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

31 March- 4 April 2008

Steamboat Ski Village, Colorado

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Executive Summary

At the Third International Workshop of the International Precipitation Working Group (IPWG) held in Melbourne, Australia (October 2006), it was recommended that a second workshop on snowfall measurement be organized within the next two years. As such, the Second International Workshop on Space-based Snowfall Measurement (IWSSM) was held in Steamboat Springs, Colorado from March 31 - April 4, 2008. The workshop was also endorsed by the GEWEX Radiation Panel (GRP) and the NASA's Global Precipitation Measurement (GPM). In total 50 participants from America, Europe and Asia attended the workshop. The Workshop was hosted by the Storm Peak Laboratory (SPL) which is a continuously operating snow and microphysics measurement facility administered by the Desert Research Laboratory of Reno, Nevada.

This workshop is a follow-up on an initial workshop held in October 2005 in Madison, Wisconsin. Since 2005 significant progress was made in several areas, most notably the development of surface emissivity models and databases, development of radiative transfer models, and the use of active radar data for snowfall measurement using CloudSat.

The workshop consisted of five plenary sessions followed by working group break out discussions with focus on applications, global and regional detection, modeling, new technology, and validation. The scientific presentations covered various research and programmatic aspects involving new sensors 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 together with the evaluation of the status of the recommendations of the first workshop were condensed into seven high priority recommendations.

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Participants were provided tours of the SPL situated at the top of Mt. Werner. As a state-of-the art snow microphysics observation facility, SPL elucidates many of the challenges and possibilities of snowfall measurement in orographically dominated regions.

The high priority recommendations that emerged from the working group discussions and subsequent plenary sessions are presented in Section (1) 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 (2) briefly assesses the current status of the recommendations made at the first workshop. Section (3) is subdivided into four parts and contains the detailed report of the three working groups. In section (4) 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.

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1. 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 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:** Encourage the generation of **community CRM/NWP model profile databases** that represent natural variability. A parallel effort for databases from observations or combined model simulations and observations is also encouraged.

- **Recommendation 2: Use "modeling chains" as a basic research tool to develop an understanding of the relationship between snowfall and radiative transfer**. A modeling chain begins with a detailed cloud resolving model (CRM) employing a physically robust microphysical model of the ice process, relying on known physical principles and on as few assumptions as feasible. The second component of the "modeling chain" is the representation of the complex optical properties of the ice hydrometeors, employing as few "simplifying " assumptions as possible. The final component of the "modeling chain" is formation of a robust radiative transfer model through the complex ice fields, also with a minimal set of assumptions. Although the complex models employed in such a "modeling chain" may be impractical for real-time retrieval or assimilation, it can provide a basis for making simplifying assumptions that enable retrieval and parameterized microphysical calculations.

- **Recommendation 3: Recognize "Data Assimilation" as a necessary component of snow analysis from space-based measurements.** It was recognized by virtually all of the working groups that a full direct measurement of snowfall by any single space-borne measurement alone is most likely an unattainable goal. Nearly all working groups arrived at the conclusion that space-time distribution of snowfall can be potentially diagnosed most accurately by combining all space based observations with surface based observations over space and time in a physically consistent manner through cloud resolving data assimilation. Although the assimilated analyses could be used as a starting platform for prediction, the emphasis here is strictly on providing a space-time analysis of snowfall from a diverse system of observation tools using a physically robust cloud resolving model as the space-time interpolator and as a tool to build in realistic variability into the analysis resulting by the modulation by small scale features such as topography.

- **Recommendation 4:** Community efforts led by the International TOVS Working Group (ITWG) have successfully led to the emissivity databases and inventories. **Continuing community efforts to study and development of high-latitude surface emissivity products** (10-200 GHz) including error estimates are strongly recommended.

- **Recommendation 5:** The use of **combined active and passive satellite data** for snowfall detection/retrieval should be further encouraged. Active space-borne instruments need to have a low detectability threshold (smaller than roughly 5 dBZ) to detect light rainfall and snowfall. CloudSat as well as the planned missions ACE and EarthCare will provide space-borne cloud radars. In particular, the combined use of CloudSat with AMSR-E and/or AMSU is encouraged.

- **Recommendation 6: Future space borne measurement platforms must have high sensitivity and be able to detect reflectivity down to within 100-200 m of the surface and with a sensitivity of -20 to -30 dBz.** Snowfall occurs primarily from shallow stratiform , orographic or clouds of a CBL producing light snow over long periods. Moreover the low-level snowfall is divided often between blowing and falling snow. Active sensors designed to detect this process must be able to detect reflectivity in the lowest $500m^{-1}$ km of the atmosphere with high sensitivity of -20 dBz or better.

- **Recommendation 7: New passive microwave instruments and new channel combinations need to be studied.** Initial results using the 118 GHz oxygen absorption band and also extended use of the window frequencies between 130 and 170 GHz are promising. Aircraft sensors together with extended channel selection studies provide an excellent testbed for future satellite instruments.

- **Recommendation 8: High level coordination of international GV programs for snowfall (e.g., through GPM, GEWEX, IPWG) should be enhanced** 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. An effort to establish a focal point of past field campaigns has been started and will be followed up by IPWG. This should ultimately include other regional assets (e.g., measurements from power companies, volunteer networks, web-based data sets, long-term measurement sites etc.). GV programs (in support of national programs and international programs) should focus on developing technologies and routine measurements of such information. Data should be made freely available to international research community.

- **Recommendation 9: Dedicated validation:** MW transmission links with parallel particle probing, inter-sensor validation in radiance/reflectivity space, and statistically robust datasets for (frozen) cloud processes are needed. Especially two types of instruments will potentially have a high impact: 1. Vertically pointing micro radars such as (Precipitation Occurrence Sensing System) POSS or Micro-Rain-Radar (MRR). 2. Microwave transmission links that measure attenuation of a microwave beam. Those 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.

2. Assessment of recommendations from the first workshop

2.1. First workshop recommendations with respect to modeling

- *Encourage the generation of **community CRM/NWP model profile databases** that represent natural variability. A parallel effort for databases from observations or combined model simulations and observations is also encouraged.*

Coordinated community modeling development efforts are underway, particularly at the Joint Center for Satellite Data Assimilation (JCSDA) and within the European Numerical Weather Prediction Satellite Applications Facility (NWP-SAF). These efforts are geared toward data assimilation and do not necessarily focus on frozen hydrometeors or snowfall retrievals.

