CGMS-39 EUM-WP-19
v1A, 9 September 2011
Prepared by EUMETSAT
Agenda Item: G.II/5
Discussed in WG II

REPORT ON THIRD INTERNATIONAL WORKSHOP ON SPACE-BASED SNOWFALL MEASUREMENT

This paper presents the results of the Third International Workshop on Space-based Snowfall measurement which was held in March/April 2011 in Grainau, Germany.

The workshop was endorsed by the International Precipitation working group (IPWG) the GEWEX Radiation Panel (GRP) and NASA's Precipitation Measurement (GPM) and CloudSat Mission.

Recommendations proposed from the Workshop directly relevant for CGMS-39 are:

Recommendation 1: The snowfall community is confident in the capabilities of Space-borne **multi-frequency Doppler radar** for global snowfall measurement and we urge national space and science agencies to plan missions that implement double-frequency capability at a minimum.

Recommendation 3: Space agencies should continue to favour integrated science teams that encompass the measurement, modelling and data assimilation communities through proposals, campaigns and free dataflow.

Report on Third International Workshop on Space-based Snowfall Measurement

1 Introduction

The Third International Workshop on Space-based Snowfall Measurement (IWSSM-3) was held in Grainau, Germany from March 30 - April 2, 2011. The workshop was organized as part of the International Precipitation Working Group (IPWG) and endorsed by the GEWEX Radiation Panel (GRP), NASA's Global Precipitation Measurement (GPM), and NASA's CloudSat Mission. In total 49 participants attended the workshop, which was a follow-up on two earlier workshops held in October 2005 in Madison, Wisconsin and in March 2008 in Steamboat Springs, Colorado. Since the inaugural workshop in 2005 significant progress was made in several areas, most notably the development of particle scattering models and databases, the development of radiative transfer models, and the use of radar data for snowfall measurement using CloudSat.

The full report is presented in the Annex to this paper, while some important aspects of it are highlighted here.

2 General Considerations

The high priority recommendations that emerged from the working group discussions and subsequent plenary sessions are presented in the report. They cover scientific as well as programmatic aspects that the conference participants viewed as essential for a further scientific progress over the coming years. The high priority recommendations are further substantiated and a detailed list of open programmatic and scientific issues associated with each working group topic is presented.

A possible path forward is first to implement a research mission that can demonstrate the impact and feasibility of the new required measurements. Once said mission is accomplished, the design of multi-platform constellations could be considered to increase global coverage (spatial and temporal) with higher data/observation update rates. It is not clear yet what repeat time is required. A diurnal cycle in the Arctic is largely nonexistent but there are ice edge-ocean circulation effects and there are summer-winter differences.

3 Satellite Observations in Mountainous Regions

Finally, there was some discussion on the role of satellite observations for providing snowfall information in mountainous regions. Although these regions are important for hydrology, they also pose significant challenges to both active and particularly passive snowfall retrievals due to the highly variable terrain and extremely inhomogeneous nature of orographic precipitation. The question was posed: what can observations contribute to improve orographic precipitation from NWP models? It was concluded that the CloudSat and EarthCARE radars may be capable of providing a first cut at estimating snowfall in mountainous regions but that radar measurements would benefit greatly if clutter was reduced through a combination reducing pulse width and clutter-removal software.

4 Mission definition Guidelines

It was stated that there is convergence on the importance of radars and radiometers in addressing the observational gaps left open by current missions. However, observations from lidar and far-IR passive sensors are useful (and necessary for certain goals) and they complement the radar and radiometer measurements. If such instruments cannot be included in a given mission, synergies with other missions operating in the same timeframe should be explored, encouraged and coordinated.

It is highly desirable to have meteorological information to aid in the retrieval of snowfall. So, it is recommended to co-fly with other meteorological instruments on the same platform and in a "train" formation with other satellites. Similarly, it is highly desirable to have other related physical and micro-physical measurements with many co-locations and at all latitudes but this requires considerable planning and coordination amongst missions.

5 Conclusion

The snowfall community is confident in the capabilities of space-borne multi-frequency Doppler radar for global snowfall measurement and they urge national space and science agencies to plan missions that implement this capability at a minimum. These capabilities could be greatly enhanced through the following technological advances: (1) reduced radar pulse width to enhance near surface detectability and (2) the inclusion of a sub-millimeter-wave radiometer to provide additional constraints on ice water path and constrain ice particle sizes.

In the next few years, there are several upcoming opportunities, suitable to propose a snowfall process, a snowfall mapping mission or both. Such opportunities include EE9, NASA Venture missions or the NASA-ESA Joint call. A process mission implies a radar to profile the precipitation and microphysical processes in a column through the atmosphere, while a mapping mission implies a radiometer mission to provide spatial coverage. A joint radar-radiometer mission is preferred since the complementary information from the two sensors can be used to address a wide range of scientific applications. Detection of ice crystals, snow fall and light precipitation require high sensitivity suggesting the inclusion of lidar and Far Infrared measurements. It is recommended for the scientific community to be aware of coordinated (via IWSSM) mission proposals. Measurements of snowfall from space are still within the realm of research and not operations. It is recommended to portray it accurately.

Annex I Workshop Report

Report on the Third International Workshop on Space-based Snowfall Measurement

30 March - 2 April 2011

Grainau, near Zugspitze, Germany

Ralf Bennartz[1], Paul Joe[2], Ulrich Loehnert[3], Jarkko Koskinen[4], Gail Skofronick-Jackson[5], Deborah Vane[6]

(Editors)

1. University of Wisconsin – Madison
2. Environment Canada
3. University of Cologne
4. Finnish Meteorological Institute
5. NASA – Goddard Space Flight Center
6. Jet Propulsion Laboratory

Executive Summary

The Third International Workshop on Space-based Snowfall Measurement (IWSSM-3) was held in Grainau, Germany from March 30 - April 2, 2011, endorsed by the International Precipitation Working Group (IPWG), the GEWEX Radiation Panel (GRP), NASA's Global Precipitation Measurement (GPM), and NASA's CloudSat Mission. The following top-level recommendations emerged from the workshop:

- **Recommendation 1:** The snowfall community is confident in the capabilities of spaceborne **multi-frequency Doppler radar** for global snowfall measurement and we urge national space and science agencies to plan missions that implement double-frequency capability at a minimum.

- **Recommendation 2**: **Radar capabilities could be greatly enhanced** through the following technological advances: (1) reduced radar pulse width to enhance near surface detectability and (2) the inclusion of a submillimeter-wave and/or high frequency microwave radiometer to provide additional constraints on ice water path and constrain ice particle sizes. It is further recommended the scientific community explores potential synergies between radar and lidar observations.

- **Recommendation 3: Space agencies** should continue to favor integrated science teams that encompass the measurement, modeling and data assimilation communities through proposals, campaigns and free dataflow.

- **Recommendation 4:** Encourage **NWP modeling community** to facilitate external user access to their physics package via up-to-date interfaces like single column models (SCM), allowing the observation/validation community to have real-time access to model response. Model location time series data output at ground research sites should be made easily accessible on a routine base. In addition, data assimilation should be recognized as a necessary component of snow analysis from space-based measurements.

- **Recommendation 5: Continue using "modeling chains"** as a basic research tool to develop an understanding of the relationship between snowfall and radiative transfer.

- **Recommendation 6: High-level coordination of international GV programs for snowfall (e.g., through GPM, GEWEX, IPWG)** should continue to be pursued to advance the current state of snowfall retrievals. Focal points are needed to (1) insure that current international assets are utilized and (2) help in the planning of upcoming GV programs/field campaigns. Engagement with other disciplines (e.g., atmospheric chemistry, cryosphere, etc.) for mutually beneficial collaboration, including the free exchange of unique data sets such as SNOTEL observations, etc is strongly encouraged.

