The assimilation of cloud and rain-affected observations at ECMWF

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Abstract

This paper presents a short overview of the most important issues related to the assimilation of cloud and precipitation-affected satellite observations in global numerical weather prediction models with a focus on the developments at ECMWF.

1. Background

The assimilation of observations affected by clouds and precipitation in regional or global numerical weather prediction (NWP) models represents a great challenge for data assimilation but promises to offer substantial improvements to forecasting skill in otherwise largely unobserved areas. In particular in the Tropics, where vertical mass transport and diabatic heating drive the circulation, clear-sky observations located away from regions of updraft constrain mass and energy fluxes only weakly and thus current NWP analyses do not produce optimal initial conditions.

In the early 1990s, first attempts were made to overcome this problem by experiments on including diabatic forcing through normal mode initialization employing infrared imagery (or outgoing long-wave radiation, OLR) that relates the occurrence of cold cloud tops to areas with intense updrafts (Puri and Miller 1990, Heckley et al. 1990). Similarly, methods for the physical initialization were developed that allow the forecast model to spin up when rainfall observations are used to nudge, e.g., latent heating parameterizations (Krishnamurti et al. 1991). Other developments mainly related to cases studies and experiments of limited value for operational systems. For a more comprehensive review of research in this are, please refer to Errico et al. (2007).

At ECMWF, first attempts of assimilating rain-affected observations in the full four-dimensional variational (4D-Var) assimilation framework were initiated in 1998 through the European contribution to the Tropical Rainfall Measuring Mission (TRMM) project (EuroTRMM) that was co-funded by the European Community and the European Space Agency (ESA). In this context, the ‘1D+4D-Var’ methodology was developed by Marécal and Mahfouf (2000, 2002) that used derived TRMM rain rates in a 1D-Var retrieval of total column water vapour (TCWV) that was subsequently assimilated as a pseudo-observation in 4D-Var. First attempts of a direct assimilation of rain rates in 4D-Var were made shortly after but proved to produce difficulties in the minimization (Marécal and Mahfouf 2003). However, various impact studies, also involving, rain rates derived from Special Sensor Microwave / Imager (SSM/I) data were performed and demonstrated the generally valuable contribution of such observations in a global operational NWP model (Mahfouf et al. 2005).

The 1D+4D-Var framework was further developed to be used with microwave radiances instead of derived rainrates (Moreau et al. 2003) and these developments were greatly supported by improved physical parameterizations of large-scale condensation processes (Tompkins and Janisková 2004) and convection (Lopez and Moreau 2005). Eventually, a largely improved system was derived for assimilating SSM/I radiances which was operationally implemented in 2005 at ECMWF (Bauer et al. 2006a, b). Over the last few years, the methodology was greatly improved with respect to data screening, bias-correction, and application with other microwave radiometers (Geer et al. 2007) and widely tested within Observing System Experiment (OSE) studies (Kelly et al. 2008) that established its value in today's forecasting system at ECMWF.

In parallel, various experimental studies were performed that followed a similar strategy focussing on cloud-affected High-Resolution Infrared Sounder (HIRS) and Advanced Microwave Sounding Unit (AMSU-A) radiance assimilation (Chevallier et al. 2001, 2002, 2004), TRMM Precipitation Radar (PR) assimilation (Benedetti et al.) as well as various ground-based applications with cloud radar (Janisková 2004, Lopez et al. 2006) and rain radar network data (Lopez et al. 2007).

All these developments indicated that the assimilation of such observations involves issues related to the observations themselves, data assimilation and physical parameterization with equal shares. The observation issues are related to the development of accurate observation operators that simulate observation-equivalent fields from the model state as well as error and bias estimation. Data assimilation issues focus on dealing with non-Gaussian probability distributions and possibly a non-unique relationship between observations and model simulations, non-linear operators, non-optimal control variables and the difficult definition of short-range forecast errors in cloudy areas. The parameterization of moist processes is generally difficult and in particular sub grid-scale processes such as convection are only crudely represented in global models.

In 2005, the Joint Center for Satellite Data Assimilation (JCSDA) hosted a first workshop on the assimilation of cloud and precipitation observations from satellites that attempted to address the basic underlying issues[1]. The workshop produced a special issue of the Journal of the Atmospheric Sciences (Errico et al. 2007) that covers most of the topics in depth.

