals perform better than the CS retrievals when considering correlation and root mean squared error statistics. However, the XT performance is slightly less well in terms of skill score due to poorer detection, but better false-alarm occurrences.

Therefore, this project aims to build upon the success of the XT MMF-based database scheme to further refine and improve precipitation estimates from these sensors. In particular, the proposed project will include addressing the following issues:
i) testing and evaluation of the current MMF-based retrieval scheme to identify situations where retrievals differ from the CS scheme and other precipitation products; causes of the discrepancies will be investigated and feed back to the MMF development;
ii) assessing and quantifying dependences of the retrieval scheme upon sensor-dependent characteristics. Scan position dependency is currently accounted for through post-retrieval correction; changes in earth incidence angle affect resolution, polarization and atmospheric path;
iii) representativeness of the single (all surfaces, all scan positions) database generated by the MMF model. Modifications include better MMF-observational comparisons, particularly with the GPM core satellite (GMI, DPR and combined) products; and,
iv) processing efficiency of the retrieval scheme, from the database generation, preprocessing system and the actual retrieval itself. In particular, can the database be adequately represented by fewer profiles without degradation in performance?

This research will contribute greatly to the overall aims and objectives of NASA's Precipitation Measurement Mission by providing precipitation estimates from operational instrumentation and to the wider scientific community.

Min-Jeong Kim/Morgan State University
All-Sky GPM Microwave Imager (GMI) Radiance Data Assimilation Global Products from the GEOS-5 System in Support of the GPM Mission

We propose contributions to the PMM science team by developing (1) global modeling and assimilation methodologies to utilize all-sky GMI radiance data in the Goddard Earth Observing System (GEOS-5) 4D-EnsVar atmospheric data assimilation system (ADAS),

(2) prototypes of all-sky GMI radiance data assimilated global atmospheric and surface analysis products and (3) global downscaling methodologies to produce fine scale precipitation products based on GEOS-5 analyses that actively assimilate GMI radiance data, along with millions of other satellite and conventional observations currently utilized to produce near real time global weather forecasts at the NASA Global Modeling and Assimilation Office (GMAO). This effort builds upon an ongoing, funded research project at the GMAO to assimilate cloud- and precipitation-affected satellite radiance data in GEOS-5 system. These proposed developments will extend the existing assimilation framework for all-sky GMI radiance data over the ocean to all-sky GMI data over land by enhancing methodologies to consider surface contributions properly in the observation operator during the analysis process so that information from GMI observations can be projected in the analysis to improve precipitation forecasts over land.

It is expected that assimilating the GMI all-sky radiance data will improve the GEOS-5 atmospheric analyses and will complement GEOS-5 land surface analyses. The GMI instrument's wide range of frequencies will improve GEOS-5 precipitation analysis and forecasts, especially over land. The improved analysis of precipitation will enhance the inputs for the GEOS-5 land surface model, which simulates hydrological processes. The quality of land-surface model fields such as skin temperature, soil moisture and snow coverage are critical for maximizing the impacts of microwave radiance data on the atmospheric analyses. By leveraging GMI radiance data assimilation components that directly impact the atmosphere and land, we propose to investigate the development of GEOS-5-derived analysis products and downscaled precipitation products.

 The aforementioned efforts will support the original goal of the GPM mission to estimate global precipitation, validation of precipitation retrieval products, and applications in algorithm developments, while enhancing the GMAO's satellite data assimilation components in GEOS-5.

Dalia Kirschbaum/NASA Goddard Space Flight Center
A Regional Analysis Framework for Evaluating Satellite Rainfall Extremes in Complex Terrain for Landslide Hazards Applications

Extreme rainfall in steep, complex terrain is the primary trigger of landslides and flash floods in many parts of the world. Advances in regional hazard assessment and prediction have been limited, however, in part by the challenge of quantifying the relationships between the intensity, duration, and frequency (IDF) of extreme rainfall in such terrain. Rainfall estimates derived from TRMM and GPM offer a path forward due to the relatively long records and high spatial and temporal resolutions. Instead of focusing on individual events or on point/pixel-based analyses, we propose a regional analysis framework that examines large populations of storms using multiple satellite data sources. This framework will use a new technique to quantify biases and heterogeneities in rainfall extremes, facilitate the synthesis of regional extreme rainfall climatologies from multiple data sources, and provide more robust inferences about rainfall IDF relationships and how they relate to landslide triggers. The goal of the proposed work is

to better understand the characteristics of extreme rainfall in complex terrain and evaluate the limits of extreme rainfall estimates from satellites within the context of natural hazards. This regional analysis framework will be applied in three well-instrumented study areas to better understand how rainfall extremes vary within and across regions: Macon County, North Carolina; western Washington and Oregon; and Rio de Janeiro, Brazil, and is organized around three main objectives: 1) Develop regional-scale extreme rainfall metrics based on Extreme Value Analysis comparing TRMM, GPM and in situ/ground validation sources; 2) Synthesize the regional extreme rainfall climatology using satellite rainfall estimates (TRMM, GPM) and downscaled rainfall estimates from NASA Unified Weather Research and Forecasting (NU-WRF) within the RainyDay tool to generate high-resolution rainfall "scenarios" with realistic spacetime structure and associated recurrence intervals; 3) Analyze long-term regional-scale recurrence intervals and intensity thresholds for landslide triggering to establish metrics that help to characterize potential spatial discrepancies in satellite-based estimates of rainfall extremes across complex terrain as they relate to observed hazard events. This work is directly responsive to Section 2.3 of the proposal call, "Methodology development for improved applications of satellite products" and will leverage both TRMM and GPM satellite products as well as GPM Ground Validation field campaign and other in situ information to establish a new regional methodology to examine rainfall extremes within these three topographically complex study regions.

Pierre-Emmanuel Kirstetter/University of Oklahoma, Norman
A Research Framework to Bridge the Global Precipitation Measurement (GPM) Level II and Level III using Multi-Radar/Multi-Sensor (MRMS)

Objectives: The overarching goal of this research project is to leverage Multi-Radar Multi-Sensor (MRMS) quantitative precipitation estimation applications to provide a useful research framework for bridging CONUS-wide ground validation and TRMM/GPM algorithm enhancement. The research focus is on microphysics and precipitation error characterization by taking full advantage of the MRMS multi-scale precipitation information merged with GPM Validation Network and ground validation (GV) field study datasets (e.g., working from point-based microphysical profiles and rainfall measurements, site-based multi-frequency research radars, to CONUS-wide mosaicked radar network). Ultimately the research seeks to improve, in a self-consistent fashion, GPM retrieval algorithms for both Level 2 (e.g., retrieval algorithms) and Level 3 (e.g., IMERG) products. Tasks are:
1. Perform an in-depth comparison analysis between space radars TRMM-PR / GPM-DPR, combined GCI and MRMS under various regimes of performance. Complementary insight will be extracted by conditioning the analysis by respective MRMS-based and GPM-based algorithm assumptions and methods. We will check consistency regarding precipitation detectability, analyze the impact of small-scale precipitation variability and evaluate the reflectivity attenuation correction algorithms applied to space radar data. Comparison of 3-D precipitation structures, microphysical properties (hydrometeor types – e.g. hail, snow-, particle size distribution), and surface precipitation between ground-

and space-based retrievals will improve understanding and quantification of precipitation processes.

2. Perform an in-depth comparison analysis between space-borne radiometers TMI, GMI and other constellation sensors and MRMS products. Aspects like precipitation detection, characterization and quantification will be addressed. The results of this error analysis will be compared to an equivalent analysis using the PR/DPR/GCI as a reference in the perspective of task 1. We will focus on the land surface state, which is critical for the new passive microwave algorithm for GPM. Future error analysis of GPM core and constellation satellites algorithms will target regional precipitation biases over different surface conditions (e.g. soil moisture, vegetation), surface precipitation type and phase (e.g. snow).

3. Bridge comparison analyses across the Level-2 GPM constellation and propagate to Level-3 precipitation products. Because satellite coincidences within a few minutes are rare, as a consistent reference MRMS is the ideal tool to bridge in-depth characterization across constellation sensors from the GPM core to the constellation, directly assessing the influence of surface types, precipitation properties and sampling properties among sensors. We will break down the error "components" from the individual Level-2 products and propagate these along through IMERG fully understanding the errors across scales, for a more realistic, dynamic and end-to-end error quantification. Major differences across scales conditioned on several physical factors contributing to erroneous retrievals will be quantified to properly target regimes and/or relevant precipitation physics required for analysis.

Relevance and Broader Impact: This proposal directly addresses the research category 2.1: Algorithm/Product validation and enhancement. It will leverage the accommodation and integration of MRMS dual-pol and GPM products, integrating various GV activities from field campaigns to national networks. The work is a larger multi-team effort designed to further cement the links between space and ground-based precipitation remote sensing so that synergistic physical validation and development of multi-sensor algorithms can proceed. The research represents components of a scientific framework for implementing meaningful GV activities to future missions doing precipitation monitoring and research.

Tiruvalam Krishnamurti/Florida State University
Two Decades of Variability in the Life Cycle of Asian Summer Monsoon Seasons as Seen from TRMM/GPM

The proposal falls in the category 2.3 of the proposal solicitation for the Precipitation Measurement Mission (PMM). Our specific interests are in the area of Methodology Development for Improved Applications of Satellite Products. A vast area, nearly 180 degrees longitude wide, of the tropics experiences a progress of monsoon through a life cycle from an onset phase to a withdrawal phase. That vast area can be studied in better detail using observations and modeling to address the transitions and variability of monsoon activity within a season and its variability over at least 2 decades using the TRMM GPM datasets and the modeling compliments. That is the goal of this proposal.

A host of recent studies have emphasized the variability of a number of features of the Asian summer monsoon that include regional precipitation, extreme rains, heights of cloud base, cloud populations and areas effected by deep and shallow clouds, the monsoonal link to the Arctic ice melt, atmopsheric moist rivers and imbedded streams of buoyancy, wet and dry spells and the monsoonal Hadley/Walker circulations. The currently available continuous datasets for precipitation estimates from TRMM and continuing on with GPM provides us with a unique opportunity to examine the monsoon variability for the two decades (1998 through 2017).

Our primary goal would be to address the variability of thermodynamical, dynamical, hydrological and cloud/precipitation features from one monsoon season to the next. The timing, duration and amplitudes of monsoon activity are known to vary from one year to the next. Issues such as an early or delayed onset, shorter or longer duration of each dry or wet spell, and an early or late withdrawal phase, are all influenced by a number of dynamical and thermodynamical factors. In this context we have already made an important start on the examination of the components of surface energy balance during these phases of the monsoon covering a few years.

In our proposed research we shall make use of a global model, (global WRF at a horizontal resolution of 25 km and 50 vertical levels) as the primary vehicle for assimilation and diagnosis of the different phases of the monsoon. The specific research areas will include: (1) Use of global physical initialization for rains and clouds (as inferred and composited from TRMM/GPM radar and CALIPSO and integrated within the model. (2) Variability of monsoon rainfall during the 20 years within the above phase transitions. (3) Vertical structure of clouds and precipitation as inferred by the TRMM/GPM radar and CLOUDSAT images for the 20 summer monsoon seasons. We shall find ways to include this information to improve the cloud radiation and the related surface energy balance during the phases within each season. (4) Examination of the variability of the components of the surface energy balance of a summer monsoon belt following Krishnamurti and Biswas (2006). This includes the surface radiation, and the surface fluxes of sensible and latent heat. This information is very important for the understanding of the variability within the phases of the monsoon from one year to the next. The TRMM /GPM datasets would be directly used to improve these computations of variability. (5) Treatment of the water balance of the monsoon for each of the phases of the monsoon season covering the 20 years. This would require reanalysis datasets, moisture profiling data from AQUA and the ocean state for the neighboring ocean basins from a mix of surface and space based estimates. Our procedure for computations would follow our previous studies.