- ***Intensification of data assimilation studies** for the inclusion of precipitation observations in NWP analysis systems (including aspects like short-range forecast errors inside precipitation, observation operator errors/linearity, control variables, model resolution). Investigation of assimilation schemes without linear model assumptions. Systematic studies to evaluate model error covariances used for constructing retrieval databases; possibly error databases.*

Evaluation of errors and error covariances for the entire passive microwave frequency range (e.g., 6 – 200 GHz) is currently being performed as research directed by the JCSDA and ECMWF. These efforts are geared toward data assimilation but include frozen hydrometeors or snowfall retrievals. In May 2005 the International Workshop on Assimilation of Satellite Cloud and Precipitation Observations in Numerical Weather Prediction Models, was held in Lansdowne, Virginia, in May 2005. An overview on issues related to assimilation of snow, rain, and clouds is given in Errico et al. (JAS, Nov. 2007).

- ***Establishment of modeling chain:** Two-dimensional spectral cloud models with multiple ice particle and frozen precipitation categories -> non-spherical (inhomogeneous) particle optical property (permittivity, size, shape) modeling - > development of parameterizations for general use in cost-driven applications.*

Several groups reported progress toward the development of modeling chains as well as toward dedicated observation system simulation experiments (OSSE). A further consolidation and refinement of these activities was deemed valuable by several working groups.

- ***Development of high-latitude surface emissivity products** (10-200 GHz) including error estimates.*

Significant progress has been made in the area surface emissivity modeling. A workshop organized by the International TOVS Working Group was held in June 2006 in Paris about emissivity related problems in the microwaves and in the IR. A summary of the meeting and the presentations are available at http://cimss.ssec.wisc.edu/itwg/groups/rtwg/meetings/sfcem/. Following this workshop, a web site has been developed to collect the various possible sources of emissivities (models, atlases...). The information is available through:

http://www.metoffice.gov.uk/research/interproj/nwpsaf/rtm/emissivity/index.htm. A second workshop is tentatively planned for the spring/summer of 2009.

2.2. First workshop recommendations with respect to new technology

- ***The development and further refinement of inexpensive ground-based remote sensing instruments** for snowfall should be encouraged. Especially two types of instruments will potentially have a high impact: 1. Vertically pointing micro radars such as (Precipitation Occurrence Sensing System) POSS or Micro-Rain-Radar (MRR). 2. Microwave transmission links that measure attenuation of a microwave beam. Those 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. The feasibility of developing new upward looking radiometers to span frequency range of satellite radiometers should be studied (for validation of absorption models).*

The continuing importance of this action item was recognized by several working groups. While various measurement sites have been equipped with passive radiometers (see below under validation), microwave transmission links are still outstanding and yet provide potentially the highest benefit in constraining optical properties of snowfall and mixed phase precipitation.

- *The use of **combined active and passive satellite data** for snowfall detection/retrieval should be further encouraged. Active space-borne instruments need to have a low detectability threshold (smaller than roughly 5 dBZ) to detect light rainfall and snowfall. CloudSat as well as EarthCare will provide space-borne cloud radars. Development of spaceborne rain radars with lower detectability threshold should be encouraged.*

Significant progress has been made in this field, mostly triggered by the availability of CloudSat data. It is recognized that the combination of CloudSat with AMSU-A/B/MHS as well as with AMSR-E will provide opportunities to test combined retrieval methods. There is unanimous consensus that a formalized relationship between GPM and EarthCARE would be extremely useful.

- ***New passive microwave instruments and new channel combinations need to be studied.** Especially the use of channels in the 118 GHz oxygen absorption band and extended use of the window frequencies between 130 and 170 GHz seems promising. Aircraft sensors together with extended channel selection studies provide an excellent testbed for future satellite instruments.*

Several groups reported progress using high frequency channels. Recent studies at ECMWF indicate that 118 GHZ channels might be well suited to detect snow over land surfaces. Studies at ECMWF are ongoing.

2.3. First workshop recommendations with respect Validation

- ***High level coordination of international GV programs for snowfall (e.g., through GPM, GEWEX, IPWG) is urgently needed** to advance the current state of snowfall retrievals. Need focal points 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 There is a need for an inventory (and focal point?) of past field campaigns that might have useful information. Additionally, an inventory of all possible technologies for snowfall/parameter retrievals should be developed. Also, this should include other regional assets (e.g., measurements from power companies, volunteer networks, web-based data sets, etc.).*

Consolidated efforts toward ground-based validation snowfall remote sensing estimates were reported from the Finnish Helsinki testbed and from an integrated German research program. As a result of part two of this action item (inventory) a questionnaire was designed during this meeting and will be sent out. This questionnaire will form the basis of an inventory hosted on the IPWG website.

- ***Dedicated validation:*** *MW transmission links with parallel particle probing, inter-sensor validation in radiance/reflectivity space, statistically robust datasets for (frozen) cloud processes. Microphysical parameters are lacking; GV programs (in support of national programs and international programs) should focus on developing technologies and routine measurements of such information. Data should be made freely available to international research community.*

The continuing importance of this action item was recognized by several working groups. While various measurement sites have been equipped with passive radiometers (see below under validation), microwave transmission links are still outstanding and yet provide potentially the highest benefit in constraining optical properties of snowfall and mixed phase precipitation.

3. Appendix: Working Group Reports

3.1. Applications (Chair D. Lettenmayer)

Recommendations

1. There is a strong need to better measure snowfall, and in many cases satellite measurement is the only viable option. This needs to be communicated in a unified fashion by the community. In so doing, the snowfall community needs a stronger link to the applications community – not just scientists who can “see over the fence” to applications, but to those who actually do applications.

2. General scientific understanding of snow processes is a key application in itself and should be considered as such. The scientific need for information that could be provided by remote sensing should be better articulated – as should the opportunities and limitations for satellite snowfall measurement.

3. There is a need for the SWE (e.g., SCLP) and snowfall communities to work together more closely. Measurement of snowfall at the surface, and remote sensing of SWE, both are confronted by formidable challenges, and it may be that the best hope, at least from the standpoint of land hydrology (and perhaps other) issues is combined estimation.

4. There is a potential to exploit existing point ground measurements for large area validation and diagnosis of snowfall algorithms. For instance, snow depth, and possibly periodic SWE measurements, could be made at many more of the cooperative observer stations in the U.S. (and equivalent elsewhere) at relatively low cost. In the U.S., this would require a partnership with NCDC.

5. Accurately quantifying uncertainties is extremely important. If we can do better than current capabilities, then it's a positive development and we know the benefits of new observations.

6. There is a need for better integration of numerical weather prediction models with observations, especially at fine spatial resolutions (regional) or when higher temporal resolution is important. Furthermore, the use of data assimilation schemes in OSSE-type experiments to evaluate both the interaction of space-time resolution, and error characteristics of snowfall measurement and/or data assimilation should be undertaken.

