Summary of The 3rd Joint JCSDA-ECMWF Workshop on Assimilating Satellite Observations of Clouds and Precipitation into NWP Models

Theme: Simulation, Inversion, NWP Assimilation, Modeling and Actual Measurements of Radiometric, Microphysical & Optical Properties

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The Problem:

Satellite observations in the visible, infrared, and microwave (active and passive) provide a great deal of information on clouds and precipitation and therefore are strongly linked to hydrometeors (ice, non-precipitating cloud, liquid and frozen precipitation, mixed phase) geophysical characteristics (Particle size, distribution, density, shape, amount, etc). Both satellite observations and measurements from ground (or field) experiments have been and are continuing to be studied in order to (1) understand the interaction and correlations between the various hydrometeor parameters and the state parameters supporting the clouds and precipitation, (2) simulate their optical and radiative properties, (3) invert the satellite observations to provide cloud and precipitation parameters, (4) assimilate the same observations into NWP models and to (5) improve cloud modeling parameterizations. The workshop intends to bring together the scientific communities involved in these applications in order to make progress and learn from each others' results. The outcome is hoped to lead to improved data assimilation and therefore initialization of clouds and precipitation in models, to improved accuracy in the simulation of cloud and precipitation- impacted measurements, to higher-quality inverted cloud and precipitation products and to a full utilization of the field campaign results. Since clouds and precipitation often occur in sensitive regions for forecast impacts, such improvements are necessary for continuing significant gains in weather forecasting.

Background:

In 2005, the JCSDA sponsored an international workshop that covered the three main topics related to assimilating observations in cloudy/precipitating regions: satellite observing capabilities, modeling radiative transfer and cloud/precipitation formation, and data assimilation. The papers presented at the 2005 workshop were published as a Special Section of the Nov. 2007 issue of JAS. In spring 2010, the European Centre for Medium-Range Weather Forecasts (ECMWF) hosted a joint ECMWF–JCSDA workshop to document the developments since the 2005 workshop and to produce recommendations to ECMWF, JCSDA, and other NWP centers and scientific communities for future research developments and collaboration. About 65 participants attended the workshop, representing most major NWP centers around the world as well as research institutes and universities. See more details in this summary article: http://journals.ametsoc.org/doi/pdf/10.1175/2011BAMS3182.1

Since then, and because of their importance and expected significant value to extreme weather prediction and NWP forecast skill, major efforts are being undertaken in operational and research centers to tackle the problem of assimilating data impacted by cloud and precipitating. In parallel, the remote sensing community involved in cloud and precipitation retrievals have invested significantly in the improvement of the physical methods employed to invert the same data used in the NWP assimilation, for the determination of cloud and precipitation and other atmospheric and surface products obtained in these areas. In addition, major efforts have taken place, in particular in preparation of the Global precipitation Mission (GPM), to understand hydrometeors parameters interaction, correlation, through multiple field campaigns. Some of this progress was recently highlighted in the International Precipitation Working Group (IPWG) meeting held in Tsukuba, Japan.
The purpose of this workshop follows the tradition of 5-year cycle joint ECMWF-JCSDA workshops dedicated on tackling this problem, this time extending the invitation to scientific communities involved in tackling the interpretation and utilization of satellite observations impacted by hydrometeors for the purpose of the simulation, inversion, NWP assimilation and modeling and actual measurement of microphysical and optical properties.

Purpose of this workshop:

Accelerate the cross-fertilization of knowledge in the different communities to benefit all activities. Document recent developments and make recommendations to ECMWF, JCSDA, and other NWP centers and scientific communities for future research developments and collaboration.

Workshop Objectives:

- Critically review the current state of the art in:
    - Modeling of clouds and precipitation in NWP (specific attention to what current and near future generation models can realistically represent, and therefore what observations could be ingested).
    - Science validation: Reviewing the findings from the field campaigns, targeting the hydrometeors and their microphysical and macrophysical properties: *focusing on uncertainties*.

- Satellite observations of clouds and precipitation: *focusing on what exists and information content*
- Simulating the optical properties and radiative transfer in cloudy and rainy conditions: *Focusing on how accurately can we model observations*
- Physically-based Inversion methodologies using satellites data impacted by cloud and precipitation.
- Assimilating satellite observations of clouds and precipitation.