2. Issues

2.1. Analysis/forecast sensitivity

One of the most fundamental underlying questions is the sensitivity of the forecast in general and the precipitation forecast in particular to the initial conditions in cloud/precipitation-affected areas. With respect to the former, only few studies have been performed. McNally (2002) produced one of the first analyses of forecast sensitivity to initial conditions employing a cost function that measures forecast error and the forecast model's adjoint to trace back the areas that, most likely, contribute to the largest forecast error growth (Klinker et al. 1998). Employing a simple metric for relating temperature forecast error to cloud occurrence, McNally concluded that the largest part of the Northern hemisphere over which the forecast would benefit from accurate temperature observations is covered by clouds and therefore not accessible to classical sounder observations.

Based on the solution of forecast sensitivity to observations introduced by Cardinali (2007), a similar cost function as in McNally (2002) can be calculated and the contribution of each observation type to the reduction of the forecast error can be calculated. Figure 1 shows an example from T511L91 (40 km) ECMWF model calculations over five weeks (05/01-12/02/2007) comparing the impact of clear-sky (Figure 1a) and rain-affected (Figure 1b) SSM/I observations over oceans. Both observation types produce a similar total impact. When compared to the mean accumulated precipitation shown in Figure 1c the rain-affected observations clearly show their largest contribution to forecast error reduction in the inter-tropical and South-Pacific convergence zones in the presence of intense rainfall.

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[1] http://www.jcsda.noaa.gov/satellitecloud2005.php

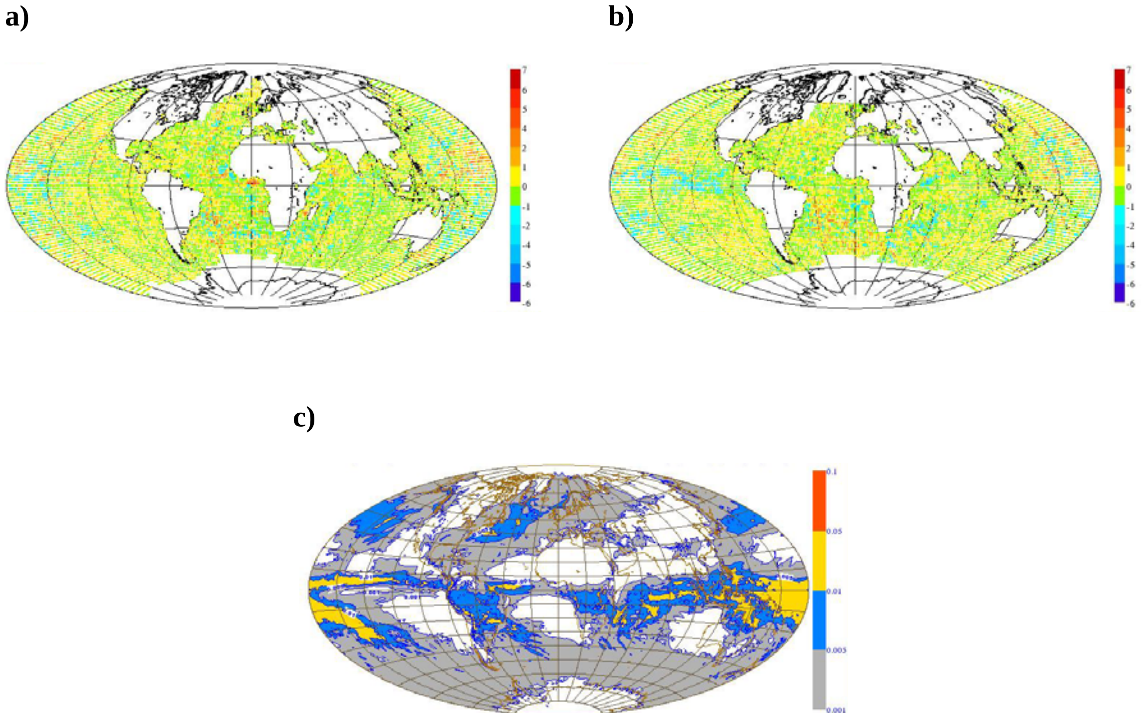

Figure 1: Mean (05/01-12/02/2007) impact on change of cost-function (in J/kg) by SSM/I clear-sky (a) and rain-affected observations (b). (c) Mean accumulated precipitation (in 10^{-3}*mm; Courtesy Carla Cardinali). Negative numbers refer to a cost-function reduction and therefore forecast error reduction.*

Another issue with respect to sensitivity is the impact of rain observations on the analysis in terms of (1) at what time of the adjoint integration and (2) with respect to which model control variable the observations produce the largest gradient.