- **Recommendation 7: MW transmission** links with parallel particle probing, inter-sensor validation in radiance/reflectivity space, and statistically robust datasets for (frozen) cloud processes are needed to establish links between bulk mass properties and bulk radiative properties of falling snow. MW transmission links should cover frequency ranges between 10 and 200 GHz to directly observe extinction properties of frozen precipitation and should be linked to disdrometers and other in-situ instruments that characterize precipitation particles.

- **Recommendation 8**: **Dedicated case studies/aircraft campaigns:** Encourage studies to fully describe the microphysics of clouds of different type and geographical areas using existing datasets. Fill existing gaps associated with major uncertainties in radiative properties with measurement campaigns that offer closure, e.g., constrained measurements of radiative properties with collocated in situ measurements; particularly in the Arctic.

Table of contents

1. Overview

The Third International Workshop on Space-based Snowfall Measurement (IWSSM-3) was held in Grainau, Germany from March 30 - April 2, 2011. The workshop was organized as part of the International Precipitation Working Group (IPWG) and endorsed by the GEWEX Radiation Panel (GRP), NASA's Global Precipitation Measurement (GPM), and NASA's CloudSat Mission. In total 49 participants attended the workshop, which was a follow-up on two earlier workshops held in October 2005 in Madison, Wisconsin and in March 2008 in Steamboat Springs, Colorado. Since the inaugural workshop in 2005 significant progress was made in several areas, most notably the development of particle scattering models and databases, the development of radiative transfer models, and the use of radar data for snowfall measurement using CloudSat.

The workshop consisted of plenary sessions interspersed with working group break out discussions with focus on Applications and Validation, Global and Regional Detection and Estimation, Radiative Properties, and Missions and Concepts. Scientific presentations covered various research and programmatic aspects involving different missions such as GPM, EarthCare, CloudSat and other planned missions, snowfall modeling for radiative transfer, retrieval algorithms, and the potential for data assimilation. Questions for the break out sessions were prepared before the meeting by appointed working group chairs who afterwards organized the breakout session notes in the form of draft reports. These draft reports were condensed into seven high priority recommendations.

The high priority recommendations that emerged from the working group discussions and subsequent plenary sessions are presented in Section (2) of this report. They cover scientific as well as programmatic aspects that the conference participants viewed as essential for a further scientific progress over the coming years. Section (3) is subdivided into four parts and contains the detailed report of the five working groups. In section (3) the high priority recommendations are further substantiated and a detailed list of open programmatic and scientific issues associated with each working group topic is presented. Section (4) provides the workshop program and a list of attendees.

2. High priority recommendations

In this section, we list the high priority recommendations that originated from the working groups and subsequent plenary discussions. Some of the below recommendations are modified and updated from those of the first and second workshop. A more detailed discussion of the recommendations can be found in the subsequent working group reports. It would be highly desirable if the recommendations from this workshop be regularly tracked and reported by the IPWG, GPR and GPM programs. The following items were considered high priority recommendations:

- **Recommendation 1:** The snowfall community is confident in the capabilities of spaceborne **multi-frequency Doppler radar** for global snowfall measurement and we urge national space and science agencies to plan missions that implement double-frequency capability at a minimum.

- **Recommendation 2**: **Radar capabilities could be greatly enhanced** through the following technological advances: (1) reduced radar pulse width to enhance near surface detectability and (2) the inclusion of a submillimeter-wave and/or high frequency microwave radiometer to provide additional constraints on ice water path and constrain ice particle sizes. It is further recommended the scientific community explores potential synergies between radar and lidar observations.

- **Recommendation 3: Space agencies** should continue to favor integrated science teams that encompass the measurement, modeling and data assimilation communities through proposals, campaigns and free dataflow.

- **Recommendation 4:** Encourage **NWP modeling community** to facilitate external user access to their physics package via up-to-date interfaces like single column models (SCM), allowing the observation/validation community to have real-time access to model response. Model location time series data output at ground research sites should be made easily accessible on a routine base. In addition, data assimilation should be recognized as a necessary component of snow analysis from space-based measurements.

- **Recommendation 5: Continue using "modeling chains"** as a basic research tool to develop an understanding of the relationship between snowfall and radiative transfer.

- **Recommendation 6: High-level coordination of international GV programs for snowfall (e.g., through GPM, GEWEX, IPWG)** should continue to be pursued to advance the current state of snowfall retrievals. Focal points are needed to (1) insure that current international assets are utilized and (2) help in the planning of upcoming GV programs/field campaigns. Engagement with other disciplines (e.g., atmospheric chemistry, cryosphere, etc.) for mutually beneficial collaboration, including the free exchange of unique data sets such as SNOTEL observations, etc is strongly encouraged.

- **Recommendation 7: MW transmission** links with parallel particle probing, inter-sensor validation in radiance/reflectivity space, and statistically robust datasets for (frozen) cloud processes are needed to establish links between bulk mass properties and bulk radiative properties of falling snow. MW transmission links should cover frequency ranges between 10 and 200 GHz to directly observe extinction properties of frozen precipitation and should be linked to disdrometers and other in-situ instruments that characterize precipitation particles.

- **Recommendation 8**: **Dedicated case studies/aircraft campaigns:** Encourage studies to fully describe the microphysics of clouds of different type and geographical areas using existing datasets. Fill existing gaps associated with major uncertainties in radiative properties with measurement campaigns that offer closure, e.g., constrained measurements of radiative properties with collocated in situ measurements; particularly in the Arctic.

3. Working group reports

3.1. Applications and Validation (D. Hudak and J.-P. Blanchet)

Validation goes beyond direct comparisons of surface precipitation rates between ground and satellite measurements in order to provide the means for improving satellite simulators, retrieval algorithms, and model applications. It is necessary both in pre-launch algorithm development and in post-launch product evaluation/improvement.
It necessarily needs to encompasses a wide variety of scales, technologies, and scientific methodologies

From the basic scientific method of theorization and experimentation, applications of snow measurements to model precipitation in forecast and climate simulations is closely linked to the need for reliable *in situ* data in a validation effort. These efforts must include longer term enhanced ground measurement observation sites as well as Intensive Operational Programs campaigns that also include research aircraft. The validation programs need to account for regional variation in precipitation characteristics. This encompasses latitudinal variation (mid vs high) as well as precipitation regimes (maritime vs continental). They must also take into account the underlying dynamic meteorology context: baroclinic synoptic systems, orographic, cold air over open water, and cold lows. An urgent need for a High Arctic measurement campaign was highlighted, especially for investigating the ice nucleation processes, the initiation of ligh snow precipitation and the role of aerosol composition in the cloud formation, including the effect of variation of anthropogenic acid content.

In our group discussion, the applications and validation issues were joined in a single working group to examine the status of the field and to propose recommendations for the next few years.

Programmatic Recommendations:

In order to optimize scientific yield toward improving our understanding of snow precipitation processes in applications to forecast and climate modeling, it is essential to promote further integration of instrumentation at sites and in field campaigns to the highest degree. Comprehensive and effective synergetic retrieval from multiple platforms leading to reference databases remains one important goal to achieve. We have identified some steps to make progresses in that direction:

- Modeling community should facilitate external user access to their physics package via up-to-date interfaces like single column models (SCM), allowing the observation/validation community to have real-time access to model response.

- Model location time series data output at ground research sites should be made easily accessible on a routine base.