- Identify the key issues for successful assimilation of cloud and precipitation information
- Develop a prioritized list of additional examinations of issues, further evaluations of techniques, and needed new developments
- Plan coordination mechanisms to facilitate progress on needed developments

How:

By bringing together experts in: cloud/precipitation remote sensing, radiative transfer in cloudy or precipitating atmospheres, modeling clouds and precipitation, and assimilating cloud and precipitation-impacted observations as well as the actual measurements of the hydrometeors microphysical and macrophysical characteristics.

There were three specific working groups that were formed during this workshop: The radiative transfer and observations working group (IBG-1); Physical Inversion and Data Assimilation of cloud- and precip- impacted measurements (IBG-2); and Hydrometeor microphysica and models – coordination with data assimilation (IBG-3).

Below are the summarized findings of each working group. It is important to note that the discussion of "clouds" or cloud-impacted radiances also includes the impact of precipitation implicitly.

There are a few specific items for IPWG and IWSSM, particularly focusing on the continued need for accurate and robust microphysical databases and associated scattering databases. These databases can be utilized to create lookup-tables for the fast radiative transfer models used in operational NWP frameworks. In general, operational NWP models are far behind the capabilities of individual retrieval algorithms in terms of optimally extracting information content from satellite observations. A key recommendation that bridges IWPG and the international DA communities is for cloud and precipitation retrieval algorithm developers to attend data assimilation science meetings and vice-versa.
Alan Geer and Ben Johnson will continue to cross-represent ECMWF and JCSDA interests (respectively) at future IPWG and other international working groups where there is significant overlap between data assimilation and precipitation retrieval science. One recent meeting, the International TOVS working group (ITWG), ITSC-21 in Darmstadt Germany, included discussion of the requirements needed for NWP and DA centers to improve their physical and RT models in support of cloud and precipitation data assimilation.

Presentations made at this workshop are located at:
https://www.jcsda.noaa.gov/meetings_JointEC-JC_Wkshp2015_agenda.php

[IBG-1] Working Group on Radiative Transfer and Observations (Chairs: Alan Geer, Quanhua Liu)

This working group looked to future developments in radiative transfer in support of cloud and precipitation retrievals and data assimilation. Also, future observing system requirements were considered.

Many presenters and participants were interested in the single-scattering properties of non-spherical hydrometeors, so this item was first on the agenda. Scattering databases like those of Liu (2008) allow radiative transfer models to simulate the effect of frozen hydrometeors (e.g. snow, ice and graupel) across the microwave and infrared. Many all-sky microwave assimilation efforts rely on bulk scattering properties computed from Liu (2008) and embedded, for example, in the RTTOV-SCATT model (Geer and Baordo, 2014) but this relies on a 'one shape fits all' approach. The modelling and retrieval community is making progress in modelling snow aggregates and hence avoiding discrete particle shapes and allowing smooth transitions across ensembles of particles (e.g. Morrison and Milbrandt, 2015). There is also much interest in better representing the uncertainty associated with unknown particle shapes and size distributions; for example observation operators could simulate an uncertainty alongside the observation equivalent. Finally, the recent development of the T-matrix to represent non-rotationally symmetric particles (the Invariant Imbedding T-Matrix method; Bi et al., 2013; Bi and Yang, 2014) may offer an order-of-magnitude decrease in the cost of simulating scattering properties, compared to the current Discrete Dipole Approximation (DDA).

Beyond these specific developments, it was recognised that scattering databases are used by a wide community across the microwave, sub-millimeter, infrared and visible, for active and passive applications, for ice clouds and large-scale processes as well as convection, from basic research on cloud microphysics through to operational all-sky assimilation. Scattering databases are being generated and used across this community and it is in everyone's interests to come together to share expertise and find ways of making these databases even more generally useful. For example:

- Is it possible to recommend a standard set of frequency anchor points on which scattering properties are generated? Can we recommend a required range of frequencies? For example current and future microwave applications need scattering properties from around 1 GHz to 900 GHz.
- Currently scattering lookup tables in RTTOV and CRTM are based on only one ice density, of 0.9 g/m^3. It will be beneficial to include a range of densities for application within data assimilation and retrieval systems. The density can affect both effective dielectric constant and the effective particle size.
- What set of scattering properties is required? What about the full scattering amplitude matrix for each direction of interest? Should fully polarimetric scattering properties be archived to support ground radar users and users using spaceborne polarimetric measurements (e.g. Windsat)?

- Is it possible to standardise data formats so that, for example, databases could be inter-operable between different radiative transfer models (e.g. CRTM and RTTOV)?

