ECMWF-JCSDA-EUMETSAT NWP-SAF 4th workshop on assimilating satellite cloud and precipitation observations for NWP

3 - 6 Feb 2020, ECMWF, Reading, UK

Working group summaries, first draft, 10th June 2020

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0 Overview

Workshops on the assimilation of satellite cloud and precipitation observations for NWP are held every 5 years, organised jointly between the Joint Centre for Satellite Data Assimilation (JCSDA) and European Centre for Medium-range Weather Forecasts (ECMWF), and this time, also EUMETSAT NWP-Satellite Application Facility (NWP-SAF). The fourth workshop in this series was held at ECMWF in Reading, UK, from 3rd-6th February 2020, an invitation-only event bringing together 80 scientists from weather centres, research organisations, universities and private companies.

Cloud and precipitation assimilation has applications at all space- and time-scales of weather forecasting - from convective-scale nowcasting and local area, short range forecasting, through to the global medium-range, so the workshop gathered scientists from all these areas. It is also a highly interdisciplinary problem, combing detailed models of microphysical and macrophysical (sub-grid) cloud and precipitation processes, scattering radiative transfer models, and specialised observations from passive and active satellite sensors at frequencies from the microwave to the solar. These are all brought together using data assimilation to create better initial conditions for weather forecasts, or to improve the quality of cloud and precipitation modelling.

Cloud and precipitation processes are often strongly nonlinear, error distributions are often highly non-Gaussian, predictability is low, and physical modelling is difficult, so this is an area that pushes the science of data assimilation and weather forecasting well beyond its original limits and assumptions. Hence progress is dependent on specialists from many different areas of NWP working together. This workshop appraised the state of the art in the assimilation of cloud and precipitation observations from satellite, identified the main issues that need to be solved for further progress, and charted ways forward.

The workshop was organised around four main areas feeding into four working groups. Each area was covered by invited talks and a plenary-panel discussion before the creation of parallel working groups for the final day. Presenters of the longer invited talks covered not just their own work but also gave overviews of all work in the field. The areas, and the broad questions associated with them, were:

1. Assimilating satellite observations sensitive to cloud and precipitation

What are we aiming to get from these observations? How can we achieve this and what more needs to be done?

2. Cloud and precipitation modelling

How can forecast models support cloud and precipitation assimilation, and how can cloud and precipitation assimilation help improve models?

3. Observation operators in cloud and precipitation

How do we go from the forecast model's representation (e.g. hydrometeor water content) to what the observations see?

4. Data assimilation methods

How can data assimilation support greater use of cloud and precipitation observations?

This document provides the reports of the four working groups. A full synthesis and overview of the workshop will be prepared for more formal publication in the future. Presentations and video recordings are available from:

https://www.ecmwf.int/en/learning/workshops/4th-workshop-assimilating-satellite-cloud-and-precipitation-observations-nwp

0.1 Reports from previous workshops

The **1st workshop (2005)** is documented in a special collection of JAS (Errico et al., 2007)

The **2nd workshop (2010)** is covered by an ECMWF proceedings at:

https://www.ecmwf.int/en/learning/workshops-and-seminars/past-workshops/2010-assimilating-satellite-observations-clouds-precipitation-NWP-models)

along with a BAMS meeting summary (Bauer et al., 2011) and a special issue of QJ (Ohring and Bauer, 2011)

The **3rd workshop (2015)** working group reports can be found at:

https://www.ecmwf.int/sites/default/files/medialibrary/2020-02/Summary_of_The_3rd_Joint_JCSDA-ECMWF_Workshop_on_Assimilating_Satellite_Observations_of_Clouds_and_Precipitation_into_NWP_Models.pdf

0.2 Organisers

Main organisers:

- Alan Geer (ECMWF)
- Niels Bormann (ECMWF)
- Thomas Auligné (JCSDA)

Scientific organising committee:

- Stephen English (ECMWF)
- Richard Forbes (ECMWF)
- Ben Johnson (JCSDA)
- Andrew Collard (NCEP)
- Christophe Accadia (EUMETSAT)
- Philippe Chambon (Meteo France)
- Christina Köpken-Watts (DWD)
- Chiara Piccolo (Met Office)
- Kozo Okamoto (JMA)
- Masahiro Kazumori (JMA)

1 Working group 1: Assimilating satellite observations sensitive to cloud and precipitation

Chairs: Andrew Collard (NCEP) and Peter Weston (ECMWF)

Participants: (list to be added)

1.1 Progress since the previous workshop

In the past five years since the previous workshop there has been very strong progress at many different NWP centres on assimilating more radiances at many different frequencies in the presence of cloud and precipitation. At ECMWF the all-sky MW observations are now one of the leading observing systems in terms of improving forecast accuracy and many other centres now also operationally assimilate all-sky MW observations including NCEP, GMAO and the UK Met Office. Efforts to develop all-sky IR assimilation have also progressed to the point where many centres are getting close to neutral results. It is worth remembering that the initial all-sky MW results at ECMWF were mostly neutral and that the clear benefits we now see are down to years of careful research in extending and improving the assimilation methods, observation operator and NWP model itself. Therefore it is definitely worth persevering with all-sky IR in the future. At DWD significant work has been done to develop MFASIS, a fast forward operator for visible channels. This means that the assimilation of visible channels is now a possibility and initial work mostly by DWD at the convective scale is showing encouraging results.

Recommendation 1.1, to NWP centres: Given the promising initial developments for visible assimilation, the WG recommends NWP centres to develop capabilities to assimilate visible channels, including in global NWP systems.

1.2 Observations

The WG considered aspects of all-sky assimilation of presently available observations and identified ways forward for some observations that appear currently under-used in all-sky assimilation.

The lowest frequency MW channels that are currently assimilated in the atmospheric data assimilation system at ECMWF are 18.7GHz. AMSR2 has channels at 6.9, 7.3 and 10.6 GHz which are sensitive to heavy precipitation. However, efforts to assimilate these channels have been held back by a few issues. First, these channels are highly sensitive to the surface so successful assimilation relies on an accurate estimate of the surface characteristics to be available including the surface emissivity. The current surface emissivity models, e.g. FASTEM, are sufficiently accurate above 20GHz and at L band (1-2GHz) but not as accurate at frequencies in between. There are efforts to improve this by developing a reference quality emissivity model at these frequencies.

Recommendation 1.2, to the emissivity modelling community: The WG recommends continued efforts to develop a reference quality ocean surface emissivity model at all frequencies, and notes in particular the need for better emissivity modelling between 2 and 20 GHz.

