# Report on the IPWG/GPM/GRP Workshop on Global Microwave Modeling and Retrieval of Snowfall

## October 11-13, 2005

## University of Wisconsin, Madison, WI

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## Executive Summary

During the last meeting of the International Precipitation Working Group (IPWG) in October 2004 an expert workshop on the status of global satellite estimates of snowfall was proposed. This workshop was later endorsed by the GEWEX Radiation Panel (GRP) and the NASA's Global Precipitation Measurement (GPM). As a result of this initiative, the IPWG/GPM/GRP Workshop on Global Microwave Modeling and Retrieval of Snowfall was held at the University of Wisconsin's Pyle Center October 11-13, 2005 with 42 participants from America, Europe and Asia.

The workshop consisted of one day of overview presentations and one and a half days of extensive working group discussions with focus on modeling, applications, new technology, and validation. The scientific presentations covered various scientific and programmatic aspects associated with snowfall modeling for radiative transfer, retrieval algorithms and the potential for data assimilation.

Within this report we summarize the results and findings of this workshop. The report is organized in the following way. In section (1) we give a brief overview on high priority recommendations that emerged from the working group discussions and subsequent plenary sessions. These high priority recommendations 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) is subdivided into three parts and contains the detailed report of the three working groups. In section (2) 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. The appendix gives the abstracts of the invited presentations, defines acronyms and has the contact information for all of the workshop participants.

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## 1. High priority recommendations

In this section, we list the high priority recommendations that originated from the three working groups and subsequent plenary discussions. A more detailed discussion of each single recommendation 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.

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

**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 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.

- **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.

**<u>Validation</u>**

- **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.).
- **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.
- **Long term surface based measurements must continue to insure long term continuity for climate assessment and monitoring.**

# 2. Working Group Reports

## 2.1. Modeling and Retrieval

**Working Group Chair and Rapporteur:** Peter Bauer (chair), Chris O'Dell (Rapporteur)

**Attendees**: Bauer, O'Dell, Kim, Weinman, Skofronick Jackson, Johnson Wu, Huang, Austin, Doherty, Deblonde, Eito, Aonashi, Liu, Loehnert, Mejia, Kulie, Borg, Mahani, Greenwald, Hernandez

**Summary**

In this section we summarize the discussions in the modeling and retrieval working group.

*User requirements for frozen precipitation detection/observation*

User group identification and individual user group requirements are covered in Ground Validation and Global Application/New Technology groups because modeling efforts are less user group dependent.

*Cloud and precipitation modelling:*

Current status of cloud and precipitation modeling summarized in reports from JCSDA workshop on the assimilation of cloud and precipitation observations in NWP models (Summary to appear in EOS, science papers in special JAS issue).

- *Ice production, snowfall generation in explicit microphysical schemes*: This is the probably most important but least well known part of microphysical modeling. Cloud resolving models are targeted at modeling cloud dynamics rather than cloud microphysics. Different model formulations that are initialized/forced with identical initial/boundary conditions may produce largely different hydrometeor distributions, in particular with respect to cloud ice and frozen precipitation (TOGA-COARE model intercomparison studies). More sensitivity studies and model microphysics validation studies are required.
- *Parameterizations for global models* are simple for being computationally efficient and producing reasonable cloud-radiation properties and precipitation accumulation at the surface. There is no distinct difference in skill between cloud water and ice as well as liquid and frozen precipitation representation (parameterized mainly as a function of T only). However, frozen precipitation parameterizations are generally less well validated. Frozen precipitation that is more typical for convective clouds (graupel, hail) is not represented. Smaller scale (sub grid-scale) moist convective systems not well represented.

*NWP Data assimilation:*

Current status of cloud and precipitation data assimilation summarized in reports from JCSDA workshop on the assimilation of cloud and precipitation observations in NWP models (Summary to appear in EOS, science papers in special JAS issue).

- Only very few *operational systems assimilate cloud and/or rainfall* affected observations (NCEP SSM/I+TMI surface rainrates in global 3D-Var, JMA Amedas surface rainrates in regional 4D-Var, ECMWF SSM/I radiances in global 1D+4D-Var). No specific effort for assimilating observations affected by frozen precipitation, therefore analysis/forecast sensitivity to such information mainly unknown. Climatological validation of global model reanalyses suggests similar quality of accumulated snowfall and rainfall predictions.
- Currently, most *data assimilation systems* do not contain clouds and precipitation (liquid and frozen) as part of the control variable. Most global but also many regional systems only have diagnostic precipitation schemes so that no memory of precipitation exists between time steps. Adjoint sensitivity studies provide no clear evidence that precipitation is a crucial part for the control variable, cloud water and ice may be sufficient. Currently available data assimilation systems are not optimized for assimilation of precipitation.
- *Modelling error covariances* (moist physics parameterizations and multiple scattering radiative transfer) are not well quantified. Moist physics parameterization errors most likely to dominate; linearity issue is crucial in incremental data assimilation systems. Off-diagonal errors of error covariance matrices mostly ignored. Model short-range forecast (background) errors are not well specified near saturation. The impact of spatial representativeness (scaling, cloud overlap, 3d effects) included in a simplified fashion.