The proposed study is very relevant to the objectives of NASA, the TRMM and GPM. It goes well beyond studies of Atlantic hurricanes to the vast reaches of the planetary scale Asian, African and Australian monsoon. Global precipitation datasets enable us to examine the tropics as well as the interactions of the tropics with the rest of the globe.

Mark Kulie/University of Wisconsin, Madison

Snowfall in the GPM Era: Assessing GPM Snowfall and Ice Microphysical Retrievals Using Independent Spaceborne and Ground-Based Observations

The Global Precipitation Measurement (GPM) mission has successfully collected the first combined microwave radiometer and dual-frequency precipitation measurements, including frequently sampling surface snowfall events in the extratropics. Since snowfall plays a vital role in the Earth's energetics and hydrology, evaluating and advancing GPM's snowfall detection and snowfall rate retrieval capabilities are high priority tasks to ensure high-quality GPM datasets. This project will therefore utilize precipitation retrievals from GPM and affiliated GPM constellation sensors, as well as independent spaceborne, modeling, and ground-based datasets, to conduct the following snowfall-centric tasks:

1. Create a GPM snowfall census and evaluate with independent datasets. A global GPM snowfall census will be created from Level 3 GPM products and rigorously compared to reanalysis (MERRA, ERA-Interim) and spaceborne observational (A-Train) datasets. This multi-dataset evaluation exercise will provide a holistic global snowfall perspective and identify possible systematic differences between independent datasets.

2. Investigate the combined radar and microwave radiometer response to different snowfall modes using GPM and independent observations. GPM, A-Train, SSMIS, and NEXRAD data will be used to study the multi-frequency microwave response to different snowfall modes. Preliminary results from pre-GPM datasets have identified regions where shallow convective snow is prevalent, yet this unique snowfall mode does not display systematic ice scattering signatures despite elevated surface snowfall rates. GPM and SSMIS datasets will be exploited in these same regions to assess the scattering signal – and potential increased information content – contained in higher frequency channels (e.g., GMI 166 GHz). GPM's GPROF precipitation retrieval performance will also be assessed in shallow convective snowfall regions, with special attention devoted to the sensitivity of GPROF retrievals to the a priori retrieval database employed.

3. Collect extended coincident ground-based radar and snow microphysical observations. Independent, multi-year ground-based Micro Rain Radar and Precipitation Imaging Package microphysical observations will be collected in a location that receives frequent snow from different snowfall modes. These observations, especially when combined with similar NASA field campaign datasets, will allow us to characterize systematic snowfall microphysical differences associated with unique snowfall modes. GPM microphysical retrievals will be improved through modeling and GPM retrieval evaluation exercises using these observational datasets.

The research activities outlined in this proposal closely align with the Algorithm/Product Validation and Enhancement component described in the PMM Science Team NASA Research Announcement. The proposed work will directly assess GPM precipitation retrievals at higher latitudes through evaluation activities and improve GPM precipitation retrievals via improved recognition of possible systematic retrieval deficiencies

associated with different snowfall modes, as well as improved snowfall microphysical representation in GPM algorithm components.

Christian Kummerow/Colorado State University
Entraining Large Scale Environmental Information to Improve the GMI Rainfall Product
The overall objective of this proposal is to quantify, understand, and potentially mitigate errors and uncertainties that are present in GPM's passive microwave rainfall retrieval algorithm. There are three fundamental issues that affect the algorithm performance that are not sufficiently well understood to implement at this time. They can be summarized as: Dealing with cloud/rain transitions and post-frontal precipitation over oceans; Dealing with regime dependent errors over land, and the specification of uncertainties. We propose to here to use the improved sensitivity of DPR to further investigate the relationship between cloud liquid water content and the onset of precipitation as a function of the large scale stability as obtained from GANAL as well ECMWF reanalyses and SPRINTARS derived aerosol concentrations. Likewise, we plan to use the improved DPR sensitivity to identify post-frontal precipitating cells which can be too small for the low frequency channels on GMI to observed to assess if hybrid approaches can be used over ocean if certain meteorological regimes are known to exist. Over land, aside from continuing to investigate statistical relationships between ice aloft and surface rainfall as a function of the large scale environment (including water vapor, CAPE and wind shear), we plan to focus much of the attention in this effort on orographic precipitation. This includes both rain and snow but because of the low information content of the passive microwave sensors alone, will look very carefully at coincident operational model data from NOAA's High Resolution Rapid Refresh model available in-house to improve overall precipitation estimates in mountainous regions. This work will rely heavily on validation data that will be collected during the Olympex experiment to constrain the total snow accumulation over the peninsula. The work will further leverage NOAA efforts that the PI is involved in focusing on the Colorado River watershed to estimate the best possible rain and snow accumulations from a combination of remote and in-situ observations in that basin. The final aspect of the proposal deals with uncertainties. Two very distinct uncertainties are addressed here. The first is the channel uncertainty that must be defined as part of the Bayesian algorithm. It encompasses both the sensor noise and the errors that are introduced by the forward model assumptions. The latter tend to dominate cloud and precipitation retrievals but are not well known. We address the channel uncertainty issue by experimenting with a number of approaches that have been suggested by the community and measuring the retrieval quality in a realistic but synthetic framework. The second problem deals with quantifying the uncertainties of the GPROF 2014 product. This requires careful consideration of not just the random errors (which can be obtained by properly specifying channel uncertainties), but also knowledge of meteorological regimes as these become the defining aspect at large time and space domains. We will seek to understand these regime dependent biases through the types of precipitation and large scale environmental forcings accompany them in an attempt to expand the results to a global framework.

Kwo-Sen Kuo/University of Maryland, College Park
Improved and Augmented Database of Hydrometeor Single-Scattering Properties to Support Algorithm Development

The key quantities in the retrieval of particulate matter by remote sensing means are the single-scattering properties (SSPs) of the particles involved. This fact has been incontrovertibly demonstrated by a radar-and-radiometer combined retrieval exercise carried out in current PMM-funded projects using field campaign observations, where SSPs obtained from synthetic ice aggregates constructed from realistic pristine crystals yield the best simultaneous agreement with all observations.

For hydrometeors exhibiting spherical symmetry, the fast and robust Mie solution may be used. Ice and melting hydrometeors, however, generally possess no symmetry to exploit and thus render Mie solution inapplicable. Due to its higher latitude coverage, the Global Precipitation Measurement (GPM) mission observe significantly more frequently these irregular hydrometeors than its predecessor, the Tropical Rainfall Measuring Mission (TRMM). However, obtaining the SSPs for irregular hydrometeors requires more sophisticated solution methods, such as those based on discrete dipole approximation (DDA) or generalized T-matrix.

In projects awarded in the previous funding cycle, we have 1) implemented an innovative ice crystal growth model to generate astoundingly realistic pristine ice crystals, 2) aggregated these pristine ice crystals to form snow aggregates, and 3) applied an open source DDA code, DDSCAT, to calculate the SSPs for both types of hydrometeors. Resulting from this effort is an extensive database of SSPs for nearly 10,000 ice hydrometeors at 15 microwave frequencies ranging from 3 to 190 GHz.

In the process, we have improved the ice crystal growth model by relaxing some of its original limitations and parallelized it with domain decomposition, using Message Passing Interface (MPI), to speed up the growth simulation and to obtain larger sized crystals. More notably, we have also domain decomposed using MPI the open source DDSCAT code. The improved version of DDSCAT is more efficient and capable of calculating SSPs for targets at least an order of magnitude larger, which is important for constructing fuller size distributions containing larger hydrometeors.

In addition, in order to obtain SSPs for realistic melting hydrometeors, a parallelized melting algorithm based on the Smoothed Particle Hydrodynamics (SPH) has been implemented and demonstrated using Graphical Processing Units (GPUs). This melting algorithm distinguishes itself from previous attempts in the following respects: 1) it is more amendable to parallelization and 2) it is explicitly physics-based. Thus, it will allow us to obtain more realistic melting hydrometeors in less time.

Furthermore, we have successfully implemented a parallelized version of the Invariant Imbedding T-Matrix (IITM) method for calculating SSPs. IITM employs a more analytical solution method than DDA and is also capable of handling arbitrary target geometry. We can now compare IITM and DDSCAT to perform cross validations of SSP calculations that have been lacking for irregular targets.

An important objective of this proposed project is to construct an improved version of the SSP database to better envelop the natural range of variations. The improvements will include:

1) Grow synthetic pristine ice crystals to the maximum size observed in nature.
2) Simulate the growth of naturally occurring polycrystals, e.g. bullet rosettes.
3) Generate larger and more diverse synthetic aggregates to mimic nature.
4) Mature the SPH algorithm to relax simplifying assumptions and simulate realistic hydrometeor melting.
5) Obtain the SSPs for all the synthetic hydrometeors.
An extensive SSP database derived from realistic hydrometeors is the prerequisite of our ultimate goal: To identify effective parameters, analogous to the medium volume diameter and shape factor for spherical hydrometeor size distribution, that characterize the scattering of ensembles consisted of diverse hydrometeors.

William Lau/University of Maryland, College Park
Organization of Tropical Convection and Relationship with Extreme Precipitation Events

The re-distribution of heat and water by precipitation and clouds associated with the organization of tropical convection is arguably the most fundamental atmospheric processes affecting weather and climate. The organization of tropical convection influences not only the occurrence of extreme precipitation events (EPE) in the tropics, but also EPE's outside the tropics, through atmospheric teleconnection. In spite of advances in understanding gained from a large body of past research, the organization of tropical convection, in relationship to diabatic heating processes and EPEs remains one of most challenging problem in atmospheric processes and climate research. According to IPCC Report (2013), the frequency occurrence of extreme precipitation events (EPE) with major adverse societal impacts is likely to increase in a warming world. The need to better understand organization of tropical convection and connections to, EPEs and their potential predictability have never been more urgent. The unprecedented rich array of rainfall data products, and modeling tools supported by the Precipitation Measuring Mission that includes the TRMM and GPM satellite mission, offer a great opportunity for the scientific community to tackle this challenging problem.

The objectives of the proposed research are to improve understanding of a) the organization of tropical convection, in terms of precipitation and cloud systems characteristics and relationships with extreme precipitation events (EPEs) in the tropics, and b) the contributions of organized convections through atmospheric teleconnection to occurrence and potential predictability of extratropical EPEs over the Pacific Northwest of the US. We plan to carry out data analysis using TRMM (1998-2014) and GPM (2014-present) data products, together with Cloudsat, and MODIS cloud regime datasets, and MERRA reanalysis, as well as observations from the pending PMM field campaign over the Olympic Peninsular (OLYMPEX). These data will also be used to validate numerical experimentations to explore the relative contributions of physical processes to MOTC and to test hypothesis using the NASA Multi-Model Framework (MMF) global model, and NU-WRF high-resolution regional model.

The proposed research is directly relevant to Research Category 3 in the PMM proposal call, i.e., The use of satellite and ground measurements for physical process studies to gain a better understanding of the global water cycle, climate, and weather and

concomitant improvements in numerical models on cloud resolving to climate scales. Because of the use of TRMM/GPM, GV and field campaign observations, and ancillary data from other sources, the proposed research will also contribute to Research Categroy 1 "Development, evaluation and validation of TRMM and GPM retrieval algorithms", particularly in evaluation and cross-validation with other datasets. Additionally, the use of MMF to simulate EPE's with state-of-the-art microphysics schemes will likely lead to improvement of microphysical processes in cloud-resolving models, that can be incorporated into global and regional forecast models to increase the skill of extending range weather and climate predictions.

Xiaowen Li/Morgan State University
Constraining the Ice-Particle Collection Efficiency Using TRMM/GPM Observations, Field Campaign Data, and Cloud Models with Explicit Bin Microphysics

Ice-phase microphysics play a crucial role in precipitation formation. Ice particle size distributions (PSDs) and their spatial and temporal variations are essential to many physically-based satellite precipitation retrieval algorithms, including those from the recently launched GPM core and its constellation satellites. Unfortunately, many ice-phase microphysical processes are poorly understood, and therefore poorly represented in models. This proposal aims at reducing one of the largest uncertainties in modeling ice-phase processes, i.e., the growth of particles through collision/coalescence.