Another issue for the assimilation of lower frequency MW observations is related to the relatively low resolution and large FOV of these channels. This makes it more important to model the FOV properly when running the observation operator which has not been done in most assimilation systems until now. There was a suggestion that the fact that these channels are often oversampled could be used to gain more spatial information and/or to reduce the noise. This would be a change from the usual approach of thinning the data to avoid having to take account of spatial observation error correlations. Finally, previous work showed that the pdf of simulated radiances was not able to match the pdf of observed values due to inaccuracies in the observation operator. It is possible the above two issues were contributing to this.

In the IR one issue that has not had a lot of attention is the treatment of cloud fraction in the assimilation framework. In areas with optically thick clouds, any inaccuracies in cloud fraction could lead to very large departures between observed and simulated radiances. In the IR all-sky assimilation systems currently being developed the cloud fraction is treated differently with some schemes keeping it fixed throughout the assimilation. It should be possible to allow cloud fraction to vary between outer loops or middle loops although it may be tricky to link it directly to the control variables.

Recommendation 1.3, to NWP centres involved in all-sky IR assimilation: The WG recommends paying close attention to the role of cloud fraction in all-sky IR assimilation.

There were presentations and posters summarising efforts to assimilate active sensors such as DPR on GPM-Core and Cloudsat and CALIPSO in the context of preparations for EARTHCare. These are potentially very important observations for getting information on the cloud structure and, as well as direct assimilation, could be used to help model development too. To allow simpler implementation and maintenance, the WG considers it best if these observation operators are packaged with the observation operators that are already coded up in our systems. This will also allow these new observation operators to be shared more easily throughout the community.

Recommendation 1.4, to developers of fast radiative transfer modellers: The WG recommends that modelling for active sensors is included in existing standard fast radiative transfer models, i.e. RTTOV and CRTM.

Recently a new observing technique has emerged, based on polarimetric GNSS radio occultation. These observations can detect cloud hydrometeors and there is potential for them to be used to analyse frozen particle size distributions. More work in this area is encouraged.

Recommendation 1.5, to observation providers and NWP centres: The WG recommends further investigations into the capabilities of polarimetric GNSS radio occultation for potential future all-sky assimilation.

The benefit of instruments providing measurements of the full Stokes vector were briefly discussed by the WG, though the group did not express a clear view on these.

1.3 Biases

The treatment of biases, and in particular cloud modelling biases, remains a critical topic for all-sky assimilation. Some centres showed approaches to bias correction where the sample of observations used to calculate the bias correction coefficients in all-sky is limited to certain situations. For example at NCEP this sample is limited to areas where the observed and model cloud agree with each other. At ECMWF this has not been required so far, possibly due to a better quality model. However, it may be something to consider in the future. Environment Canada are running an entirely separate 3D-Var assimilation system to calculate bias coefficients.

Model biases are generally larger in cloudy areas than clear areas and are difficult to handle in current assimilation systems. Katrin Lonitz' talk focused on a number of cases where the best approach varies depending on the characteristics of the bias. Sometimes it is best to screen out the data in biased areas e.g. cold air outbreaks, sometimes you can ignore a bias e.g. marine stratocumulus and sometimes you should attempt to correct the bias. The biases seem to vary by cloud type so a cloud-type dependent bias correction could be considered in the future. One possible data assimilation formulation that could be used to separate the correction of model and observation biases is the weak-constraint formulation. At ECMWF this is currently used only in the stratosphere where the model error length scales are much longer than the background error length scales. Efforts to use weak-constraint in the troposphere have not been as successful due to the lack of scale separation but if this issue could be overcome it may be possible that weak-constraint could help to correct model cloud biases.

1.4 Verification

Verification for some aspects of all-sky assimilation remains a challenge, and there was consensus that different forecast ranges and scales require different verification approaches and metrics. For example traditional forecast verification based on RMSE of forecasts against own analysis should be limited to the longer-range forecasts and larger scale features. At shorter-range and smaller scales model fits to observations and more neighbourhood-based approaches should be used to try to avoid the double penalty problem associated with the more traditional approaches. In addition, verifying against own analyses will always be challenging for cloud and precipitation assimilation where invariably more structure is introduced to the analysis that is not carried forward into the forecast. The use of independent analyses as verification references is one way to get around this problem. In addition, a lot of current verification methods are deterministic and we should try to look at more probabilistic approaches by getting advice from verification experts.

It was highlighted that the background fits to observations that many centres use are very powerful in diagnosing which areas and variables are being improved or degraded. There are caveats including making sure the bias correction and quality control are behaving correctly because otherwise conflicting results can be obtained. Also, non-specialists sometimes struggle to interpret the fits to radiances and it is up to our community to educate them on these aspects. The fits to observations can be extended to looking at longer range forecasts verified against all observations.

Recommendation 1.6, to NWP centres: The WG recommends making better use of observations for verification, in particular those that are not assimilated, as these will be more independent of the analyses and forecasts.

Recommendation 1.7, to NWP centres: The WG recommends educating other NWP experts who are not specialists in radiance assimilation in the interpretation of verification against radiance observations.

When verifying cloud forecasts it was suggested to look at fractional skill scores and simulated imagery. Possible ways of quantifying impacts on simulated imagery would be to use pattern recognition or some machine learning approaches.

There was a warning on the sole use of FSOI. This should be combined with other measures or approaches such as OSEs when thoroughly assessing the impact of different observing systems.

1.5 Communication

The success of the workshop in bringing people from many different communities (model, observation operators, assimilation, verification etc.) together was highlighted and it was suggested that we should have more of these meetings. One suggestion was to have more regular virtual meetings to share latest results more frequently than once every 4-5 years at these workshops.

Recommendation 1.8, to the wider all-sky community: The WG recommends holding further meetings that bring together the different communities involved in all-sky assimilation (ie, cloud modelling, observation operators, assimilation, verification, observation providers, etc).

It was also highlighted how people working on the model, observations, assimilation etc. should talk to each other more often because the assimilation system can be a very powerful diagnostic tool for diagnosing model biases. Richard Forbes' talk demonstrated how combined expertise from modelling and all-sky assimilation experts can lead to the identification and improvement of cloud modelling issues.

Recommendation 1.9, to NWP centres, and in particular management at NWP centres: The WG recommends fostering better internal and external communication between model, assimilation, and verification teams, aimed at maximising the benefit of all-sky assimilation for model development as well as for initial conditions. The WG recommends that management actively facilitates and sustains such communication, including facilitating the development of appropriate tools for cross-team collaboration on the use of observations for verification.