<u>*Radiative transfer modelling:*</u>
- There are mainly two *radiative transfer modeling* approaches: Fully polarized, 3D models for benchmarking and simplified but fast models for wider application. There are only few accurate models available (SHDOM, ARTS) and they are not necessarily user friendly, however, they are particularly important for frozen precipitation calculations. 3D-Eddington models are potentially valuable for operational applications but have not been further developed.
- *Dielectric properties* of ice are highly uncertain. New models exist for pure ice, more research for realistic cloud ice composition is needed.
- *Inhomogeneous particles* (mixing of air-ice, air-water-ice) is underdeveloped. Most mixing formulations are not applicable to required frequency range. Most problematic issues is melting particles due to complicated melting process of non-spherical particles and inadequate combination of permittivity, shape, and size-density distribution models.
- *Particle size-density distributions* are not well known in frozen precipitation but important for particle scattering estimates. Combination of spectral cloud modeling and in situ particle probing required.
- Modeling evidence suggests that *spherical particle* assumption represents worst assumption for frozen particles (for solid ice spheres with x>2.7 or for fluffy spheres in general).
- There are two main approaches to *land surface emissivity* estimation: modeling from remotely sensed proxy fields and semi-empirical models vs. derived emissivity from multiple sensor remote sensing data. This issue is particularly important at higher latitudes due to larger variety of surface types and more

intense seasonal change in conjunction with atmospheres that are more transparent for microwave radiation.

- *Community radiative transfer model*s (NWP-SAF RTTOV, JCSDA community RT model) important step forward. Community databases of supporting parameters recommended.
- *Convergence of individual models* with high physical detail into *parameterizations/databases* important for operational community (great value of SHIPS-like activities, i.e. explicit 2D spectral cloud model simulations with multiple ice types feeding DDA-like simulations -> parameterizations that do not require detailed knowledge of particle shape, size distributions, density).
- More systematic *forward modeling sensitivity studies* needed for signal vs. noise assessment depending on application.

*Snowfall retrievals*

- *Frozen precipitation detection* skill evaluation (e.g through freezing level) is widely neglected. Frozen precipitation frequency of occurrence as important as frozen precipitation amounts.
- Diverse *database development* approach must be continued. CRM-only databases lack representativeness and suffer from model errors but contain all fields required for radiative transfer modeling. Observation-only databases are more realistic but may lack representativeness and input for radiative transfer modeling. Combined CRM+Observation databases contain all fields with better representativeness. Trade-off studies required.
- *Community databases* (CRM, e.g. CDRD, potentially also HIRLAM, global models etc.) important for realistic modeling, sensitivity and retrieval studies.
- *Modelling errors* widely neglected so that most database driven retrievals have large but unconstrained databases. Potential for ensemble modeling and administration in modeling error databases.
- *Scale difference* between regional/global model applications crucial because algorithms trained with/applied to data/observations with incompatible scales may introduce large retrieval biases.
- *Physical methods* providing constraints for *empirical methods* are important for near-real time applications with less hard requirements on retrieval accuracy (e.g. employing IR/MW data plus bulk NWP data).

Requirements for validation

- *Large-scale validation* with IR/MW satellite data (sensors that are not used in retrieval) that is cross-sensor validation in radiance/reflectivity space. The advantage is the global/continuous availability of such observations; however the physical link between diagnostics in observation space with error sources in state space requires interpretation.
- *MW-links* for transmission + particle sampling will allow a direct measurement of volume extinction together with particle (spectrum) imaging to support single/multiple scattering modeling.
- *Laboratory measurements* of single scattering properties of realistic particles will allow full scattering phase function observation to be used in particle optical property modeling.
- Installment of *long-term* ground based radar observations at high latitudes (Koistenen) for statistically stable retrieval validation / observational database generation,
- + everything covered in GV

*Requirements for new sensor development*

- Encouragement of *passive* + *active microwave instrument combination* with channels/polarizations etc. that are potentially not yet optimized (requires dedicated simulation studies that optimize instrument specifications).

*High priority recommendations*

- Encourage generation of *community CRM/NWP model profile databases* that represent natural variability. Parallel effort for databases from observations or combined model simulations and observations.
- Systematic studies to evaluate *model error covariances* used for constructing retrieval databases; possibly in from of error databases.
- 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. Refer to summary of JCSDA workshop on the assimilation of cloud and precipitation observations in NWP models.
- Establishment of *modeling chain*: 2D 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.

*Table 1: Recommended research priorities for modelling (1: highest, 5: lowest). Liquid precipitation included for comparison.*

| | Liquid | | Frozen | | Comments |
|---|---|---|---|---|---|
| | Land | Ocean | Land | Ocean | |
| Radiative transfer modeling | 5 | 5 | 5 | 5 | |
| 3D-Effects | 3 | 3 | 4 | 4 | Cloud geometry, layer overlap model |
| Particle optical property calculation | 5 | 5 | 5 | 5 | Calculation methodology |
| Particle permittivity | 5 | 5 | 3 | 2 | (im)pure ice: 3, melting: 1 |
| Particle size distribution | 3 | 3 | 2 | 2 | |
| Particle density | 5 | 5 | 3 | 3 | |
| Particle shape | 5 | 5 | 3 | 3 | |
| Hydrometeor profiles | 1 | 1 | 1 | 1 | |
| Surface emissivity | 1 | 5 | 1 | 5 | |
| Meteorological environment | 2 | 4 | 1 | 2 | LST, T-, q-profiles |

- Development of high-latitude *surface emissivity* products (10-200 GHz) including error estimates.
- Exploitation of *physical algorithms* for derivation of proxy variables for constraining *empirical algorithms*.
- *Dedicated validation*: MW transmission links with parallel particle probing, inter-sensor validation in radiance/reflectivity space, statistically robust datasets for (frozen) cloud processes.

