Status of Cloud and Precipitation Assimilation at ECMWF

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A brief overview of the past ECMWF activities on the use of cloud and precipitation observations in the 4D-Var data assimilation system is given. Initial studies focused on single-column sensitivity and variational retrieval experiments based on ground or space-based observations to characterize the accuracy of forward operators and the combined sensitivity between these operators and moist physics parameterizations. These studies were extended to global experiments within 4D-Var focusing on microwave and infrared satellite radiometer radiances. Both are assimilated operationally today and the systems are continually being refined. Ground- and space-based cloud/rainfall radar observations are currently investigated with the same methodology. All developments related to observations are supported by dedicated improvements of model parameterizations and the data assimilations system to enhance the medium-range impact of these observations.

1. Introduction

At ECMWF, about 10 million observations are assimilated per day, 95% of which originate from satellite radiance data. Most of this data is used to constrain atmospheric temperature at large scales in the free atmosphere. Over the past years data providing information on lower tropospheric temperature, particularly over land surfaces and atmospheric moisture have been added. In addition a substantial effort has been invested to better constrain areas in the analysis where forecast error growth is expected to critically depend on the initial conditions (McNally 2002). These areas are prone to cloud cover and the presence of precipitation. Assimilating observations under these conditions requires a different approach to most components of the data assimilation system, namely observation operators, quality control, control variables and their error covariances, and it adds substantial complexity to the required model physics.

Initial studies on this subject have begun about 10 years ago at ECMWF, mostly focusing on the sensitivity of observations to clouds and performing simplified retrieval/assimilation experiments to gauge the response of the analysis system to this new type of observations.

For example, one-dimensional variatinoal (1D-Var) cloud retrieval studies have been carried out by Chevallier et al. (2002) that provided insight into observation operator and minimization performance from sensitivity testing based on global model statistics. For rain observations Marécal and Mahfouf (2002, 2003) applied a similar approach using Tropical Rainfall Measuring Mission Microwave Imager (TMI)-based surface rain-rate estimates that was extended from 1D to 4D-Var assimilation.

Their work was crucial for all further studies at ECMWF because most of the fundamental issues extensively discussed by Errico et al. (2007) were already mentioned.

Later, Chevallier and Bauer (2003) showed that microwave radiances that are simulated from global model fields are quite realistic and thus could replace derived products in the assimilation. The direct use of microwave radiances instead of rain-rate observations was further established by Moreau et al. (2002) helping to avoid the dependence on sensor-specific retrieval algorithms and to simplify the rather uncertain level-2 product error estimation.

While the work on microwave imager radiance assimilation has lead to the first operational implementation, parallel efforts on infrared sounder radiances (Section 2.3), derived products from visible/infrared imaging radiometers (Benedetti and Janisková 2008) and ground-based radar network and spaceborne radar/lidar observations (Section 2.1, 2.2) have been pursued (see Fig. 1). Some of these have also led to operational systems. The main strands of current research at ECMWF are microwave/infrared radiances and both ground-based and space-based radar observations.

This paper summarizes the status of the employed methodologies and recent experience with these systems (Section 2) and provides and outlook for future work (Section 3). Important in this context is the parallel work on model physics and data assimilation system formulation without which the assimilation of cloud and precipitation affected observations would not be possible.