2 Working Group 2: Cloud and precipitation modelling

Chairs: Derek Posselt (JPL) and Richard Forbes (ECMWF)

Participants: (to be added)

The discussions consisted of a panel session with questions and answers and a round-table working group discussion. Specific issues from the panel session were discussed in more detail in the working groups and included:

- the potential to extract more information from data assimilation systems to help to constrain cloud, precipitation and microphysical processes,
- increasing the range of channel frequencies from observations to constrain increasingly complex microphysical schemes,
- filling the observation gaps including improved vertical profiles of cloud and precipitation, more information on mixed-phase and ice hydrometeors and higher time-resolution to help in understanding processes,
- increasing the availability and use of forward operators to match model with observations,
- representing subgrid heterogeneity more accurately with improved macrophysical parametrizations,
- improving the representation of uncertainty for parametrizations, forward operators and observations,
- exploring the potential roles for machine learning in model parametrizations and evaluation techniques,
- encouraging the trend for researchers on model parametrizations, data assimilation systems and observations to interact and work more closely together.

The working group discussion is summarised below as a number of topics in two main areas: (1) the future directions for model cloud and precipitation parametrization development with implications for data assimilation and (2) using data assimilation to evaluate and inform model developments. For each topic, we summarize the discussion and provide recommendations for future research and development.

2.1 Cloud parametrization development and implications for data assimilation

2.1.1 Improved representation of subgrid heterogeneity

Both observations and forward modelling the observations can be very sensitive to the heterogeneity of cloud and precipitation within the observed footprint or model grid box. At a basic level, subgrid heterogeneity of cloud and precipitation is represented by macrophysical assumptions on cloud/precipitation fraction and overlap in the vertical in both model parametrizations and observation operators. However, there is a trend towards an improved more physical representation of subgrid heterogeneity in model parametrizations that connects the dynamics, thermodynamics, clouds and precipitation. This can take the form of diagnostic relationships, such as empirically representing in-cloud and precipitation specific hydrometeor mass PDFs and their covariance, which modify process rates such as precipitation formation. Alternatively it can be represented with more complex prognostic schemes that predict higher order moments (variance, skewness) for multi-dimensional PDFs (vertical velocity, temperature, humidity, cloud), such as the CLUBB scheme for unifying boundary layer subgrid turbulence and convection. A third (computationally expensive) alternative is to use superparametrization or ultraparametrization that explicitly represents the subgrid scale dynamics and heterogeneity within each grid box with a small-domain high-resolution model.

In principle, a more accurate and consistent representation of the PDFs of subgrid variability can lead to better scale-invariance for the model across different resolutions and improve the representativity for comparing with observations on scales smaller than the grid scale. It is also important that radiative transfer/forward models used for data assimilation and model evaluation are able to use the additional information on the PDFs of subgrid variability effectively. There is also a question for the future whether data assimilation will be able to provide information on, or even modify directly higher order moments of the PDFs if they are prognosed in the model.

However, whereas process rates in microphysics schemes tend to be converging between parametrization schemes, developments in macrophysical assumptions are not converging and there remain many uncertainties and challenges in how to link subgrid heterogeneity of cloud and precipitation with subgrid turbulent flow. The recommendation is to continue to improve the representation of subgrid variability of dynamical, thermodynamical and cloud/precipitation quantities in models and the ability for radiative transfer models to use this information for improved representativity with observations. It is expected that high resolution models (e.g., cloud resolving and large eddy simulation models) will continue to serve as a reference against which representations of sub-grid variability may be compared.

1.2 Explicitly representing particle properties

A recent development in cloud and precipitation microphysics parametrization is the explicit representation and prediction of the properties of particles in the ice phase (size, density, and potentially even shape and orientation) rather than with discrete hydrometeor categories (ice crystals, snow aggregates, graupel, hail). We know that ice-phase hydrometeors in nature do not fit neatly into discrete categories but instead have a wide spectrum of smoothly varying particle properties. For example, the process of riming gradually changes the density as well as the mass of particles. An example of a particle-property parametrization is the P3 scheme which has already been implemented in the Canadian high-resolution model.

Representing smoothly varying particle properties, and the removal of discrete hydrometeor types and process thresholds, could in principle also be beneficial for data assimilation. Although these developments are being applied to the microphysics parametrization, corresponding developments have not yet been applied systematically to radiation schemes and forward operators, which generally continue to assume discrete hydrometeor inputs. Further work is therefore recommended on consistent developments in both radiation schemes and forward operators to be able to use more continuous information on particle properties. For example, databases covering a wide range of rimed particles are needed, not just for discrete crystal types. Machine learning could play a role in efficiently representing the scattering properties of particles based on small numbers of parameters from the microphysics scheme, for example the degree of riming. There has already been some success in this area with the use of a neural network to reduce large lookup tables to a few variables and a much smaller memory footprint that could have potential to be implemented in future operational NWP modelling systems.

The challenge for wider take up of particle-property parametrization schemes in global NWP and climate models will be to ensure they have sufficient degrees of freedom in their formulation and numbers of variables to capture the global radiative, diabatic heating and hydrological impacts across cloud regimes and time/space scales, from small ice particles in cirrus, to snow aggregates in deep frontal cloud systems, to graupel/hail in convection. It is recommended that the community continues to explore the development of schemes that predict smoothly varying particle properties to replace schemes that divide particles into discrete categories.

2.1.2 Using Lagrangian super-particle schemes

An active area of research is the development of Lagrangian super-droplet, or super-particle, microphysical parametrization schemes, where a number of representative particles and their changing sizes and properties are tracked individually. Traditional bulk schemes assume a particle size distribution that may artificially constrain hydrometeor interactions and sedimentation. Spectral/bin schemes, where the particle size distribution is represented with discrete size bins, may allow a more realistic treatment of particle interactions. However, bin schemes are sensitive to the numerical formulation and transfer processes between bins, and are not guaranteed to converge with increasing number of bins. In contrast, Lagrangian schemes have better convergence as the number of particles is increased, allow flexibility in the representation of the particle size distribution, and track the history of particles with smoothly varying properties. Sedimentation and other processes can also be treated in a more explicit and continuous way with fewer thresholds and assumptions, making it easier to forward model observations. Lagrangian super-particle schemes are currently too computationally expensive for NWP, but they could be used in high resolution research models to aid in understanding processes and deriving improved bulk microphysical parametrizations. It is recommended the research community continues to explore and improve the super-particle parametrization approach.

2.1.3 Coping with an increasing range of predictability time and space scales

Cloud, precipitation and dynamics are closely coupled on a wide range of space and time scales. As global models increase in resolution and start to permit explicit representation of deep convection, the increasing range of predictability space and time scales brings additional challenges for data assimilation. The choice of control variables, observation types, observation processing (e.g. thinning, averaging) and the grid resolution of the assimilation system may all depend on the particular application, whether the focus is short-range convective-scale forecasting or global medium-range skill. An important example is the impact of deep convection, which affects when and where it will rain in the next few hours, as well as influencing the longer predictability time scales of the large-scale environment. Assimilating radar reflectivity directly affects the rain/snow/graupel content for deep convection in a convective-permitting model, and may improve the location and intensity of the storm. However, assimilating satellite temperature and humidity related observations will likely have a longer lasting impact on larger scales. There remain many questions on this topic that need to be explored:

- What control variables result in the most effective use of the data at different scales?
- Is there a scale-break dividing short-term and long-term predictability that is relevant for data assimilation?
- What is the best way to cope with the increased non-linearity and weaker dynamical balances at smaller scales?
- How do we deal with displacement errors in cloud and precipitation that are more significant at higher resolution? Is it better to try to correct them, or to assimilate only larger scales? The answer may depend on the predictability space/time scales of interest for the particular application.
- How can we use an ensemble approach more effectively for this problem?