Detailed working group response to questions

Q1: Under what conditions is snowfall rate, as contrasted with accumulated depth and/or water equivalent of snow, the controlling variable for hydrologic prediction?

There is no "right" answer as to whether measurement of SWE on the ground, as opposed to snowfall, is preferred. From the standpoint of atmospheric physics, it's clear that understanding the processes leading to snowfall, and/or assimilation of atmospheric variables that will improve snowfall prediction, must be the primary emphasis. On the other hand, from a (land surface) hydrologic standpoint, the rate of snow accumulation generally does not matter as much as does the accumulated SWE at the beginning of melt periods – either spring snowmelt, which for the most part dominates the hydrology of regions like the western U.S., or at the onset of rain-on-snow floods (e.g., 1997 Grand Forks, one of the NOAA $1B weather-related natural disasters).

Q2: What other uses of snow information require snowfall rate as opposed to accumulated depth and/or water equivalent of snow (e.g., prediction of soil thermal processes)

There are a host of scientific issues related to atmospheric physics for which a focus on snowfall, as contrasted with accumulated SWE on the ground, are most appropriate. In addition, measurement of falling snow over the ocean and large lakes is key to estimation of the Earth's fresh water budget. Aside from these, in the applications area, snowfall (rate) is a key concern for weather nowcasting in the following sectors:

- **Aviation: visibility and airport operation**

- **Transportation/public safety – including all aspects of visibility**

- **Communications (signal attenuation), and snow accumulation on dishes, especially in remote regions**

- **Avalanche forecasting**

- **Winter recreation**

Q3: What are the critical spatial scales at which the variability of falling snow and/or accumulated snow must be measured for hydrologic prediction purposes, and how do those spatial scales relate to the catchment scale at which hydrologic predictions are to be performed?

There are three dominating scenarios to be considered for prediction and/or application of snowfall measurements: a) orographic systems, b) widespread stratiform systems, and c) hydrologic prediction:

a) Most snowfall occurs in orographic systems, at scales order of a few hundred meters. At these spatial resolutions both atmospheric and hydrologic modeling are heavily affected by error propagation from the synoptic scale initialization and the intrinsic chaotic nature of the simulated processes. Also, snowfall rate retrievals from spaceborne sensors are least accurate over mountainous regions (radiometric measurements are affected by the highly variable background and radar measurements are limited to snowfall rate aloft by increased ground clutter effects). On the other hand, orographic situations are one of the more deterministic atmospheric flow systems once the wind field and other atmospheric state parameters are known. It follows that the most promising approach to estimate snowfall over mountainous regions may be to assimilate all conventional measurements, and all space-borne measurements into a high-resolution model that predicts orographically modulated snowfall patterns.

b) Spaceborne observables at a scale of about 500m and with a sampling time of say 5 minutes would be necessary to explicitly resolve snowing cells in a convective boundary layer such as one finds in lake effect or coastal stratocumulus (type I cellular or roll convection) boundary layers. ***This probably is not a realistic goal as convective activity is inherently probabilistic and a deterministic analysis should not be sought.*** **Instead, a coarser resolution measurement of snowfall rate for stratocumulus in a CBL would likely be useful as a data assimilation constraint, similar to the orographic case described above.**

b) In order to provide accurate 'point' snowfall measurements over widespread systems a horizontal resolution of 1 to 5 km should be adequate to resolve Rayleigh-Benard bands, but one sample every about 5 minutes would be necessary to reconstruct the lifecycle of individual cells. However, if the interest is focused on the

overall large-scale snow contribution of one system, the temporal requirement can be relaxed to 30 minutes (and possibly more) to capture the variability of the first stochastic moments of the snow fall distribution. Since these scenarios are characterized often by low snowfall rates, high-sensitivity, rather than high-resolution should be pursued for spaceborne instruments.

c) For hydrologic prediction purposes, the catchment scale to some extent governs the spatial resolution required of the inputs (e.g., snowfall). However, this is not entirely helpful, as it drives one eventually to the hillslope scale, o(100 m) as stream order (hence catchment size) decreases. On the other hand, the major river systems of most parts of the world – and particularly those where snowfall is a dominant process – are reasonably resolved at the 5-10 km spatial resolution. Furthermore, much of the world is very poorly represented be precipitation gauge networks. This suggests that a focus on snowfall estimation accuracy at the relevant spatial resolution, rather than spatial resolution per se.

Q4: What other applications require snowfall data that are not adequately provided by existing observing networks?

The existing network for observation of snowfall rate is quite sparse, and consists for the most part of (possibly a subset of) weather stations that report in real-time – probably at most a few thousand stations globally. Therefore, essentially all applications that require snowfall information in real-time are under-represented by existing in situ networks (see Q2 as well).

Q5: What are the spatial and temporal characteristics of observing errors of both falling and accumulated snow, and how are those error characteristics affected by vegetation cover and topography?

In general, the errors in estimation of falling as contrasted with SWE on the ground from existing and proposed sensors are not well characterized. Dense vegetation (especially conifer forest) is a critical problem for passive microwave estimation of SWE on the ground. This problem presumably is not an issue to satellite snow observations. On the other hand, it is not likely that critical orographic scales can be resolved by proposed snowfall sensing methods (see also Q3), and it is not clear how variations in topography over the satellite footprint will affect the signal. These are issues that will require more attention by both the SWE and snowfall communities.

3.2. Global and regional detection and estimation (Chair C. Kummerow)

Recommendations

Detailed working group response to questions

Working Group II tried to establish the current state of the art in the remote sensing of falling snow and what goals, both near and longer term, should be emphasized in order to move the field forward.

The first question asked specifically what short goals (less than 3 years) might be achieved through some coordination of activities. The response from four of the five groups was to essentially to move existing algorithms into a framework in which the products could be routinely compared to each other and in-situ data. Four concrete steps were proposed by the breakout panels:

- Identify the algorithms that run routinely
- Identify how often and under what conditions these algorithms can positively identify that snow is occurring through direct comparisons with CloudSat and Sfc radars.
- Assess statistical differences between algorithms through comparisons of PDF of precipitation over large space/time domains
- Assess snow intensity by comparing snow accumulation products among algorithms and to monthly snow accumulations from station data where available

Question 2 was aimed at elucidating the investments that would lead to the greatest impacts in a medium range defined as a 3-10 year time frame. For this question, the five breakout groups converged more or less upon two activities:

- A focused effort to create multi-sensor, specifically active and passive microwave snowfall products such as from AMSU and CloudSat. These efforts would also serve as preparatory for AMSU/GPM synergistic algorithms. For lighter snow in the GPM era, at least two breakout groups suggested that stronger ties should be established between GPM and the EarthCare mission.
- To continue the set-up of integrated modelling chains as proposed in the 2005 workshop. These chains begin with an “atmospheric modelling” component which is then combined with “surface and radiative modelling” to create an end-to-end simulation that can be compared directly to the satellite radiometric observations. Analysing systematic differences between model and observation w.r.t assumptions made for the cloud microphysics parameterization schemes, the single scattering properties (and parametrizations) of hydrometeors and surface properties will help to gain knowledge about weaknesses inherent in each of the components.