- Observation/validation community should develop software analogs of their instruments for implementation into comprehensive atmospheric models at proper scale for sampling the simulation in a comparable way to real observations. This includes the translation of measurements into model/simulator relevant parameters.

- Advanced data assimilation methods should encouraged for integrating complex data streams into a unified database format, consistent with model analysis and validation needs.

- Emphasis should be placed on training HQP working at the measurements/ validation and modeling interface.

- Continue to favor integrated science teams that encompass the measurement, modeling and data assimilation communities through proposals, campaigns and free dataflow.

- The production of an inventory of network observational facilities (e.g. radar, surface gauges) and useful contacts for the acquisition of the data and communication.

- Make better use of data of past validation experiments by providing well documented and unified formats for most efficient application into validations exercises.

Scientific Challenges

Although many applications of snow precipitation relates to surface hydrology, requiring only 2D surface accumulation field, it is becoming increasingly important to consider the links between clouds and precipitation as 3D volume snow fields. Priority areas to address these issues are:

- Vertical and temporal resolution of precipitating ice clouds and mixed phase clouds (MPC), both in observations and models in a consistent way.

- Arctic TIC and MPC are synoptic scale precipitating snow clouds poorly addressed in atmospheric model and deserving to be investigated in greater details from, both, applications and validations perspectives. CloudSat-CALIPSO satellites have shown that thin ice clouds (TIC) are a dominant (in occupancy volume) type in cold regions of the globe, including equatorial tropopause and Polar Regions. Light snow and diamond dust precipitations accounting for a substantial fraction of total snow precipitation during polar winter are also clouds playing key roles in the internal atmospheric water and radiative budget.

- Mixed-phase clouds are another major issue. The current sensors and retrievals are insufficient to quantify supercooled water in mixed-phase clouds. Any information about the vertical distribution of the supercooled liquid water, e.g. a liquid water top height, would be valuable to constrain microphysical parameterizations in model.

- Sampling IFN composition (e.g. SPLAT) in TIC and MPC remains a challenge deserving more attention, especially to verify laboratory experiements suggesting key role of the acid fraction in nucleation andprecipitation efficiency.

- Blowing snow remains a challenge to discriminate precipitating snow from upper cloud layers.

Microphysics Applications

In order to close the gap between cloud microphysics and the radiation budget physical validation studies are required. They should be targeted to investigate the following areas:

- Vertically resolved measurements directly related to physical formulations embedded in algorithm designs.

- Improved understanding of underlying dynamical and microphysical properties of weather systems throughout their life cycles.

- Natural variability and error characterizations/covariance of measurements.

- Specific scientific questions to be addressed:
  - Development of robust density vs particle size/type relations;
  - Shape vs size, dependency on T, meteorological regime
  - Mixed phase clouds – where is the liquid?
  - Importance of details of the radiative properties of the snowpack
  - Aerosols and their effect on snowfall;
  - The measurement of blowing snow;

Scale dependencies Applications

Scale dependencies are a major issue in climate and NWP models. Instead of characterizing the grid-box mean of climate models by satellite observations, it might be more attractive to have high resolution data (with horizontal resolution of 1-3 km) which can constrain the sub-grid variability in such models, and help to validate high-resolution NWP and research models (which can then be used to address the issue of scale-dependency in climate models). In addition, hydrological modeling requires a connection be made between the physical measurements at the surface and what the satellite measures.

Progress in this area can be achieved firstly through network validation studies that leverage of National Meteorological Service operational radar and weather observing networks. Attention needs to be paid to the development of quality control procedures and standards and accessibility to the raw data where possible. Specific network validation studies to understand and resolve first order variability include:

- The identification of bias discrepancies between satellite and ground-based measurements.
- Developing statistics on different climate regimes and the associated variability of cloud and precipitation properties.

Integrated validation studies are required to advance our understanding of scale dependencies in a major way. It involves the integration of satellite precipitation products into weather, climate, land surface, and hydrological prediction models. In so doing, a fundamental principle to be established is whether there is a temporal or spatial scale below which it is simply not practical to worry about the satellite observations.

Instrumentation Issues

Technological advances need to be embraced within a variety of measurement programs. These developments include

- Better use of high resolution measurements from instruments such as new model 2D Video Distrometer for detailed particle microphysics applications.
- The expansion in the use of dual polarization radar measurements for precipitation type characterization and precipitation rate estimation.
- Combining remote sensing measurements of vertical profiles, both the combination of radar and lidar measurements and, more generally, measurements from active and passive sensors.

Two priority areas for instrument improvement are bulk measurement of snow mass by aircraft and ground-based sensors and the ability to carry out in-situ of lowest few hundreds metres of the atmosphere.

The measurement principles recommended, particular in physical validation studies, are:

- The incorporation of redundancy in the measurements.
- Concentrating instruments through a multi-sensor (active, passive, *in situ*), multi-platform (surface, airborne, space-borne sensors) approach.

- The sampling of a variety of scales through both bulk and detailed measurements.
- Experimental data collection strategies that emphasize the characterization of precipitation processes.

3.2. Radiative Properties (A. Heymsfield and G. Liu)

Our group identified six areas where more knowledge and data are needed to advance our understanding of ice and snow formation processes and physical properties, their radiative properties, and their retrieval from ground-based and satellite passive and active remote sensing. The six areas are:

1. Particles' Microphysical Properties: More information based on observations is needed to characterize and represent ice and snow particle properties. The most basic property discussed is how to represent the dimension of an ice particle: how do we define the size, maximum dimension and aspect ratio? How do these depend on temperature and cloud formation mechanism? Other major questions and uncertainties include ice particle mass as a function of size and cloud type, the fall orientations of ice particles as a function of their shape, the dependence of shape, degree of riming and where on the ice particles the riming occurs, on cloud type (stratiform, convective, deep versus shallow), distance below cloud top, and temperature. A crucial question is when, where and how aggregates of ice crystals form, what are the habits and sizes of the component particles and why are they selected, and which sizes aggregates represent in particle size distributions and where they are located within clouds, as a function of the cloud's formation mechanism. How do these properties vary geographically, by latitude and longitude, and by maritime or continental locations. How does particle phase vary with temperature and cloud type?

2. Particles' Radiative Properties: Methods for modeling the scattering properties of ice particles with complicated shapes are well-developed, such as Discrete Dipole Approximation (DDA). How accurate are these DDA approximations? Accurate modeling of the scattering properties of these ice and snow particles requires the knowledge of their properties as discussed above and further a full representation of the 3D structure of ice particles of the various types and sizes and the mixture of ice and water within their structure. In particular, the mass-dimension relation for various particle shape and aggregates is desired. What is the relationship between an ice particle 3D structure and its 2D projections from airborne particle probes and ground-based video distrometers? New instrumentation and analysis techniques are needed to make the necessary measurements. Additionally, controlled-testing by running DDA scattering models is needed to understand how much detail is needed in representing a particle in order to capture their scattering properties for actual applications. For example, if we configure a particle with a reasonable mass-dimension relation, do the details, such as aspect ratio, the position of a constituent crystal in an aggregate, etc. affect the scattering properties. And if so, by how much? How do we represent these properties for ensembles of particles and for their distribution with height in a cloud layer?

3. Scattering Tables: There have been several groups who have been/are generating scattering tables for ice particles of different types. It is time to compile/combine these tables and to document them. This is action item. It is very desirable to make available to investigators a set of ice particle scattering tables with clear definitions of the various scattering properties and with the analytic recipes used to construct the particles and the refractive indices used on a central site that are available to the radiative transfer community. Because shape and mass information is available for these ice particles, fallspeeds could and should be included in the tables. This would allow for consistency checks with other aspects of the modeling process.