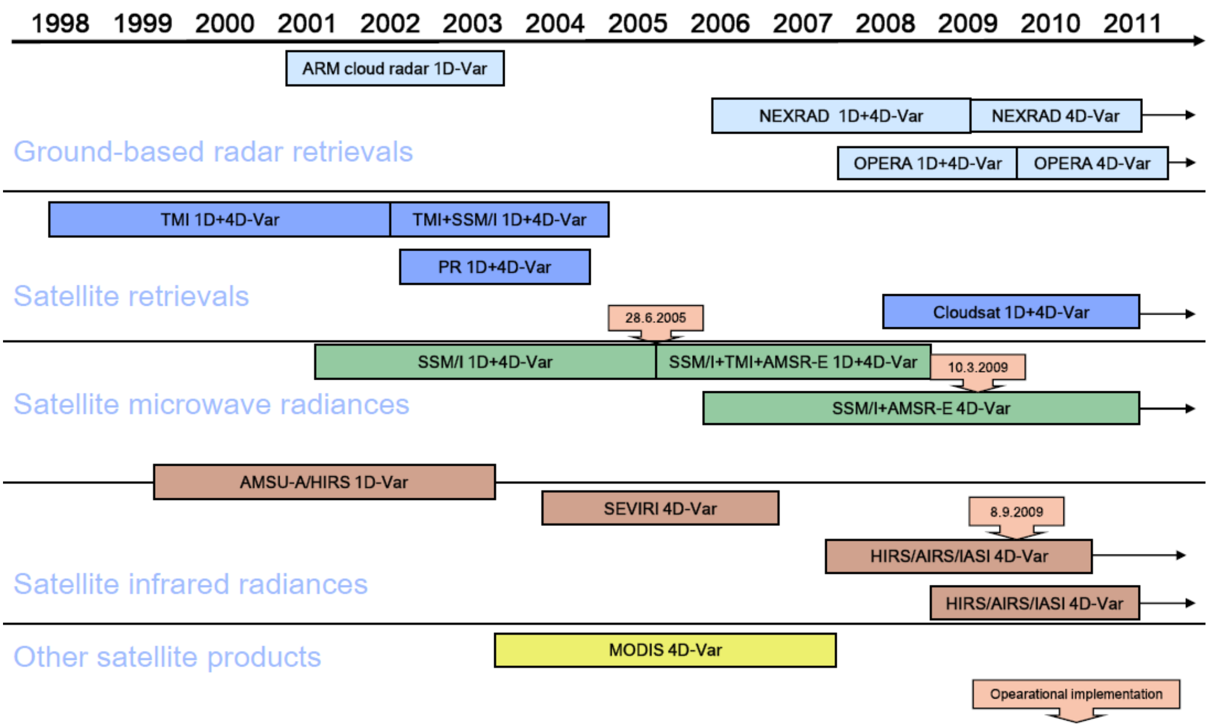

Figure 1: Evolution of cloud and precipitation assimilation efforts at ECMWF.

2. Recent progress

2.1. Ground-based radars

ECMWF has performed various feasibility studies to investigate the potential of assimilating ground-based rainfall radar observations in the global 4D-Var system, either through the intermediate 1D-Var retrieval of total column water vapour (TCWV) using radar rainfall and the subsequent assimilation of TCWV in 4D-Var (Lopez and Bauer 2007, Lopez et al. 2007), or through the direct assimilation of radar observations in 4D-Var (Lopez 2010). It was found that short-range forecasts of rainfall could be improved but that the impact on large-scale dynamics is weaker. In the 4D-Var system the assimilation of 6-hourly rainfall accumulations proved to be superior to hourly rainfall due to more consistent observation-minus-model statistics and the enhanced sensitivity of 4D-Var for accumulated rain over the 12-hour assimilation window.

This system is currently prepared for an operational implementation in autumn 2011 with the Stage IV accumulated rainfall product over the US and is expected to be applicable in a similar way to the European observational network once consistent and inter-calibrated rainfall products will be available.

The latest studies in this area focused on a generalized formulation for rain gauge observation errors and their spatial covariance obtained from comparison of high-resolution rain gauge and radar networks (Lopez et al. 2011). These errors require proper formulation in variational data assimilation and assume rather complex spatial and temporal structures due to the sparseness of gauge networks.

2.2. Space-based radars

In the context of TRMM rainfall product assimilation mentioned in the Introduction first experiments assimilating TRMM Precipitation Radar (PR) reflectivities and rainfall rates were performed by Benedetti et al. (2005). These experiments employed 1D-Var retrievals of moisture from PR profile observations and demonstrated that assimilating reflectivities or rain rates could produce largely different retrievals as a result of different assumptions on rain microphysics and observation errors made for retrieval algorithms or forward operators.

In preparation for ESA's EarthCARE mission, studies using cloud radar observations from Cloudsat have been carried out that will soon be extended to include Calipso lidar observations (Janisková et al. 2010). Substantial time has been spent on the development of appropriate forward operators to calculate model equivalent radar reflectivities to be compared to observations (Di Michele et al. 2011). Contrary to PR both Cloudsat and EarthCARE radars are not scanning and the general problem of spatial representativeness dominates the error budget. Stiller (2010) developed a statistical error model to simulate state-dependent representativeness errors that will soon be tested together within a 1D+4D-Var assimilation system of Cloudsat radar reflectivities at ECMWF.

2.3. Infrared satellite radiometers

After the experiments of Chevallier et al. (2002, 2004) infrared radiances in the presence of clouds have not been considered due to the apparent non-linear response of radiances to changes in cloud state and due to the lack of appropriate forward modelling capabilities.

After the launch of the first advanced infrared sounder AIRS in 2002 followed by IASI in 2006, initial work only upgraded the existing radiance assimilation system such that channels above clouds were assimilated (McNally and Watts 2003). While this upgrade still avoided dealing with the direct contribution of cloud layers to the observable radiances it greatly enhanced data yield.