Questions on scattering database development were addressed by a focused workshop at the International Precipitation Working Group (IPWG) and International Workshop on Space-based Snowfall Measurement (ISSWG) in October 2016, and during the 1st International Summer Snowfall Workshop, 28. - 30. June 2017 at the Institute for Geophysics and Meteorology, University of Cologne, Cologne, Germany.

One focus of these meetings were non-spherical scattering databases,with the goal of guiding future scattering database development. This participation is welcomed by the IPWG and ISSWG organisers, and one of the present co-chairs has been added to the organising committee of ISSWG to help ensure broad participation.

Beyond the issue of non-spherical particles, the priority for further developments in support of fast microwave radiative transfer models for cloud and precipitation (such as CRTM and RTTOV-SCATT) is fairly clear:

1. Current fast surface emissivity models only provide emissivity and non-specular corrections along the beam. This is not suitable for multiple-stream discrete-ordinate solvers so a fast new bidirectional reflectance distribution function (BRDF) model is required in the microwave. This is a blocking issue for CRTM and though RTTOV-SCATT is not affected because it uses the delta-Eddington solver, a BRDF may be required if it moves to multiple-stream scattering in the future. Further, it is necessary to better understand the non-specular correction under cloudy skies and to make sure that emissivity models work well at low (e.g. sub 10 GHz) and high (e.g. greater than 183 GHz) frequencies to support new and existing instruments, as well as continuing the improvement of land, snow and sea-ice emissivity modelling.
2. Fast models must include a treatment for sub-grid heterogeneity of cloud and precipitation, in other words the beam-filling effect. It was noted that even on the scales of radar beams (e.g. 20 m) strong heterogeneity is still present; there is no currently modelled scale at which beam-filling issues can be neglected.
3. 3D effects need to be considered, as they can impact brightness temperatures by up to 10-15 K (e.g. Bennartz and Greenwald, 2011). The first step is likely to be the use of tilted independent columns (Hong et al., 2000). For local-area models, the tilted path may traverse many grid boxes; this is a technical issue that may need attention in some systems.

Fast radiative transfer modelling in the infrared and visible is lagging developments in the microwave, but this is at least as important. Particularly for mesoscale and local area modelling, the geostationary satellites Himawari, GOES-R and MTG will offer very high temporal resolution cloud images whose assimilation could strongly benefit nowcasting and short-range forecasting. Although many teams are working towards this, there is much scope for development and there is as yet no operationally proven fast forward model including scattering. For example, RTTOV is operationally ready for water vapour sounding channels (e.g. 6.7 micron) but struggles in terms of speed and accuracy in window channels (e.g. 10.8 micron). Just as in the microwave, the continuing development of BRDF models is crucial. The working group hopes to see a lot of progress in this area by the next workshop.

Beyond the passive microwave, infrared and visible, there is a need to develop other sources of cloud and precipitation data. Existing broadband OLR and SW radiation budget measurements could be a quick win for operational assimilation because forecast models already simulate broadband fluxes. Rather than direct assimilation, the initial aim would be validation and development of forecast models and improved understanding of the use of cloudy IR and visible observations. To support this, **NOAA is asked to consider making CERES data available in near-real time (NRT)**. For active assimilation of broadband fluxes, tangent-linear and adjoint models are as yet only available internally at ECMWF, though a future broadband scheme is in development that will likely be publicly available, and could potentially be included in fast radiative transfer models (pers. comm. Robin Hogan).

A second existing source of data is the DPR precipitation radar on GPM, which is available in NRT. **The operational forecasting community is encouraged to use DPR data**, both for passive monitoring in support of forecast and radiative transfer model development, and also to help develop a capability for active assimilation. It is important to understand the usefulness of a spaceborne precipitation radar in NWP while it is still available. To support this, fast RT models like RTTOV and and CRTM could develop an active capability. Although many radar simulators exist, the benefit of integration into existing fast models (beyond simple convenience) is that consistent particle shape and size distribution assumptions can be made, so that the combination of passive and active sensors can help to better constrain these assumptions.