4. Liquid Water in Clouds: Observations have shown that there is substantial liquid water in some subfreezing clouds. More studies are needed to characterize the liquid water distribution, such as their relation to other meteorological variables, their typical locations (top, middle, bottom of the clouds?), etc. In addition, accurate modeling of the radiative properties of subfreezing cloud will require improved information on the refractive index of supercooled water, which is not now available for low temperature conditions. These efforts are important both for better understanding of the microphysical interaction of supercooled liquid and cloud ice/snow as well as for the improvement of snowfall retrievals that use passive MW measurements.

5. Validation: Ice scattering models/tables that represent these properties have been developed but need validation and closure using data sets with a complete set of information on cloud microphysical structure, both horizontally and over the domain of remote sensing measurements. Idealized/well-constrained conditions, such as measuring the extinction of microwave radiation between two surface-based sites, were discussed.

6. Surface Measurements: Measuring ice particles at the surface (outside of clouds) using a 2D video distrometer (for particle morphology and terminal velocity) and hot-plate (for ice water content and snow precipitation rate) was also discussed. It is believed that there might be some difference between particles inside clouds and those outside due to evaporation, breaking, etc. Measuring particle size distribution differences between those inside and outside clouds is also needed.

Programmatic Recommendations:

1. Develop instruments to fully describe 3D structure of ice particles. In particular, instruments simultaneously determining particle's mass-dimension relation, size distribution, fall speed, etc.;

2. Encourage studies to fully describe the microphysics of clouds of different type and geographical areas using existing datasets, including habit descriptions, mixture, mass, size distribution, orientation, phase, degree of riming, fall speeds, as well as these parameters as a function of meteorological parameters;

3. Fill existing gaps associated with major uncertainties in radiative properties with measurement campaigns that offer closure, e.g., constrained measurements of radiative properties with collocated in situ measurements;

4. Standardize definitions and reporting of microphysical and radiative properties: e.g., the definitions for dimension of ice particles, aspect ratio, aggregation for particle

microphysical properties, specifying models/formula used for computing effective radar reflectivity factor, refractive index, etc.

3.3. Global and Regional Detection and Estimation (G. Skofronick-Jackson, T. L'Ecuyer)

Summary

The primary goal of this working group was to discuss and establish the current state of global/regional snowfall occurrence/intensity estimation and to provide recommendations and action items to further improve snow detection and estimation. Our overarching questions included:

1. What are the maturity levels of active and passive falling snow detection and estimation algorithms?
2. What else is needed to improve these retrievals in the near term, intermediate 3-5 year timeframe, and in the future 5-10 year window?

There has been significant progress in recent years toward improving both active and passive snowfall retrievals from space. At present most global snow algorithms remain empirical in nature but there has also been progress toward physical approaches, particularly for the W-band radars aboard CloudSat and EarthCARE, and these new algorithm are anticipated to emerge in the next few years. Some components of passive microwave (PMW) algorithms are also becoming physically-based but we it is likely that the development and validation of completely physical approaches may take longer. The WG members expect significant progress along these lines in the GPM era. Our remaining discussions revolved around five major themes: detecting falling snow, estimating its intensity, prospects for future global snowfall missions, the role of ground radar and other ground-validation (GV) assets for improving global snowfall retrievals, and single particle versus bulk snowfall characteristics. Particular consideration was given to the problem of discriminating rain and snow in the lowest 500 m of the atmosphere, identifying the presence of super-cooled water, extending snowfall estimates into mountainous regions, and the potential value of using ancillary measures of total accumulation from IceSat and GRACE to provide constraints on total snowfall.

This report begins with an overall statement generated by this group regarding the future of global snowfall estimation followed by a list of high priority recommendations. The remainder of the report documents the motivation for these high-level recommendations and summarizes specific action items that emerged from the group's discussions.

Programmatic Recommendations

Overarching Statement: The snowfall community is confident in the capabilities of spaceborne multi-frequency Doppler radar for global snowfall measurement and we urge national space and science agencies to plan missions that implement this capability at a minimum. These capabilities could be greatly enhanced through the following technological advances: (1) reduced radar pulse width to enhance near surface detectability and (2) the inclusion of a submillimeter-wave radiometer to provide additional constraints on ice water path and constrain ice particle sizes.

Other Programmatic Recommendations

1. Airborne submillimeter measurements of falling snow and ice aloft are necessary to assess their full role in estimating ice particle characteristics from space. We urge the funding of airborne submillimeter instruments and their deployment in field campaigns.
2. Measured and validated relationships between the *bulk* physical properties of falling snow and their *bulk* radiative properties essentially do not exist. We urge the funding of ground-based microwave "link" systems for directly measuring these bulk properties at multi-spectral wavelengths sensitive to falling snow.

High Priority Recommendations for Near Term Action Items:

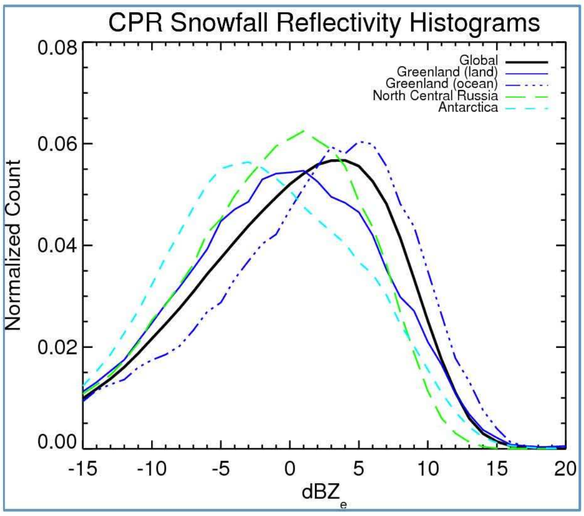
1. The group strongly recommends theoretical and airborne instrument flight studies to quantify the added value of combining sub-mm (200-874 GHz) and multi-frequency radar for snowfall measurement and process studies.
2. We further recommend that existing ground-based radar data be carefully examined to define vertical resolution/blind zone and sensitivity requirements for future spaceborne radar snowfall missions. It is important to consider vertical correlation lengths, height of the melting layer, and the effects of sublimation/evaporation in different geographical climate zones (eg. polar vs. lake effect regimes).
3. In situ direct measurements of bulk physical (eg. bulk PSD, IWC, fall speed, precipitation rate) and multi-spectral radiative properties (eg. scattering, backscattering, extinction, asymmetry) of dry and melting snow are sorely needed to improve global snowfall estimates.
4. Matchups of spaceborne PMW observations with CloudSat and ground-based radar networks and radar/lidar profiling stations are critical for improving the global snowfall detection capabilities of passive instruments. Radar reflectivity, polarization, and in situ datasets should all be considered where available.

