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Introduction and summary of the Working Group reports

1. Background

Satellite observations in the visible, infrared, and microwave provide a great deal of information on clouds and precipitation as well as the atmosphere in which the clouds are embedded. A major issue is how to use this information to initialize cloudy and precipitating atmospheric regions in NWP models. Most cloud- and/or rain-affected observations are discarded in current data assimilation systems. The major problems are the discontinuous nature, in time and space, of clouds and precipitation, and the complex non-linear and not well modelled processes involved in their formation. As a result, cloud/rain affected radiances are much more difficult to assimilate than clear sky radiances, which are sensitive to the smoother fields of temperature and water vapour that are controlled by more linear processes. Since clouds and precipitation often occur in sensitive regions in terms of forecast impact, improvements in their assimilation are likely necessary for continuing significant gains in weather forecasting, and in particular, the prediction of two key weather elements affecting human activities: precipitation and cloudiness.

In 2005, the NASA-NOAA-DoD Joint Center for Satellite Data Assimilation (JCSDA) sponsored an international workshop that covered the three main topics related to assimilating observations in cloudy/precipitating regions, namely satellite observing capabilities, modelling radiative transfer and cloud/precipitation formation, and data assimilation. From 15-17 June 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 centres and scientific communities for future research developments and collaboration. About 65 participants attended the workshop, representing most major NWP centres around the world as well as research institutes and universities.

The workshop sessions covered the current status of cloud/precipitation assimilation at NWP centres, special issues related to cloud and precipitation affected observations, radiative transfer modelling, cloud and precipitation representation in numerical models, and problems of integrating such data in operational data assimilation systems. A novel approach to working group organization was adopted. Rather than forming groups according to discipline area - the typical method - integrated groups composed of experts in observation, modelling and data assimilation ran in parallel. Each group was asked to discuss the same set of questions and to produce recommendations across these disciplines.

Working group summaries and recommendations were discussed in a final plenary session and were integrated into a set of recommendations to ECMWF and JCSDA, and other NWP centres, to advance the assimilation of cloud/precipitation observations. More details on the workshop and all presentations can be accessed from:
http://www.ecmwf.int/newsevents/meetings/workshops/2010/Satellite_observations/index.html

2. Current Status of Assimilation of Satellite Observations of Cloudy/Precipitating Areas

Schemes aiming at operational application mainly focus on assimilating infrared (IR) and microwave (MW) radiometer observations rather than measurements from active (radar/lidar) systems due to the smaller scale discrepancy between observations and models and the lack of spatial coverage by active systems. Further, there is longer lasting experience with assimilating the same radiometer observations in clear skies.

Since 2005, most operational NWP centres have begun to assimilate hyperspectral IR radiance observations, from the AIRS and/or IASI instruments, in cloudy regions. The fundamental assumption is that a single layer of cloudiness is affecting the radiances. Several different methods are being used to characterize the cloud layer from the observations: 1) cloud fraction and pressure are retrieved assuming a grey cloud emissivity, 2) the cloud fraction is assumed to be unity (overcast sky) and a CO2 slicing technique is used to determine the cloud emissivity and cloud top pressure, and 3) only observations that indicate that the cloud fraction is unity and that the cloud is uniform over several pixels are used. With this information on the clouds, the observations can be assimilated with the use of a radiative transfer (RT) model that includes a cloud RT component and with a fairly high vertical resolution at the cloud top. In method 3, sounding information is obtained only from the atmosphere above the cloud top. Assimilation of these cloudy IR radiances provides critical sounding data in active regions of the atmosphere. Currently, cloudy radiances are assimilated only over the oceans, and the cloud information extracted from the observations is not assimilated.

Satellite observations of bulk cloud water and precipitation from MW imagers, e.g., SSM/I, TMI, AMSR-E have been assimilated at the operational centres for some time now. The ECMWF has recently implemented a system to assimilate the radiances for such instruments for all sky conditions.

The all-sky system is the first operational 4D-Var assimilation system for clear, cloud and precipitation affected radiances and represents a significant step towards satellite usage in areas which have been largely unexploited until now. An all-sky system is easier to develop for MW observations than for IR observations because of the more continuous and linear sensitivity of MW brightness temperature to the transition from clear to cloudy conditions and as a function of cloud and precipitation state.

3. Major Issues

Major issues that were identified by the workshop's working groups are:

- *Modelling*

  Parameterization of cloud and precipitation forming processes in NWP models is still rather crude and model biases are significant in terms of cloud/precipitation frequency and occurrence as well as intensity. A prominent model problem is the quick loss of observational information gained in the analysis during the early time steps of the model forecast that limits the impact of cloud observations on dynamics and inhibits more pronounced large-scale forecast impact. A basic question is how much medium-range impact can be gained from constraining clouds and precipitation (vs. temperature and moisture in clouds) in the analysis.

Cloud modelling also includes the development and maintenance of linearized/regularized models used in the assimilation process that have characteristics similar to the non-linear versions that are used in the prediction model. With increasing complexity of the moist physics model and better spatial resolution, the non-linear and linear models may diverge. Development of fast, accurate radiative transfer models for clouds and precipitation remains a critical issue.

- *Data assimilation*

The link between the accurate characterization of the initial conditions and the sensitivity of forecast skill to this characterization is still uncertain. In addition, model errors in clouds and precipitation are not well known and need explicit definition in weak constraint systems.