Our previous studies have successfully used long-term TRMM observations to constrain various microphysical processes in a spectral bin microphysical scheme. In that study, ice-ice collection efficiencies stood out as the largest uncertainty. Collection efficiencies used in cloud models can sometimes differ by more than two orders of magnitude. There is an urgent need to understand the underlying physics and to constrain the collection efficiencies used in cloud-resolving models. Here we propose to extend our previous study to include both GPM DPR and GMI high-frequency channels (which are more sensitive to small particles), add more/better field campaign data (both radar and in-situ flight data), and use the improved 3-dimensional versions of the Goddard Cumulus Ensemble (GCE) and Weather Research and Forecasting (WRF) models with an updated spectral-bin microphysics scheme. We plan to focus on four field campaigns and their associated precipitation systems: MC3E (the US central Plains), DYNAMO (the equatorial Indian Ocean), IPHEx (Appalachian Mountains), and the upcoming Olympex (Olympic Peninsula). MC3E and DYNAMO have deep convection and extensive stratiform rain areas, which have been proven to be an optimal test bed for constraining ice collection processes. The uniform structure of stratiform regions allows for comparisons between model case studies and the long-term statistics derived from TRMM/GPM observations. IPHEx and Olympex have heavy topographic influences that result in steady airflow. They are also suitable for studying the ice collection process.

A spectral bin microphysics scheme is required in this study because it explicitly simulates PSDs and various interactions among different particle sizes. The Goddard

Satellite Data Simulator Unit (GSDSU) will be used to simulate TRMM/GPM observed signals using the modeled PSDs, phases, and effective densities to ensure fair comparisons. In addition, we will also carry out ensemble 2D simulations driven by the kinematic fields derived from the 3D dynamical simulations. The goal is to quantify errors introduced by uncertainties in related processes (e.g., ice innitiation, riming). These analyses can potentially help improving passive precipitation retrieval algorithms by quantifying the retrieval errors.

The specific objectives of this proposed study are:
1). To constraint the ice-particle collection efficiencies through detailed spectral bin microphysical simulations and long-term TRMM and GPM observations augmented by data from four field campaigns;
2). To quantify errors and uncertainty margins with sensitivity tests on known uncertainty factors, e.g., particle density assumptions, terminal fall velocities, uncertainties in simulated dynamics, and observation errors;
3). To provide improved, realistic vertical profiles of ice-phase particle size distributions over a wide range of systems and locations to facilitate GPM algorithm testing and development.

Liang Liao/Morgan State University
Rain and Snow Particle Size Distribution Models and Their Application to the DPR Retrieval Algorithm

An important goal of the Dual-frequency Precipitation Radar (DPR), aboard the Global Precipitation Measurement (GPM) core satellite, is to derive rain rate and snowfall rate by estimating parameters of the rain drop size distribution (DSD) and the snow particle size distribution (PSD). These distributions are often modeled by an analytical function. The inability of the modeled DSD/PSD to represent actual hydrometeor spectra and characterize their intrinsic variations in time and space lead to uncertainties in the estimates of precipitation rate obtained from the DPR. Understanding the uncertainties in precipitation estimation that depend on DSD/PSD parameterizations and scattering models of individual particles is important not only in evaluating the overall performance of DPR retrieval algorithms but also in gaining insight into ways to improve the algorithms.

We will first investigate uncertainties in the rain estimates from the DPR caused by differences between actual DSD spectra and the assumed model function. To do so, we will apply a comprehensive and qualitative evaluation procedure using measured DSD data. Several DSD models will be assessed, and the impact of the maximum diameter (Dmax) of the DSD spectra on the retrieval and DSD model selection will be investigated. With use of high-quality DSD data during past and future NASA-sponsored field campaigns, it is anticipated that our evaluation of DSD models will provide insight into choosing a DSD model that is most appropriate for the GPM DPR retrieval algorithm. To investigate the uncertainties in radar rain retrievals resulting from attenuation effects, the dual-wavelength radar profiling algorithms will be tested with the

reflectivity profiles simulated from measured DSD for the retrieval of the DSD and rain rates.

The proposed work will also focus on the estimation of snow microphysical properties and the associated bulk parameters such as snow water content and water equivalent snowfall rate. The aim of this study is to explore a suitable scattering model and the proper PSD assumption that accurately represents, in the electromagnetic domain, the micro/macro-physical properties of snow. A combination of the scattering databases that are computed from simulated aggregates for small to moderate particle sizes and validated simple scattering models for large particle sizes will more accurately characterize snow scattering properties over the full range of particle sizes. With use of single scattering results, new forms of the DPR-like snow retrieval look-up tables will be introduced. Sensitivity of the tables to the PSD and scattering models will be investigated to advance our understanding of DPR retrieval uncertainties. To aid in the development of the Ku- and Ka-band dual-wavelength radar technique and to further evaluate its performance, measurements of the snow PSD and fall velocity acquired from the Snow Video Imager/Particle Image Probe (SVI/PIP) and the Two-dimensional Video Disdrometer (2DVD) will be used. It is expected that a collection of long-term PSD data, fall velocities and information on particle mass spectra will provide an effective means for evaluating the DPR snow retrieval algorithm, and lead to an improvement of the snow retrieval algorithms.

To achieve accurate and physically consistent estimates of precipitation rate and equivalent water content throughout the hydrometeor's profiles, the normalized DSD/PSD-integrated scattering tables will be generated for rain, snow and melting layers. Implementation of accurate and physically consistent scattering tables into the DPR algorithms will improve the overall performance of DPR precipitation retrieval. Our proposed research is directly relevant to NASA Research Announcement Precipitation Measurement Missions (PMM) Science Team in the specific area of "Algorithm/product validation and enhancement".

Chuntao Liu/Texas A&M, Corpus Christri
Validation of GPM Precipitation Retrievals Under Different Precipitation Regimes Using Precipitation Features and Ground Validation (GV) Observations

The overarching goal of our research under NASA's TRMM, GPM, and PMM programs has been to understand the physical differences between different precipitation systems and quantify their effects on satellite estimation. One of the most valuable tools that has enabled our research group and collaborators to pursue physical process studies throughout the TRMM domain is the "U. of Utah" precipitation feature (PF) database, started at Texas A&M at the time of TRMM launch, and now residing on servers at both U of Utah and Texas A&M Corpus Christi. In the past 12 years, under the leadership of the PI, we have greatly expanded this database and shared it with the community. We place great importance on its further development and adaptation to the GPM era, as its

use is the underpinning of most of the research plans outlined in this proposal, both for ourselves, and in partnership with our many collaborators.

This proposal includes specific objectives that both expand and improve the PF databases, including additional properties of GPM PFs with information of DSD retrievals and GMI high frequency channels, and validation of GPM PF database with coincidence TRMM PFs during the overlapping period in 2014. Other science objectives require the extended use of these expanded TRMM/GPM PF databases around the world. The first will be a comprehensive analysis of the global distribution of extreme rainfall events on various time and space scales, and comparison with high quality coincident non-attenuating (S-band) GV radar databases. Others include assessment of the precipitation retrieval differences between precipitation radar and passive microwave observations, validation and improvement of latent heating retrievals, and participation in the OLYMPEX field campaign. As in most of our past work, these are all planned as collaborative efforts with other members of the U.S. and International PMM Science Teams.

Guosheng Liu/Florida State University
Building Algorithm Components for GPM Snowfall Retrieval

Launched on February 24, 2014, the GPM core observatory satellite carries a dual-frequency precipitation radar (DPR) and a multi-frequency microwave imager (GMI); the latter measures microwave radiation from the Earth at 13 channels with frequencies ranging from 10 to 183 GHz. In particular, the millimeter-wave channels (166 and 183 GHz) are specifically designed to detect and retrieve light rain and snow precipitation. Responding to the NASA PMM proposal call's topic on "validation and enhancement of radiometer retrieval algorithms for improved detection and estimation of light rain and falling snow over land and ocean in the middle and high latitudes", we propose continued research on building algorithm components for GPM snowfall retrievals. Built upon our previous research, we propose to conduct the following research in the next funding cycle:
(1) Basic studies for precipitation algorithm development. The main foci are: (i) Snow-rain separation. Since either radiometer or radar cannot separate between snow and rain pixels, it is necessary to use auxiliary data to identify snowing pixels from raining ones before actual retrievals are to be performed. We have been using long-term surface station data to develop a separation algorithm, the current version of which has been implemented in current GPM algorithms. Further refinement of the algorithm is underway. (ii) Scattering of nonspherical ice/snow particles. In developing physically-based precipitation retrieval algorithms, forward simulation of radar backscattering and radiometer brightness temperature is a necessary step. We have been building a nonspherical ice scattering database for these simulators. In the next funding, we will focus on large aggregate particles, of which current database is still lacking. (iii) Characterization of the structure of water content of snowing clouds, particularly cloud liquid water in them based on observational data. The results of this characterization can be used to validate the database used in snowfall retrieval algorithms.

(2) Developing detection and retrieval method of falling snow over land. In a previous study, we have developed a CloudSat-trained high-frequency microwave radiometer algorithm for snowfall detection and retrieval over land. We applied the same approach to SSMIS and NexRad radar matchups, and made several interesting findings, i.e., high-frequency channels (85, 150 and 183 GHz) are necessary and sufficient for snowfall retrievals; detecting snowfall occurrence and retrieving snowfall rate have similar skill, etc. Now, GPM satellite is in orbit, and we have accumulated matchup data for GMI+DPR-CloudSat for more than one year. Using these matchup datasets, we propose to further develop, test and refine the GMI snowfall retrieval technique for snowfall over land. The preliminary version of the GMI algorithm is developed, and has produced reasonable results. The technique will be validated and improved by surface-based measurements - radar network data from U.S.(NMQ/MRMS), Japan (AMeDAS) and S. Korea, as well as NASA-funded future field experiments, etc.).

(3) Developing snowfall vs. brightness temperature database over ocean using a library of snow cloud profiles based on GMI/DPR/CloudSat observations and radiative transfer modeling. Since a large portion of snowfall events will be missed by DPR (with a minimum detection ~12 dBZ), CloudSat data will also be used to fill the missing portion. The snow cloud profile library will contain snow water content profiles from CloudSat and DPR, liquid water content from GMI, ECMWF atmospheric variables, and surface emissivity calculated based on SST and surface wind. The new database will be based on observed snow water profiles from CloudSat and GPM DPR, and brightness temperatures from GMI.

W. Timothy Liu/Jet Propulsion Laboratory
Oceanic and Terrestrial Rainfall Linkage in Global Water Balance

We will validate and apply the extended time series and improved capability in measuring precipitation (P) over extra-tropical ocean and over land provided by Global Precipitation Measurement (GPM) mission, as the pivotal factor of global water cycle changes. We will characterize and understand water balance in an atmospheric column, in oceanic and continental mass change, and its manifestation in ocean surface salinity. Our study will draw upon the integrated moisture transport between ocean and land and the evaporation over ocean that we have estimated from a combination of operational space sensors. The study will be complemented by our on-going efforts in evaluating and improving estimations of evaporation over land and river discharge from land. We will examine the hypotheses of the amplification of the water cycle and expansion the Hadley cell. We will find out how ocean processes affects precipitation high in the atmosphere at frontal scale over extra-tropical ocean. We will joint oceanic and terrestrial water cycle through monsoon and reveal the reason behind pre-monsoon drought and heat waves in India.