The first priority for the future observing system is to maintain existing capabilities. Nowadays both retrievals and operational weather-forecasting are making extensive use of spaceborne microwave sensors, including ATMS, four MHS instruments, three SSMIS, GMI, AMSR-2 and Windsat. The future provision of microwave sounders is relatively safe, but there is need to preserve capabilities in conical scanners, where in ten years the only firm commitment may be the European microwave imager (MWI) on the next generation of Metop satellites. Such instruments should be considered a core part of the operational global observing system. Further, as the community is increasingly making use of space radars, these capabilities also need to be maintained beyond GPM and the future EarthCARE mission. **It is recommended that the weather forecasting and retrieval communities come together to produce a report making the case for ongoing provision of active and passive microwave instruments, and considering possible tradeoffs in terms of cost, resolution and frequency.** In particular, it must be possible to start reducing the cost of sending these long-proven instruments into space. Further, water vapour, cloud and precipitation are phenomena that occur on small time and space scales, with fast growing errors, so both for retrievals and particularly for nowcasting and mesoscale forecasting, there would be great benefit in increasing temporal coverage, i.e. even more satellites. Alongside this, the research and operational communities need to be aware of possible future commercial smallsats. As a new Decadal Survey is now taking place in the US, the organisation of this report should be a US-led activity and JCSDA would be well placed to do this.

[IBG#2] Physical Inversion and Data Assimilation of cloud- and precipitation impacted measurements (chairs: Stefano Migliorini and Ben Ruston)

All-sky for IR and MW: Both could benefit from cloud-dependent error models. In the IR we cannot rely on direct estimate of cloud. Cloud water retrievals in MW may depend on scan angle. Perhaps the Huber norm approach can be more applicable to both.

Do we need superobbing in the IR? Perhaps with imagers it is more meaningful given their higher spatial resolution, but with sounders we may have more homogeneity within the footprints which may provide more difficulties due this heterogeneity of cloud.

Can we model cloudy radiance well enough in IR? Realistic cloud overlapping schemes can be too expensive. How can we deal with mismatch between vertical resolutions of the observations and model? Note that the assumption will be different in regional models versus the global model.

Another issue is there needs to be tools for calculating optical properties tables for MW to be imported to the radiative transfer models (CRTM and RTTOV).

Recommendation: Investigate common approaches for all-sky radiance error models that can be used both in MW and IR. Simplicity is desirable: e.g. OmB based (e.g., through the Huber norm). Move away from empirical cloud retrievals.

Recommendation: It is desirable to “superob” IR imager radiances to achieve more homogeneous scenes and scale matching between NWP model and obs.

Recommendation: Make use of fast RT models with cloud fraction as an input variable. Also, there is a need for accurate schemes that model the cloud radiative effects well in IR (e.g. as the one in RTTOV) but that are also not too computationally expensive.

Recommendation: Make available tools for calculating optical properties table for MW to fast RTM users. Also reach out to Bryan Baum for optical property tables in IR, to see if it addresses the issues with modelling the ~10.8um channels in the presence of cloud.

Variational vs Ensemble DA: cloud in the control vector can produce cloud increments even in absence of all-sky assimilation. Ensembles can provide a way to “solve” the cloud-control variable problem but there are issues due to sampling errors. Also forecast error distribution may not be Gaussian (e.g. when you have a multi-physics approach). Hybrid could help in regularizing the problem? Methods need to maintain the important balance between dynamical and microphysical variables: if not we risk degrading the analysis. Flow dependent errors can help. But it would be important to rely on cloud control variable(s) to improve the reliability of the static (i.e. climatological) forecast error covariance B .

Recommendation: Flow dependent errors are a very useful way to make use of cloud information in DA. But cloud-based control variables are still desirable.

Nonlinearity issues: Outer loops can be very useful. A 1D-Var step can be used to preprocess the all-sky radiances before assimilating them. It should be possible to feed the observation operator a better first guess, and reduce nonlinearity of the forward operator. This can open the possibility of using more sophisticated retrieval schemes (ensemble based?). Other possibility is to avoid linearizations by using EnKF systems. But there may be issues with the vertical localization in observation space.

Recommendation: Investigate pre-processing the radiances (1DVar) to help with QC and achieve a better linearization state

Correlations in cloudy conditions: We should include correlations in the cloud-dependent observation error model.

Recommendation: Advisable to estimate spectral error correlations in cloudy conditions with the aim of complementing the cloud-dependent observation error model with (state-dependent?) correlations

Can we exploit sub-grid scale info from active or Vis/IR imagers?
Co-located imagers to IR sounders can help QC: clustering can give us information on presence of multilayer cloud that is difficult to model. In the future, hyperspectral imagers can help us achieve more sophisticated QC and even help on assimilating IR and high frequency MW data including over land.