The non-linearity of physical parameterizations and radiative transfer models and the need to linearize these models for assimilating the observations, as well as the non-Gaussian error characteristics of the models, can be limiting factors for data assimilation. The difficult match between spatial representativeness of satellite observations and model grid points and the frequent miss-location of clouds in model forecasts are additional barriers to assimilation progress.

- *Verification*

While satellite data have a large potential for verifying cloud and microphysics parameterizations, the apparent scale mismatch and miss-location of clouds in model forecasts produce statistics that are noisy and may not be a true measure of forecast accuracy. The verification of the impact of satellite data affected by clouds and precipitation is very difficult since this data produces only short-range impact so far, and verification with relevant observations is sparse and noisy. General forecast skill score evaluation with model analyses often shows neutral impact and strongly depends on the verifying analysis. The 500 hPa field may not be the best way to examine the impact on forecasts of assimilating observations of cloudy/precipitating regions.

- *Observations*

Due to the fact that the most recent improvements in cloud and precipitation forecasting were mainly obtained by improved models and data assimilation systems, current observational capabilities are probably under-exploited. A preference for radiance observations rather than derived products has been expressed, also recognizing the skill of existing radiative transfer models.

4. Recommendations

- *Modelling*

  - Improve cloud and precipitation physical parameterizations and their linearized version to reduce current biases. Focus on short-impact bias problem and characterize rate of dissipation of analysis increments into forecast.

  - Improve in particular sub grid-scale process representation like convection and their linearized model versions. Increase the vertical resolution of models to generate more realistic cloud features.

  - Improve the characterization of systematic and random errors of moist physics variables in models by, for example, facilitating interactions between the data assimilation and modelling communities.

  - Foster increase collaboration between the global modelling and cloud resolving model communities to develop improved parameterizations of moist physics processes in global models (in particular sub grid-scale) and to investigate linearity validity, optimal 4D-Var window length, data assimilation prognostic variable choice, microphysics, background error covariances, observation types and frequency across wider spatial/temporal scales.

  - Compare model cloud with associated observation statistics (probability distribution functions, PDF) in radiance/reflectivity and model parameter space (e.g. cloud optical depth, cloud water, melting level heights, timing of convection) to improve models.

- *Assimilation*

  - Identify and quantify critical analysis errors governing the sensitivity of forecast skill to accuracy of initial conditions.

  - Improve applicability of the linear assumption in variational and ensemble Kalman filter assimilation by smoothing the observations or the nonlinear trajectory.

  - Entrain the research community to investigate alternative methods, e.g., particle filters or hybrid approaches (nudging, variational and ensemble, also with outer loop updates, multiple steps) to avoid the linearity constraint for moist physics. Explore more statistical assimilation of observations than point-by-point.

  - Foster increased collaboration between the modelling and data assimilation communities to develop coherent nonlinear and linearized parameterizations, investigate linearity validity, optimal 4D-Var window length and model error formulation, prognostic variables.

- Determine optimal schemes for handling scale-mismatch between observations and model by, for example, encouraging cooperation between mesoscale and global data assimilation groups and investigate optimal observation smoothing.

- Improve the specification of model error covariances by, for example:

  - better flow dependence, anisotropy, and diabatic balance;

  - use of variable transforms that yield control variables with Gaussian statistics;

  - propagation of covariances in 4D-Var using ensemble and (possibly) adaptive ensemble covariance localization because ensemble covariances respect error saturation bounds associated with fast, small-scale moist processes whereas tangent linear models and adjoints do not.

- Treat IR and MW observations in a similar (all-sky like) framework.

- *Verification*

In addition to the standard, e.g., 500 hPa anomaly correlation statistics, use additional verification approaches:

- Examine the impact of cloud/precipitation assimilation on forecasts of high impact weather events.

- Investigate statistical spatial verification and smoothing techniques for comparing cloud/precipitation observations with models.

- Evaluate wavelet or scale-dependent verification to eliminate the effect of weather system misplacements on traditional statistics.

- Expand verification activities to include cloud and precipitation related variables, with efforts focused on creating verification datasets from:

  - Cloud/precipitation profile information from surface and spaceborne radar and lidar observations,

  - Radiances and cloud/precipitation products from visible, IR, and MW observations from LEO and GEO satellites

  - Surface rain gauge data.

- Compare PDFs of variables between models and observations, for instance, cloud fraction PDF versus vertical velocity, or rain PDF versus cloud type PDF.

- *Observations*
    - Make use of higher temporal resolution data to resolve cloud evolution.
    - Better exploit information on cloud and precipitation from hyper-spectral IR and MW observations, both in polar and geostationary orbits.
    - More complementary use of active and passive observations from space and ground stations.
    - Investigate value of vertical wind observations as a complement to cloud parameter observations.

An important overarching result of the discussions across working groups was that it was recognized that while non-linearity of processes and non-Gaussian error characteristics are ultimately limiting factors to assimilating observations in clouds and precipitation, there are fundamental developments that can be performed to mitigate these problems in existing assimilation frameworks model errors. In particular the reduction of model biases and the more specific definition of background error statistics as well as weak-constraint and smoothing approaches, promise immediate impact. In the longer term, non-linear and non-Gaussian data assimilation systems and hybrids between linear and non-linear systems need to be considered. These developments should be undertaken across the modelling, data assimilation verification communities and should be encouraged by common projects between operational NWP centres and universities.