Question 3 was designed to seek input regarding longer term (beyond 10 years) requirements for snowfall observations. Many of the responses focused on potential future mission opportunities. There was some consensus for the need to fly combined dual frequency radar and radiometers, with Doppler capabilities of 20-30cm/sec over 1 km spatial scales. This requirement was based upon JPL studies indicating that different ice species could be distinguished with 20-30 cm/sec Doppler capabilities due to the fall velocity versus density relationships. Dual frequency was recommended to distinguish among diverse size distributions while the radiometer was proposed to further constrain the solution while also providing a tool to develop sufficient sampling.

In addition, a number of less ambitious ground based sensors were recommended

- Follow-up on the installation of a micro-radar (vertically pointing, X-Band possibly) radar network, especially to capture snowfall with very low cloud tops (i.e. “lake effect”) which frequently is responsible for intensive snowfall.
- Renew emphasis (especially towards WMO) for the absolute need of a dense ground observing network via “classical” methods, promote (voluntary) observations of consistent observation (i.e. not only total snow depth, but also newly fallen snow)

Question 4 was designed to explore ways in which current snowfall rate observations could be compared to equivalent products from the current operational forecast models as well as Analyses from ECMWF, JMA and or NCEP. Overall, this question did not receive a lot of attention from the breakout groups. While listed separately here, the responses generally suggested that these forecast models and reanalyses could be treated in the same way that algorithms evaluations being proposed under question 1.

Question 5 asked if there were promising techniques to blend models and observations other than data assimilation. The breakout groups emphasized the ability of models to determine the freezing level and wind fields that may be important for blowing snow considerations but stopped short of recommending any specific promising new techniques. A consensus among participants emerged that early work to assimilate higher frequency channels that are sensitive to snow and ice scattering into global models seem promising and should be pursued.

3.3. Modeling of Snow and its Radiative Properties (Chair G. Petty)

Recommendations

The remote sensing of snowfall poses a number of unique challenges relative to other atmospheric remote sensing problems. These include

- The relatively weak and variable passive microwave signature of snowfall as compared with numerous other environmental properties, especially the emissivity of the underlying land, ocean or ice surface.
- The typical shallowness of snow-bearing cloud systems.
- The commonly light precipitation rates associated with snowfall.
- The central role of nonspherical particles (e.g., snowflakes) whose shapes, sizes and scattering properties are undoubtedly highly variable and have not , in any case, been particularly well characterized.
- The relative dearth (globally speaking) of *in situ* measurements suitable for direct training, validation, and calibration of models and algorithms

For these and other reasons, it is recognized that physical models have an essential role to play in the refinement and validation of space-based snowfall retrievals, both passive (e.g,. , AMSR-E, PMM) and active (e.g., CloudSat). This Working Group was tasked with examining the current state of the physical models essential for continued progress in the retrieval of snowfall. In particular, it attempted to characterize the current state of confidence in the physical models and to identify specific areas in which additional theoretical efforts and/or measurements would yield the greatest benefit.

To put these issues into context, it is helpful to describe the chain of individual models and physical assumptions leading from, say, a 3-D representation of a precipitating cloud generated by a cloud-resolving model (CRM) to the presumed passive and active microwave signatures of that cloud:

Component	**Output**	**Quality of output depends on…**
1. Cloud-resolving models (CRM)	3-D fields of temperature, bulk hydrometeor concentrations (usually by category), humidity	1. Realistic initialization and boundary conditions 2. Realistic parameterization of microphysical and other processes 3. Appropriate spatial and temporal resolution
2. Hydrometeor models	Presumed distribution of particle sizes, densities, shapes, phases in each grid box	1. Quality of CRM output 2. Quality of assumptions, which are often driven more by convenience or analytical tractability than by reality
3. Microwave scattering and extinction models	Local extinction coefficient, single scatter albedo, phase function (including radar backscatter cross-sections)	1. Quality of hydrometeor models 2. Quality of dielectric model used 3. Computational method employed (e.g., Mie, DDA, FDTD, etc.) 4. Parameterization or tabulation of computational results

4. Surface model	Emissivity at passive microwave wavelengths, including spectral dependence	1. Knowledge of surface type (soil, vegetation, snow cover, ocean, etc.) and temperature 2. Physical or empirical basis for model, including availability of direct measurements 3. Degree of simplification (e.g., specular, Lambertian, full BDRF)
5. Radiative transfer code	Full resolution brightness temperatures and/or reflectivties	1. Plane-parallel vs. 3D geometry 2. scalar vs. fully polarized 3. single vs. multiple scattering (esp. radar) 4. simplified vs. full scattering phase functions
6. Averaging and resampling algorithm	Observables remapped to sensor scan geometry and resolution	1. Model of effective field-of-view (EFOV) 2. Correct specification of sampling geometry

Inappropriate assumptions or methods in any one or more of the above steps can compromise the value of the entire modeling chain. This is especially true for retrieval methods that explicitly depend on a calibrated forward model (as opposed to those that use models for guidance only). Also, the greater the dependence of the retrieval method on multi-sensor and/or multi-frequency data, the more susceptible the method will be to errors in the characterization of the spectral dependence of key properties, such as attenuation or backscatter.

Detailed working group response to questions

1. How accurately do we believe we are modeling or parameterizing the microwave properties (attenuation, absorption, scattering, radar backscatter, and their spectral dependence) of frozen and melting precipitation, and what is the evidence for that belief?

Generally speaking, we have little direct evidence of how well we are doing with the modeling of snowfall radiative properties. Nevertheless, there is considerable reason to be at least skeptical of the adequacy of current models.

The largest uncertainties in modeling the microwave properties of frozen and melting precipitation probably arise not so much in the numerical solutions of the Maxwell equations as in the large variability (and poor characterization) of particle shapes. The evidence for this belief stems in previous work that shows that numerical approaches such as DDA, FDTD, the generalized Mie approach yield similar results for identical particles.

Nevertheless, further work needs to be done to assess whether the existing numerical tools (DDA, FDTD, Finite Element) used to derive scattering properties as a function of wavelength, refractive index and particle shapes are as accurate as believed. In particular, there remain some concerns about the sensitivity of these methods to the fine-ness of the discretization of the particle shape, especially when dealing with very complex, sparse structures like dendrites.