Lopez et al. (2006) investigated this problem with a 2D-assimilation framework for surface rain gauge measurements as well as using the full 3D-Var system over a limited area in the Northern Atlantic. The 2D-adjoint sensitivity analysis indicated that, regardless of the rainfall evolution in the data assimilation window, the strongest sensitivity of the analysis of temperature and moisture was to observations near the beginning of the window and usually stronger for moisture than temperature. The 3D-case revealed sensitivity to observations with a lead-time of up to 36 hours and, again, the moisture seemed to dominate the temperature impact.

A similar adjoint sensitivity study was performed by Mahfouf and Bilodeau (2007, 2008) with the Canadian model and a 4D-Var system applied to a tropical as well as a mid-latitude cyclone. Their results indicate a stronger impact of temperature perturbations on rainfall accumulation which must be related to the different choice of moist physical parameterizations.

In summary, forecast sensitivity evaluations suggest that cloud-covered areas coincide with regions of largest forecast error growth, and they associate a significant impact of existing rain-affected observations on forecast error reduction. As a function of moist physics parameterizations, current variational data assimilation systems seem to be able to make use of rainfall observations through common control variables such as temperature and moisture.

2.2. Some technical issues

The technical issues associated with the assimilation of infrared and microwave satellite observations are substantial and were considered insurmountable with previous forecasting and data assimilation systems:

- Potential violation of Gaussian probability distribution function of model vs observations: Assimilation systems that rely on model linearity and quadratic cost functions may not be able to cope with potentially non-linear moist physics parameterizations and multiple scattering radiative transfer models. For example, ECMWF's incremental approach is based on the assumption of linearity of the model in the vicinity of the first-guess. However, the implementation using outer loops where the non-linear model trajectory is updated three times (with increasing resolution) per analysis provides an efficient means of including moderate non-linearities that greatly alleviates this fundamental problem and is likely to cope with multiple cost function minima. The linearity of radiative transfer models and their combination with moist physics parameterizations has been investigated by Chevallier et al. (2004) and Bauer et al. (2006a). Chevallier et al. combined a diagnostic cloud model with a non-scattering radiative transfer model and calculated the deviation of this combination from linearity for profiles covering the Meteosat field-of-view and infrared wavenumbers between 600 and 2600 cm^{-1} (spectrum of Atmospheric Infrared Sounder, AIRS). They concluded that with proper first-guess quality control testing, a substantial number of channels in the short-wave (4.3 μm), water vapour (6.3 μm) and carbon dioxide bands (14.3 μm) are suited for assimilation. Bauer et al. also concluded that for a large number of situations with clouds and precipitation (including convection) microwave frequencies between 10-40 GHz exhibited sufficient linearity.

  In geophysical space, observations of rain and clouds also introduce a problem for 'no rain' or 'no clouds' (0-value problem) where the gradients of the cost function with respect to changes in cloud/rain amount are not defined. If radiances are used as observations instead, there is always sensitivity to temperature and moisture as well as hydrometeor contents so that this problem does not exist (e.g. Moreau et al. 2003). The definition of observation (operator) errors is similarly facilitated if radiances are used instead of geophysical state variables at 0-values.

- Apart from linearity, the accuracy of operators and forecast model is crucial in cloud and rainfall assimilation for ensuring that the operator applied to the first-guess fields produces results that are already close to the observed values. With the spatial resolution and skill of model physics that is available today this objective seems realistic as shown by Chevallier et al. (2001, 2002, 2004) for HIRS, AIRS, Medium Resolution Visible-Infrared Imager (MVIRI), and AMSU-A instruments and by Chevallier and Bauer (2003), Bauer et al. (2006a), and Geer et al. (2007) for SSM/I, TRMM Microwave Imager (TMI) and Advanced Microwave Scanning Radiometer (AMSR-E). The operator's accuracy is also important to avoid aliasing because the inversion problem is underconstrained on a general principle. In multi-incremental systems as run at ECMWF, the consistency between non-linear and linearized moist physics is of importance in this case because the non-linear model is used for calculating the first-guess departures while only the linearized physics are used in the minimization. Based on Geer et al. (2007) this issue has been revisited at ECMWF and the linearized physics parameterizations have been revised accordingly.