- *Dedicated new technology developments*: Improved combined active-passive sensing, targeted observation sampling strategies (e.g. unmanned aircraft), sensor optimization – channel selection.

## 2.2. Applications, Requirements, and Technology

**Working group co-chairs:** Paul Joe, Jim Wang

**Attendees**: George Huffman, Lothar Schueller, Ralf Bennartz, Tristan L'Ecuyer, Benjamin Ruston (partially), Rasmus Lindstrot (partially), Martin Stengel (partially).

**Summary**

In this section, we present a table indicating how to address the various requirements of the applications and indicate which technologies are most appropriate. We adopt a high level approach at this stage, quantifying the requirements for sensor specification is left as future work.

The Requirements column (2$^{nd}$ column) captures the important categories of requirements that apply to each of the Application areas, and which the Technologies must seek to satisfy. Many of the requirements apply to most of the application areas, but to different degrees. Therefore, the list for each application only includes those requirements that are particularly stringent or critical to the application. Common requirements include minimum period of record, consistency within datasets and between datasets from different sensors, coverage (frequency and regularity of observation for each grid box), timeliness of data delivery, time and space resolution, dynamic range, and minimum accuracy. The parameters required are precipitation detection (yes|no), precipitation rate (liquid water equivalent), precipitation type (solid, liquid, mixed), and error for each. The important exercise remains to develop user input to validate this listing of requirements and to assign quantitative values for each requirement, where appropriate.

The development of error estimates, both bias and random error, is a research topic. We recognize that the error must be expressed in a form that the users find useful, and we must work with users on integrating error information into their applications.

The last column summarizes the technologies this group felt are most relevant to the different application areas. It can be broadly categorized into active versus passive sensors. A second distinction line can be drawn between operational (or near operational) versus experimental sensors. We do at this point not explicitly discriminate between existing, planned or desirable systems. We do however define a Standard Instrument Suite of existing and planned instruments that in our understanding will form the backbone of passive microwave snowfall detection and retrieval within the next decade or so. This list can be used to illustrate the suite of technologies required to address the particular application. It gives an overview over the particular sensors or observations systems that were considered:

- Current and forthcoming operational NOAA and EUMETSAT passive microwave sounders. Those include AMSU-A/B on NOAA-15 to NOAA-17, AMSU-A/MHS on NOAA-18 and Metop-1 and Metop-2, as well as ATMS on NPP and NPOESS. Those instruments typically cover a frequency range between 23 GHz and 190 GHz and have a spatial resolution of several 10s of kilometers. Their main purpose is operational temperature and moisture soundings. However, especially the high frequency window channels in the 150-160 GHz region are well suited to identify the scattering signature of precipitation-sized ice. In addition, the 50-60 GHz sounding channels provide currently the only opportunity to derive freezing level estimates over land surface that can be used to identify frozen precipitation at the ground. We refer to these instruments plus GMI and SSMI/S in the Table as SIS (Standard Instrument Suite).
- Current and forthcoming passive microwave sensors dedicated to precipitation retrieval. These include the TMI, AMSR, GMI, CMIS, SSM/I as well as SSMI/S on DMSP-16 and beyond. Those sensors typically provide high spatial resolution observations in the frequency range 80-90 GHz. The newer instruments SSMI/S and GMI also have channels in the higher window region 150-170 GHz and around the water vapor absorption line at 183.31 GHz. There currently is little experience in high latitude precipitation retrieval with those sensors. Especially, integrated validation efforts have only recently been started within the framework of IPWG or are currently in their planning phase for example in the framework NASA's GPM Ground Validation efforts. Note, that both GMI and SSMI/S could also be considered under the first item.
- Planned experimental nadir looking active instruments such as the EarthCARE radar and lidar, CloudSat, CALIPSO, and EGPM. Those instruments will for the first time allow to derive vertical profiles of precipitation related properties for two dimensional cross-section and thus provide an excellent opportunity for process studies as well as calibration validation efforts for passive sensors.
- The current and planned active scanning radars PR (on TMI) and DPR (on GPM Core). Those instruments provide three-dimensional reflectivity estimates. However, detectability of light snow and rainfall might be problematic under some conditions.
- Proposed geostationary microwave imagers. Those instruments would potentially provide a better coverage of the diurnal cycle of precipitation related parameters. Those instruments require a delicate trade-off between spatial resolution and frequency selection. The particular design of these instruments might affect their usefulness for snowfall detection/retrieval.
- Proposed scanning sub millimeter radiometers. Those instruments will be of great potential interest to determine cloud ice and thus might help to indirectly assess precipitation as well.
- A variety of different new ground based sensors are highly advantageous for validation purposes of current and forthcoming global applications. Those instruments include upward looking passive microwave radiometers, a hot plate snow sensor, vertically pointing precipitation sensors like the Precipitation Occurrence Sensing System (POSS) or the Micro Rain Radar (MRR), as well as

microwave transmission links that measure path extinction along a finite path, crystal imaging probes, and others.