While confidence in the EM modeling techniques themselves is relatively high despite the above caveat, it is increasingly clear that when the particle shape changes, significantly different results are obtained for the same particle mass and average density.

Furthermore, while "mass" is an unambiguous property of any particle, "density", "volume", and "shape" are not. It is not even clear that the gross properties measured by a 2D particle imager are directly translatable to the parameters relevant to EM calculations.

While the geometric description of an ensemble of snow particles has an extremely large number of degrees of freedom, it is widely accepted that most of these degrees of freedom must "average away" for radiative transfer purposes. Work needs to be done to identify the minimum number of parameters actually needed to adequately characterize "what's in clouds".

The identification of the minimum number of variables needed to uniquely describe a particle shape from the absorption, scattering, and backscattering point of view, as well as their joint variability, must be done by combining modeling and *direct* (e.g., aircraft- and surface-based) observations – models are useless in the absence of the constraints provided by observations, and limited observations are of little value unless they can be extrapolated to a wider parameter space with the help of models.

In view of the wide use of the "fluffy sphere" approximation for snow flakes, one that is primarily undertaken for reasons of computational tractability and convenience, it is essential that the validity and range of applicability of this approximation be carefully evaluated for real snowfall. Note that "validity" is strongly context-sensitive – approximations that are adequate for single- and dual-frequency measurements may fail when applied to a multi-sensor retrievals, especially when combining active and passive observations.

As snowfall remote sensing research increasingly explores microwave frequencies in the range 100-500 GHz, it must be recognized that very little has been done either theoretically or observationally at the higher end of this range. It is understood that computational methods such as DDA will be increasingly difficult to apply at high frequencies owing to the need for finer discretization.

An additional concern is that water vapor absorption models are still not in full agreement, which suggests uncertainty in the modeling of absorption by water vapor. In view of the potential importance of water vapor channels for retrieving snowfall over land, further work is needed to identifying the most appropriate water vapor model.

2. What measurements or new modeling efforts are required in order to further reduce the uncertainties?

The key properties of snowfall relevant to the remote sensing of snowfall rates include

- The bulk microwave extinction cross-section *per unit mass* of falling snow in various forms,
- The single-scatter albedo of the falling snow,
- The radar backscatter cross-section per unit mass,
- The scattering asymmetry parameter and, possibly, higher moments of the scattering phase function.
- The mass-weighted mean fallspeed associated with the above properties.

The frequency dependence of the above properties is critical in view of the growing reliance on multi-frequency and even multi-sensor retrieval methods. In addition, all of the above variables are expected to be sensitive to the size, density, and shape distributions of the falling snow particles – their ranges and joint variability need to be carefully documented.

Specific recommended strategies included the following:

- Focus on measurements tests at local level – i.e., validate and improve individual components of the modeling chain described in the introduction to this section. Comparison of end-to-end model results with observed brightness temperatures (the more common approach to date) does not provide clear guidance on how to isolate or repair any deficiencies identified.

- Exploit existing field campaigns (e.g, C3VP, aircraft icing experiments, others) and propose new campaigns with an optimal suite of instruments in a variety of diverse snowfall regimes in order to document the physically and radiatively important range of snowfall properties encountered globally. The IWSSM community should compile a list of relevant existing campaigns together with key contacts. Possible synergies with snow-on-the-ground field experiments should not be overlooked.

- Aircraft campaigns are critical. C3VP and Wakasa Bay campaigns are examples of highly successful field experiments. GPM ground validation will be a major campaign. Those experiments will yield the highest benefit if the data is made available to the entire scientific community.

- A more systematic, community-based, modular approach to the forward modeling chain should be encouraged. It should be possible to define a standard interface between key elements, including particle shape and size models, dielectric models, etc., so that error characteristics of the forward modeling may be more easily explored .

- It is not yet known to what extent combined active and passive observations will reduce uncertainties in the identification and retrieval of snowfall. Further studies combining active and passive observations should therefore be encouraged. The use of higher frequencies (>200 GHz) is largely unexploited and the additional benefit of those frequencies should be investigated.

- Ground-based observations collected on mountaintops or mountain sides are essential, cost-effective complements to airborne observations. Instruments placed at various altitudes on mountain sides can provide continuous cloud measurements and give insight into how the vertical dimension should be incorporated in parameterizations. Microwave attenuation links, ideally co-located with radar observations of backscatter as well as of precipitation homogeneity along the link path, can provide observations invaluable for validating parameterizations of microwave properties. To be most informative regarding the quality of radiative parameterizations, these measurements must be made simultaneously at three or more frequencies spanning a range from below 50 GHz to at least 150 GHz.

- Community test cases should be developed, thoroughly documented and made publicly available to allow modelers to intercompare methods and results on a common basis.

- Generating a large community database of results for the widest range of assumptions about particle properties, using the most sophisticated computational tools available, will allow modelers the opportunity to derive and/or evaluate simpler parameterizations.

3. How accurately do we believe we are modeling or parameterizing cloud dynamical and microphysical processes relevant to the remote sensing of snowfall, and what is the evidence for that belief? In particular,

- **How sensitive are CRM snowfall simulations to the choice of microphysical scheme?**
- **Which microphysical scheme(s), if any, yield demonstrably superior results?**

Snowfall simulations are very sensitive to the choice of microphysical scheme. When only domain-averaged suspended snow mass is considered, established microphysical schemes employed in the same model (e.g., WRF) often yield factor-of-three or greater differences, even when surface precipitation rates are in good overall agreement. The differences become far larger still when comparisons are made on a point-by-point basis. We do not yet have the ability to identify any one microphysical scheme as superior.

More complex cloud microphysical schemes based on fundamental physics will eventually yield better results than simple parameterizations. In the cloud physics community two-moment bulk schemes are thought to be much better than one-moment schemes because they may capture at least mean growth of hydrometeors and can improve sedimentation. Spectral bin models should be better than two moment schemes by removing constraints on particle size distributions, but they are computationally very expensive to run in 3D setup. Dr Tao's presentation showed that spectral bin models improved the forward calculations compared a bulk scheme.

To improve microphysical schemes, several aspects need to be considered

a) Crystal morphology is important not only in the parameterization of microwave properties but also in the development of cloud processes. Crystal morphology appears to depend on a relatively limited set of variables that can be controlled in a lab experiments. It is therefore possible through laboratory experiments to specify how crystal morphology depends on variables that are predicted by CRMs and thus predict the crystal morphology in CRMs.
b) More complex cloud microphysical schemes based on fundamental physics will eventually yield better results than simple parameterizations. In the cloud physics community two-moment bulk schemes are thought to be much better than one-moment schemes because they may capture at least mean growth of hydrometeors and can improve sedimentation. Spectral bin models should be better than two moment schemes by removing constraints on particle size distributions, but they are computationally very expensive to run in 3D setup. In addition, higher moment information is crucial to accurately modeling microwave properties, especially radar backscatter.
c) CRMs appear to capture reasonably well the gross horizontal structure of clouds and the mesoscale hydrodynamics, which is another indication that modeling efforts should be focused on microphysics.