- The difficulty of observation error definition and bias correction modelling is fairly general for most observations but particularly difficult for those related to clouds and precipitation. Since the observation operators become more complex, the operator errors dominate the error budget but are almost impossible to characterize due to the lack of accurate and representative independent measurements. Of particular concern is error correlation that is mostly produced by the operator rather than the instrument. In general, systematic studies on observation error formulation are still missing (e.g. Desrozier et al. 2005).

The same applies to bias correction. Biases may be dominated by errors in the location of clouds and precipitation that are very difficult to parameterize. This may require corrections that do not rely on point-wise but area-wise intercomparisons between model and observations.

Summarizing this section, it may be concluded that observation operators are fairly accurate and that - with a thorough quality control – a sufficient number of cloud-affected radiance observations may be used in today's operational systems across infrared and microwave spectra and with existing sounding and imaging instruments. The issue of error and bias characterization deserves greater attention.

2.3. Current system

Current operational data assimilation systems are clearly not optimized for using cloud and rain-affected observations. Some of the issues to raise are that in most systems, the control variable do not include condensate and therefore do not produce a balanced analysis near saturation regimes. With the standard set of control variables (at ECMWF temperature, normalized relative humidity, divergence, vorticity, surface pressure) and the lack of inter-correlation in the background error covariance formulation, information from cloud observations must be channelled through temperature and moisture and will not directly affect the dynamics but only through the 4D-Var integrations. The coarse spatial resolution and inactive moist physics in the first inner loop minimization in ECMWF's system greatly attenuate the potential impact of cloud observations that are often related to strong gradients at small scales. However, the fact that the existing system and past experiments consistently demonstrate feasibility and beneficial impact highlight the potential of assimilating these observations in the future.

As an example of the current system's impact, Figure 2 shows a time series obtained from the current ECMWF interim reanalysis. The interim reanalysis represents a prototype of the next 70-year reanalysis and that employs a full 4D-Var system and the latest model cycle. The figure shows the difference in tropical specific humidity, cloud cover and vertical wind speed between two identical experiments in which the 1D+4D-Var rain assimilation was switched off in one of the experiments on 1/1/1992. The illustration shows that the analysis takes about one week to adjust to the difference in observation system. Withdrawing the rain observations produces, on average, less moisture in the tropical boundary layer that mainly affects high cloud cover through a reduction of vertical mass transport. This example demonstrates the basic link between moisture and vertical dynamics through 4D-Var; however, the current system does not exploit the full potential of these observations.

