Final Report

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Project Title: High-latitude precipitation studies using combined active and passive microwave satellite observations

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Project Objectives

The following research themes are to be addressed in the project (excerpt from proposal abstract):

- We propose to adapt our combined active/passive modeling framework that was developed using currently available CloudSat, Advanced Microwave Scanning Radiometer (AMSR-E), and Advanced Microwave Sounding Unit-B (AMSU-B)/Microwave Humidity Sounder (MHS) observations to coherently simulate all GPM passive microwave frequencies and radar returns at DPR frequencies. This approach can be applied to mesoscale model output to generate synthetic observations, as well as to actual observations using CloudSat, AMSR-E, and AMSU/MHS as proxies for GPM instruments. This combined modeling platform allows the active and passive response to precipitation to be modeled in a physically consistent framework and also enables uncertainties associated with the simulations to be readily obtained.

- We plan to continue our current higher latitude precipitation studies with the combination of AMSR-E, AMSU/MHS, and CloudSat as proxies for GPM. Based on our forward model approach we will determine errors and uncertainties associated with snowfall retrievals due to the choice of ice particle model and particle size distribution parameterization. The utility of these errors and uncertainties can be further enhanced by stratifying them regionally or by precipitation category or cloud type.

Final Progress Report:

1. Research Progress

This project has focused primarily on developing microphysical modeling tools for microwave precipitation retrievals and performing combined active and passive remote sensing of higher latitude precipitation using proxy GPM observations comprised of CloudSat, AMSR-E, and MHS data. A core effort has been the continual development of an ice model scattering database using both non-spherical and variable density spherical and ice models. This database synthesizes scattering properties for a wide range of microwave frequencies onto a consistent particle mass or dimension grid by interpolating results from the original investigators' datasets to provide scattering results that are easily accessible for testing and retrieval applications.

The scattering database and/or combined active/passive modeling system has been heavily utilized in the following manuscripts from our group that have been published with project support:

- Kulie et al. (2010) transformed native CloudSat observations into hydrometeor profiles using radar reflectivity factor (Z_e) to ice water content (IWC) conversions based on the different ice model scattering properties contained in the standardized database. Forward radiative transfer calculations were then performed using the hydrometeor profiles to obtain simulated multi-frequency passive microwave brightness temperatures. The simulated results were compared to AMSR-E and MHS observations to eliminate implausible ice models whose scattering characteristics did not possess the backscatter and extinction properties requisite to produce comparable observational results, and uncertainties in simulated passive microwave brightness temperatures due to ice particle model scattering properties for various precipitation categories were tabulated. Error correlations between different scattering-sensitive GMI-like microwave frequencies under precipitating conditions were also developed and offer an improved ability to account for off-diagonal error covariance matrix elements in retrieval and data assimilation schemes.

- Hiley et al. (2011) also used a combination of CloudSat and AMSR-E data to study W-band radar snowfall retrieval uncertainties using empirical Z_e to snowfall rate (S) relationships developed from the ensemble of ice models in the scattering database. Global snowfall estimates with uncertainty bounds were also produced with direct relevance to the GPM mission. This study also investigated coincident microwave-derived cloud liquid water path and snowfall occurrence, and a validation exercise also compared snowfall retrievals with Canadian ground-based measurements.

- Kneifel et al. (2011) compared modeled Ku-/Ka-/W-band snowfall radar signatures using a subset of ice models and highlighted the potential for snowflake habit to be determined (and thus obtaining a critical microphysical retrieval constraint) from distinctive triple-frequency radar signatures of larger, aggregated snowflakes.

- Di Michele et al. (2012) used non-spherical ice model Z_e-IWC relationships from the scattering database to assess global circulation model errors by comparing globally-averaged model results to CloudSat observations.

- Kulie et al. (2013) performed an triple-frequency radar analysis on an airborne dataset from the NASA-sponsored Wakasa Bay field campaign to assess the Kneifel et al. (2011) modeling results and highlight similar distinctive features between radar modeling and observational results.