*Table 2: This Table lists critical requirements and corresponding technology needs for various snowfall retrieval application areas.*

| Applications | Critical Requirements | Technology |
|---|---|---|
| Climate | ▪ Long term (30 year) consistent datasets with unbiased averages.<br>▪ Inter/intra dataset calibration<br>▪ Capture diurnal cycle (implicit/explicit)<br>▪ Sampling all latitudes<br>▪ Dynamic range needs to capture extreme events. | ▪ Heritage/legacy record.<br>▪ Overlap for calibration.<br>▪ Reprocessing & homogenization.<br>▪ Need surface data to monitor consistency and for validation.<br>▪ Gauge undercatch correction.<br>▪ Sampling/coverage<br>▪ SIS (see footnote below)<br>▪ high sensitivity scanning radar. |
| Hydrological cycle (atmospheric) | ▪ Vertically resolved atmospheric profiles such as precipitation rate & average latent heating (resolution 1.0-2.5°) | ▪ SIS, CloudSat and future sub-mm mission.<br>▪ geostationary MW<br>▪ GPM<br>▪ high sensitivity scanning radar |
| Data assimilation in NWP (mesoscale experimental.) | ▪ Improve process knowledge.<br>▪ Error estimation critical. | ▪ space borne radar<br>▪ SIS. |
| GCM/NWP validation | ▪ 3-D products | ▪ SIS.<br>▪ Sub-mm, high sensitivity scanning radar |
| Model parameterization development | ▪ Parameterization studies<br>▪ Dielectric properties of snow and ice<br>▪ Microwave transmission paths<br>▪ $GV_2$ sites*, WAKASA2003<br>▪ Evaluate RT microphysics<br>▪ Global domain on model scale | ▪ High frequencies, sub-mm, CloudSat, high sensitivity nadir/scanning radar<br>▪ High sensitivity Doppler (EarthCare)<br>▪ Dual frequency radar (DPR)<br>▪ MW Transmission links.<br>▪ Colocated synop. observations.<br>▪ POSS-networks. |
| Cryosphere, complex terrain | ▪ Surface precipitation<br>▪ Blowing versus falling snow. | ▪ High spatial resolution.<br>▪ Research needed to identify suitable sensors (e.g., spaceborne |

| | | |
|---|---|---|
| | ▪ Complex terrain | lidar, EarthCare, CloudSAT/Calipso.)<br>▪ PASSIVE: Need to determine response functions (surface blind) that peak above ground. Surface emissivity issue.<br>▪ ACTIVE: High performance radars with good ground clutters characteristics. |
| Oceanography | ▪ Fresh water flux | ▪ •All passive mw.<br>▪ •Needs better algorithms/validation<br>▪ (Some precipitation missed by current algorithms) |
| Nowcasting | ▪ Snowfall Intensity<br>▪ Very high refresh rate<br>▪ High resolution<br>▪ Visibility (aviation, traffic) | ▪ SIS + scanning radars. Geostationary MW.<br>▪ Timeliness <-> Direct broadcast (< 5 minutes) needed<br>▪ Global distribution continues to be on short time scales (15-60 minutes)<br>▪ Realized, with Metop, N-XX, NPOESS-1/2,<br>▪ NPP, EUMETCast |
| Surface hydrology and water resource management | ▪ Timeliness<br>▪ Snowfall rate<br>▪ Fine scales (10km, 1hr) | ▪ Timeliness: See Nowcasting<br>▪ High spatial resolution<br>▪ Active/passive combination<br>▪ SIS.<br>▪ Geostationary MW |

*High priority recommendations for new technology:*

- The development and further refinement of inexpensive ground-based remote sensing instruments for snowfall should be encouraged. Especially two types of instruments have a high potential 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 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 rain radars with lower detectability threshold should be encouraged.

- 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. Dedicated high/latitude aircraft campaigns for snowfall remote sensing are encouraged.

### 2.3. Validation

**Working Group Chair and Rapporteur:** Ralph Ferraro (Chair), Paul Kucera, (Rapporteur)

**Attendees**: Kazumasa Aonashi, Richard Austin, Lori Borg, Hisaki Eito, Jarmo Koistinen, Ulrich Leohnert, Andrew Newman, Piotr Struzik, Joe Turk

**Working Group Summary**

The validation working group (VWG) began their session by trying to address three key questions:

- What measurements of frozen precipitation are currently available?
- What are the user applications that need such measurements?
- What information needs to be validated and how to accomplish it?

In addressing these three basic questions, the VWG was able to develop six major findings:

- Operational radars are in sufficient density for validation of rainfall, but not for snowfall due to several limitations such range, ground clutter and overall data quality for observing snowfall.

- Rain gauges offer poor quality measurements for snow water equivalent (SWE). There is a requirement for longer integration times and improved correction factors (e.g., wind).

- SWE and depth measurements are both needed depending upon the application. Additionally, the visibility in snowfall is needed for some applications and may actually provide the best proxy for snowfall rate.

- There are other emerging technologies and validation opportunities that either exists of will exist shortly, but the VWG does not have information on all of them and/or how to use them. Examples cited include advanced radars such as the one that will be flown on CloudSat or the use of hydrological models and SWE forecasts.