4. For which processes can targeted measurement or modeling efforts yield the greatest benefit at reasonable cost?

The impact of uncertainties in cloud models on snow retrievals have not been well quantified; therefore it is difficult to state a priori where the highest priorities lie. With this fact in mind,

- Cloud modelers should make simulated data available for radiative transfer calculations and comparisons with observations. Likewise, observationalists should make data available as soon as possible for use by modelers, even while still preliminary. Some data have already been made available; these data sets should be better publicized.

- It is extremely important that modelers systematically vary all key assumptions and characterize the sensitivity of results to those assumptions.

- There is a need to systematically document key snow particle properties – e.g, habits, masses, fallspeeds, degree of aggregation, degree of riming, etc. – encountered in different precipitation regimes. To the extent possible, this effort should include the creation of public data bases of particle images with careful documentation of associated environmental conditions.

- To the greatest extent possible, multi-sensor in situ and short-range remote sensing methods (e.g., profilers, lidar, etc.) should be closely coordinated.

- Ice nucleation processes are extremely important and may be at the root of some of the variability in CRM microphysical schemes. These processes should continue to be investigated using laboratory experiments in controlled environments. A-train observations of precipitating cloud systems may shed additional light on

5. What is the current state of the art in the modeling of the microwave properties of the lower boundary (land, sea, ice, snow)?

- Broadly speaking, there is agreement that far more is known about this problem at lower frequencies (i..e., less than 100 GHz, and especially below 40 GHz) than is the case for higher frequencies.

- Coordinated efforts for improving surface emissivity databases and models are already being undertaken via the IPWG and the International TOVS Working Group. Other efforts are coordinated via the Joint Center for Satellite Data Assimilation (and others?)

- Data assimilation methods are seen as having considerable potential to assist in updating surface properties required by remote sensing methods – for example, soil moisture, snow pack, etc.

- Over snow-covered land, blowing snow appears to be a potentially significant source of uncertainty in snowfall retrievals, as the radiometric signature of blowing snow may not be sufficiently distinct from that of either falling snow or snow on the ground.

- The tradition of requiring a remote sensing method to "figure out everything" is no longer necessary – there are numerous external resources and assimilation techniques that can and should be used to constrain surface conditions. Where these resources are not yet adequate, there should be targeted efforts to refine and expand these. Other working groups (e.g., ITOVS) are looking intensively at this problem.

6. How well do we believe that we are able to account for the dynamical and microphysical diversity of snowing cloud systems in various seasons and regions of the world, and what is the evidence for that belief? In particular,

- **How sensitive are ice processes to variations in IN concentrations and types?**
- **What is currently known about variations in precipitation properties (e.g., particle density, size distribution, shape, etc.) associated with snow events in different environments?**

A wide variety of fairly distinct snowfall regimes exist, though an agreed-upon classification scheme has not yet emerged (unlike the case for ice crystal habits, for example). It is generally acknowledged that microphysical and dynamical differences are likely to be important in the relationships between remote sensing measurements and the quantitites to be retrieved. Examples of major snowfall types might include:

a) lake effect snow
b) orographic snow
c) synoptically forced snow

Regardless of the precise categories and their definitions, there is clearly a need for better understanding of how the snowfall regime bears on the snowfall retrieval problem. Both modeling and analysis of data from field experiments can shed light on this question.

It is also apparent that IN and CCN concentrations and compositions are likely to play a significant role in the regional and temporal variability of cold cloud microphysics. Unfortunately, we are far from having an adequate understanding of this issue.

It should be recognized that a number of microphysical parameterizations employed in CRMs are based on observations obtained from a single field experiment (i.e., one point in space and time). More effort is needed to assess the validity of these parameterizations under other conditions.

While a variety of environmental factors can influence cloud and hydrometeor properties, it must not be forgotten than real-time regional information from NWP and from other sensors can help constrain the environment in which the retrieval is being undertaken.

7. All things considered, what appear to be the fundamental upper and lower limits of detectability of frozen precipitation under various conditions and using various combinations of current and planned remote sensing technologies?

While the question is important, we are far from being able to provide confident answers. Nevertheless, a few important points are noted:

In many regions of the globe, especially at high latitudes, the bulk of annual snowfall is contributed by light but frequent snowfalls. The threshold of detectability will play a crucial role in achieving direct retrievals of snowfall in these regions. The minimum detectable signal for the the GPM precipitation radar will be +12 dBZ; this is probably insufficient to catch light snow under even ideal conditions.

A great deal of snow falls from shallow cloud systems. While CloudSat and EarthCare have very high sensitivities (-29/-33 dBZ), they are unable to measure snowfall originating within 1 km of the surface due to ground clutter effects. Retrieval of very shallow snowfall is likely also impossible for methods usings sounding channels (e.g., AMSU). There are currently no obvious solutions to this problem apart from greater reliance on NWP assimilation techniques as a basis for snowfall estimation.

Radiometric methods are thought to be useful over the range 0.5 to 1 mm/h up to 10 mm/h (liquid equivalent) within a single pixel; for 1 degree boxes, the range is probably 0.2 to 50 mm/h. This assumes ideal surface conditions and reasonably deep clouds. Even so, a great deal of very light precipitation may be missed entirely, and heavy rates may be underestimated.

While hard to quantify, the detectability of frozen precipitation is strongly a function of the surface type. Frozen precipitation over open bodies of water is probably easiest to detect, especially using polarization techniques, followed by precipitation over flat, snow-free land. Reliable precipitation retrieval over snow-covered land or ice remains to be demonstrated and may be impossible if the snowfall is light and/or shallow. Frozen precipitation in mountains is probably most challenging, especially in view of the heavy localized snowfall rates and deep snowpacks often encountered. Again, there is a preliminary consensus that NWP assimilation methods have the greatest potential for success in these difficult situations.