Active instruments from space can provide detailed information on cloud and precipitation but over narrow swaths. They could provide information on microphysics that can be used in MW RTMs. Also used for validation of MW retrievals. Radar refractivity information can be assimilated. But to have impact we need to exploit correlations between rain errors and those on other part of the state. This may require the implementation of a rain-dependent control variable, as currently investigated by JMA.

Recommendation: Importance of co-located advanced imagers to help assimilation of IR sounders and MW (especially > 160 GhZ for ice scattering)

Recommendation: Consider developing rain-dependent control variable

Recommendation: Use of broadband SW and LW fluxes (e.g. from Ceres) to evaluate impact. Also scale dependent techniques (e.g. FSS) to be used in global models so as to evaluate the potential of all-sky assimilation on improving spatial predictability.

Evaluate problems in balance and in initializations over initial forecast time steps.

Consider 2D time averaged maps (e.fg. DA increments) for verification. Importance of investigating specific problems (e.g. lack of liquid water in stratocumulus region).

[IBG#3] Hydrometeor microphysics and models – coordination with data assimilation (Chairs: Jean-Francois Mahfouf and Brad Ferrier)

It has been recognized that there are still many uncertainties (particularly in cold clouds) regarding the specification of cloud microphysics necessary both for the atmospheric models in order to describe the conversions between water species and for the radiative transfer schemes in order to simulate either satellite radiances or reflectivities. Despite recent progress in numerical models, where cloud formation and dissipation are now described through condensed water prognostic variables and bulk microphysical processes, the level of details remains insufficient to provide unambiguous properties for radiative transfer computations.

It is recommended to perform more systematic evaluations of clouds and precipitation in observation space, as currently done within data assimilation systems. It is important to underline that systematic errors in a data assimilation system (when observations are corrected from known biases) are usually the signature of a model deficiency. Such weaknesses should be corrected through an improved description of physical processes after a proper understanding of their origins. For example, at ECMWF the examination of background departures for all-sky microwave radiances has allowed to identify weaknesses in the prognostic cloud scheme (lack of supercooled droplets in cold-air outbreaks over the storm track regions of the Southern Hemisphere) and to define « optimal » microwave radiative properties for solid precipitation (in terms of shape and density) in order to produce more Gaussian and unbiased statistics. To allow such comparisons, it is important to make available adequate numerical tools to generate simulated observations (radiances, reflectivities) to the community developing cloud and precipitation schemes in atmospheric models, even though some of them already exist (e.g. RTTOV, CRTM).

There is also a need for improved consistency between the microphysics developed in Numerical Weather Prediction (NWP) models and the one specified in radiative transfer models. This concerns the Particle Size Distributions (PSDs), together with their shape and density (often lumped in a mass-diameter law). This requires more interactions between the communities of model developers and data assimilation. The synergy between active and passive instruments (radar-radiometer) could help in that context. The level of detail of microphysical processes in NWP models should be examined not only in terms of increased level of details but also for insuring a better compatibility with the requirements in terms of data assimilation (e.g. preparation of new missions like METOP-SG where the sub-millimeter imager ICI will provide unprecedented information on ice clouds). The interest of new approaches based on higher moment microphysical schemes (providing additional information to better constrain the shape of the PSDs) and also on more continuous schemes in terms of frozen species (e.g. prediction of particle properties such as rime mass and volume) should be explored in the data assimilation framework.

Along these lines, the uncertainties in the microphysical description both for cloud processes and radiative transfer calculations should be assessed and used in ensemble data assimilation systems that need to account for model uncertainties in order to generate the ensemble spread. For achieve this goal, it is recommended to set-up a focused project towards the improvement cloud and precipitation modeling (at high resolution where microphysics description is critical) through the use observations (all-sky radiances) in order to quantify the uncertainties and the joint behavior of microphysics parameters and variables (through dedicated sensitivity studies). It has been recognized that, when moving towards higher model resolutions, non-linearities and discontinuities induced by moist physical processes are likely to be exacerbated, raising issues on the suitability of variational or/and ensemble approaches.

Therefore, new data assimilation techniques accounting for non-gaussian error statistics should be explored. They could lead, in the long term, to a more efficient usage of all-sky radiances and radar reflectivities.

Summary article of international NWP activities regarding all-sky satellite data assimilation:

Geer, A.J., Lonitz, K., Weston, P., Kazumori, M., Okamoto, K., Zhu, Y., Liu, E.H., Collard, A., Bell, W., Migliorini, S. and Chambon, P., 2017. All-sky satellite data assimilation at operational weather forecasting centres. *Quarterly Journal of the Royal Meteorological Society*.