Falling Snow Detection and Estimation

One of the primary topics addressed by this working group was the problem of assessing current spaceborne capabilities for the detection of falling snow. Members of the WG reminded us that detection is a function of both the instrument characteristics and the retrieval algorithm employed to extract information from its measurements. The general consensus of the WG members was that detection is easier with radar instruments because of the direct link between reflectivity and particle size/particle presence. The WG participants felt that radar retrievals will be physically-based (not empirical) within 5 years, however, even with radars much needs to be resolved. First one must unambiguously determine that there is no melting layer in the radar profile in order to conclusively determine that the particles remain frozen to the surface and are considered "snow". Because current spaceborne radars have relatively large vertical resolution (~500 m) and suffer from surface clutter in the lowest 2-4 range gates, there was a general consensus that temperature information from NWP models might provide the only current method to determine if falling snow melts, sublimates, or evaporates in the lowest levels above the Earth's surface. However this reliance on NWP models is not desirable under certain circumstances given the large uncertainties associated with modeling temperature structure in the boundary layer. Furthermore, some snow systems can be very shallow, particularly at higher latitudes, and may, therefore, be completely missed by current spaceborne radars due to surface clutter effects. Our working group determined that an examination of existing ground-based radar data should be used to define vertical resolution/blind zone and sensitivity requirements for future sensors and to determine vertical correlation scale lengths, height of the melting layer, and the effects of sublimation/evaporation in different geographical climate zones (Recommended Action #2).

Initial results from CloudSat also that suggest that, with a sensitivity of 10 dBZ, the GPM Dual-wavelength Precipitation Radar (DPR) may miss a significant fraction of snow occurrence (see Figure 1). However, these results are very sensitive to methods used to convert W-band reflectivity observations to Ka/Ku-bands. The extent to which W-band reflectivities 'saturate' due to non-Rayleigh effects is also unclear motivating the use of theoretical studies and ground radar networks to investigate the frequency and detectability of heavy snow events at W, Ka, and Ku bands and to fully populate the PDF in Figure 1. More generally, the challenging regions at the limits of snow detectability should be targeted for more comprehensive study using ground radars.

Figure 1: CloudSat W-band (94 GHz) Cloud Profiling Radar (CPR) reflectivity histograms for snowfall in several different regions (courtesy Mark Kulie).



In terms of passive radiometer detection and retrievals of falling snow, the consensus was that the problem was much harder due to surface emission, column water vapor, and weak signatures from light snow fall events. There was general agreement

18

that for passive retrievals of falling snow, a majority of the problem is detection of snow (versus rain or surface noise/snow covered surfaces). Passive instruments inherently measure the integrated quantity of the liquid or ice water path (LWP, IWP), not vertical information such as radars. The performance of PMW algorithms depends strongly on how the channels are used: methods for minimizing the noise contribution from the surface emission are important, especially over land surfaces. Nevertheless, progress is being made with the 89, 150/166, and 183 GHz channels. From simple theoretical studies, for example, IWP of ~0.5 kg m^{-2} can be detected using only 150 GHz with reasonable (but not perfect) assumptions. Again using simple back of the envelope calculations and a few assumptions about how the IWP is distributed within a cloud, an IWP of 0.5 kg m^{-2} results in a melted rate of ~1.25 mm hr^{-1}. This is a rather heavy snow rate of maybe 1-2 cm an hour but with better algorithms, detection should drop to lower IWP and, therefore, lower snowfall rates.

In order to assist in determining the detection and estimation capabilities of PMW instruments, our WG recommended promoting the analysis of match-ups between AMSR-E/AMSU-B/MHS with CloudSat and corresponding ground radar and lidar measurements to investigate the relationships between W-band radar observations of snow and the 89-183 GHz channels of AMSU-B/MHS. Specifically, the matched data set can be used to test PMW detection thresholds and to develop multi-sensor retrieval methodologies. Further, these matchups can be used to evaluate PMW detection characteristics on an approach-specific basis. Ground-radar data, in particular, may provide an important tool for improving algorithms and has yet to be incorporated in several of the existing matched datasets. Any useful quality controlled ground data (e.g. radar reflectivity, polarization, lidar, and in situ snow observations like those collected during C3VP and GCPEx) should be included in the datasets. The ground data serves the role of providing near surface snow characteristics to be used in surface clutter analysis, near surface melting, sublimation, evaporation studies, and in validating the detection and estimation. Our WG recommended that such match-up datasets or links to them (multiple teams are generating the datasets) be collected and advertised on the corresponding instrument websites (Recommended Action #4). The WG identified at least three sources of such information including satellite matchups being produced by Gousheng Liu and Gerrit Holl (Holl et al, AMT 2010) and the GPM climatological GV prototype featureing matchups of TRMM and NEXRAD observations. Environment Canada and the Finnish Meteorological Institute are also generating matchups of ground-based C-band radar and CloudSat observations (e.g., Canadian NRP radars, FMI radars).

Specific Action Items:

- Collect and examine ground-based vertically-pointing radar data to assess the vertical structure of snowfall near the surface to guide the development of future space-based radar platforms.
- Undertake a study inter-comparing radar-based snowfall estimates and document this state of the art in the literature.
- Coordinate/archive matchups of spaceborne PMW observations with spaceborne and ground-based radar networks. Determine important analyses that should be performed with these matchups.

Bulk Properties of Falling Snow

The WG further determined that the current emphasis on microphysical (single scattering) models is inefficient and that models of the bulk properties of falling snow over larger-scales are more useful for algorithm development. With single scattering models of snowflakes one must integrate over the PSDs to obtain bulk radiative properties. Each scientist's interpretation of the PSD and its minimum and maximum sizes can cause differences in the bulk properties that would then propagate to the detection and retrieval performance. Furthermore, the wide range of single scattering models available can lead to large uncertainties owing to the specific choice of crystal shape and density. Nevertheless, there is a role for microphysical models in that they are important for improving NWP, mesoscale and cloud resolving model simulations and provide a baseline for building bulk models. The WG members suspect that there is most likely a stable relationship between type of snow event (e.g., lake effect, synoptic, blizzard) and its bulk scattering properties and that careful observations of bulk properties in these environments could help determine the most appropriate models in each case. The resulting generic/bulk ice particle models may, in fact, tie in better to model parameterization needs instead of multiple complex habits used in single scattering microphysics.

The WG asked the following questions:

- How do we test/select snow scattering models, mass-dimension relations, and fall speed parameterizations and for application in global retrievals?"
- Can we exclude some models under certain conditions?
- What is the joint behavior (correlations) of these quantities?
- Can we demonstrate that more complex shapes are more realistic than simpler approaches or pristine particles?
- What other observations (or regimes) are of highest priority for future testing for global retrievals?

These questions all point toward needing bulk properties over instrument fields of view. In order to obtain bulk properties of the physical characteristics of dry and melting snow, the WG recommended that in situ direct measurements of bulk physical properties (e.g., bulk PSD, IWC, fall speed, precipitation rate) be made in conjunction with multi-spectral radiative properties (e.g., scattering, backscattering, extinction, asymmetry) (Recommended Action #3). A suggested system for measuring the bulk properties included a combination of multiple radar frequencies set up in combination with a microwave "link" system consisting of a transmitter and receiver separated by ~10 km to measure snow attenuation. Along the path of the "transmitting and receiving" links in situ or ground measurements of the physical properties should be collected. The link system should include measurements applicable to the 89, 150, 183 GHz passive radiometers and collect, for example, spectral dependence, IWC, fallspeed, and particle habits. It may be possible to infer IWC provided the fall speed and total precipitation rate can be measured. These bulk relationships could then be used to determine which integrated single-scattering microphysical models are correct. It was noted, however, that in designing a snow link system, sensitivity is important. In order to measure attenuation in dry snow, sensitivities of at least 0.1 K may be required. Once again, correlations between the bulk scattering properties and corresponding microphysical properties should be investigated in a variety of snowfall regimes.

Specific Action Items:
- Explore and develop the concept of microwave links (Programmatic Recommendation #2)
- Coordinate long-term observations of bulk physical and multi-spectral radiative properties of falling snow with a combination of microwave links and multi-frequency radar.