- There is a wealth of data that has been obtained from field campaigns that can help in the validation of snowfall.  Not all of these campaigns were organized for a direct validation of frozen precipitation; however, they may have vital information that can be utilized and these data should be readily available.  It was noted the NCAR has an inventory of such data.

- There seems to be a lot of potential international partnerships that are talked about, but are never really formalized and coordinated.  The VWG noted that for some projects, this does not seem to be an obstacle, yet for others, it is.

In order to best summarize the validation needs, a matrix of parameters, applications and the level of maturity (1=uncertain, 5=highly accurate) was assembled by the group and is summarized below.  It should be noted that the application areas are denoted by letters as follows: SAT=Satellite snowfall rate product validation, H=Hydrology, C=Climate, AC=Atmospheric chemistry, T=Transportation, R=Recreation, A=Avalanche, WR=Water resources, F/N=Forecasting/Nowcasting, CRM=Cloud resolving models, RTM=Radiative transfer/forward modeling, NWP=Numerical weather prediction parameterization/validation, Ra=Ground radar quality

| **Measurement** | **Technology** *(indirect)* | **Primary Applications** | **Temporal/ Spatial Sampling** | **Maturity** *1=uncertain5=highly accurate* | **Comments** |
|---|---|---|---|---|---|
| Areal extent | Passive MW<br>VIS/IR<br>SAR<br>Synoptic obs | H, T, C<br>NWP, Rec | Daily<br>30 m – 5 km | 4-5 | Global |
| Snow Depth | Acoustic snow sensor,<br>Synoptic Obs<br>Regional networks | H, WR, C<br>Rec, A, T | 6 – 24 hr;<br>1-100 km (application dependent) | 4-5 | Point measurements on a global network (large data voids) |
| SWE (from snowfall and already existing on ground) | Rain gauges (w/correction factors)<br>*Doppler Radar*<br>*Satellite*<br>Gamma ray sensors | H, WR, C<br>Rec, A, T | 5 min – 24 hr; 1-100 km (application dependent) | 2-4 | Point and areal measurements |
| Cloud and Ice Water | Satellite & ground MW radiometers<br>Satellite vis/near IR<br>Cloud radar<br>Lidar<br>Aircraft<br>Scanning radars | F/N, C<br>T (aviation)<br>NWP, RTM | 3-hourly<br>1 – 50 km | 3 (small IWP)<br>1 (medium IWP)<br>1 (vertical dist.) | Point to global |
| Snowfall Rate (<5 min accumulation) | Doppler Radars<br>Hot plate sensors<br>POSS sensors<br>Disdrometers<br>MW radiometers,<br>WM links<br>Rain gauges | NWP, CRM<br>RTM, H, A, T | Instantaneous<br>1 – 25 km | 1 | Point to areal measurements; many assumptions |
| Velocity | Vertical profiler<br>Manual observations<br>Disdrometers | SAT<br>T | Hourly<br>100 km | 4 | Regional network; continuous observations |

| | | | | | |
|---|---|---|---|---|---|
| Shape and size distribution | Disdrometers Polarimetric radar Aircraft in situ (microphysical) Vertically pointing radar | NWP RTM | Instantaneous 50 km | 1-2 | Low availability (field campaign/GV site) |
| Density (particles) | Disdrometer Microphysical aircraft probe | T, A, NWP RTM | ??? | < 1 | Very few observations |
| Density (Snowpack) | Requires snow depth and SWE observations | H, WR Rec, A, T | Daily 100 km | 4 | Regional & basin scale (perhaps more dense in complex terrain) |
| Vertical Structure of Snowfall | Cloud radar Scanning radar Spaceborne radar Airborne radar Vertically pointing radar | NWP, CRM RTM T (aviation) | Instantaneous 30 – 500 m (V) 1 – 2 km (H) | 1 - 2 | 1 – 3 dimensional |
| Orientation | Polarimetric radar Disdrometer | RTM | Instantaneous 1 m – 2 km | < 1 | Point to areal measurements; very few data sets exist |
| Aggregation | Insufficient observations | NWP, CRM | ??? | 0 | |
| Phase Classification and Hydrometeor Type | Polarimetric radar Surface observations Disdrometer Airborne observations, Scanning radar | NWP, RTM H, T, A, F/N | Instantaneous to 1 hour 1 m – 2 km | 1 - 2 | Point to areal measurements |

The recommendations for the VWG are as follows:

- High level coordination of international GV programs for snowfall (e.g., 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!
- Need 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.)
- Long term surface based measurements must continue to insure long term continuity for climate assessment and monitoring.
- Uncertainty estimates would be desirable, realizing that it may not be possible to obtain this information for all measurements
- 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 (as identified in table). Data should be freely available to international research community.
- Investigate feasibility of developing upward looking radiometers to span frequency range of satellite radiometers. (absorption models).
- Need to engage 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.
- Need more useful radar observations of snowfall. There are several candidate sites within the operational weather radar networks that could address the over land and over ocean snowfall process.

## 3. Acknowledgements

The workshop organizers would like to acknowledge the co-chairs of the IPWG, Joe Turk and Peter Bauer, for their support, suggestions and contributions to this valuable meeting. We would like to acknowledge the logistical help of the University of Wisconsin’s Cooperative Institute for Meteorological Satellite Studies (CIMSS). In particular, we would like to thank Maria Vasys for her major efforts in organizing the conference and Bill Bellon for setting up the website. We would also like to acknowledge EUMETSAT and the WMO for their financial support.