Gerald Mace/University of Utah, Salt Lake City
The Effects of Ice Crystal Population Properties on Radar-Radiometer Retrievals of Precipitation Processes in Stratiform Clouds

The principal objectives of the NASA Precipitation Measurement Mission (TRMM and GPM) and the supporting Ground Validation (GV) campaigns in recent years has been to characterize the physical properties of precipitation and to understand the physical processes that result in precipitation at the surface. These research objectives have been in response to the well-known biases (e.g. Stephens et al., 2010) that predictive models of the Earth's climate system continue to demonstrate in key hydrological processes such as precipitation and radiative forcing. Deriving precipitation properties and diagnosing the processes that produce precipitation from remote sensing measurements in ice-phase regions of clouds is an inherently ill-posed problem many degrees of freedom and few independent measurements with which to constrain it even under the best of circumstances. This challenge is not likely to be substantially mitigated in the foreseeable future, although data sets have been created recently by the GV and other campaigns that address these issues to some extent. Assumptions in algorithms regarding certain properties of hydrometeors are unavoidable, that results in substantial and largely unquantified (and perhaps even unquantifiable) uncertainties in retrieval results. It is imperative that current algorithms used in operational retrievals are provided with the best statistics regarding ice crystal microphysical properties such as mass- and area-dimensional relationships and an understanding of how those relationships influence single scattering properties in the microwave channels of interest. Furthermore, future Earth-observing satellite missions, in order to address pressing science questions while minimizing cost, will need to account for these uncertainties while exploring the tradeoffs between science goals, cost, and complexity.

We propose to analyze the in situ and remote sensing data sets that have been collected campaigns supported by the GV effort (Category 2.2 of the PMM AO). A unique aspect of these campaigns is that they provide critical ice cloud characteristics by combining traditional 2-D image probe size distributions with other bulk constraints such as total condensed water. In many cases, the in situ data sets are augmented with state-of-the-art remote sensors. Such is the case for the data set created during Spring 2014 in the IPHEX campaign. A data set of similar breadth will also be created during November and December 2015 in the OLYMPEX campaign. These measurements include accurate observations of the ice crystal particle size distribution (PSD) that range from the smallest crystals to the largest snowflake aggregates and critically provide independent measurements of bulk condensed ice mass. Our objectives in this proposed project are to

1.   Analyze in situ measurements collected with the GV and other suitable campaigns to quantify the covariance of mass- and area-dimensional relationships and use that knowledge to quantify uncertainty in radar backscatter and microwave single scattering properties.

2.   Use this knowledge to understand the implications of ice crystal property uncertainties on precipitation property retrievals.

3.   Use the remote sensing data from GV campaigns to continue development and planning of future satellite missions that are relevant to PMM goals.

Darren McKague/University of Michigan, Ann Arbor

Intercalibration of the GPM Constellation Radiometers: Constellation Monitoring, Anomaly Resolution, and Uncertainty Quantification

This proposal is in response to the Precipitation Measurement Mission Science Team solicitation for research focusing on "Development of methodologies for the intercalibration of measurements from microwave sensors." The proposing team will consist of the Principal Investigator (PI), Darren McKague, and one graduate student. The specific topics of study within the general focus will be the further development and refinement of PMM radiometer monitoring methods, the identification and resolution of anomalies within the constellation, and the detailed quantification of uncertainties in the PMM intercalibration methods.

The PI has been a part of the PMM radiometer intercalibration team (XCal) for over 7 years. During that time, the PI has helped XCal develop a number of ways for intercalibrating the radiometers of the PMM constellation. The processes involves investigation of each radiometer for calibration issues (anomalous observations traceable to non-geophysical sources), resolution of these issues (what XCal refers to as pre-screening), the quantification of the relative differences between members of the constellation, and methods to address these differences in order to develop a consistent set of observations between the constellation radiometers (intercalibration). Many sources of calibration issues are relatively static, but others vary with time as a given instrument ages, as orbits drift, and as the observation environment changes (e.g., sources of radio frequency interference change). Furthermore, the constellation itself evolves as old instruments leave and new instruments join. It is important to monitor each instrument and to resolve anomalies as they arise. This is particularly true of the GMI instrument that, with the passivation of TMI, is now the cornerstone of PMM intercalibration. In this GPM core satellite era, XCal anticipates significant growth in the use of the intercalibrated, level 1C brightness temperatures by the PMM science team. It is therefore also important for the XCal team to develop a detailed budget of the uncertainties in the intercalibration process.

The effort described in this proposal will take the tools developed on the predecessor award for the calibration and intercalibration of the PMM constellation and refine them in order to 1) improve their accuracy, precision, and stability, 2) develop near real-time monitoring tools for the early detection of on-orbit calibration issues, and 3) develop a detailed uncertainty budget to go with XCal products.

Robert Meneghini/NASA Goddard Space Flight Center
Path Attenuation Estimates from the Dual-Frequency Precipitation Radar

Initial results from the DPR-SRT (dual-frequency Precipitation Radar- Surface Reference Technique) algorithm are encouraging in that the dual-frequency version of the method shows improvements in the estimates of path attenuation, particularly at Ku-band. Nevertheless, there are a number of areas for potential improvement including the formation of a low-variance temporal reference data set, use of dual-frequency

information in the outer swath, improved estimates of the attenuation ratio, p, and the use of the multi-beam cross-track surface data to address the non-uniform beam-filling issue. Direct validation of the path attenuation estimates can be addressed by a retrieval module that uses only the SRT to correct for attenuation. In this way, comparisons between the attenuation-corrected reflectivity fields from the DPR and ground radar can be linked directly to the performance of the surface reference technique.

Stephen Munchak/University of Maryland, College Park
Improved Representation of Active and Passive Surface Characteristics in the GPM DPR-GMI Combined Precipitation Algorithm

The GPM Combined Radar-Radiometer Algorithm (CORRA), by incorporating information from both instruments on the GPM Core Observatory, is, in theory, capable of producing the most accurate instantaneous precipitation estimates possible within the DPR swath. Because these estimates are consistent with GMI, the observational databases for passive microwave precipitation algorithms are based upon CORRA output. The proposed work aims to develop statistical and, where possible, physically-based models to represent the surface backscatter cross-section ($\sigma0$) and emissivities for use in the forward model component of CORRA. This work addresses Research Category 2.1 of the NRA (Algorithm/Product Validation and Enhancement), specifically, "validation and enhancement of surface emissivity estimation methods and datasets, both static and dynamic, for use in GPM radiometer and combined radar-radiometer algorithms to improve the extraction of precipitation information from microwave signals over land." •

As currently formulated, CORRA generates an ensemble of hydrometeor profile solutions to the observed Ku reflectivity profile. The path-integrated attenuation (PIA) at both DPR frequencies, Ka reflectivities, and GMI brightness temperatures (Tbs) are simulated for each of these solutions. The solutions are then modified (filtered) to more closely match the observed PIA, Ka reflectivity, and GMI Tbs. Both the PIA and Tbs are sensitive to surface properties: The observed PIA is derived by comparison of $\sigma0$ to a rain-free reference (surface reference technique; SRT), and surface emissivity is required to model the Tbs.

Although the SRT PIA can be used by CORRA, since $\sigma0$ and emissivity depend on physical properties of the surface (e.g., roughness, dielectric constant), and should therefore be correlated (which has been demonstrated), it is logical to replace the PIA with $\sigma0$ and model the joint behavior of $\sigma0$ and multi-channel emissivity in CORRA rather than treat them as independent random variables, which is implicit in the current practice of using the SRT PIA and randomly perturbed emissivities. This effectively constrains the solution space to realistic combinations of $\sigma0$ and emissivity.

As a test of this concept, the PI has developed a model for $\sigma0$ over water surfaces that is a function of 10m wind speed and incidence angle and implemented this in CORRA, demonstrating improved agreement between simulated and observed $\sigma0$ and Tbs and reasonable agreement between observed and retrieved wind. We propose to further

extend this model by accounting for wind direction and the effects of rain on the surface in order to further reduce the ensemble variance in simulated σ0, which in turn reduces the uncertainty in retrieved precipitation rate.

Over land surfaces, a statistical approach will first be implemented using empirical correlations of the multi-channel emissivity and σ0 in the self-similar surface classes that are currently used in the passive microwave GPROF algorithm. We will also explore alternate classifications such as the Microwave Polarization Difference Index (collaborator Y. Tian). To improve upon the statistical approach, we will investigate the extent to which emissivity and σ0 can be dynamically constrained by estimates of snow cover and water equivalent, vegetation properties, and soil moisture, while accounting for the impact of falling or recently accumulated precipitation on the surface properties as well. This task will use data from sources such as NOAA MRMS, GPM IMERG, SMAP, and Terra/Aqua products, and will be performed by Co-Is S. Ringerud (vegetation), L. Brucker (snow and ice), and Y. You (impact of precipitation). Collaborators W. Olson and M. Grecu lead the CORRA team and will facilitate the incorporation of our work into future versions of CORRA.

Catherine Naud/Columbia University
Analysis of GPM Observations to Improve our Understanding of Midlatitude Precipitation: a Process-Oriented Study of Extratropical Cyclones

Understanding how precipitation will change with global warming remains a key challenge in climate science. In the midlatitudes, the changes will be tightly coupled to extratropical cyclones. This is because extratropical cyclones generate the bulk of precipitation in the midlatitudes, as much as 70% in the northern hemisphere winter. In the context of a warming climate, there is still no consensus as to how these cyclones will change. Furthermore, the general circulation models (GCMs) used for climate projections as well as those used to generate historical reanalysis products have to rely on parameterizations for their representation of precipitation. To help with the accuracy of these parameterizations, a better understanding of moist processes in extratropical cyclones is needed.

The Global Precipitation Measurement mission provides a high spatial and temporal resolution global dataset that combines observations from a whole constellation of satellites, and extends to higher latitudes than previous missions. This unique dataset will be used to tackle two different tasks: 1) evaluate a general circulation model (NASA-GISS ModelE2) and a reanalysis (MERRA-2) for their ability to correctly represent precipitation in extratropical cyclones; 2) explore the seasonal changes in extratropical cyclone precipitation and their underlying production processes, including convection and isentropic lifting.

To conduct these two tasks, we propose to create a new GPM-based product, called GPM-ETC, which will be a database of cyclone centered precipitation properties, extracted from both the combined product "IMERG"and the more refined core mission "CMB" products. To evaluate the GCM and reanalysis, we will use this database to construct a series of precipitation rate and frequency cyclone-centered composites to

obtain a climatology for different seasons, the two hemisphere and different oceanic regions. In turn, this process-based information will be used to examine the evolution of precipitation though the lifetime of the extratropical cyclones. Additionally, conditional subsetting will be used to constrain the climatology on cyclone strength and moisture availability.

These cyclone-centered climatological means will be also constructed using the NASA-GISS ModelE2 and the MERRA-2 reanalysis output to investigate their ability to reproduce the right amount and frequency of precipitation in extratropical cyclones. Our familiarity with the physics of ModelE2 will allow us to create specific model experiments. We propose a series of tests that will help isolate aspects of these models that may need improvement to increase our confidence in long-term prediction of precipitation changes in the midlatitudes. In case of the reanalysis, despite the large volume of observations they assimilate, they still have to rely on parameterizations for their representation of precipitation. However, their assimilation of temperature and winds and temporal coincidence with observations allows a one to one comparison of precipitation and to target the underlying parameterizations specifically.

Conjunctly, the database will also be used to explore the seasonal characteristics of strong precipitation events amongst extratropical cyclones. The rational is that in a warming climate, extratropical cyclone characteristics in what is now fall and spring may help inform on future winter cyclones. Conditional subsetting will be used to analyze cyclone-centered precipitation, vertical stability, moisture and upper-level dynamics during these storm events. Separately, an analysis is proposed that leverages GPM's ability to classify convective precipitation. We will explore how the partitioning of cyclone precipitation between convective and isentropic lift evolves with the dynamical changes the cyclones experience through their life, and how it relates to large scale conditions in which the cyclones evolve. This task will be in turn useful for model evaluation.