Ground Measurements of Falling Snow

A significant aspect of the problem of relating bulk scattering properties to snowfall rates is high quality ground-based measurements of falling snow in multiple regimes. The WG suggested specific recommendations be made to the GV community to provide specific data in selected regimes. Our observations and results from a CloudSat/AMSU-B database analysis may help identify regimes where additional GV could benefit our algorithm. Some concerns remain, however, regarding the quality of ground-based measurements of snowfall rate and accumulation and it was recommended that improving such observations be a top priority of the GV community.

The WG also discussed the role of larger-scale ground observing networks for climatological evaluating accumulations on the basin or even continental scale. Ground radars or GV in combination with hydrological models can be used to provide closure on larger scales that might reduce uncertainties in instantaneous measurements. Examples of hydrological evaluation at watershed scales include the proposed HMT or Olympix experiment but the WG wondered: How well can hydrologic cycle be closed over such areas? What additional observations might be needed? How can such studies make better use of ground-based radars?

Specific Action Items:
- Work with the GV and hydrology communities to assess the quality of current ground-based snowfall rate measurements and water cycle closure models.

Future Missions

To address the need to improve snowfall detection and estimation capabilities in the future, the working group discussed future technologies and missions to detect and estimate falling snow from space. Our statement to urge for a spaceborne mission including multi-frequency Doppler radar results from the following discussion items. (1) Multi-Frequency: The CloudSat CPR radar has provided a useful PDF of falling snow reflectivities (and hence snow rates). This PDF indicates that the GPM DPR radar may miss a significant fraction of falling snow (Figure 1) but it is unclear how much non-Rayleigh effects may alias heavier snowfall events to lower reflectivities in the CloudSat observations. We thus recommended a multi-frequency radar consisting of a W-band and either Ka or Ku-band. (2) In addition to linking microphysics to dynamics, Doppler capability may provide an additional resource for helping to discriminate snowfall from faster falling rain drops and perhaps a crude distinction of rimed vs. unrimed snowflakes. (3) Reduced pulse length modes are highly desirable for future satellite-based snowfall measurement to provide a finer vertical resolution near the Earth's surface. This is important for snowfall detection over mountainous regions where vertical gradients in surface height cause significant increases in surface clutter. In addition, for falling snow, sublimation, evaporation, or melting may occur near the Earth's surface and having a fine vertical resolution would assist in capturing such events. The Detection WG has recommended an internal action item of analyzing existing data to define the vertical resolution/blind zone and sensitivity requirements for future spaceborne radar snowfall missions (Recommendation #2). (4) Submillimeter-wave radiometer technologies are anticipated to provide information about particle size and IWP. While many of the exploratory studies involving this technology to date have centered on ice aloft, there is a potential for sub-mm observations to provide these additional constraints in retrievals of falling snow. Because of concerns about the penetration depth of the weighting functions for submm, however, the Detection WG recommends further theoretical studies to quantify the added value of combining sub-mm (200-874 GHz) specifically for snowfall measurement near the surface (Recommended Action #1). Aircraft observations of falling snow at submm frequencies are needed to confirm these theoretical results (Recommended Action #1). Given the importance of accurate IWP information for process studies, including processes related to falling snow, the WG strongly recommends funding agencies to support sub-mm airborne instrument development and test flights in snowfall environments. Several aircraft instruments have been developed or are in the development process including the NASA Goddard Conically-Scanning Submillimeter Imaging Radiometer (CoSSIR) with channels at 183.3±1, 183.3±3, 183.3±7, 325±1.5, 325±3.5, 325±9.5, 448±1.4, 448±3, 448±7.2, 642 (H&V), and 874 GHz. The CoSSIR was flown to investigate cirrus ice clouds. However, both of these instruments need partial funding to make them ready for additional flights to investigate falling snow.

Specific Action Items:

- Expand the theoretical studies of sub-mm radiometer capabilities to include snow scenes, particularly in high-latitude, low-humidity environments.
- Conduct flight campaigns featuring a combination of airborne multi-frequency radar and sub-mm radiometer measurements (Programmatic Recommendation #1).

Other Discussion Topics:

Over the course of the workshop the WG also commented on the importance of identifying and constraining the vertical structure of supercooled cloud water in snowing scenes. The general consensus was that this is a very challenging task with current observing systems and there were few specific suggestions regarding how to address this problem specifically. It was suggested that lidar observations may provide an indication of super-cooled water under some circumstances and that combined radar-PMW snowfall retrievals may offer some potential for extracting the supercooled water signal but more study is needed to determine whether either of these approaches provide a viable solution.

It was also suggested that the polarization difference at 89 GHz may provide a means of detecting the presence of a melting-layer that could be obscured by ground clutter in radar observations. This further highlights the need for exploring synergies between active and passive observations for global snowfall estimation.

It was also suggested that snow accumulation measurements from IceSAT and possibly GRACE may offer a potential constraint on large-scale accumulation estimates from other satellite sensors. The IceSAT community should be engaged to determine the extent to which their measurements may be used as an alternative to the large-scale ground network validation approaches described in Section III, especially considering the fact that IceSat-II will launch in 2016.

Finally, there was some discussion on the role of satellite observations for providing snowfall information in mountainous regions. Although these regions are important hydrologically, they also pose significant challenges to both active and particularly passive snowfall retrievals due to the highly variable terrain and extremely inhomogeneous nature of orographic precipitation. We posed the question: what can observations contribute to improve orographic precipitation from NWP models? It was concluded that the CloudSat and EarthCARE radars may be capable of providing a first cut at estimating snowfall in mountainous regions but that radar measurements would benefit greatly if clutter was reduced through a combination reducing pulse width and clutter-removal software. The PMW may be a much more difficult challenge in mountainous regions and it was concluded that it would be better to focus on the more general problem of snowfall detection over flatter terrain before addressing mountainous regions.

Specific Action Items:

- Engage the IceSAT/IceSAT-II community to explore using IceSAT observations to constrain large-scale snowfall accumulations.
- Target detailed evaluation of the quality of CloudSat snowfall estimates in mountainous areas.

3.4. Missions and Concepts

(P. Joe and S. Tanelli, contributions from P. Kollias and S. Buehler)

Summary

The primary goal of the mission and concepts working group was to identify and establish the observational and scientific gaps of current and planned missions (discussed in 3.3) for snowfall applications (understanding, process, mapping, weather, climate, hydrological and cryosphere;) and identify potential solutions (single, coordinated or multiple missions).. Some key overarching questions include:

- What are the science objectives and requirements? What are the resulting instrument requirements?
- What mission concepts and/or individual missions are needed and also ready to be implemented?
- What type of instruments are planned or conceived so far? Which have not, but have complementary skills that we should explore more in depth?

The first part of the first/second questions are addressed in other WG'S and their input was adopted as the starting point. The existing Observational Gaps (OG) that we need to address can be summarized as:

1) Hydrometeor detection and measurement,
    a. over ground, snow-covered ground, water and ice,
    b. in the lowest 500 m above the surface (and lower)
    c. vertical resolution on the order of 250 m
    d. in mountainous regions.
    e. high latitude
    f. global coverage
2) Hydrometeor phase and type identification
    a. discrimination between rain and snow,
    b. habit classification, even just in broad classes (e.g., rimed and non-rimed aggregates, graupel)
3) identification of the presence of supercooled water

Opportunities

In the next few years, there are several upcoming opportunities, suitable to propose either a snowfall process, a snowfall mapping mission or both. Such opportunities include EE9, NASA Venture missions or the NASA-ESA Joint call. A process mission implies a radar to profile the precipitation and microphysical processes in a column through the atmosphere, while a mapping mission implies a radiometer mission to provide spatial coverage. A joint radar-radiometer mission is preferred since the complementatry information from the two sensors can be used to address a wide range of scientific applications. Detection of ice crystals, snow fall and light precipitation require high sensitivity suggesting the inclusion of lidar and Far Infrared measurements. It is recommended for the scientific community to be aware of coordinated (via IWSSM) mission proposals. Measurements of snowfall from space are still within the realm of research and not operations. It is recommended to portray it accurately.