# 4. Appendix A: Abstracts of invited presentations

## 4.1. Turk, J. and Bauer, P.: Recent Satellite Activities Within the International Precipitation Working Group (IPWG)

J. Turk (NRL), P. Bauer (ECMWF)

In early 2004, the International Precipitation Working Group (IPWG) began a satellite precipitation algorithm validation/intercomparison project over three domains (continental United States, Australia, and northern Europe) covered by quality-controlled surface networks. Its aim is to provide information to users on the daily-scale performance metrics (bias, RMSE, skill score, etc) relative to ground networks, and give algorithm developers a better understanding of the strengths and weaknesses of different algorithmic approaches and satellite data blends. A secondary aim is to investigate when and where satellite rainfall estimates generally perform better or worse than short-term rainfall predictions from NWP models.

To expand this to other rainfall regimes, the IPWG has recently initiated the Pilot Evaluation of High Resolution Precipitation Products (PEHRPP). PEHRPP is an effort that will bring together scientists who develop and product High Resolution Precipitation Products (HRPP), those who provide the basic data (principally observations from earth orbiting satellites), and those who have a need for high resolution precipitation fields to conduct their research. The principal goal of PEHRPP is to characterize as clearly as possible the errors in various HRPP on many spatial and temporal scales, over varying surfaces, seasons, and climatic regimes. Furthermore, errors of and differences between HRPP are meaningful in that they can be systematically related to precipitation characteristics and/or algorithm methodology, therby potentially improving HRPP's by combining products or methods based on the observed errors and differences. Although PEHRPP is in its early stages I will present an update of the project.

I will also show some examples of the recently released data from the Special Sensor Microwave Imager/Sounder (SSMIS) onboard the DMSP F-16 satellite, which contains a suite of channels between 19-183 GHz that hold promise for improved retrievals of precipitation over cold surfaces, and whose datasets will be of interest to the IPWG and the wider precipitation science community.

Planning is also underway for the 3rd CGMS-WMO Workshop of the IPWG, which is currently scheduled to take place in Melbourne, Australia in October 2006, hosted by the Australian Bureau of Meteorology.

### 4.2. : Hou, A. and Skofronick-Jackson, J: Global Precipitation Measurement and High Frequency Passive Microwave Observations

Arthur Y. Hou, (NASA), Gail Skofronick-Jackson, (NASA)

The Global Precipitation Measurement (GPM) Mission will measure precipitation with sufficient Earth coverage, spatial resolution, temporal sampling, retrieval accuracy, and microphysical information to advance the understanding of the physics of the Earth's water and energy cycle and to improve predictions of the Earth's climate, weather, and hydrometeorological processes. The recent confirmation of high frequency microwave channels on the GPM Microwave Imager (GMI) expands its research capabilities into the precipitating snowfall arena. The specific channels selected will help provide measurements of precipitation drop size distribution, rainfall structure and intensity, including information on light rain, warm rain, and snowfall over land and at higher latitudes. The combination of the GPM Dual-frequency Precipitation Radar (DPR) and the 166 and 183 GHz channels further ensures opportunities to estimate falling snow parameters.

The GPM Mission is being executed within the context of the Global Water and Energy Cycle (GWEC) research program with the foremost science objectives focusing on better weather, climate, and hydrological predictions through enhanced space-based capability to measure precipitation around the globe. The GPM Mission is a partnership between NASA and the Japanese Aerospace Exploration Agency (JAXA). Additional partnerships have been and continue to be established with other domestic and international space agencies, and other operational and research organizations -- for purposes of: (1) populating the satellite constellation needed to improve the GPM observational capability, (2) developing a network of ground validation (GV) sites, and (3) building up robust international teams of scientists. Currently the GV team is exploring options and defining requirements necessary for successful ground validations. This talk will summarize the GPM concept, science, and instruments, as well as discuss the status and challenges of precipitating snow retrieval algorithms.

### 4.3. Hufman, G.J. et al: GPCP STATUS AND NEEDS AT HIGH LATITUDES

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The Global Precipitation Climatology Project (GPCP), which is an activity of the Global Energy and Water Experiment of the World Climate Research Program, routinely produces monthly, pentad (5-day), and daily precipitation estimates that are globally complete. All products are provided on a 2.5°x2.5° grid for 1979 (monthly, pentad) or late 1996 (daily) to the present, with a delay for data access and processing. Data coverage at high latitudes (and over frozen and snow/ice-covered surfaces at middle latitudes) is currently provided by approximate schemes that depend on Television-Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) data over the bulk of the record, and the Outgoing Longwave Radiation (OLR) Precipitation Index (OPI) in the early years. It is planned that the entire suite of GPCP products will be upgraded to a new version in the next 2-4 years. As such, GPCP has a strong interest for obtaining accurate estimates of snowfall for any part of the record, as well as schemes for better inferring snowfall from legacy data. There is also interest in inferring precipitation type for as much of the record as possible, preferably based on satellite indicators, but perhaps involving reference to ancillary data as well.

### 4.4. Schueller, L: EUMETSAT Perspective for Precipitation

Lothar Schüller (EUMETSAT)

EUMETSAT is active in developing and operating precipitation related products in its central facility in Darmstadt, Germany and in the framework of EUMETSAT's Satellite Application Facilities (SAFs).