Stephen Nesbitt/University of Illinois, Urbana-Champaign
Impact of a Priori Assumptions on GPM Retrievals

The overarching goal of the proposed work is to contribute to the evaluation and improvement of Global Precipitation Measurement Mission (GPM) precipitation retrieval algorithms by consolidating, performing scientific investigations with, and providing value added information from the use of microphysical and remote sensing data collected during the GPM Ground Validation (GV) field campaigns. Our group at Illinois has been heavily involved in and the PI has co-led the Particle Size Distribution (PSD) Working Group under the current Precipitation Measurement Missions (PMM) funding cycle, and our unique collaboration at the University of Illinois provides the science team with deep expertise in remote sensing and in situ microphysics for the improvement of GPM algorithms through tailored analysis of GPM field campaign data.

The specific aims of the proposed project include:
(1) use data from all GPM field campaigns to statistically characterize cloud and precipitation properties, including PSDs, mass and scattering properties, and ancillary cloud properties such as cloud liquid water and axial/aspect ratios, from the surface and through the vertical column, and across columns, for use in current and future

probabilistic retrieval algorithms, and to quantify to what degree uncertainties in observed PSDs, particle morphologies, hydrometeor mass properties, scattering and emission properties, and ancillary cloud properties impact retrievals for uncertainty estimation in precipitation algorithms.

(2) identify regimes by which a priori column microphysical characteristics should change (based on GPM-GV observed column microphysical and radiative characteristics, and physical process understanding), and examine the observable structural characteristics and relationships between environmental conditions that lead to these regimes such that they can be identified in spaceborne precipitation retrievals. We will focus on mid- and high-latitude precipitation where GPM-GV has collected measurements and high uncertainty exists in PSD characteristics in the vertical column. We will bring into our analyses the recently-collected IPHEx and to be collected OLYMPEx data where the highest quality aircraft and radar data have been/will be collected, extending our extensive multi-faceted investigations using LPVEx, MC3E, and GCPEx data. We envision our analyses, through the collaborative nature of the PIs, to have direct impact on the radar, passive microwave, and combined algorithms, as well as provide datasets for future precipitation measurement missions. The GV datasets collected in GPM represent some of the most comprehensive ground and aircraft-based in situ and remote sensing datasets ever collected, and it is the goal of our proposal to ensure that these datasets be used to their full potential for the benefit of global precipitation retrievals.

Branislav Notaros/Colorado State University
Toward a More Statistically Robust, Generalized Process Evaluation Framework of Bin and Bulk Microphysics in Winter Precipitation Using NASA GV and GPM-DPR Data

Measurement and modeling of winter precipitation is a challenge because of the sheer variety of physical properties of ice particles, many of which can exist simultaneously. Therefore, advanced measurement and observational analysis techniques are necessary to further our understanding of mixed and frozen phase microphysical processes. Advanced modeling capabilities such as bin microphysics allow for more direct comparisons to the advanced observations. This project proposes to use the NASA Global Precipitation Measurement (GPM) Ground Validation (GV) campaigns and initial GPM satellite data along with a mesoscale model with state-of-the-science bin microphysics to advance understanding of mixed and frozen phase microphysics.

The NASA GPM GV campaigns and GPM satellite data provide the advanced observations necessary to understand the intricate processes in mixed and frozen phase precipitation events. Critical measured properties include: (i) fall speed, V_f, (ii) mass, m, (iii) density, ρ, (iv) apparent '3D' size, D_{app}, and particle size distributions (PSDs), (v) an effective shape parameter, and (vi) ice/water/air composition of particles (e.g., Pruppacher and Klett 2010; Mason 2010). The PSD can also be characterized by a characteristic diameter and spectral width. Some integral quantities of importance in characterizing frozen phase precipitation are ice water content (IWC), liquid equivalent

snow rate (henceforth snow rate or SR), and equivalent radar reflectivity (Ze). Additionally from dual-polarized and/or dual-wavelength radars, the dual-wavelength ratio (DWR), bulk hydrometeor type, and polarimetric observables (Zdr, Kdp, ρhv) are important. We use environmental conditions across the events to cluster them via K-means clustering. The clustering will use microphysically relevant observations such as: temperature, relative humidity, bulk particle type, and surface precipitation rate. Grouping observations across sites and events will provide sufficient data for clustering and uncertainty analysis.

For the modeling component, we will rely on the Advanced Research Weather Research and Forecasting Model (abbreviated WRF) coupled with the spectral bin microphysics from the Hebrew University of Jerusalem, Israel (HUCM). Many recent studies using the HUCM scheme with WRF have focused on examining specific case studies identified in the various GV campaign and have shown important results related to the HUCM scheme. We propose taking this foundational analysis further by applying the methodology of idealized simulations to winter precipitation events. This will be done by simulating idealized three-dimensional extra tropical cyclones in WRF using representative environmental conditions in our observational clusters.

Model output will be grouped using the observational clusters and the comparisons made in observation space, e.g. PSDs, density-size, fall speed-size for in situ observations and radar observables for remotely sensed observations. Currently available radar forward operators are able to compute simulated Doppler Spectra from model output for comparisons to vertically pointing radars. Particle backscattering properties and radar observable quantities for the scanning radars will be estimated using advanced scattering models for the observed PSDs. This code will then be used to develop an advanced dual-wavelength, dual-polarization forward operator for calculation of radar observables from model output such as the dual wavelength ratio and polarimetric fields. Comparing the clustered idealized model output and observations will strengthen any conclusions regarding scheme deficiencies because all comparisons should have similar microphysical processes as their environments will be very analogous.

William Olson/University of Maryland Baltimore County
Integration and Testing of Improved Ice and Mixed-Phase Precipitation Models for GPM Combined Radar-Radiometer Retrieval Algorithm Applications

In the Global Precipitation Measurement mission, the combined radar-passive microwave radiometer precipitation algorithm can provide, in principle, the most accurate and highest resolution estimates of surface rainfall rate and precipitation vertical structure from a spaceborne observing platform. In addition to direct applications of these estimates, they will serve as a crucial reference for "cross-calibrating" passive microwave radiometer-only precipitation profile estimates from the GPM radiometer constellation. And through the microwave radiometer-only estimates, the combined algorithm calibration will ultimately be propagated to GPM infrared-microwave multi-satellite estimates of surface rainfall.

However, to ensure that combined radar-radiometer estimates of precipitation provide an unbiased reference for the radiometer-only and multi-satellite algorithms, the physical parameterizations utilized in the combined algorithm must be accurate. In particular, the proper specification of the microwave single-scattering properties (specific extinction and scattering, and the angular distribution of scatter) of ice- and mixed-phase precipitation will be crucial at higher latitudes, where the ice- and mixed-phase layers typically represent a greater proportion of the total depth of precipitation in the atmosphere. In previous PMM grant cycles, the investigator team developed realistic models for the shapes and single-scattering properties (calculated using the discrete dipole approximation) of nonspherical snow and melting precipitation particles. Using data from an airborne radar and microwave radiometer similar to the GPM instruments, they demonstrated that distributions of the nonspherical snow particles could be adjusted to obtain consistency with simultaneous radar and radiometer observations of stratiform precipitation from a recent field campaign, while it was not possible to do so with spherical snow particle models. The adjusted distributions of nonspherical snow also showed greater fidelity with in situ particle probe observations from underflying aircraft. Simulations of the nonspherical snow particles were extended to the melting layer by computationally "melting" individual particles and then mapping their single-scattering properties to particles with the same mass and melt fraction in 1-D, steady state thermodynamic model descriptions of stratiform melting layers.

The primary aim of the proposed investigation is to continue to develop and integrate the nonspherical snow and melting particle models, and then test these particle models for consistency with airborne and GPM radar-radiometer observations, as well as independent validation data. To this end, we propose to

• extend the current database of nonspherical snow particles to include larger particle sizes as well as rimed particles; then calculate the single-scattering properties of these particles.

• simulate the melting of a subset of particles in the snow particle database and compute their single-scattering properties, and also generalize the 1-D thermodynamic model of the melting layer by adding particle aggregation.

• introduce the bulk single-scattering properties of the snow and melting particles into a combined algorithm framework suitable for testing the radiative consistency of the particle properties with simultaneous airborne radar and radiometer observations from field campaigns, and use in situ particle probe data to independently check radiatively-consistent particle distributions.

• evaluate the particle models in GPM combined radar-radiometer algorithm applications, and use available ground observations to perform a preliminary validation of estimates.

The expected benefits of the proposed investigation will be improved combined radar-radiometer estimates of precipitation profiles, as well as greater accuracy of the radiometer-only and multi-satellite algorithms that are supported by these precipitation estimates.

Walter Petersen/NASA Goddard Space Flight Center

Validation of GPM Precipitation Retrieval Algorithms Across the Precipitation Continuum

Global Precipitation Measurement (GPM) Mission precipitation retrieval algorithms require quantitative, multi-scale descriptions of naturally-occurring liquid and frozen precipitation and its spatial variability. Of interest are distributed ground validation (GV) observations that can be used to quantify the intrinsic characteristics of precipitation such as precipitation size, number concentration, rate, radar reflectivity, type (rain, snow, ice, mixed), water content and precipitation class (convective/stratiform). Observations of these parameters can in turn be tied to a description of the precipitation process and coupling of that process to its spatial variability along and across individual to multiple GPM instrument rays/pixels. The research proposed herein leverages extensive and continued use of numerous GPM GV field-campaigns and NASA Wallops GV radar and hydrometeor datasets together with targeted and coincident GPM constellation overpass data to investigate constraints on the variability and spatial correlation structure of precipitation in the column, and across GPM fields of view. The work naturally extends into snowfall regimes to evaluate impacts of snowflake variability (habit, fall-speed, density etc.) on estimation of falling snow water equivalent rates. Finally, in order to bridge physical and direct validation of GPM Level II and Level III (IMERG) products, the team will continue its external collaborations to apply GV datasets to rigorous and physically-based evaluation of uncertainties in IMERG products; i.e., in the context of precipitation scales of variability and processes impacting level II algorithms.

Specific research objectives include:
1. Use of available GPM GV field, Validation Network and GPM overpass datasets to relate intra/inter GPM-pixel-scale horizontal spatial variability/correlation of precipitation physical characteristics to variability/correlation and process in the vertical column. The results will apply to further refinement of precipitation profile constraints in GPM DPR, radiometer, and combined Level II retrieval algorithms and will be useful for testing approaches to mitigating non-uniform beam filling and path integrated attenuation.
2. In collaboration with international partners, analyze pre/post-launch GV field datasets consisting of NASA and Tier-1 partner multi-parameter radar datasets with coincident and redundant measures of frozen/melting hydrometeor characteristics and snow-water equivalent rate (SWER) derived from GPM disdrometer, Precipitation Imaging Package (PIP), hot-plate, Micro-Rain Radar and Pluvio snow-gauges to develop internally-consistent distributed maps of bulk water-equivalent precipitation rates and spatial variability. These will be compared to GPM satellite falling snow algorithm products as related to snow detection and SWER estimates. Implicitly included is analysis of satellite overpass and GV datasets to improve precipitation identification and estimation in situations of complex melting layer/rain-snow transitions.
3. Collaborate with a larger external team to use validated, nested, and internally consistent GV surface rainfall products (Wallops, field campaign networks, MRMS) covering IMERG pixel to continental scales toward isolating platform and algorithm-specific uncertainties in Level II products as they propagate into/through IMERG.

The research is most properly aligned with the ROSES2015 A.23 Announcement, Section 2.1 and directly supports the topic of Algorithm/Product Validation and Enhancement.