2. GPM Algorithm Development Team Activities

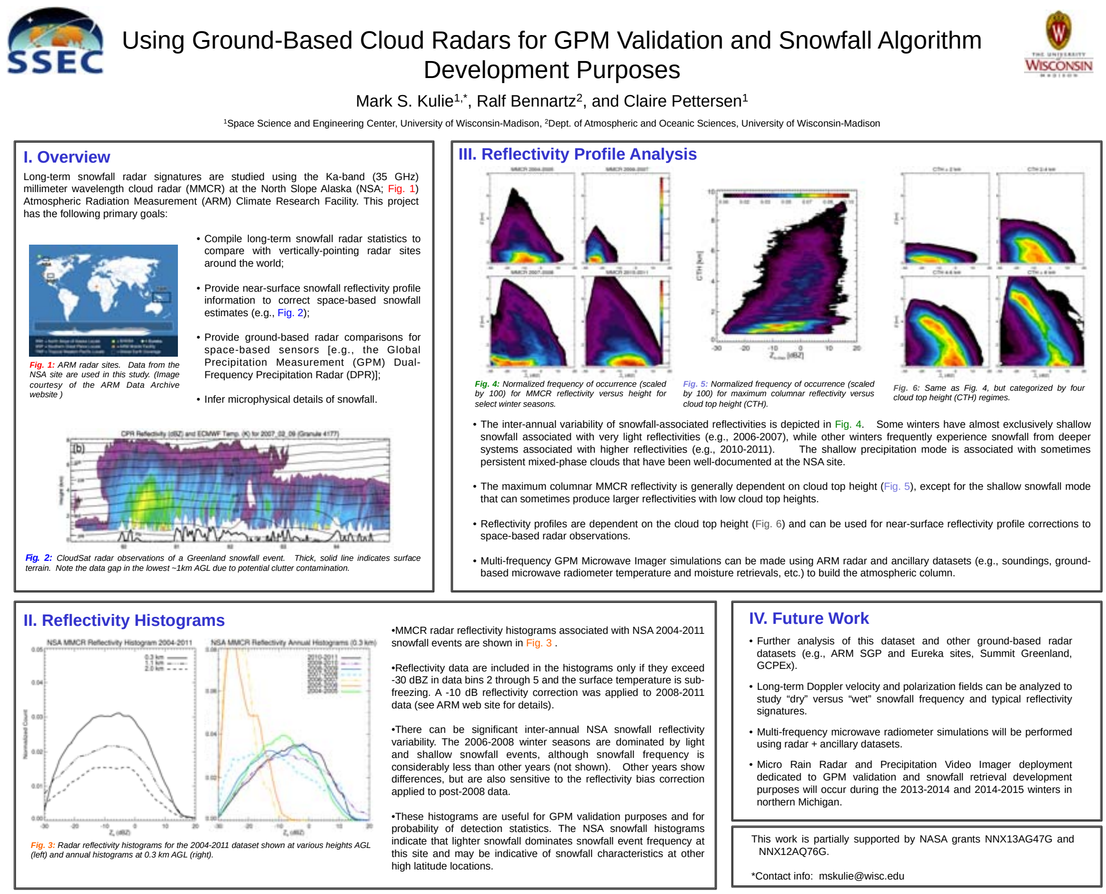
We continue to work closely with the GPM Radiometer Algorithm Team to assist with Day 1 algorithm development activities. Our initial limited CloudSat/AMSR-

E observational and empirical cloud property profile dataset (~30 A-Train orbits) was expanded to include near-coincident CloudSat, AMSR-E, and MHS observations for a 5-year period. We also produced end-to-end code to bin these combined radar-radiometer observations by skin temperature, precipitable water vapor amount, and surface emissivity class to conform to the GPROF algorithm environment. Furthermore, all profiles in this 5-year database were matched with numerical model-generated profiles based on a unique set of observational-modeling matching criteria that considered both radiometer and radar properties in the matching procedure. This updated higher latitude dataset was delivered to C. Kummerow at Colorado State University and integrated into the GPM the Day 1 passive microwave precipitation algorithm.