The recommendation is for further research on the most appropriate data assimilation and observation usage methodologies as model resolution increases towards convective-resolving scales and encapsulates a wider range of predictability time and space scales.

2.1.4 Improving linear approximations of non-linear microphysics

Cloud and precipitation microphysical processes are highly non-linear, are generally represented with discrete variables that can vary from zero to many orders of magnitude, and typically include switches and thresholds which are not directly differentiable. This makes it particularly challenging to incorporate microphysical processes in differentiable code, required for sensitivity analysis techniques and 4D variational assimilation. In practice a simplified linear scheme (tangent linear) and its adjoint are derived as an approximation to the non-linear parametrization. The recommendation is to further explore methodologies to improve the tangent linear and associated adjoint, making non-linear parametrizations more differentiable where possible and investigating the potential of machine learning to approximate the tangent linear parametrization, from which the exact adjoint can be obtained. It is possible that the development of particle property schemes, which naturally contain fewer thresholds and discrete categories, may be more amenable to linearization and differentiation.

2.1.5 Non-Gaussian error distributions

The non-linearity inherent in cloud and precipitation processes leads to non-Gaussian errors that are challenging for data assimilation. There is potentially a need for modifications to data assimilation systems to better incorporate non-Gaussian error distributions that are hard bounded, skewed, and/or multi-modal.

2.1.6 Quantifying uncertainty in cloud and precipitation parametrizations

Uncertainty in model parametrizations is poorly known and poorly constrained. This is due, in part, to the challenge of directly observing key particle shape and size distribution properties. An additional challenge arises from the fact that the time evolution of hydrometeor properties in the interior of clouds is rarely, if ever, directly observed. Constraining cloud and precipitation fields and processes will require integration of observations from diverse sources within the same framework. Data assimilation accomplishes this by design, and it is recommended that DA systems be used more explicitly to quantify parameterization uncertainty and identify which observations may be used to improve cloud and precipitation processes.

In addition, parameterization schemes commonly utilize set values of rate constants and other model parameters, while these quantities are known to vary in time and space. For example, the Marshall-Palmer exponential rain drop size distribution is commonly used in models but represents a time-integrated mean. The true size distribution may vary in time and from location to location, so using a PDF of realisations of the drop size distribution may be more realistic than making a single assumption based on average properties. It is recommended that ensembles of parameter values, and stochastic parameterization techniques, be used to explore model uncertainty and represent known variability in cloud processes.

2.2 Using data assimilation to evaluate and inform model development

2.2.1 Improving consistency of microphysical assumptions

It makes physical sense to have as much consistency as possible in microphysical assumptions, such as particle size distributions, both within the forecast model (microphysics, radiation) and the forward operators used for data assimilation and model evaluation. There will be exceptions where significant approximations need to be made for computational efficiency, or where there are known model cloud parametrization shortcomings or uncertainties that could specifically impact the comparison with observations. An example of the latter is enhanced radar reflectivity in the melting layer, which may not be important to represent for the model physics, but is important when comparing the model to radar observations. It may also be difficult to achieve consistency in an NWP environment where, for example, changing one aspect may improve the fit to observations but degrade the predictive skill in the forecast.

Consistency should be the aim, and in cases for which inconsistency improves the forecast, this may point towards a need for more complexity in the microphysics representation. In order to improve consistency, radiation parametrization and forward operators need to have the flexibility to define the same microphysical assumptions that are used in the microphysics scheme. There is current work on common frameworks for radiation code (RRTM) and forward operators (RTTOV, CRTM), and the recommendation is to make sure effort goes into providing flexibility to allow consistency of microphysical assumptions to be made across modelling systems, and in the longer term, to be able to use distributions of microphysical parameters.

2.2.2 Encouraging wider use of forward operators and synergistic retrievals

There are two approaches to evaluating models with observations; the obs-to-model approach, which estimates model geophysical variables (e.g. cloud liquid water content) via retrievals from the raw observations, or the model-to-obs approach which uses forward operators to estimate the observed quantity directly from the model (e.g. satellite radiances). The most important factor for an accurate assessment of the model errors is that we are comparing like-with-like, and retrievals from limited data or single instruments can be under-constrained and suffer from systematic deficiencies because the observed quantity only represents a partial description (e.g. different electromagnetic frequencies are sensitive to different aspects of and locations within the cloud). Although the forward operator approach is the most direct method for a like-with-like comparison, a synergistic retrieval combining co-located observations from complementary instruments (e.g. A-Train, EarthCare, ACCP) can also be of value. While the model-to-obs approach is used in most data assimilation techniques, it is not used as much as it should be for model evaluation. As more radiative frequency channels are assimilated in models (microwave, infra-red, visible, lidar, radar) appropriate forward operators can be used increasingly for model evaluation to constrain hydrometeors and their properties (particle size distribution, density, habit). The recommendation is to continue to make forward modelling tools available (like the RTTOV and COSP packages), through open source community platforms, with standardised yet flexible interfaces to encourage wider use in the research community.

2.2.3 Quantifying uncertainty in forward operators and retrievals

There are assumptions made in both forward operators (model-to-obs) and geophysical retrievals (obs-to-model), and scope for better uncertainty quantification in both. It is easier to quantify errors in the forward modelling approach, but this is often not done systematically. Uncertainties from retrievals are often underestimated, particularly when there may be significant bias (for example the uncertainties due to the systematic effect of drizzle/rain and partial cloudiness on liquid water path retrievals can be larger than the estimated error from the retrieval). It is recommended that uncertainty quantification is performed more comprehensively and systematically for both forward operators and in retrieval products.

2.2.4 Increasing accessibility to data assimilation systems

A data assimilation system provides a comprehensive and consistent framework for model evaluation. Diagnostics, such as assimilation increments/innovations, can provide useful information on model systematic errors and can encourage collaboration between forecast model developers, data assimilation scientists and observational experts. In addition, regional and weather-state dependent errors and innovations may provide useful information to guide the development and improvement of model parameterizations. Outside of operational NWP centres most researchers do not have access to a data assimilation system, and the recommendation is to make intermediate products produced during data assimilation (e.g., innovations), and DA frameworks themselves, more accessible to a wider research community. There are already examples, such as the flexible DART framework in the US which can take input from most models, and the JEDI system which has the goal of being “plug and play” in research mode. Such systems should be encouraged to be open, flexible and user friendly.