Christa Peters-Lidard/NASA Goddard Space Flight Center
Dynamic Emissivity Estimates to Support Physical Precipitation Retrievals for GPM

Objective: The objective of this proposal is to provide dynamic emissivity estimates over land surfaces to support physical precipitation retrievals for GPM. Our previously-funded work has shown that surface emission, particularly over the range of frequencies to be included in GPM, is sensitive to land surface states, including soil properties, vegetation type and greenness, soil moisture, surface temperature, and snow cover, density, and grain size. Recent work has shown that a regression-based approach trained on clear air emissivity estimates can reproduce dynamic emissivities as effectively as a calibrated microwave emission model (Harrison et al., 2015; Tian et al., 2015) or a semi-physical model (Ringerud et al, 2015). Providing a robust land surface emissivity estimation capability in a simplified framework suitable for real-time retrievals is essential to support GPM-era physical radiometer algorithms over land.

Relevance: This proposal addresses primarily Research Category 2.1 of the NRA, which focuses on Algorithm/Product Validation and Enhancement. In particular, the proposal addresses the element "Development, testing, and validation of radiometer retrieval algorithms over land, with emphasis on physically based techniques to extract precipitation information from measurements over the range of 10-183 GH". In addition to building on prior work with the PMM Land Surface Working Group (LSWG; collaborator Joe Turk), we will extend our previous work to demonstrate that the method is suitable for global application, with the goal to provide a viable GPROF S2 (i.e., fully dynamic) overland retrieval algorithm ready for PPS.

Approach: The approach for this proposal is to first provide global regressions for land surface emissivity using a combination of GMI, AMSR-E and AMSR-2. This requires global clear air surface emissivity estimates from GMI, AMSR-E and AMSR-2, which have already been derived (GMI, by collaborators Joe Turk and Joe Munchak, AMSR-E, by NOAA/CREST). We will evaluate the regression relationships as well as calibrated semi-empirical emissivities at GMI frequencies ranging from 10-183GHz in a manner similar to Tian et al., 2015. Next, we will work with collaborators Sarah Ringerud, Dave Randel and Chris Kummerow to update the GPROF databases and its real-time retrieval module using instantaneous emissivity values derived from our fully empirical or semi-empirical models, to support the full-fledged S2 retrieval. With the updated databases, we will test the impact of regression-based indexing and the semi-empirical model on GPROF precipitation retrievals over land. Finally, we will evaluate the physical GPROF retrievals against the standard GPROF retrievals using regional reference data such as the MRMS.

Grant Petty/University of Wisconsin, Madison
Passive Microwave Retrievals of Precipitation at High Latitudes

We propose to continue contributing toward the development and refinement of algorithms for retrieving global precipitation information from the Global Precipitation Measurement (GPM) Microwave Imager (GMI), emphasizing high latitude land, snow, and ice surfaces.

Under the PI's current grant through the Precipitation Measurement Mission (PMM) Science Team, we published an innovative conceptual approach to Bayesian rain rate estimation, relying on an empirical dimensional reduction technique that (1) improves the robustness of the solution matching algorithm and (2) optimizes the detection and estimation of precipitation in the presence of problem surface types. We demonstrated that the method markedly improves TMI rainfall retrievals relative to the standard TRMM 2A12 rainfall product over both ocean and land surfaces, especially problematic areas such as coastlines, deserts, and high plateaus.

The new methods serve as the basis for "surface blind" (a.k.a. S0-style) retrievals for GMI, complementing S1- and S2-style retrievals that require more detailed information and/or models concerning surface emissivities. Some elements of the approach have already been incorporated into the standard algorithm for TMI. Additional refinement and testing is needed for GMI retrievals, as the method depends on a geographically and seasonally diverse set of real GMI observations matched with (relative) truth from Dual-Frequency Radar (DPR) observations of precipitation.

These research objectives are central to the PMM Science Team effort to ensure quality retrievals at high latitudes from the GPM Core Observatory, especially over surface types for which surface emissivity models remain unreliable.

Steven Rutledge/Colorado State University
Radar Studies of Convection in Support of PMM

The Radar Meteorology Group at Colorado State University has been involved in TRMM and now PMM-related research for over 20 years, first playing lead roles in TRMM field campaigns such as TRMM-LBA, followed by key involvement in TRMM and GPM ground validation campaigns such as C3VP, LPVEx, MC3E, IFLOODS and IPHEx. Group personnel will also deploy for the upcoming OLYMPEX field campaign planned for November-December 2015 on the Olympic Peninsula in Washington State.

The group has made substantial contributions to the GPM GV effort through analysis of polarimetric data collected in the various projects, and spearheaded efforts to deduce cloud microphysical quantities from radar datasets. They have also undertaken studies of tropical convection using TRMM PR and LIS data, recently completing a study to analyze the role of thermodynamics and aerosols in promoting intense convection in the

tropics. A key, limiting factor to the impact of aerosols is the depth of the warm cloud layer, with deeper warm cloud depths abating the impact of aerosols.

The proposed effort centers on two major components: analysis of ground validation data from recent GV campaigns and the upcoming OLYMPEX project and study of the MJO using TRMM and GPM climatological data. In particular, efforts will be focused on the development of convection tied to MJO initiation and the interaction of the MJO with the vast land and ocean waters of the Maritime Continent (MC). There is much uncertainty regarding the time frame and mechanism over which the MJO initiates, which is marked by the transition from shallow to deep convection. MJO initiation is poorly simulated in general circulation models. Furthermore, the interaction of the MJO with the MC is poorly understood. Our GV-related research will be directed towards characterizing the drop size distributions and ice microphysics in a column sense to facilitate comparisons to GPM footprint observations with a goal to improve GPM retrieval algorithms. We will also utilize GV data to improve bulk microphysical parameterizations used in the Goddard Cumulus Ensemble model. Collaborations with key GPM scientists will be a central component of this proposed work.

Carl Schreck/North Carolina State University
Multiscale Interactions Between the MJO, Equatorial Waves, and the Diurnal Cycle over the Maritime Continent

The Madden–Julian Oscillation (MJO) is the largest source of tropical intraseasonal variability with impacts spanning the globe. Unfortunately, numerical models fail to adequately simulate its convection, limiting their opportunity to harness its long-range predictability. Nowhere is this shortcoming more apparent than over the Maritime Continent (MC). Many MJO events terminate before crossing the MC, a tendency that is exaggerated in most numerical models. The MC poses complex topography that may reduce the MJO's moisture source from surface fluxes and impede the MJO's low-level circulation. The exceptional diurnal cycles in the vicinity of the large islands in the MC can also drain the MJO's energy. Most models fail to capture this diurnal cycle properly and result in large biases in rainfall over the MC.

Many studies have examined the interactions between the MJO and convection over the MC. Far fewer have looked at the role of convectively coupled equatorial waves, even though models that faithfully represent these waves also tend to produce more representative MJO signals. The proposed study will identify avenues for model improvement by investigating the interactions between the MJO, equatorial waves, and the diurnal cycle over the MC. It will be conducted in two intertwined branches that will each complement a major international field campaign, the Year of Maritime Convection, proposed for 2017-2018.

The first branch will identify the MJO and equatorial waves using Fourier filtering of GPM IMERG data. These data will be used to identify the modulation of the diurnal cycle in GPM IMERG by equatorial waves. They will also be compared with TRMM and

geostationary satellite datasets that identify convective cloud populations. These results will show differences in the interactions between equatorial waves and convection over the MC during MJO events that cross the MC barrier with those that do not.

The second branch will compare these observational results with reforecast data from the Climate Forecast System Reanalysis and Reforecast (CFSRR). It will test a novel approach for combining observed GPM IMERG data with CFSRR forecasts to identify the MJO and equatorial waves. With this method, it is hypothesized that the model can predict the convective envelope of the MJO and equatorial waves better than it can forecast the individual convective elements. The results will also be used to identify differences in the equatorial wave state over the MC that might lead to more or less skillful forecasts of the MJO.

Courtney Schumacher/Texas A & M, College Station
From the Tropics to the Midlatitudes: A Seamless Analysis of Convective and Stratiform Rain and Latent Heating Using GPM

The TRMM precipitation radar (PR) provided an unprecedented view of precipitation and storm structure in the tropics and subtropics for 17 years. The launch of the GPM dual-frequency precipitation radar (DPR) has expanded this view into higher latitudes with an enhanced radar system that includes two wavelengths (Ku- and Ka-band) with higher sensitivity to smaller particles. This enhanced view allows the ability to better explain regional rain patterns (e.g., what contribution of rain comes from convective or stratiform processes) and the latent heating associated with the production of rain across the globe. This proposal is focused on assessing the GPM DPR convective-stratiform rain classification algorithms (both the TRMM-era single frequency algorithm and the new GPM dual-frequency algorithm) in the tropics and at higher latitudes. This work is especially relevant to GPM since rain type information is integral to the radar rain retrievals and it is remains to be shown how the convective-stratiform classification algorithms compare to each other across the GPM domain and how well they perform outside of the tropics, where the differentiation of convective and stratiform rain processes is less well observed and understood. The proposed research will also assess the application of the TRMM-era latent heating algorithms, which are based on convective and stratiform rain inputs, to the GPM DPR and extratropics.

James Shepherd/University of Georgia, Athens
The Energy-Water-Food Nexus Within the Backdrop of an Urbanized Globe: How Can GPM Help?

The economy of this risk, as noted by a 2011 Global Risk report, is manifested by global projections for a 50% increase in food demand, 30% increase in water demand, and 40% increase in energy demand by 2030. Such demands are, in part, driven by urbanization and population increases. The PMM has funded a coordinated research effort over the past decade to explore connections between urbanization and precipitation. We now turn

our attention to the Energy-Water-Food Nexus (EWFN). Tomas et al. (2015) note that the many frameworks have been used to study the EWFN, however, we find very little attention to the hydroclimate implications and interactions. Herein, we approach EWFN from the perspective of NASA's PMM Program.

Our motivation is to link PMM data and other NASA data to support the EWFN nexus related to urban transitions related to agriculture. Our Precipitation-Based Framework seeks to address the following research questions in 3 broad topical areas:

Metrics for Precipitation within the EWFN framework
1.   Can precipitation per capita or per individual be quantified and used as a variable in the assessment of the EWFN capacities and vulnerabilities?

Ecosystem Services and Water
2.   What are the implications of transition of cities to urban agriculture on water and energy demand in cities?
3.   How will addition of urban agriculture and irrigation affect urban microclimate and regional precipitation patterns?
4.   How resilient is urban agriculture to hydroclimate variability and extreme events?

Urban-Agricultural Interactions
5.   Can PMM data augment NOAA-NASA efforts to evaluate and manage urban/suburban water resources and impacts on agriculture?
6.   How can NASA precipitation data be used as part of a global urban agriculture management toolset?

Data and Methodology: We propose to use the new GPM-based IMERG blended, global precipitation product to developed global precipitation indices as a function of several societal indicators Our goals are to develop indices that can be used to diagnose trends in "precipitation stress" and how that manifests as "water stress". Our Precipitation Productivity measures will be derived as a function of population, urban land cover, and agricultural land.

We also build upon team member Burian et al's (2015) PMM-based analysis of ecosystems services and rainwater harvesting in India with the explicit goal of advancing our understanding of the urban-agriculture complexity and demands for water. We will build on the TRMM MPA-based analysis with IMERG and for other relevant study regions.

Daily gross primary production (GPP) and annual net primary production (NPP) at the 1 km spatial resolution are now produced operationally for the global terrestrial surface using MODIS. In addition, satellite observations of atmospheric and land surface temperatures, humidity sounding, together with PMM rainfall data, will be used to first identify the urban impact on agriculture GPP and NPP and then to develop new schemes for the current Weather Forecasting Model coupled with land schemes (Noah model) to simulate such impact. We will build upon ongoing team partnerships with the NOAA

NCEP land modeling team (Mike Ek) on improving the GFS NOAH urban scheme to enhance urban simulations. We will incorporate rain and snow information from the PMM program, coupled with with NOAA operational efforts, will help predict, evaluate and manage urban/suburban water-agriculture resources.