3. International Workshop on Space-based Snowfall Measurement

We have been actively involved in the planning the 4th International Workshop on Space-based Snowfall Measurement (IWSSM) to be held in Mammoth Lakes, CA in May 2013, with PI R. Bennartz serving as the lead member of the Program Committee for this workshop. The IWSSM is jointly sponsored by the International Precipitation Working Group (IPWG), the GEWEX Radiation Panel (GRP), NASA's CloudSat Mission, and NASA's Precipitation Measurement Missions (PMM) Program. The IWSSM will build upon the previous workshops and will once again feature a focused agenda to discuss both the current state of the science related to space-based snowfall measurements that is highly relevant to GPM, and to steer future research and technology development related to this field.

4. Overview Poster – PMM Science Team Meeting 2013 (Annapolis, MD)



5. Presentations and Posters (Year 3)

Kulie, M. S., R. Bennartz, M. J. Hiley, S. Kneifel, and S. Tanelli, 2012: Constraining microwave snowfall retrievals with multi-frequency radar observations: A combined modeling and observational perspective. GPM GV Workshop. Toronto, CA, 10-12 July 2012.

Bennartz, R., and M. S. Kulie, 2012: Evaluating microwave ice particle scattering models using multi-frequency radiative closure studies. American Geophysical Union Fall 2012 Meeting. San Francisco, CA, 3-7 December 2012.

Kulie, M. S., N.-Y. Wang, R. Bennartz, and R. Ferraro, C. Kummerow, G. Liu, T. Matsui, K. Mohr, S. J. Munchak, D. Randel, and G. Skofronick-Jackson, 2012: Leveraging currently available spaceborne microwave observational datasets for GPM-related algorithm development purposes. American Geophysical Union Fall 2012 Meeting. San Francisco, CA, 3-7 December 2012.

Kulie, M. S., and R. Bennartz, 2013: Improving GPM-era higher latitude precipitation retrievals using enhanced microphysical modeling tools and multi-frequency radar observations. PMM Science Team Meeting. Annapolis, MD, 18-21 March 2013.

Kulie, M. S., R. Bennartz, and C. Pettersen, 2013: Using ground-based cloud radars for GPM validation and snowfall algorithm development purposes. PMM Science Team Meeting. Annapolis, MD, 18-21 March 2013.

6. Peer-Reviewed Publications (2010-2013) Supported by this Project

Kulie, M. S., R. Bennartz, T. Greenwald, Y. Chen, and F. Weng, 2010: Uncertainties in microwave optical properties of frozen precipitation: Implications for remote sensing and data assimilation. *J. Atmos. Sci.* **67**, 3471-3487.

Kneifel, S., M. S. Kulie, and R. Bennartz, 2011: A triple-frequency approach to retrieve microphysical snowfall parameters. *J. Geophys. Res*., **116**, D11203, doi:10.1029/2010JD015430.

Hiley, M. J., M. S. Kulie, and R. Bennartz, 2011: Uncertainties in CloudSat snowfall retrievals. *J. Appl. Meteor*. *Clim*. **50**, 399-418.

S. DiMichele, M. Ahlgrimm, R. Forbes, M. Kulie, R. Bennartz, M. Janiskova, & P. Bauer, 2012: Interpreting an evaluation of the ECMWF global model with CloudSat observations: Ambiguities due to radar reflectivity forward operator uncertainties. *Q. J. Royal Meteor. Soc.,* **138**, 2047-2065.

M. J. Weber, B. B. Yang, M. S. Kulie, R. Bennartz, and J. H. Booske, 2012: Atmospheric attenuation of 400 GHz radiation due to water vapor. *IEEE Trans. on Terahertz Sci. and Tech*., **2**, 355-360.

Kulie, M. S., M. J. Hiley, S. Kneifel, R. Bennartz, S. Tanelli, 2013: Triple frequency radar reflectivity signatures of snow: Observations and comparisons to theoretical ice particle scattering models. *J. Appl. Meteor*. *Clim*. In revision.