3 Working Group 3: Observation Operators in Cloud and Precipitation

Chairs: Benjamin Johnson (JCSDA) and Robin Hogan (ECMWF)

Participants: (to be added)

3.1 Problem Statement

The use of satellite information in a numerical weather prediction (NWP) context requires the capability to accurately (and rapidly) simulate the radiance information observed by numerous and disparate satellite-based radiance sensors. Given information about the physical state of the atmosphere, surface, and the instrument itself; the goal of the "Observation Operator" software is to create a faithful representation of the observed radiances (aka the "Forward Operator"). Furthermore, the simulation of the response of observed radiances to changes in the atmospheric state (aka the "the Jacobian") enables satellite data assimilation.

Problem statement #1: How can we accurately and rapidly simulate observations (e.g., satellite observations) given limited model physical information?

Problem statement #2: The observations are, in general, not direct measurements of the atmospheric and surface state variables (i.e., the "state vector") – how can we ensure the validity and characterise the uncertainty of the physical relationships needed to create the appropriate mapping?

3.2 Working Group Questions

There exist many models for simulating radiance-based observations. Although most NWP centres focus on assimilating radiances from satellite-based sensors, there are also ground-, sea-, and air-based platforms that provide observations that are increasingly being exploited in both operational and research NWP assimilation systems. The primary radiance-based observation operators (for satellite data) used in NWP centres is either Radiative Transfer for TOVS (RTTOV) or the Community Radiative Transfer Model (CRTM), but many others exist. This working group primarily focused on satellite-based radiance operators: RTTOV and CRTM.

In the interval since the 3rd workshop held in 2015, there are several specific questions identified for the Observation Operator working group, couched within the context of the two problem statements above:

- What are the current and future capabilities of radiance operators relating to cloud and precipitation?
- Are modern radiance operators practical for data assimilation applications, meaning are they fast enough, are they memory efficient?
- What capabilities are missing relative to the current and future requirements of NWP?
- How do we represent the often-unknown parameters to which observations are so sensitive, such as size distributions and particle shapes, overlapping cloud layers, sub-field-of-view variability and 3D structures?
- How can we best quantify the errors associated with the fast and approximate methods used for data assimilation?

3.3 Progress since previous workshop

The previous observation operator working group (from the workshop in 2015) focused heavily on cloud and precipitation scattering database development and possible implementation into RTTOV and CRTM. Since that time, much progress has been made. Both RTTOV-SCATT and CRTM now employ non-spherical hydrometeor scattering/absorption properties within their publicly released models. The key element of discussion was to support radiance simulation/assimilation of current and future satellite missions that will have a critical sensitivity to the non-sphericity of hydrometeor particles.

At the 2015 workshop, there was also a strong recommendation that the NWP community begin to assimilate satellite-based radar observations, such as the GPM-DPR and CloudSat, enabling more accurate information on the vertical distribution of cloud and precipitation, along with a more physically direct relationship between hydrometeor properties and reflectivity/attenuation observations.

Related to this, the 2015 group also recommended the use of the combined "active-passive" observation datasets in support of improving the information content within cloudy / precipitating scenes, and to extend that knowledge into nearby scenes where no radar data was available.

To date, these combined passive-active datasets have not been used in NWP context, primarily because combined databases replicate the function of variational data assimilation, without the rigorous framework. Instead, the focus for RTTOV and CRTM has been on development of accurate forward operators for radar and lidar observations.

The CRTM model has implemented a simple forward operator for radar observations, called the Community Active Sensor Module (CASM), but does not include polarisation. RTTOV developers and collaborators have also been develop a radar operator for inclusion in RTTOV-SCATT.

The MFASIS model (https://www.nwpsaf.eu/publications/vs_reports/nwpsaf-mo-vs-051.pdf) has been implemented in RTTOV enabling fast, accurate visible radiative transfer capabilities.

CRTM has an alpha version of a full-stokes polarised RT solver, CRTM v3.0-alpha, and is currently undergoing testing. UV simulation support has also been added and tested, and will be available in CRTM v3.0 (2021 release).

3.4 Summary of outcomes/recommendations of the working group

The working group was composed of a wide range of expertise across the NWP community. The issues addressed within the Panel Review and Working Group discussions covered significantly more territory than the prior workshop. Below is a summary of the issues and our recommendations.

3.4.1 Improving Observation Operators and other General Issues

Joint evaluation of observation operators is needed using 3D reference models and scenes

RTTOV and CRTM are 1D radiative transfer models, and consequently, cannot explicitly account for 3D radiative transfer effects commonly found in satellite observations. One issue is scene heterogeneity or non-uniform beam-filling (NUBF), wherein the field of view of the sensor (sometimes referred to as the "pixel") is not fully filled with a homogeneous material, resulting in a 3-D non-linear response. Another common 3-D issue is emission / scattering of radiation by clouds reflecting off of the surface and entering the FOV even when the cloud itself may not be within the FOV.

Recommendation 3.1: To improve the accuracy of fast RT models, we need to develop schemes to incorporate 3-D effects either through explicit simulation or through fast methods approximating these effects. This requires comparisons between CRTM/RTTOV and a suitable 3D reference model, with a common "case study" scene to ensure a consistent comparative basis.

Consistency with broadband radiation schemes

Broadband radiation models (e.g., RRTMG) have sophisticated schemes (both stochastic and deterministic) for cloud structure that fast-model developers can learn from and be consistent with.

Recommendation 3.2: Work with broadband-model developers to identify mechanisms for establishing physical consistency between inputs and outputs between broadband and fast RT models.

Specific areas where RT modelling improvement is needed

Fast RT models in support of NWP requirements are constantly evolving to meet the increasing accuracy and scope of DA systems. Many areas in fast RT modelling continue to need specific attention. Some of these areas are surface contributions from land/ocean/snow/ice/complex terrain; water vapour continuum in millimetre and sub-millimetre regions; support for UV and Far-IR RT capabilities per upcoming missions; full polarization and backscattering properties for future planned improvements to both RTTOV and CRTM.

Recommendation 3.3: Work with reference model developers to identify mechanisms for incorporating knowledge of accurate RT simulations into the fast-model schemes. The MFASIS implementation in RTTOV is a great example of how this can occur.

Operators need to be more flexible with regard to cloud/precipitation microphysics

There exist many disparate single-particle scattering property tables from several research groups around the world. Some efforts have been made to bring these tables together under a unified format (e.g., iceDB https://rhoneyager.github.io/libicedb/). Having a consistent portable framework for accessing these particles would be enormously beneficial to all RT model developers.