Our research is most closely aligned with element 2.2 and 2.3, respectively, of the PMM Science Team RFP. Our project has elements clearly aimed at improvement of land surface models and development of applications related to agriculture, water availability, and food supply (as detailed at http://pmm.nasa.gov/applications). Our team also has over a decade of experience working within the PMM team framework, science teams, and programmatic expectations.

Brian Soden/University of Miami, Key Biscayne
A New Method for Statistical Downscaling of Precipitation and Application to South Florida Water Management

A robust projection of all climate models is the tendency for wet regions to become wetter and dry regions to become drier as the climate warms under increased greenhouse gases. This presents a clear problem for water resource managers as future rainfall patterns may be well outside the historical range of variability on which many managed systems are based. Such is the case in South Florida, where multi-billion dollar efforts to restore the Everglades ecosystem and upgrade municipal water management facilities are underway without explicit consideration of future rainfall change due to the absence of credible projections. Because of their large regional biases, rainfall simulations from coupled global climate models (GCMs) have proven to be inadequate for direct use by water resource managers in this region. Moreover, GCMs differ substantially in their prediction of regional changes in precipitation. Recent research has shown that much of the intermodel spread in regional projections of precipitation change is due to differences in the models'climatological distribution of rain. The fundamental premise of this proposal is that correcting for spatial displacements in the GCMs' climatology of rainfall using satellite observations from TRMM (and GPM) will yield more consistent and more accurate regional predictions of precipitation change. The veracity of this hypothesis will be tested in two ways: First by evaluating the reduction in spread in the downscaled model projections of future rainfall change, and second through their application for water management in South Florida.

Many GCMs simulate recognizable rainfall patterns, however they are often displaced spatially due to regional biases in the models climatology (e.g., SST biases, etc.). Existing statistical downscaling techniques do not have an explicit method to account for spatial displacements in the base climate. Here we propose a new approach for statistically downscaling GCM predictions that goes beyond traditional quantile mapping by first performing a spatial re-mapping to explicitly adjust for regional displacements in their climatologies using TRMM (and GPM) measurements in conjunction with a spatial feature-mapping algorithm. This algorithm has previously shown to be effective in mapping pattern displacements in other geophysical fields. By statistically correcting for

biases in the spatial structure of the model's unperturbed precipitation climatology, we can improve the consistency of model projections of precipitation change at the regional scale and provide improved products for planners and stakeholders. To accomplish this goal, we will complete the following tasks:

1) Generate high-resolution regional simulations using NASA TRMM and GPM measurements to provide target climatologies for statistically downscaling climate forecasts from the new GFDL seasonal forecast model GFDL-FLOR and the CMIP5 ensemble of GCM simulations.

2) Use the high resolution downscaling of precipitation change to force the South Florida Water Management Model (SFWMM) and evaluate the utility of the downscaled precipitation for seasonal to decadal planning and management options within this framework.

A key element to this work is the collaboration with South Florida Water Management District (SFWMD). The hydrological model they have developed for the South Florida region takes into account the diverse stakeholders incorporates the management processes that satisfy policy-based rules (both existing and proposed) to meet flood control, water supply and environmental needs. Management options will be tested within this model framework using downscaled projections of precipitation change on seasonal to decadal time scales. This work addresses the PMM objective to develop improved "downscaling of satellite precipitation information for hydrological modeling and prediction." •

Simone Tanelli/Jet Propulsion Laboratory
Enhanced Algorithms for the Dual Frequency Precipitation Radar

Within our ongoing PMM'12 funding we have developed datasets and algorithms to tackle the following second-order effects impacting the products of the Dual-Frequency Precipitation Radar (DPR): multiple scattering, non-uniform beam filling, surface clutter. Some of the algorithms have been prototyped and preliminary validation has begun with the recent or upcoming GPM Ground Validation datasets. We focus first on an algorithm referred to as the 'Trigger': it aims at pre-screening DPR profiles to enable targeted selection of a specific solver module that is best suited - and most computationally efficient - to tackle one particular category of profiles (for example: affected by significant multiple-scattering but no significant non-uniform beam filling, or by both, or neither but with extensive surface clutter due to orography, etc.). The first prototype of this algorithm is completed and functional, and preliminary validation of the prototype is expected to complete by the end of the current PMM funding cycle. Here we propose to further refine, finalize its validation and implement a module that could be integrated in the DPR or Combined algorithms. Second, we propose to implement a module based on our published Multiple-Scattering Optimal Estimation (MS-OE) profile retrieval algorithm for profiles affected by substantial multiple scattering as possible candidate solver for that category of profiles. This module is not proposed to replace the current, or other standard solver modules. Instead, under the DPR L2 framework modified by the insertion of the trigger solver, this module is designed to complement them. Third will advance the development of algorithms aiming at assessing land surface classification to

improve the performance of the Surface Reference Technique (SRT) module over land and apply the improved land classification also to the assessment of impact of soil wetness on PIA.

Wei-Kuo Tao/NASA Goddard Space Flight Center
Advancing the Retrieval of Latent Heating for PMM with Improved Simulations of Convective, Synoptic, and Cold Season Systems and Their Associated Microphysical and Precipitation Processes

Overview and Proposed Research: The proposed modeling and algorithm development effort will begin with the improved simulation of a wide range of precipitating cloud systems, from weak, unorganized isolated rain showers to intense mesoscale convective precipitation systems to large-scale synoptic snow storms, and their associated precipitation structures and cloud microphysical processes. The proposal will use data from several major field campaigns (i.e., C3VP, MC3E, LPVEx, GCPEx, IFloodS, IPHEX, OLYMPEX, TWP-ICE, and DYNAMO) to validate and improve the microphysical processes in high-resolution numerical models for the NASA Precipitation Missions, which in turn be will used directly to expand and improve the performance of the Convective-Stratiform Heating (CSH) algorithm for the TRMM and GPM era. The main areas of proposed research are:

(1)   Utilize GV products to identify potential weaknesses and/or strengths within the microphysical processes used in the cloud-resolving and regional-scale models and to improve their performance by resolving any deficiencies.
(2)   Conduct high-resolution (both horizontal and vertical) model simulations for a variety of different cloud and precipitation systems from different geographic locations using the improved microphysics with an emphasis on ice-phase and mixed-phase precipitation systems in middle and high-latitudes, and
(3)   Use the high-resolution simulated 3D cloud and cloud properties (including hydrometeor distributions and their microphysical characteristics, latent heating (LH), eddy transport and radiation) needed to advance GPM LH algorithm development, specifically the current operational CSH and SLH algorithms, and their validation (i.e., via synthetic consistency checks).

Relevance: Our proposed research meets the requirements and addresses the scientific problems as stated in the Precipitation Measurement Missions NRA under category 2.1: Development, testing, and evaluation of algorithms supporting the transition and extension of TRMM products into the GPM era.

The proposed research also addresses category 2.2 in the NRA: Use of satellite and field campaign data to study precipitation and microphysical processes, particularly for mixed phase and frozen precipitation, and their improved representation in cloud resolving and climate models.

In addition, the proposed research will contribute to the "collaborative analysis of field campaign data sets to support algorithm improvements and validation" (category 2.1). The collaborators include key LH algorithm developers (Takayuba, Shige, W. Olson), observational experts (W. Petersen, S. Rutledge, R. Houze, R. Johnson), a key DPR algorithm developer (R. Meneghini) and advanced modeling experts (C. Peters-Lidard, T. Matsui, X. Li). Note that LH is one of the primary GPM products.

Francis Turk/Jet Propulsion Laboratory
Enhancements to GPM Radiometer-Based Precipitation Estimates Under a Variety of Surface and Atmospheric Conditions

The first year of observations from the Global Precipitation Measurement (GPM) core observatory instruments, the Dual-Frequency Precipitation Radar (DPR) and the GPM Microwave Imager (GMI), have yielded significantly new insight into how precipitation, clouds and surface properties are revealed in Ku/Ka-band (13/35 GHz) radar and 13-channel (10-183) GHz passive microwave (MW) radiometric brightness temperature (TB) observations, respectively. Further improvements to the GPM algorithm suite hinge upon an improved capability to consistently forward model (simulate) GPM and the many constellation observations, including the 150-183 GHz high-frequency (HF) MW sounders where possible, over the range of cloud, precipitation and spatial and temporally varying surface conditions. Currently, no formulation exists to identify and account for short-term changes to the MW land surface emissivity that results from physically changing surface conditions viewed by the GPM constellation radiometers.

This proposal addresses four surface-related topics that are designed to benefit the GPM constellation radiometer-based precipitation products, which most directly influence the quality of the merged precipitation product IMERG, and overlap many of the categories listed in this announcement under Algorithm/Product Validation and Enhancement. These four topics are:

(1) To develop a means to extract the most up-to-date 10-89 GHz emissivity vector state from the GMI or constellation TB observations while maintaining a consistent channel covariance, to lessen dependencies upon ancillary data and more seamlessly accommodate temporal and spatial variations in the surface physical conditions, (2) To test and evaluate techniques to efficiently carry and index these surface properties in a-priori hydrometeor databases, working with an offline version of the GPM GPROF (Goddard Profiling) retrieval framework, (3) To utilize the large number of global GPM-CloudSat satellite coincidences, to estimate where possible the high frequency (HF) emissivity state at 89 GHz and above, needed to better model light rain and cold season TB scenes from the multitude of MW sounders, and (4) To quantify the joint variability between the surface emissivity vector and the corresponding DPR surface normalized radar cross section (NRCS) across the DPR viewing angle range, as a function of NMQ/MRMS (NEXRAD) antecedent precipitation, relevant to radar surface reference techniques (SRT) used in the GPM combined radar/radiometer algorithm.

These topics exploit the wealth of information contained in the GPM radiometer/radar observations, to contribute to an overall improved capability to simulate the constellation radiometer TB and DPR reflectivity profile under a wide variety of surfaces, and self-adapt to the surface state to minimize reliance upon pre-determined surface classifications.

Christopher Williams/University of Colorado, Boulder
Quantifying Melting Layer Attenuation and DSD Variability Within DPR Instantaneous Field-of-Views and Evaluating their Impact on DPR Observations and Retrieval Algorithms

In response to Research Category: Algorithm/Product Validation and Enhancement, the objectives of this proposed research are two-fold: first, use NASA Global Precipitation Measurement Mission (GPM) Ground Validation (GV) observations to quantify melting layer attenuation and raindrop size distribution (DSD) variability within the GPM Dual-frequency Precipitation Radar (DPR) Instantaneous Field-of-View (IFOV); and second, assess their impact on DPR observations and DPR rainfall retrieval algorithms.

These objectives will be achieved using a 3-prong approach:
* Quantify melting layer attenuation using vertically pointing radar observations
* Quantify DSD variability using scanning radar observations
* Assess the impact of melting layer attenuation and DSD variability on DPR observations and DPR rainfall retrieval algorithms

To quantify melting layer attenuation and DSD variability in GV observations, the work proposed herein will be to analyze NASA Dual-frequency Dual-polarization Doppler Radar (D3R) observations while deployed on GPM GV field campaigns including IFloodS, IPHEx, and OLYMPEX (planned for November 2015 through February 2016) and from D3R's home base near Wallops Flight Facility. Melting layer attenuation, or melting layer path-integrated attenuation (ML-PIA), will be quantified using vertically pointing observations after first estimating DSDs and frozen particle size distributions (PSDs) below and above the melting layer, respectively. Naturally-occurring DSD variability will be quantified using Range-Height-Indicator (RHI) scans by first retrieving DSD parameters and hydrometeor identifications (HIDs) along radar radials and then calculating variability statistics throughout DPR IFOVs superimposed over the GV observations.

Sub-IFOV variability has a sequential impact on satellite observations and retrieval algorithms. First, sub-IFOV variability impacts DPR measurements which, subsequently, impact rainfall retrieval algorithms. This cascading effect is addressed by developing a high resolution forward DPR radar simulator as a tool converting observed D3R observations, which include ML-PIA and DSD variability, into low resolution simulated DPR measurements. Combing microphysical information gleamed from GV field campaigns with simulated DPR measurements, statistical relationships will be explored

relating DPR measurements with assumptions and constraints used in physical-based retrieval algorithms.