3.4. New Technology (Co-Chairs S. Tanelli and T. Iguchi)

Recommendations

Until the studies mentioned below are allowed to achieve more definitive results, it is not possible to set a prioritized list of quantifiable scientific requirements for the upcoming missions. However, the following major themes emerged:

a) There is unanimous consensus that GPM and EarthCARE need to formalize relationships for formal scientific use of their datasets. IPWG should strongly encourage the agencies to build a dataset of coincident overpasses and fund the generation of combined products.

b) In order to answer most of the unanswered questions that would drive future mission requirements and algorithm development, a comprehensive dataset of ground/airborne snowfall measurements must be built including a wide array of snowfall regimes, and measurements through the full vertical extent of the precipitating system, to define the optimal minimum set of parameters needed to characterize snowfall from remote sensing, and the associated uncertainties.

c) We need to improve significantly our skill in detecting shallow snow, or in general snowfall close to the ground. Especially over Antartica and over mountainous areas. Any future spaceborne radar should aim at detecting snowfall as low as 100 m agl (definitely lower than 500 m). Further studies on sub-mm radiometric measurements should be performed to identify any potential in achieving this goal.

d) EarthCARE will provide the first ever Doppler measurements from space which will allow accurate discrimination between major hydrometeor species (e.g., rain vs snow vs hail). Future missions including Doppler measurements should be designed to provide Doppler accuracies and spatial resolutions sufficient to support discrimination of snow habits by exploiting the fact that the mean Doppler velocity is directly tied to the mean particle size. However, the existing datasets should be analyzed to estimate the uncertainties associated with the presence of underlying air mass motions which contribute to the observed Doppler velocity. Multi-frequency Doppler radar measurements are expected to provide sufficient information to determine snow habits and therefore more accurate snowfall rate estimates. This must be verified by simulations once the current modeling of scattering properties has been improved as recommended by other working groups.

e) Good resolution in space and time is more important than accurate estimation of physical parameters. For cloud-scale processes and orographic systems a revisit time of 15 minutes and a spatial resolution of a few hundred meters would be needed. For synoptic-scales and widespread stratiform systems a 10-km resolution with a 3-hour revisit time could suffice. While the latter is achievable (e.g., GPM), the former is beyond reach at this time. One possible solution could come from microwave radiometers or radars in geostationary (or geosynchronous for better coverage of high-latitudes) orbit, or other long-dwell orbits (e.g., Molniya orbit). However, a significant amount of work needs to be done as stated before to determine the full potential of radiometric measurements in detecting snowfall, especially over snow-covered regions.

f) In general, it is recommended that future missions should be deployed to maximize collocated measurements by different sensors.

Detailed working group response to questions

Exploitation of current technologies

There is general consensus that measurements from different sensors and platforms should be integrated. Efforts conducted so far have been sporadic, not part of a broader plan and, for the most part, not thoroughly validated. The amount of work necessary to bring together the diverse measurements is considerable since it involves construction of databases of collocated measurements, estimation of covariances and their variability in space and time, and expert interpretation of remotely sensed quantities that span several fields of 'specialized' knowledge. In the most common situation, algorithms are often developed on one sensor, and integrating a new sensor is an added complication.

It is therefore recommended that IPWG should encourage collaboration among scientists who have expertise in different instruments and ground data/field campaigns in a concerted and systematic effort to develop and validate multi-instrument algorithms.

Perhaps the most promising combination of spaceborne instruments is given by the A-Train, since it guarantees the highest amount of collocated measurements among instruments such as AMSU-B, AMSR-E, CloudSat's radar, CALIPSO's lidar, etc. Other instruments that should be combined with A-Train measurements are SSMIS (advantage of conical scanning, disadvantage of infrequent collocation, with respect to AMSU-B), and IR (including hyperspectral IR) sensors. The IR and microwave radiometer HF channels can provide information on the upper portion of the troposphere (e.g., particle size, humidity, temperature) that can be combined to the other measurements to decouple the contributions of the surface and to improve the retrieval of microphysical properties: the potential, and limitations, of HF and IR channels have not been investigated thoroughly yet.

As far as ground sites are concerned, the available high-quality and high-resolution data (e.g. hyperspectral lidar) should be carefully analyzed to understand, for example, the rate of cooling of airmass and its impact on cloud formation, ice nucleation and light precipitation formation. Furthermore, studies on snow habits should be reconciled and organized for systematic use in the forward electromagnetic scattering modeling and retrievals from spaceborne sensors.

Collaboration with snow cover experts should also be encouraged: estimates of snow accumulation (e.g., estimates from Icesat-2) on the ground, and estimates of snowfall rate are obtained by independent means and are likely to benefit each other if combined.

Limitation of current technologies

High snowfall rates (e.g., above 10 mm/hr) seem to be only quantifiable with radar measurements which have poor sampling and are affected by ground clutter in the lower portion of the atmosphere (hence reducing significantly information from the planetary boundary layer). Also, single frequency radar measurements are affected by considerable uncertainties: GPM/DPR's dual frequency radar measurements may increase our knowledge of snow size distributions and their profiles and help improving the estimation of snowfall near surface in other kind of spaceborne measurements.

From a climatological standpoint, shallow snowfall events, as weak as 1 mm/day, over Antarica are of paramount importance to close the mass balance. They represent probably the most challenging snowfall phenomena to observe from space since radiometers at the current frequencies do not perform well and radar are affected by ground clutter. Two fundamental discriminations are not possible with current instruments: shallow falling snow vs. blowing snow, and fresh fallen snow vs. old snow.

Many combinations of instruments have been successfully tested in airborne and ground campaigns (e.g., multi-sensor ground observations in TOSCA, radar/lidar combinations in Eureka or in TC4) but most of these data are not sufficiently advertised and disseminated to quantify the benefits that would result from adopting the same combinations in space. Could IPWG act as central point for the collection and dissemination of field campaign data?

3.5. Validation (CoChairs D. Hudak and J. Koistinen)

Recommendations

Detailed working group response to questions

Ground validation (GV) needs to go 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 an activity that is necessary both in pre-launch algorithm development and in post-launch product evaluation.

The nature of GV encompasses a wide variety of scales, technologies, and scientific methodologies to be comprehensive. However, these can be characterized by three basic approaches.

1. **Network Validation:**

The first is termed "Network Validation". The approach leverages off operational radar and weather observing networks to identify, understand and resolve first order variability and bias discrepancies between satellite and ground-based precipitation estimates. Usually it involves direct statistical comparisons. This approach is also useful in developing statistics on different climate regimes and the associated variability of cloud and precipitation properties.

Networks can be exploited better since they are the most straightforward method of validation with many of the pieces is already in place. It was felt that there are lots of low tech, high volume measurements across globe that just are not used. In fact, algorithms often fail because the long-term, spatially large validation made possible by network validation is not carried out. A challenge to network validation is to assess scale variability and sensitivity to answer the question at what scales and with what threshold do GV measurements have skill.

Issues that require close attention in network validation include the development of quality control procedures and standards that need to be applied to the various networks, as well as the consideration of the representativeness of stations in the network. Also, methods to inter-compare the network end products need to be developed.