Recommendation 3.4: Encourage and work with scattering property developers to contribute to unifying their output under a common format (such as above), and encourage RT model developers to make interfaces to the lookup tables or computational codes more flexible allowing for a wider variety of shape, size, distribution, morphology, phase, orientation, etc.

Better communication between cloud modellers and observation operator people

Cloud modellers (who focus on physical / dynamical evolution of clouds) have intricate knowledge of the macro and microphysical nature of cloud properties, and regular communication between RT modellers and cloud modellers would facilitate identification of biases in the simplistic schemes employed in fast RT models. Additionally, cloud modellers could also help fast RT modellers identify missing physical parameterisations that have a clear impact on RT modelling such as secondary ice generation (e.g., Hallett-Mossop processes).

Recommendation 3.5: Coordination at working group level, including inviting key modellers to come to RT-focused workshops and vice-versa.

Better communication between DA experts and operator/observation people

Too often in DA the approach is to "find the combination of parameters that reduces O-B" at all costs without understanding how and where the biases are coming from. Model biases should be exposed and understood, not simply bias-corrected away and ignored.

Recommendation 3.6: This is a challenging problem, but it begins with the appropriate modellers taking action to expose their uncertainties and propagate them through the end-to-end process. RT modellers can, with some effort, produce an uncertainty estimate and associated covariance for each forward model or K-matrix/Jacobian estimate that can be utilised an NWP to aid in understanding where model biases are originating from. We recommend improving communication between DA experts and Obs/Sim experts through shared projects/objectives and collaborative techniques like "code sprints".

3.4.2 Consistency of particle properties across wavelengths

Inconsistent ice microphysical assumptions between spectral regions

Description: Fast RT models tend to focus on specific instruments and/or spectral categories in the development of scattering models (e.g., IR, MW, visible). Traditionally IR scattering properties and MW scattering properties were developed separate from each other, leading to inconsistencies in the physical assumptions that underlie the lookup tables used to access the scattering properties. Hidden information, such as particle shape/density assumptions, mass distributions, and other quantities are often either unknown or poorly documented. Furthermore, physical modellers have no way of forming meaningful physically consistent relationships with the physical properties implied in the scattering tables.

Recommendation 3.7: Work with single-particle scattering property creators to determine methods for ensuring physical consistency across spectral regions where possible / computationally feasible.

Need to make more coordinated use of multi-instrument case studies

Satellite calibration/validation campaigns and other field experiments present a wealth of concentrated, high quality information that should be used as a tool for validating radiative transfer assumptions and results. From space, aircraft and the ground, to try to achieve consistency among the independent pieces of information.

Recommendation 3.8: In support of validation and uncertainty estimation, we recommend making use of coordinated field/aircraft/satellite campaigns to enable highly accurate in-situ and remotely sensed observations of the atmospheric column and surface properties. Caution should be exercised when using "retrieved" properties, since their assumptions are biased toward maximising information content from the sensors present.

Can we produce a "recipe" of physical checks of a scattering database to identify problems?

In the development of scattering databases, a series of "quality control" filters could be used to improve the veracity, validity, and applicability of a given dataset for the users' requirements. For example, one may wish to know when geometric optics limits are not being observed, or which wavelengths the physical particle models are applicable for. Another example is when the integrated scattering properties break consistency with expectations due to issues with integration or underlying physical assumptions.

Recommendation 3.9: Work with scattering database developers to implement series of QC filters to act like bounds checking on scattering database properties as a function of the desired wavelengths, sizes, morphology, etc. This could be in the form of generated QC flags.

A workshop for scattering experts from different parts of the spectrum

The International Precipitation Working Group (IWPG) has a subgroup called the International Workshop on Space-based Snowfall Measurement who meet every 2 years (nominally) to discuss snowfall related properties. Another large contingent of scattering developers also meet at the ITOVS Study Conference / ITOVS Working Group ITSC/ITWG meetings in support of developing fast RT models. There are also smaller groups of individuals who are coordinating efforts, such as the iceDB work previously mentioned.

Recommendation 3.10: Many of these scattering model developers are focused primarily on microwave radiances, with some input from the IR community. We recommend a specialist meeting that expands the spectral scope to UV, VIS, and sub-millimetre/Far-IR researchers in order to aim toward the spectral consistency recommendation previously described.

Could part of the correlation of observational error be from too much consistency

There's a reported "under-spread" in ECMWF ensemble members, that may be linked to the fact that similar assumptions are being made between microwave and IR scattering models, whereas both could be systematically different from reality.

Recommendation 3.11: Per previous recommendations, enhancing the diversity of input to scattering models and integrated model properties, perhaps leaning more on cloud physics modellers to help guide structure would result in a broader and more consistent radiance response in the ensemble spread.

3.4.3 Error Characterisation and Uncertainty Analysis

Error characterised in the observational operator should feed through to error in analysis

This is in the context that ECMWF significantly under-predicts the DA ensemble spread; currently we perturb the observations in the range of expected error but this is quite crude.

Recommendation 3.12: Similar to above, diversification and alignment of model physical assumptions may lead to a reduction in this issue.

It would be desirable to be able to propagate uncertainties rigorously through RT scheme

Current fast RT models do not generate explicit uncertainty estimates.

Recommendation 3.13: Recommend that fast RT model developers in particular create a pathway forward to enable uncertainty estimation and propagation.

Are we trying to model the most likely radiance, or a particular realisation?

Should operator include a stochastic component varying the uncertain assumed parameters such as overlap? This aims at the concept of should we be simulating a single radiance vector for a given model state or generating PDF statistics for the radiances (a posteriori distribution) given a single model state.

Recommendation 3.14: A literature review reveals a few publications that have fully propagated PDFs of radiances into a retrieval algorithm using Bayes theorem (for example, Chiu and Petty, 2006), and could serve as an example of how a fast RT system could be designed to enable a PDF based approach (which would also address error/uncertainty propagation).

Still need to better characterise error terms

At the more fundamental level of error estimation is identifying the initial sources of errors and characterising those errors in a rigorous fashion. For example, instrument error(s) (calibration, antenna correction, intrusion, scan dependencies); and sampling errors (e.g., diurnal sampling, precession, scan pattern differences, etc.)

Recommendation 3.15: Work with instrument science teams and calibration / validation teams to improve knowledge of technical elements for each instrument and define generalised techniques for capturing and propagating error terms arising from sources outside of the typical RT model structure.

Could a joint study objectively work out the size of the uncertainties associated with each assumption we make?

Even with a knowledge of sources of uncertainty, magnitude and significance of these uncertainties also needs to be objectively determined. This would help prioritise future activity sub-grid heterogeneity and cloud-overlap, 3D radiative transfer, microphysical properties, scattering properties, correlation between cloud properties and atmospheric state, and the dynamical state of the cloud (convective / stratiform, forming/dissipating, phase, melting, etc.)