As summarized above, this proposed research is responsive to Research Category: "2.1 Algorithm/Product Validation and Enhancement", addresses the important topic: "Validation and enhancement of dual-frequency (Ka/Ku-band) precipitation radar retrieval algorithms and/or combined radar/radiometer algorithms", and utilizes GV observations through: "Collaborative analysis of field campaign data sets to support algorithm improvements and validation." •

Sun Wong/Jet Propulsion Laboratory
Connecting Precipitation to Clouds and the Large-Scale Circulation by
Atmospheric Processes: Water-Budget Oriented Analyses

We propose to establish empirical relationships among precipitation, cloud properties, and the large-scale circulation by process-oriented analyses of the atmospheric water budget. Tropical and extratropical precipitating systems provide scientific test beds to link the large-scale dynamical environment to cloud formation and precipitation processes. The atmospheric water budget equation is the basic underlying theory that sets the paradigm to connect these different components in precipitating systems. The TRMM-based and recent GPM-based, high temporally and spatially resolved estimates of precipitation will be used together with MODIS, CloudSat/CALIPSO, and AIRS observed cloud properties, and MERRA2 atmospheric dynamical outputs to study two dominant precipitating systems: the Indian summer monsoon for tropical convective systems, and mid-latitude cyclones for extratropical baroclinic systems. The established relationships among precipitation, cloud properties and large-scale dynamical conditions will then be applied to evaluate simulations of these systems in the Advanced Research Weather Research and Forecasting (ARWRF) model.

Precipitation has a direct impact on society. Clouds have been recognized throughout the human history as signatures of weather systems, which are characterized by highly variable precipitation intensities. Numerical models have not yet successfully reproduced observed cloud properties and precipitation processes even for today's weather and climate. Three-way relationships between clouds, precipitation, and large-scale dynamical conditions should be able to diagnose: (1) whether under certain large-scale dynamical conditions models (either climate or weather forecast) can obtain cloud properties and distributions as observed; (2) whether the cloud morphology is associated with observed precipitation intensity and frequency; and (3) whether the precipitation intensity and frequency are consistent with the given large-scale dynamical conditions as predicted by the atmospheric water budget equation.

Annual recurrence of tropical monsoons and extratropical cyclones provide nearly repeatable large-scale dynamical conditions that serve to establish and test the three-way relationships. With the advent of the GPM constellation, advanced analyses should be tailored to efficiently tie the accurate, high temporally and spatially resolved precipitation

estimates to both clouds and large-scale dynamical conditions.   We aim at achieving the following goals:

1.   Quantify 3-D joint histograms of precipitation intensity, cloud top pressure, and cloud optical depth embedded in large-scale dynamical conditions represented by moist convergence and advection associated with the Indian summer monsoon seasonal and intraseasonal variations, and mid-latitude cyclonic systems.

2.   Identify spatial scale-dependencies of water-budget related variables (e.g., total water, precipitation, and latent heating) in the Indian monsoon and mid-latitude cyclonic systems.

3.   Use the two atmospheric processes to evaluate the ARWRF model in terms of relationships among precipitation frequency and intensity, cloud type distributions, atmospheric water budget, latent heating, and spatial scale dependencies.

This proposal is proposed under Section 2.2 of NRA A23 "Utilization of Satellite/GV Products for Process Studies and Model Development". The proposed work addresses the following questions listed in the Earth System Research Program:

1)   How are global precipitation, evaporation, and cycling of water changing?

2)   How are variations in local weather, and precipitation, and water resources related to global climate variation?

3)   How can prediction to climate variability and change be improved?

Norman Wood/University of Wisconsin, Madison
Assessing Precipitation Microphysical Structure Aloft Using Cold-Season Ground Validation Observations

Ground validation campaigns provide the most comprehensive measurements of cold-season precipitation currently available and provide the best opportunity for quantifying the spatial and temporal variations of microphysical properties, which can in turn provide constraints on microphysical processes. Campaigns supported by the Precipitation Measurement Missions, such as the Canadian CloudSat-CALIPSO Validation Project (C3VP), the GPM Cold-season Precipitation Experiment (GCPEx), and the Light Precipitation Validation Experiment (LPVEx), incorporated thoroughly-instrumented ground observing sites in conjunction with aircraft performing both in-situ and remote sensing observations during the life cycle of precipitation events. The objective of the proposed research is to leverage these concurrent observations to characterize the vertical distribution of precipitation microphysical properties in the atmosphere over the ground sites for precipitation events from these campaigns, then interpret the spatial and temporal variations in terms of microphysical processing such as aggregation, riming, and melting.

The investigators previously applied optimal estimation techniques to characterize precipitation microphysical properties at the surface using ground-based observations from C3VP. That work successfully determined characteristics such as the relationship of precipitation particle mass to size, a key feature related to both microphysical processing and microwave scattering properties. Comparisons of results for several precipitation

events suggested that microphysical differences between lake effect and synoptic snowfall events could be discerned.

These results, however, provide primarily a picture of the end state of the microphysical processing that occurred in the column over the ground site. Estimation methods developed in prior work will be extended to make use of the in-situ aircraft observations in the column as well as observations from vertically-profiling radars and passive microwave radiometers deployed on the ground and on aircraft. The estimation methodology builds upon the prior ground validation analyses performed by the investigators as well as on retrieval techniques they have developed for application to satellite-borne radar observations. The estimation method will be applied to snow and mixed-phase precipitation events with suitable measurements and used to discern information about the structure of microphysical fields aloft. With appropriate consideration for horizontal advective transport, quantified vertical variations in water content, particle mass and area distributions, and fallspeeds can allow inferences about the net effects of microphysical processes.

The resulting knowledge will have a number of uses appropriate to the ROSES A.23 program element. Foremost, it will provide detailed information about the microphysical structure and properties of these precipitation events, information which can contribute to the evaluation of model microphysical process parameterizations and to improved understanding of microphysical uncertainties in modeled cold-season precipitation. Further, the information will support the development of appropriate a priori constraints for precipitation remote sensing algorithms and, via microwave scattering simulations, contribute to understanding microwave retrieval forward modeling uncertainties. Together these applications will provide a substantial basis for microphysical model improvements and for better-performing satellite-based retrievals of both cold-season and high-latitude precipitation.

Huan Wu/University of Maryland, College Park
Improved Global Flood Monitoring and Forecasting with GPM Precipitation and Hydrological Models

Over the last few years the University of Maryland has developed the Global Flood Monitoring System (GFMS), utilizing PMM precipitation data (primarily the TRMM Multi-satellite Precipitation Analysis [TMPA]) and land surface and routing models. With substantial improvement expected in the GPM-based IMERG multi-satellite product now becoming available, we expect exciting improvements in our real-time global flood calculations.

This proposal will focus on utilizing our current GFMS system, adapting it to take full advantage of the precipitation improvements related to IMERG, evaluate the results in terms of improvement of the real-time flood calculations due to GPM, and feedback information on remaining limitations of IMERG, especially in remote areas, through hydrological validation.

Improvements in IMERG:
1) Finer spatial resolution
2) Finer temporal resolution
3) Improved over-land Level 2 precipitation algorithms/products
4) Cross-calibration of sensors
5) Application of "same" PMW algorithm to all polar orbiters.
6) Early and late versions of IMERG for best and most timely flood results
7) Rain/snow differentiation based on Level 2 algorithms and/or IMERG use of ancillary surface temperature information.

GFMS will be adapted in following ways to take advantage of IMERG:

1) Will be run at 1/10th and 1/16th degree to match IMERG (and at finer 1 km res.)
2) Will be run at overlapping time steps to take advantage of multiple IMERG runs. Latest IMERG data (a few hours old) will be supplemented with NWP model analysis of precipitation to produce "exactly real time" flood estimates.
3) Existing snowmelt calculations in land surface model will be adapted to take advantage of IMERG information.
4) Making GFMS truly global—expand to higher latitudes (e.g., 70 deg.)

Other GFMS improvements will hopefully be made as part of other funding, e.g., dam module, regional calibration and high resolution modeling, etc.

Xiping Zeng/Morgan State University
Using GPM Data to Examine the Effects of Cloud Dynamics on Microphysics

GPM (the Global Precipitation Measurement), in contrast to TRMM (the Tropical Rainfall Measuring Mission), provides additional data on optically-thin and mid-latitudinal clouds. These new data will be used in the proposed project to examine how up/down-drafts impact cloud microphysics in the Tropics and middle latitudes, providing the means for weather and climate models to better represent cloud microphysics.

It is well-known that ice crystal concentration (ICC) can change clouds and precipitation significantly, whereas little global information on ICC is available. Since GPM observes both convective cores and their anvil, its data can be used to constrain the ICC and other microphysical variables in observed clouds via cloud-resolving modeling. This procedure has been tested successfully using field campaign data over a few geographical regions. In the proposed project, using GPM data, the procedure will be extended to explore the effects of up/down-drafts on ICC in the whole of the Tropics and middle latitudes.

Specifically, the research will use the Goddard cloud-resolving model (CRM) to simulate GPM-observed clouds with differing values of microphysical parameters. The model results will then be compared with GPM data (e.g., IMERG, Ku/Ka-band DPR

data) to determine which set of microphysical parameters leads to the best agreement between model results and observations. These estimated in situ values will be further analyzed against the convective downdraft data that come from field campaign observations (e.g., IPHEx, MC3E,) and high-resolution cloud modeling.

The research will deliver a quantitative description of the effects of downdrafts on ICC (i.e., the ice crystal enhancement factor), which can then be used by weather and climate models to better represent the aerosol indirect effects on precipitation and climate. It will also provide a means to evaluate the necessity for downdraft observations in the next generation of NASA satellites.

Fuqing Zhang/Pennsylvania State University
Improving Weather Prediction and Precipitation Estimation Through Advanced Ensemble Assimilation Using GPM Microwave Brightness Temperature with Coherent Microphysics Parameterization and Radiative Transfer Models

Title: "Improving weather prediction and precipitation estimation through advanced ensemble assimilation using GPM microwave brightness temperature with coherent microphysics parameterization and radiative transfer models"

Summary: The ultimate goal of this research is to improve weather prediction and quantitative precipitation estimation through ensemble-based data assimilation of brightness temperature observations from the NASA GPM microwave imagers (GMI), as well as other in situ and remotely-sensed data, into the convection-permitting Weather Research and Forecast (WRF) model. This will be accomplished by using the Penn State University (PSU) WRF-based ensemble Kalman filter (EnKF) data assimilation system, and a modified version of the Community Radiative Transfer Model (CRTM), whose particle optical property lookup tables are consistent with the particle size distributions assumed in the WRF microphysics parameterization schemes (MPSs). Major objectives include:

1)   Examine the structure and dynamics of the correlations/covariances between the all-sky brightness temperatures generated by the CRTM at GMI frequencies and the model state variables through convection-permitting ensemble and parameter sensitivity simulations with MPSs coherently linked to the CRTM. Identify the best-performing parameter configurations for the NASA Goddard bulk MPS (compared to other bulk and bin MPSs available within WRF), along with inherent uncertainties, to be used in the data assimilation experiments.

2)   Conduct observing system simulation experiments (OSSEs) via assimilation of simulated GMI brightness temperatures and other satellite observations with special emphasis on their effectiveness for quantitative precipitation forecasts (QPFs) and hydrometeor quantification. Identify the most impactful satellite observations, most efficient assimilation algorithms, and most desirable model and ensemble configurations for the satellite data assimilation.

3)   Develop effective procedures for data thinning, bias correction and quality control of GMI microwave brightness temperatures; conduct extensive observing system experiments (OSEs) assimilating real-data GMI microwave observations as well as other in situ and remote-sensing measurements in further evaluation of the effectiveness of satellite observations in improving weather prediction and precipitation estimation.