2. **Physical Validation:**

The second approach, termed physical validation (PV), deals with cloud system and microphysical studies geared toward testing and refinement of satellite simulators and retrieval algorithms. PV experiments usually undertake vertically resolved measurements directly related to physical formulations embedded in algorithm designs in order to gain improved understanding of underlying dynamical and microphysical properties of weather systems throughout their life cycles. This improved understanding can lead to a simplification in the formulation of the algorithms and the GV measurements required to validate them.

Applications of PV include their use in creating synthetic nature that can be used as a reference point for evaluating forward models and for testing algorithm retrievals. It can also provide valuable a-priori information for the retrievals.

Issues that were discussed in relation to PV included making better use of data of past validation experiments, the importance of PV investing in new technologies, and the need to perform these experiments both with and without concurrent satellite measurements.

Elements of a successful PV experiment included:

d) well posed scientific question on what is being validated that is carried out in a representative locale
e) the incorporation of redundancy in the measurements
f) concentrating instruments through a multi-sensor (active, passive, in –situ), multi-platform (surface, airborne, space-borne sensors) approach
g) the use of remote sensing instruments on airborne experiments
h) the sampling of a variety of scales through both bulk and detailed measurements.

The sentiment was that PV experiments were the most critical component needed right now to advance satellite algorithm improvement.

3. **Integrated Validation**

The third component is termed integrated validation (IV). This involves the integration of satellite precipitation products into weather, land surface, and hydrological prediction models. This approach is required to evaluate the strengths and limitations of satellite precipitation products in a 4-dimensional context. This is considered the most effective way to test the utility of satellite retrievals in applications.

Numerical models and instrument simulators play a pivotal role in IV. They connect physical measurements at the surface to what the satellite measures. Examples of applications include water budget/hydrological modelling studies, assimilation in numerical weather prediction models, downscaling experiments using model dynamics, decision support tools for forecasters and observing system simulation experiments (e.g. sensitivity studies).

Issues pertaining to IV activities include

- Is there a temporal or spatial scale below which it is simply not practical to worry about IV of the satellite observations?
- Is there some minimal suite of parameters/processes that must be represented in order for models/simulators to be considered as an IV tool?
- How many and what type of models/simulators are required?
- Does a model have to work in all climate regimes to be considered appropriate?
- Different applications have different time/space scale requirements for IV.

It was recognized that IV relies heavily on the other validation activities, networks for large scale input and physical validation for improvements in the forward models.

4. **Scaling/Error Characterization**

It was felt that no GV campaign should start without a clear understanding of the spatial/temporal scales of the phenomena that are trying to be addressed. Distribution functions on a variety of scales were a necessary element of statistical validation. It was also recognized that providing uncertainty bounds on precipitation estimates was a critical factor.

In dealing with this issue, two important considerations were the reconciling scales of GV measurements and satellite observations and the need to account for regional variation in precipitation characteristics. However, no specific suggestions were brought forward on how to implement any of these suggestions.

More attention needs to be paid to this topic in future discussions and plans for GV activities applied to snowfall that are along the lines of the Pilot Evaluation of High Resolution Precipitation Products initiative.

5. **Instrumentation Issues:**

The most critical variables to observe in network or physical validation studies are: Snowfall occurrence, Snow Water Equivalent, snow depth, visibility, Ice Water Path, vertical profile of ice water content, snowfall rate with ~ 1 time resolution, particle size distributions, bulk density, density as a function of particle size, cloud phase (e.g. mixed phase vs all ice), and hydrometeor type (e.g. dry snow, wet snow, presence of aggregates/pristine crystals).

Observational capabilities necessary to support these types of observations include:

- Direct measurement and statistics of ice habits (both in-cloud and at the surface);
- Aerosol chemistry measurements;
- Size dependent density measurements particle size, shape and density and most importantly their distribution in a volume (via imaging and collection);
- Surface snowfall rate.

Priority areas in ground-based instrumentation that should be pursued for GV purposes include

d) the development of instrumentation such as the DRI “HotPlate” that measures the mass of precipitation;
e) the development of algorithms that make better use of high resolution measurements from instruments such as the POSS or 2DVD to estimate particle size, shape, density and snowfall rate;
f) the expansion in the use of dual polarization radar measurements for precipitation type characterization and precipitation rate estimation;
g) the use of vertical profile measurements from instruments such as a microwave radiometer or vertically pointing radar to characterize precipitating cloud systems
h) better measurements of particle, bulk and surface density of falling or freshly fallen snow

Priority areas in aircraft instrumentation that should be pursued for GV purposes include

- The deployment of high frequency radiometers (sub mm wave) on airborne platforms
- The advancement of instrumentation to measure ice water content, particularly of the larger precipitation-sized particles.

Priority science areas include:

(1) The measurement of snow at high latitudes;
(2) The detection of snow over snow, ice and ocean covered surfaces;

(3) The treatment of blowing snow (measurement and modeling);
(4) Development of robust density vs particle size/type relations;
(5) Surface emmissivity determination;
(6) Aerosols and their effect on snowfall;
(7) Mixed phase cloud systems.

6. **General**

High level international coordination and partnerships are required to better use what we have and set priorities. All GV activities proposed by various scientists constitute a wide collection of international efforts based on voluntary work or project contributions. The whole GV program would benefit from a more clear structure, which will help in the coordination and decision making. A GV Advisory Group would be useful in addressing and prioritizing the science issues. This group would

- Generate, maintain and update a GV Work Plan;
- Act as the body which receives recommendations for any global GV efforts originating from closely related international or national programmes and projects, and promote actions based on such recommendations.
- Coordinate GV projects in order to obtain maximal global benefit, cooperation and minimal overlapping in the various efforts arising all over the globe.
- Arrange regular GV forums that cover all aspects of GV.

Field campaigns, specifically for PV, must be designed to answer specific questions, but at the same time should not be constraining. It is important to identify 4-5 climatic zones/precipitation regimes for which PV studies should be encouraged and promoted. It was felt that perhaps the NCEP reanalysis could be used to help define wide variety of regimes.

Specific tools that would facilitate GV activities include:

- The establishment of a GV website to facilitate communication (data, discussion groups, feedback, documentation of successes);
- The production of an inventory of past project suitable for PV studies;
- The production of an inventory of network observational facilities (e.g.radar, surface gauges) are available;
- The production of a document that summarizes the state-of-the-art in measurement technology
- The development of guidelines to promote data accessibility and data exchange

It was concluded that GV should be a two way street between those who make observations and the modelers/algorithm developers. The observations are used to validate model parameterization and promote forward model/instrument simulator development. The results of the models and simulators help target the observations where they are most needed.

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Appendix A: Workshop Program