McNally (2009) added cloud affected radiances to the operational system in 2009 with an approach that reduces the cloudy radiance contribution to the top cloud layer whose height is retrieved from infrared sounder window channels. The above mentioned non-linearity issue for infrared radiances has been circumvented by strictly limiting the data usage to overcast scenes for which it is assumed that the clouds act as black bodies such that their radiance contribution is solely defined by the temperature at cloud top height.

The overcast option only adds about 5% data globally but a systematic impact on mean temperature in areas with systematically high cloud coverage was found that also produces a small but noticeable forecast improvement. The effect on moisture and particularly cloud physics itself is minor since radiance propagation through clouds is not accounted for and no direct link between forward operator and model physical parameterizations exists. The system's extension to stronger coupling as performed for microwave radiances (see Section 2.4) is currently investigated.

2.4. Microwave satellite radiometers

ECMWF has assimilated microwave imager (SSM/I) radiance data in clear skies through an intermediate 1D-Var retrieval of TCWV between 1998 and 2002 (Phalippou 1996), after which the radiances were assimilated directly in 4D-Var until 2005.

In 2005, ECMWF has added cloud and precipitation affected microwave imager radiances to the clear-sky stream. The initial system was also based on a 1D+4D-Var approach in which the 1D-Var retrieved TCWV in cloudy areas was subsequently assimilated in 4D-Var (Bauer et al. 2006a, Bauer et al. 2006b, Geer et al. 2008).

The ECMWF 1D+4D-Var system has been replaced by the direct assimilation of radiances in 4D-Var in 2009, the so-called all-sky system (Bauer et al. 2010, Geer et al. 2010). The all-sky approach is the first fully open system in which no a priori distinction between clear or cloudy observations or model profiles is made and the adjustment of temperature, moisture, surface and cloud state is left to 4D-Var and the involved physical parameterizations. The all-sky system has been further refined by an enhanced error and bias formulations (Geer and Bauer 2010).

The all-sky system promises by definition a much improved moisture and cloud/precipitation analysis. The positive effect on moisture is in fact measurable but little impact on clouds and precipitation has been observed except in areas with persistent cloud cover or deep precipitation systems (Geer et al. 2010, Bauer et al. 2011). Wind fields are only affected in the Tropics but larger scale circulation inside and outside the Tropics responds only weakly to the enhanced moisture analysis. The model further tends to dissipate the additional information obtained in the analysis rather quickly during the forecast due to the short time scales of moist processes and the weak impact on the dynamics in the analysis.

2.5. Model and data assimilation system

The ability to assimilate cloud and precipitation affected observations requires accurate model physical parameterizations ensuring that the clouds in the short-range forecast are already similar to observed clouds. At ECMWF, significant effort is spent to continually improve cloud and convection schemes and to carry forward these improvements into the linearized schemes. The latter need to reproduce the non-linear clouds as best as possible and must exhibit a regular and nearly linear sensitivity to changes in the input parameters ensuring convergence in the 4D-Var minimization. Lopez (2007) has summarized requirements and existing developments related to moist physical parameterizations.

The more general data assimilation design issues have been extensively discussed by Errico et al. (2007). Despite their fundamental concerns a number of implementations have proven successful and did not require basic reconstruction of the data assimilation algorithm and its governing constraints. However, the experienced moderate impact on atmospheric dynamics and forecast skill may reflect the fact that most systems are tuned to large scale processes and the associated observations.

At ECMWF, several activities towards a better representation of flow-dependent background error covariances (Bonavita et al. 2011) and a control vector enhanced by cloud variables (Hólm and Gong 2011) are expected to address this issue.

2.6. Outlook

The currently operated all-sky system for microwave imager radiances represents the most advanced and most open system at ECMWF. This is because it treats clear-sky and cloud affected radiances observations with the same observation operator and physical parameterizations throughout all steps of the incremental 4D-Var algorithm. Since its initial implementation the biggest progress has been obtained from refinements of the all-sky observation (operator) error and bias formulation.

In how far this system is extendable to infrared radiances remains to be seen since non-linearity and limited information provided on internal cloud structures are problematic. However, infrared radiances in cloudy situations seem most important for adjusting temperature structures near cloud top as opposed to integrated moisture and liquid water column adjustments by microwave radiances. The two observation types are thus fairly complementary.

Studies with radar observations from space are less advanced and currently serve cloud parameterization validation rather than forecast improvement. This may change once the data assimilation system is more advanced and is able to represent and constrain small-scale processes more accurately.

In the near future, the largest benefit from cloud affected observations is expected to come from improved background error covariance and control vector formulations in which the moist variables and their spatial and temporal scales are better represented than in the current system. This highlights the importance of an ongoing discussion between groups working on observations, models and data assimilation that has been greatly supported by the 2005 JCSDA and 2010 JCSDA/ECMWF workshops on the subject.

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