Recommendation 3.16: Similar to prior recommendations, working closely with cloud model developers and instrument scientists would enable the first steps toward creating an objective assessment of uncertainty sources and estimation of the magnitude and significance of those uncertainties

3.4.4 Things that would facilitate collaboration and coordination of effort

Share and compare codebases

CRTM is open source / open access, could RTTOV also adopt a similar model to enable rapid / transparent sharing of codes evaluation metrics? This shouldn't be limited to CRTM and RTTOV, but also ARMS, ZmVar, COSP and broadband radiation schemes.

Recommendation 3.17: We recommend that fast RT developers establish a consistent framework for evaluation and testing of various RT models. The JCSDA JEDI framework is ideal for CRTM / RTTOV comparisons currently, enabling switching RT model simulations for the exact same physical state. The ability to openly share and contribute to fast RT model development between groups and interests should help accelerate the state of the art of RT modelling by reducing duplicated effort.

Standardising scattering databases

Current scattering databases are typically limited to MW properties.

Recommendation 3.18: Extending the good work done in the microwave across all wavelengths, recommending that funding agencies continue to support these efforts to accelerate the capabilities to upgrade RT models using these new scattering tables.

Use reference models and observational case studies

Model intercomparisons provide a critical tool for identifying differences between RT models, and helping to ensure that new developments do not lead to unusual behaviour in the output.

Recommendation 3.19: Where possible to perform combined evaluation of forward operators, providing a central catalogue and repository of datasets. This could be done in github.com, for example.

Have a central discussion forum

Recommendation 3.20: To enable rapid exchange of ideas and foster collaboration, a central location for RT modellers to discuss technical and scientific issues would be useful and save effort by reducing duplication and leveraging existing effort.

4 Working group 4: Data assimilation methods

Chairs: Craig Bishop (Univ. Melbourne) and Massimo Bonavita (ECMWF)

Participants: (list to be added)

4.1 Background and Motivation

Clouds and precipitation are the biggest uncertainty source in weather and climate prediction.

In the climate realm, Köhler (2005) commented "If one could magically cover an additional 4% of the globe with low cloud, the global warming resulting from the potential doubling of CO2 could possibly be offset. …. Unfortunately, current global climate models are split into those that increase low cloud in climate change scenarios and those that produce a decrease." Bony and Stevens (2012) ventured that "Establishing the extent to which clouds will undergo changes in response to warming can be thought of as the Higgs Boson of the theory of climate, and climate change." In the weather realm, in diagnosing factors leading to anomalously poor medium range forecasts for Europe, Rodwell et al. (2013) found a strong connection between anomalous convection west of the Rocky mountains and poor weather forecasts.

Prediction is the ultimate test of scientific theory and demonstrations of improvements in forecasts of clouds and precipitation would build confidence and reduce uncertainty in our projections.

Forecasts of clouds and precipitation cannot be expected to be accurate unless models are initialized with clouds and precipitation that are consistent with observations of clouds and precipitation. Until relatively recently, cloud observation assimilation was studiously avoided by global data assimilation schemes. We can say "studiously" because a great deal of research was devoted to detecting clouds in satellite imagery Geer et al. (2018) in order to avoid assimilating them. They were avoided because observational and forecast uncertainty models of the Data Assimilation (DA) schemes were so poor that assimilating these observations damaged analyses and forecasts. As noted in Geer et al. (2018), in the last decade a more careful treatment of the uncertainties and non-linearities associated with cloud affected observations has enabled significant benefit to be gained from cloud affected low earth orbiting satellite observations.

While significant progress has been made, there is huge potential for further improvement. To date, a vast range of cloud affected observations (particularly in the IR, near visible and visible wavelengths) remain unassimilated. Observations of cloud that occur in locations where neither the model first guess nor any of the ensemble members have cloud are still largely ignored. Cloud affected observations are known to produce a net drying effect and this net drying occurs even when the distribution of innovations/departures is symmetric. Attempts to characterize and account for the flow-dependent, spatially temporally and spectrally correlated observation errors associated with cloud and precipitation observations are in their infancy.

Working group 4 of this workshop was asked to identify areas in data assimilation methodology where focussed research was needed. To this end, five ~25 minute presentations were given by leaders in the field followed by a 1 hr panel discussion with panellists Elias Holm (ECMWF), Takemasa Miyoshi (RIKEN), David Simonin (Met Office) and Olaf Stiller (DWD) and then a 2.5 hr working group discussion. Six research priorities identified by the working group together with reasons for prioritization are given below. Since differing organizations have different environmental modelling priorities, no attempt was made to rank the six priorities.

4.2 Data assimilation methodology research priorities

4.2.1 Zero spread, zero gradient problem

This is the problem in which clouds and/or precipitation are observed but neither the control forecast nor any of the members of the ensemble forecast have cloud or precipitation at the observation site. This problem is closely related to the fact that the true prior distribution of possible cloud and precipitation states typically includes a finite probability that there is zero cloud and zero precipitation. In terms of the probability density functions from which most data assimilation schemes are derived, this finite probability at zero corresponds to a Dirac delta function at zero. Ensemble Kalman Filters, Particle filters, Gaussian anamorphosis and 4DVar are all ill-equipped to deal with this problem.

Reasons for prioritization: If not overcome, this problem leads to perfectly good observations of cloud being ignored by the data assimilation scheme. In the absence of other errors, it would be expected to cause the data assimilation scheme to dry the atmosphere more than it moistens the atmosphere.

Possible ways forward: (i) Use larger ensembles including representations of stochastic model error (ii) reduce model error (iii) employ more outer loops (iv) time and space averaging of observations (super-obbing) (v) improve forecast error correlations by, for example, creating larger ensembles from smaller ensembles by randomly shifting them in space time (vi) develop new theory and methods to directly deal with this problem in a practical way.

4.2.2 State dependent observation error distributions

Clouds and precipitation are both bounded variables. They can't be negative, and in the case of cloud fraction, there is an upper limit to the fractional area of a grid box that can be covered by cloud. As shown in Bishop (2019), the observation error variance of unbiased observations of bounded variables attenuates to near zero as the true value of the observed variable tends towards a physical bound. Consequently, the likelihood probability distribution function L[y|H(x)] of observations y given the true value of the observed variable H(x) and its associated observation error variance must be a function of the unknown true state H(x).