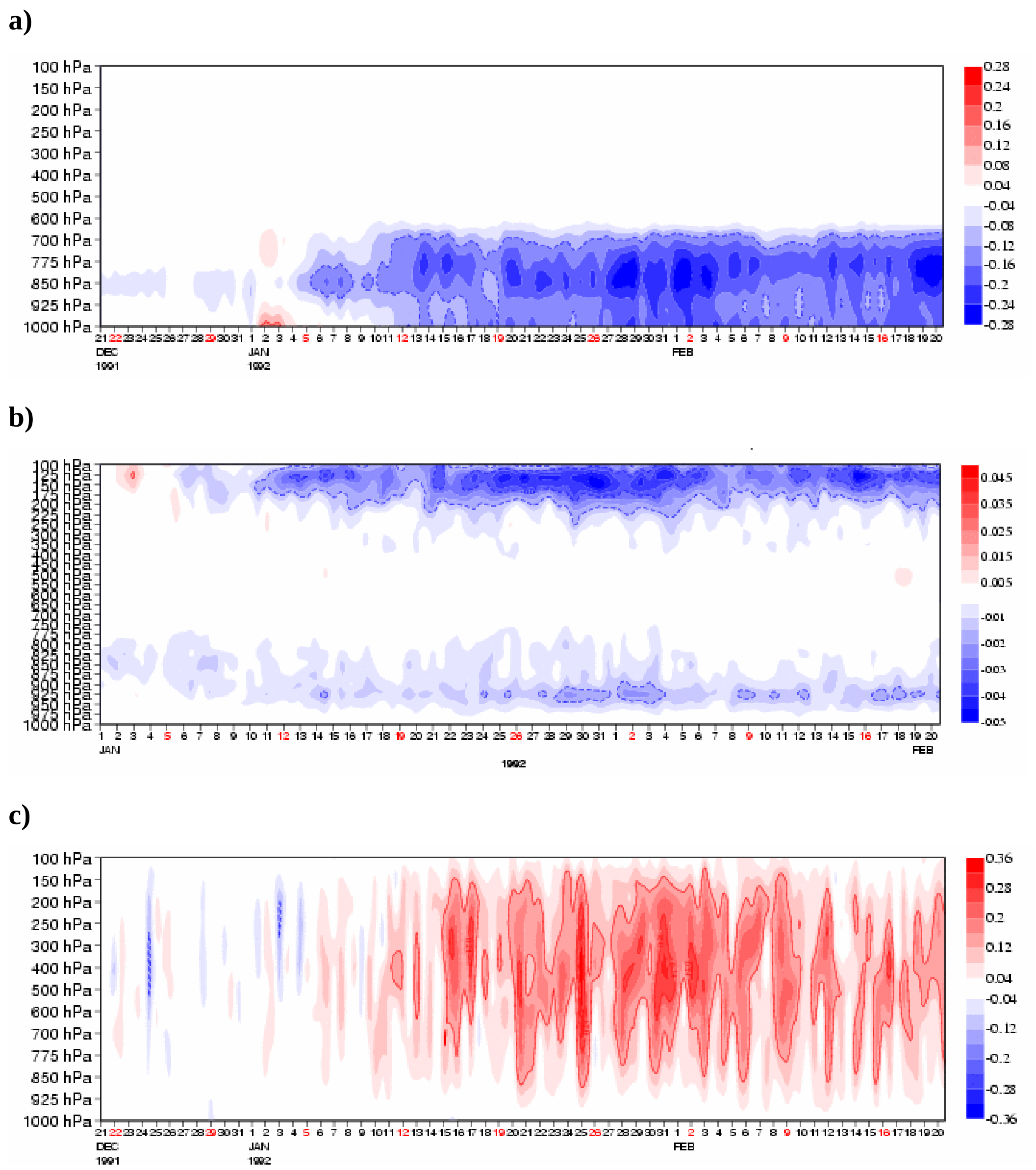

Figure 2: Analysis difference between two experiments with active 1D+4D-Var rain assimilation until 31/12/1991 that was switched off in the 2nd experiment on 1/1/1992. Panels refer to the difference in tropical specific humidity (a, in g/kg), cloud cover (b, no units) and vertical wind (c, in m/s; Courtesy Dick Dee).

3. Outlook

This paper only touched a few of the general issues of the assimilation of cloud and precipitation-affected observations. The description mainly relates to the ECMWF system but most of the problems are fairly general and apply to data assimilation in general. A more comprehensive summary of this subject is given in Errico et al. (2007). One of the driving factors is whether the assimilation system is run in an operational and global environment or for experimentation purposes only. The former requires an efficient and safe implementation and, in most cases, nearly linear observation operators and substantial effort spent on quality control, error definition and bias correction.

From the experience gained at ECMWF, the assimilation of microwave radiances over oceans seemed to provide the best compromise between nearly linear sensitivity to clouds and precipitation, accuracy of the model and computational efficiency. The 1D+4D-Var framework has the big advantage of introducing a separate quality control mechanism based on the performance of the 1D-Var algorithm. The direct assimilation of radiances in 4D-Var will greatly benefit from the lessons learnt during the operation of the 1D+4D-Var system over the last 3 years (see Geer et al. 2007).

Currently, also the assimilation of infrared (advanced) sounder data in cloud-affected situations is tested. Obviously, effects of non-linearity are more severe at these wavelengths. This requires a more stringent quality control and channel selection. However, the benefit of this development is obvious and will primarily help to avoid the aliasing of cloud information into the temperature and moisture analysis. This problem is mainly caused by the fact that cloud detection is only based on observations and disregards the presence of clouds in the model. Therefore, accounting for clouds in the observation operator will improve the utilization of radiances in general, apart from their potential to modify the model’s moist physics.

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