SAF's are specialized development and processing centres that utilize the specific expertise available in EUMETSAT's Member states and cooperating States. The SAF Network complements the production of standard meteorological products derived at EUMETSAT's central facilities in Darmstadt.

Eight SAFs are currently in the Development Phase or already in Initial Operations Phase, covering eight "themes". Two SAFs provide services related to precipitation.
The SAF on "Support to Nowcasting and Very Short Range Forecasting (NWC SAF) was established to utilize new data from MSG and the future EUMETSAT Polar System (EPS) for enhanced Nowcasting. Software packages are being developed for the operational extraction of products relevant for Nowcasting and are distributed for local installation.

The large product suite includes the "Convective Rain Rate" product, which provides information associated to convection rainfall rates coming from MSG-SEVIRI channels in the VIS, IR and WV region.

The "Precipitation Clouds" product is based on AVHRR and AMSU measurements, and shall give the forecaster a quick overview, especially in areas without radar coverage, over the probability of precipitation in a few coarse intensity classes.

The SAF on "Support to Operational Hydrology and Water Management" (H-SAF) started into its Development Phase in September 2005. The main objective of this new SAF is to provide operationally new satellite-derived products in three areas: precipitation (mainly using microwave and IR sensors), soil moisture (at surface, in the roots region) and snow (cover, melting conditions, water equivalent). In addition, the H-SAF will perform independent validation of the usefulness of the new products for hydrological applications.

At EUMETSAT central facilities, the "Multi-sensor Precipitation Estimate" (MPE) is derived operationally within EUMETSAT's Meteorological Product Extraction Facility (MPEF). This algorithm targets the Near-Real-Time estimation of precipitation intensities using IR observation from geostationary satellites (presently Meteosat 5 and Meteosat 7) and polar orbiting microwave radiometers (SSM/I on DMSP satellites). Data, images and movie loops are accessible via the Internet (www.eumetsat.int).

### 4.5. Bauer, P.: Global Precipitation Assimilation

Peter Bauer (ECMWF)

Over the least decades, Numerical Weather Prediction (NWP) systems showed increasing skill in the forecast of large-scale dynamic structures on both global and regional scales. Temperature and wind forecast accuracy is outstanding into the medium range in most meteorological conditions. This development was greatly supported by the implementatioin of sophisticated data assimilation techniques (3D-/4D-Var) and the availability of a global satellite observing system.

The moisture analysis, however, is still hampered by the insufficient use of observational data in clouds and precipitation. Recently, several organization have initiated studies on the assimilation of satellite observations related to clouds and precipitation. The main issues in this framework are the complex observation operators and the uncertain description of model and observation errors. These are particularly difficult to formulate in the presence of frozen precipitation. This is because model paramaterizations of moist physical processes for mixed-phase and ice clouds are oversimplified and because the radiative transfer modeling accuracy suffers from a lack of information on particle type, particle density, and size distributions.

Future observing systems will focus more and more on the higher latitude hydrological cycle and offer great potential to better constrain NWP analyses that initialize forecasts. This development will also be of particular importance for forecasting severe weather such as snow storms.

### 4.6. Ackerman, S. et al: Using Submillimeter wavelengths to Measure Cloud Ice Mass from Earth Viewing Satellites

S. Ackerman[1], D. O'C Starr[3], K. F. Evans[2], and H. Revercomb[1]
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The amount of water that the hydrological cycle moves through the atmosphere underpins all climate modeling efforts. While there are many satellite observations of clouds, we do not yet have the needed observations to understand the processes that control the water budget of the upper troposphere and precipitation processes. We need better satellite observations of ice mass to better determine how ice cloud processes interact with the hydrological cycle. IWP and particle size are difficult geophysical parameters to measure because of the large dynamic range in ice cloud properties (e.g. several orders of magnitude in IWP) and the highly variable spatial distributions of ice clouds. Several studies have demonstrated that observations at frequencies covering a range from approximately 183 to 916 GHz are ideally suited for observing ice clouds. Technological capabilities are now available to make measurements over this spectral band. This presentation will describe an approach to measuring ice cloud properties using combined submm and IR observations.

### 4.7. L’Ecuyer T. et al: CloudSat Snowfall Measurements: Potential, Status, and Challenges

T. S. L’Ecuyer (CSU), R. Austin (CSU), and M.-J. Kim (NASA)

When it launches this fall, CloudSat will carry the first millimeter wavelength cloud radar in space. In addition to its stated objective of making a global survey of cloud microphysical properties, the CloudSat 94 GHz Cloud Profiling Radar (CPR) is also well-suited to the problem of detecting and measuring falling snow that can be difficult to detect using current space-borne instrumentation. This presentation will provide an overview of the CloudSat mission and its expected role in improving estimates of the global distribution of snowfall as a component of the multi-satellite, multi-sensor A-Train constellation. The estimation-based inversion framework that forms the basis of many of CloudSat’s retrieval algorithms will be described and details concerning its application to the problem of retrieving snowfall will be outlined. Preliminary snowfall retrievals from Airborne Cloud Radar (ACR) data acquired in Wakasa Bay, Japan in Januray, 2003 illustrate CloudSat’s potential for studying the global distribution of falling snow. Careful analysis of the sensitivity of CPR reflectivities to assumed particle size distribution and crystal shape, however, indicate that reflectivity-based retrieval errors can be large in the absence of additional constraints suggesting the need for multi-sensor approach to quantify snowfall rate. As a result, a combined active-passive algorithm is proposed for CloudSat that merges CPR reflectivities with 89 GHz brightness temperatures observed by the AMSR-E instrument aboard Aqua.