Instrumentation

Microwave and sub-mm radiometers

Sub-millimeter radiometric technology can extend the range of measurements and is useful for ice sizing aloft. Current studies have focused on mid and upper troposphere.

To date, passive sensors are still the most effective way to obtain wide coverage from space. However, passive sensor retrievals (hydrometeor detection and identification) over land are severely challenged (especially over snow cover and mountainous regions). The use of higher microwave frequencies (89-GHz and above) has shown better potential than traditional lower emission channels and is subject of ongoing research. Furthermore, sub-millimeter radiometric technology can extend the range of measurements and is useful for ice particle information in cirrus clouds. Current studies have focused on mid and upper troposphere.

A radiometer by itself, does not satisfy the OG's listed above. On the other hand, radiometers in combination with a radar(s) are critical to address the mapping observation gaps. It is recommended that the community explore further the capability of sub-mm for the detection and measure snowfall particularly in high latitude environments (shallow systems and low intensity snowfall rates). It is recommended that the community explore snow radar and sub-mm synergies for snowfall retrievals near the surface of the earth at the product and at the raw data levels. Observations from existing sub-mm airborne instruments available (COSSIR, COSMIR, ISMAR, etc) from field campaigns (eg. GCPEX, HALO, etc) can be used to explore this synergy and assess its performance and related uncertainties. It is also recommended to re-visit the sub-mm performance in snowfall environments (Arctic, shallow). Observations from the PEARL site in Eureka and Cloudsat-Calipso data may provide insights. In addition to high latitude climates, there are several applications at tropical latitudes where a snowfall radar/radiometer will be useful. In particular, ice properties in cirrus are challenging using existing sensors and in marine stratus even the detection of these close-to-the-surface cloud types is problematic. It is recommended that these applications be articulated and be included as part of the application suite.

Radar

The findings in regards to the role of radar from the previous IWSSM report were revisited. Progress in mission formulation studies, algorithm development and in situ observations did not alter significantly the fact that radar is still the primary instrument to address the OGs. Also, no new facts or information led to a redefinition of the high-level instrument requirements.

Ka- (35.6 GHz) and W- (94 GHz) bands are confirmed to be the primary radar frequencies of interest. Results of such systems from the ground, airborne and ship-based platforms have demonstrated their potential to address the primary observational needs. Furthermore, several low-risk solutions exist for a nadir looking Ka-/W-band radar that complies with the requirements depicted in Table 3.4.1.

One area of recent progress pertains to the trade off between range resolution and radar sensitivity requirements. The highest priority for the science community remains that of obtaining improved sensitivity and improved resolution (as represented at IWSSM 2009). The simultaneous improvement in both requirements is a significant design (and therefore cost) driver for any radar instrument. Specific measurement requirement scenarios have been defined to enable a radar to acquire data at two (or more) different resolutions to achieve each goal separately. For example, the requirements for shallow snowfall detection (for hydrological or cryospheric purposes) are for very fine range resolution (goal 100m), near the surface with a sensitivity better than -10dBZ. However the measurement requirements to reconstruct the vertical cloud profile of the snow-bearing system (necessary to observe the processes) can be achieved with a coarser range resolution (250m) but with improved sensitivity (-20dBZ). There are significant advantages in considering radar designs that employ 'smart' solutions than the standard single pulse-length and single Pulse Repetition Interval (e.g., employed on TRMM, CloudSat, EarthCARE and GPM) so that information from the multiple channels can satisfy the separate scientific requirements and objectives. It is not necessary to select the most stringent performance requirement for each parameter.

There has been significant progress in the last 4 years in defining radars that can add scanning capability while maintaining the sensitivity, resolution, and Doppler accuracy requirements (at least in their nadir-looking portion of the swath). In fact, while the GPM/DPR (Ku-/Ka-band) is cross-track scanning, it does so by accepting a minimum radar sensitivity of +13 dBZ. This is not sufficient to detect a significant portion of the global snowfall amount. Thus, it limits our ability to understand the atmospheric processes that control snowfall. In addition, the GPM/DPR has no Doppler capability.
Solutions that allow: i) limited scanning at Ka-band, ii) wide scanning at Ka-band, and iii) wide scanning at W-band, respectively are being developed. While such solutions are not yet viable for immediate opportunities, it is expected that they could become viable in 1-5 years. Irrespective of their technological maturity, the act of scanning implicitly requires allocation of resources that reduce the performance with respect to a non-scanning radar. More studies are necessary to quantify the benefits vs. drawbacks of adding the scanning capability to snowfall observing radars. Should the technological advancements make scanning solutions as low-risk as, and financially competitive to, non-scanning solutions, the obvious advantages in coverage make their adoption a straightforward choice.

Triple wavelength (Ku, Ka and W) considerations are emerging given their capability of resolving the size/habit ambiguities left open by dual-frequency approaches. It is recommended that more work be conducted with triple wavelength combinations to study and articulate their benefits and at what cost, especially vis-à-vis to radar-radiometer and to dual-frequency-Doppler combinations.

Adoption of higher frequencies (e.g., in the 150-300 GHz range) bears the potential of resolving smaller particle sizes, but the technology required is not mature yet (given progress in this area in the last 5 years, it would be wise to revisit this area in a 2-3 year timeframe). Also, in this area the synergistic aspects of radar-lidar become a viable alternative solution.

The role of Doppler measurements is two-fold. At a coarse Doppler resolution (low-risk, low-cost implementations available, one being that of the EarthCARE Doppler Cloud Profiling Radar), it suffices to provide unambiguous classification of the observed precipitation returns into at least three broad categories: rain, snow aggregates with little or no riming, and graupel or heavy riming. This classification ability impacts the uncertainties in other types of measurements. It is of paramount importance for the correct interpretation of the observed radar reflectivities (e.g., choice of the most appropriate Z-R and Z-V relationships for quantitative estimation of precipitation and fluxes). At fine Doppler resolution (same technologies available, but advanced sophisticated radar design is necessary), it provides the capability of actually providing convective motions, particle habits and provide stringent constraints to the retrieval algorithms for more accurate estimates of snowfall rates. Ultimately, the community would greatly benefit of Doppler radars capable of delivering the spectrum of fall speeds (as commonly obtained from ground-based Doppler cloud radars). However the technology necessary to achieve this from space has been demonstrated only at a theoretical level. This is a another area where IWSSM should track in the future for significant progress to reassess its feasibility.

Blowing snow is a low-level phenomenon that can confound surface snowfall retrieval. Doppler fall velocities are expected to be small, less than the fall velocity of snow (generally 1-2 m/s). It is recommended to study and include Doppler velocity measurements to separate rain and snow but also snow from blowing snow. The great challenge intrinsic in this scientific question is that the instrument would need to deliver high Doppler accuracy at range bins extremely close to the surface (hence imposing significant requirements on the instrument design).