Reasons for prioritization: Optimal observation information extraction is based on Bayes' theorem and Bayes theorem requires an accurate specification of L[y|H(x)]. The importance of making further progress in this area is indicated by the fact that, to date, all successful all-sky satellite data assimilation schemes have utilized some sort of state dependent observation error variance model. The forward radiative transfer operator H can be non-linear functions of humidity, cloud water, cloud ice and cloud ice habit, special care must be taken to account for the effect of sub-grid scale variability on both the mean and the variance of L[y|H(x)]. Specifically, models are only capable of explicitly representing filtered/averaged versions of reality. For any true filtered state, there is an infinity of sub-grid states that are consistent with the one filtered state. Hence, there is a corresponding infinity of variations in the value of the observed value that are due to the sub-grid scale variations. The variance of these variations is called the observation error variance of representation. When the observation operator is non-linear, the mean of these variations will generally not be equal to zero and hence there will be a systematic difference between that is called the bias of the error of representation. Depending on the type of data assimilation scheme employed, this bias should be removed from the observed value before it is is assimilated. sub-grid variations in the state would affect the observed radiance then the sub-grid variations contribute to the observation error variance that should be used in the data assimilation scheme. As aspects of the sub-grid variability, e.g. a thin unresolved layer of stratus cloud may extend to neighbouring grid points, one might also expect the error of representation to lead to correlated observation error of representation.

Possible ways forward: (i) First principles approach such as applying radiative transfer model to differing possible sub-grid states associated with the same mean state (see workshop presentation by Janiskova and Fielding (ii) Innovation based approach. E.g. observation error variance as function of, say, symmetric cloud proxy (Geer talk) or ensemble variance (Satterfield talk) or non-linearity (Bonavita et al. poster) (iii) simultaneously account for the non-Gaussianity and state dependence of observational uncertainty by basing the data assimilation scheme around non-Gaussian bounded pdfs as in Bishop (2016) and then fitting the non-Gaussian pdf to constraints given by (i) and (ii).

4.2.3 Non-linear relation between analysed variables and observed variables

Leonhard Scheck's presentation demonstrated that the Ensemble Kalman Filter (LETKF) analysis of visible reflectance lay closer to the observed reflectance than the reflectance implied by the analysed humidity, temperature, cloud water and cloud ice. This finding highlighted a weakness of the EnKF approaches and directly reflects the fact that standard EnKFs do not respect non-linearities in the relationship between model variables and observed variables. In principle, given an accurate TLM and adjoint of the model and the observation operator, the outer loops of 4D and 3D Var can reasonably account for such non-linearities. In practice, it has been challenging to produce and maintain accurate TLMs and adjoints of the aspects of the model and observation operator associated with clouds and precipitation.

Circulations associated with convective clouds can become strongly non-linear within tens of minutes. Hence, in a convection permitting resolution model with convection resolving TLM and adjoint, long DA window (~6-24 hr) strong constraint 4DVar would likely lead to penalty functions with multiple minima and ill-conditioned matrices in the inner-loop.

Reasons for prioritization: Data assimilation schemes will not be able to ensure that model trajectories are consistent with observed trajectories unless these issues are adequately addressed.

Possible ways forward: (i) Wider use of outer-loop type steps in ensemble data assimilation schemes (ii) For variational schemes, improve accuracy of Tangent Linear Models and adjoints of the aspects of the model and the observation operator associated with clouds and precipitation (iii) Methodological advances, perhaps through innovative Hybrids of Particle Filters, mixture models, EnKFs and variational methods (iv) Broken trajectory weak constraint 4DVar (v) Shorter DA windows (vi) Continuous data assimilation approach using fast arriving observations (e.g. observations assimilated just minutes after being taken) (vii) time and space averaging of observations (super-obbing) so that the observations project more strongly onto the larger scale, more predictable and less non-linear error structures.

4.2.4 Improved representation of multiscale forecast error distributions

Clouds and their associated forecast errors occur on scales ranging from tens of meters to 1000s of kilometres. The precipitating hydrometeors, cloud hydrometeors and mass-momentum variables (u,v,T,p_s) associated with clouds all have very different error correlation length scales.

Reasons for prioritization: Accurate analyses of clouds at the smallest scales resolved by the model will help guide the model representation of such clouds and improve short-range prediction. Accurate analyses of the large-scale aspects of clouds associated with large scale atmospheric features such as the MJO have the potential to significantly improve forecasts in week 2 and possibly week 3. If models of the highly flow dependent error covariances associated with clouds are to be based on flow dependent ensemble covariances, appropriate multi-scale ensemble covariance localization methods will need to be designed and integrated within existing data assimilation schemes.

Possible ways forward: (i) Multi-scale ensemble covariance localization (ii) Variable dependent localization (iii) Incremental 4DVar with increasing resolution of inner loop (iv) Judicious attenuation and/or preservation of ensemble covariances between hydrometeors (v) Continuous data assimilation approach using fast arriving observations (e.g. observations assimilated just minutes after being taken)

4.2.5 Spatial, temporal and spectral observation error correlations

Both observation instrument errors and observation errors of representation are likely to lead to observation error correlations. Existing observation error correlation estimation techniques suggest that observation error correlations are particularly significant for cloud observations.

Reasons for prioritization: The data assimilation scheme cannot optimally extract information from the observations unless the observation error correlations are accurately represented within the data assimilation scheme. Existing "fixes" such as inflating the observation error variances while ignoring inter-observation error correlations have been shown to prevent the data assimilation system from acquiring the major information containing scales of the correlated observing platform (e.g. Rainwater et al., 2015). Current techniques such as the Desrozier et al. (2005) and Lonnberg and Hollingsworth (1986) approaches have been shown to produce observation error correlation estimates that improve clear sky data assimilation performance but they have known deficiencies so new research is required to develop more accurate and robust observation error correlation estimation techniques.

Possible ways forward: Implement Desrozier et al. (2005) and Lonnberg and Hollingsworth (1986) for cloud affected radiances where possible and see if the estimated correlations improve data assimilation. Try and develop/find better techniques for estimating the observation error correlations.

4.2.6 Data assimilation to improve model representation of clouds, precipitation and aerosols

In research, it has been shown that data assimilation can be used to successfully uncertain model parameters (Hu et al., 2010, Bouquet, 2013, Liu et al., 2014). Might operational centres make better use of such techniques? Are there better ways of producing automated observation informed model improvement?

Reasons for prioritization: Arguably, this is the holy grail of cloud affected radiance assimilation. Finding model trajectories that match observations over long periods is impossible with large model error and the model error associated with aerosols, clouds and precipitation is known to be large. Model error reduces the amount of observational information that can be passed from one data assimilation scheme to the next. Automating the model improvement procedure through some sort of advanced, observation-informed model adjustment procedure has the potential to produce a step-change in weather and climate forecast accuracy.

Possible ways forward: EnKF and 4DVar based parameter estimation. Hybrids of data assimilation algorithms with Artificial Intelligence based model estimators. Research teams to tackle the problem that combine expertise in model development/parameterization with data assimilation expertise. Special long window 4DVar data assimilation runs solely aimed at model improvement and not on initializing forecasts.

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