### 4.8. Joe, P.: Spaceborne Radar for Global Snowfall Measurements

Paul Joe (MSC)

Vertical profiles of reflectivity in snowfall show a decrease with height and lower reflectivities than in rainfall. Therefore, a radar with a better sensitivity and a finer resolution is needed to accurately measure the snowfall near the ground. The EGPM mission was focussed on the global measurement of snowfall and light rain. The radar specification changed over the EGPM project as requirements became better known and new technology became available. In a pre-phase A study, a pulse compression solid state transmitter was proposed while during the phase A, a pulsed klystron transmitter was proposed. The talk will review the snowfall detection requirements and trace the history of the EGPM radar technology.

### 4.9. Key, J.: Observational Requirements for Precipitation in the Integrated Global Observing Strategy Cryosphere Theme

Jeff Key (NOAA)

Abstract: The Integrated Global Observing Strategy (IGOS) Cryosphere Theme, currently under development, is a combined initiative of the World Climate Research Programme (WCRP) Climate and Cryosphere (CliC) project and the Scientific Committee on Antarctic Research (SCAR). The theme intends to create a framework for improved coordination of cryospheric observations conducted by research, long-term scientific monitoring, and operational programs, and to generate the data and information needed for both operational services and research. Important components of the theme development are the identification of user requirements, an evaluation of how well these requirements are currently being met, and recommendations on what can be done to close the gaps between needs and capabilities. Solid precipitation is arguably the most difficult part of the cryosphere to measure, yet it is critical for studies involving energy and mass fluxes. This talk will summarize observational requirements and capabilities for precipitation in the IGOS Cryosphere Theme in an attempt to identify the gaps in our observing system.

## 4.10. Koistinen, J.: North European Possibilities For Ground Validation Of Snowfall

Jarmo Koistinen (FMI)

The presentation deals with North European radar systems, data exchange and programmes which may be applicable for the ground reference of satellite based precipitation measurements. Such activities are performed by NORDRAD, WCRP/BALTEX, EUMETNET, EUMETSAT and by national efforts (e.g. the Helsinki Testbed). The second part presents experience gained in snowfall measurements, especially with operational C-band radar networks. Attention will be paid to the factors influencing on the accuracy of radar estimates of snowfall at surface, especially the vertical profile of reflectivity. The issue of radar data quality will be highlighted.

### 4.11. Aonashi, K. et al.: Physical validation of microwave properties of winter precipitation over Sea of Japan

Kazumasa Aonashi, Hisaki Eito, and Masataka Murakami (MRI)

Microwave radiative transfer in frozen precipitation clouds depends on various physical properties (size distribution and density of particles, hydrometer types, precipitation structure, and cloud liquid water content (CLWC) etc), other than surface precipitation rate. The purpose of the present study is to model the variations of the physical properties of winter precipitation over Sea of Japan, and to validate the magnitude of error of microwave brightness temperatures (TBs) caused by these variations.

To estimate these variations, we analyzed the WAKASA bay experiment 2003 (WAKASA2003) observation data sets and the output of a non-hydrostatic NWP model with cloud physic schemes. The results show that the particle density and CLWC largely varied independent of the precipitation rate, and that different precipitation structures and particle types were observed for distinct synoptic situations.

Then, we calculated the influence of the above variations on the error of microwave TBs from frozen precipitation, using the radiative transfer code of Liu (2004). The results shows that the observed variations of the particle density and CLWC caused significant scattering of polarization corrected temperature at 89 GHz (PCT89) for a given surface precipitation rate, and that PCT89 became higher if mixed-phase particles, such as wet snow, existed. These results were consistent with the comparison between Advanced Microwave Scanning Radiometer on EOS (AMSRE) TBs and the observed precipitation during the WAKASA2003.

### 4.12. Weinman, J. and Kim M.-J.: A Simple Model of the Mm-wave Scattering Parameters of Randomly Oriented Aggregates of Finite Cylindrical Ice Hydrometeors : An End-Run Around the Snow Problem??

Jim Weinman, (University of Washington)
Min-Jeong Kim (NASA)

Space-bone mm-wave radiometric measurements offer the potential to observe snowfall at high latitudes. There is thus a need for a relatively simple representation of mm-wave scattering parameters of snow that can be incorporated into algorithms to retrieve snowfall from remotely sensed measurements.

If snow is assumed to consist of randomly oriented aggregates of prisms or columns, then radiative transfer snowfall retrieval models can be greatly simplified. The extinction coefficients and asymmetry factors of randomly oriented finite blunt cylinders were derived from a T-Matrix scattering model. Those parameters for aggregates of more elongated cylinders were also obtained from the Discrete Dipole Approximation.

We found that the extinction coefficients and asymmetry factors could be approximated by simple analytical functions of the phase delay that is a function of the frequency and the ratio of the volume to the projected area of the cylindrical aggregates.

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