Liquid water in the column can be used as a constraint in the retrieval algorithms. It is recommended that a radiometric receiver be included in the radar design for snowfall measurement missions. The main advantage of a built-in radiometric capability in the radar is, that by virtue of looking through the same antenna, it achieves high horizontal resolution and perfect collocation to the radar reflectivity measurements (hence removing one of the main sources of error in radar-radiometer combined algorithms). The value of this type of measurements is currently being investigated by the CloudSat Science Team. An experimental radiometric product is included in the 2011 (R05) release of the official products.

OG	Parameter	Goal	Threshold/ requirement
1.a	Minimum Detectable Reflectivity (snowfall) [dBZ]	-20	-10

1.a	Minimum Detectable Reflectivity (process) [dBZ]	-30	N/A
1.b, c	Vertical resolution [m]	100	250
1.c	Horizontal resolution [m]	500	2000
2.a	Doppler accuracy [m/s]	1	1
2.a	Dual Frequency Capability	Yes	No
2.b	Doppler accuracy [m/s]	0.2	1
3.a	Radiometric Capability	Yes	TBD
3.a	Dual Frequency Capability	Yes	Yes

Open items and action items:

- Question of variable vertical resolution at different heights was discussed but need some physical characterization studies on thin ice clouds to resolve this question
- Need to quantify the impact of mis-match beams for dual wavelength radars
- Horizontal resolution measurement requirements still require some study
- Scanning is highly desirable to create a bigger swath but ground clutter issues can create data quality problems, It is recommended to study different vertical resolution scenarios and their impact on performance with a particular focus on swathing type scan strategies. Different technologies such as steerable horns, phased array, parabolic antenna need to be considered.

Lidar

The addition of a lidar to study aerosol to cloud to precipitaiton transformation and processes would extend the dynamic range and the science that could be studies. It is recommended that the scientific community explore the benefits and synergies between the lidar and radar be evaluated using available data (e.g., PEARL data, CloudSat-Calipso data).

Far IR

Measurements in the far infra-red region are useful for basic understanding of the atmosphere in the understanding of cold air outbreaks. Inexpensive bolometers have been developed to measure the thin ice clouds that have been hypothesized to be responsible for cold air outbreaks. It is recommended that such instruments be included.

Mission definition guidelines

As stated earlier, there is convergence on the importance of radars and radiometers in addressing the observational gaps left open by current missions. However, observations from lidar and far-IR passive sensors are useful (and necessary for certain goals) and complements the radar and radiometer measurements. If such instruments cannot be included in a given mission, synergies with other missions operating in the same timeframe should be explored, encouraged and coordinated.

It is highly desirable to have meteorological information to aid in the retrieval of snowfall. So, it is recommended to co-fly with other meteorological instruments on the same platform and in a "train" formation with other satellites. Similarly, it is highly desirable to have other related physical and micro-physical measurements with many co-locations and at all latitudes but this requires considerable planning and coordination amongst missions.

A possible path forward is first to implement a research mission that can demonstrate the impact and feasibility of the new required measurements. Once said mission is accomplished, the design of multi-platform constellations could be considered to increase global coverage (spatial and temporal) with higher data/observation update rates.

It is not clear what repeat time is required. Diurnal cycle in the Arctic is largely non-existent but there are ice edge-ocean circulation effects and there are summer-winter differences.

4. List of attendees

Accadia	Christophe	christophe.accadia@eumetsat.int	EUMETSAT
Battaglia	Alessandro	ab474@le.ac.uk	University of Leicester
Bennartz	Ralf	bennartz@aos.wisc.edu	University of Wisconsin
Blanchet	Jean-Pierre	blanchet.jean-pierre@uqam.ca	University of Quebec at Montreal
Buehler	Stefan	sbuehler@ltu.se	Lulea University of Technology
Crewell	Susanne	crewell@meteo.uni-koeln.de	University of Cologne
Di Michele	Sabatino	sabatino.dimichele@ecmwf.int	European Centre for Medium-Range Weather Forecasts
Gaertner	Volker	volker.gaertner@eumetsat.int	EUMETSAT
Galligani	Victoria	victoria.galligani@obspm.fr	LERMA, Observatoire de Paris
Gorodetskaya	Irina	Irina.Gorodetskaya@ees.kuleuven.be	Katholieke Universiteit Leuven
Haddad	Ziad	zsh@jpl.nasa.gov	Jet Propulsion Laboratory
Hagen	Martin	martin.hagen@dlr.de	Deutsches Zentrum fuer Luft- und Raumfahrt
Heymsfield	Andrew	heyms1@ucar.edu	NCAR
Hiley	Michael	hiley@wisc.edu	University of Wisconsin-Madison Atmospheric & Oceanic Sciences
Holl	Gerrit	gerrit.holl@ltu.se	Lulea University of Technology
Holl	Gerrit	gerrit.holl@ltu.se	Lulea University of Technology
Hoose	Corinna	corinna.hoose@kit.edu	Karlsruhe Institute of Technology
Hudak	David	David.Hudak@ec.gc.ca	Environment Canada
Illingworth	Anthony	a.j.illingworth@reading.ac.uk	Dept Meteorology, University or Reading
Joe	Paul	paul.joe@ec.gc.ca	Environment Canada
Johnson	Benjamin	jbenjam@gmail.com	University of Maryland Baltimore County
Kidd	Christopher	christopher.kidd@nasa.gov	University of Maryland
Kneifel	Stefan	skneifel@meteo.uni-koeln.de	University of Cologne
Koskinen	Jarkko	jarkko.koskinen@fmi.fi	Finnish Meteorological Institute
Kulie	Mark	mskulie@wisc.edu	University of Wisconsin-Madison
Kuo	Kwo-Sen	K-S.Kuo@nasa.gov	NASA Goddard SFC
L'Ecuyer	Tristan	tristan@atmos.colostate.edu	Colorado State University
Leinonen	Jussi	jussi.leinonen@fmi.fi	Finnish Meteorological Institute
Leonard	Katherine	leonard@slf.ch	WSL Institute for Snow and Avalanche Research SLF
Liu	Guosheng	gliu@fsu.edu	Florida State University
Loehnert	Ulrich	loehnert@meteo.uni-koeln.de	University of Cologne
Maahn	Maximilian	maahn@uni-bonn.de	University of Bonn
Mech	Mario	mech@meteo.uni-koeln.de	University of Cologne
Mendrok	Jana	jana.mendrok@ltu.se	Lulea University of Technology
Meng	Huan	Huan.Meng@noaa.gov	NOAA/NESDIS/STAR
Moisseev	Dmitri	dmitri.moisseev@helsinki.fi	University of Helsinki
Petty	Grant	gwpetty@wisc.edu	University of Wisconsin-Madison
Prigent	Catherine	catherine.prigent@obspm.fr	CNRS/Observatoire de Paris
Seifert	Axel	axel.seifert@dwd.de	Deutscher Wetterdienst
Simmer	Clemens	csimmer@uni-bonn.de	University Bonn
Skofronick-Jackson	Gail	Gail.S.Jackson@nasa.gov	NASA Goddard Space Flight Center
Tanelli	Simone	simone.tanelli@jpl.nasa.gov	JPL
Teschl	Franz	franz.teschl@joanneum.at	Joanneum Research
Thoss	Anke	anke.thoss@smhi.se	SMHI
Tyynela	Jani	jktyynel@mappi.helsinki.fi	University of Helsinki
Vane	Deborah	dvane@jpl.nasa.gov	JPL
Wang	Nai-Yu	Nai-Yu.Wang@noaa.gov	University of Maryland/ESSIC
Wood	Norman	nbwood@lamar.colostate.edu	Colorado State University
Xie	Xinxin	xxie@smail.uni-koeln.de	Institute for Geophysics and Meteorology, University of Cologne