EXPERIMENTAL ASSIMILATION OF SPACE-BORNE CLOUD RADAR AND LIDAR OBSERVATIONS AT ECMWF

Marta Janisková, Sabatino Di Michele, Edouard Martins

ECMWF, Shinfield Park, Reading, U.K.

Abstract

Space-borne active instruments, providing a three-dimensional characterization of clouds, promise a new dimension of information to be used in numerical weather prediction (NWP) systems. Observations from CloudSat and CALIPSO (Cloud- Aerosol Lidar and Infrared Pathfinder Satellite Observations) provide unique insights in cloud processes. Research activities are on-going at the European Centre for Medium-Range Weather Forecasts (ECMWF) to exploit these data for monitoring and assimilation. The work paves the way to the use of similar observations from the planned EarthCARE (Earth Clouds, Aerosols and Radiation Explorer) mission in the ECMWF system. The results from assimilation experiments using a variational technique to assimilate cloud observations from CloudSat and CALIPSO (separately or in combination) are presented.

INTRODUCTION

During the last decade the representation of precipitation and clouds in the global NWP models has greatly improved and it reaches a reasonable degree of realism. This opens the possibility of assimilation of data related to clouds from active and passive instruments. Observations providing three-dimensional information on clouds from the space-borne active instruments on board of CloudSat and CALIPSO are already avialable and new ones, such as EarthCARE should appear in the near future.

In order to study the impact of the new observations on analyses and subsequent forecasts, a technique combining one-dimensional variational (1D-Var) assimilation with four-dimensional (4D-Var) variational data assimilation has been selected since it would be difficult to start our study in the framework of the full 4D-Var system which is very complex and thus quite difficult to interpret. In the past, it was proven that the 1D-Var approach can provide very useful experience on how to assimilate new types of observations (for example, ECMWF studies towards the assimilation of cloud/rain-affected microwave/infrared radiances - Bauer *et al.* 2006a, b). In this two-step 1D+4D-Var approach, 1D-Var retrieval first runs on the set of cloud related observations to produce pseudo-observations of temperature and specific humidity, which are then assimilated in the ECMWF 4D-Var system.

1D-VAR ASSIMILATION

(a) Methodology

The principle of 1D-Var is similar to that of 4D-Var, but the control vector $\mathbf{x}$ represents a single column only and the time dimension is not included. The goal of 1D-Var is to search for the optimal model state that simultaneously minimizes the distance to the observations $\mathbf{y}^o$ and to a background model state $\mathbf{x}^b$ (i.e. a short-range forecast valid at the time of assimilation). The model state $\mathbf{x}$ consists of vertical profiles of temperature and specific humidity. The cost function minimized during the assimilation processes is defined as:

$$J(\mathbf{x}) = \frac{1}{2}\left(\mathbf{x} - \mathbf{x}^b\right)^{\mathrm{T}} \mathbf{B}^{-1}\left(\mathbf{x} - \mathbf{x}^b\right) + \frac{1}{2}\left(H(\mathbf{x}) - \mathbf{y}^o\right)^{\mathrm{T}} \mathbf{R}^{-1}\left(H(\mathbf{x}) - \mathbf{y}^o\right)$$

where $\mathbf{B}$ is the covariance matrix of the background error. Its role is to pass to the variational analysis the appropriate information about statistical structure of the forecast errors. $\mathbf{R}$ represents the observation and representativeness error covariance matrix. H is the observation operator providing the equivalent of the data from the model variable $\mathbf{x}$.

(b) Observation operator

In the case of radar/lidar assimilation, the observation operator H employs physical parametrization schemes for moist processes, i.e. convection scheme and cloud scheme simulating large-scale condensation and precipitation processes (Lopez and Moreau 2005, Tompkins and Janisková 2004, Janisková and Lopez 2013). Further parametrizations of cloud radar reflectivity and lidar backscatter due to clouds (Di Michele *et al.* 2012, 2013a,b) are required to convert model fields to reflectivity and backscatter, respectively. Input cloud and precipitation fields to radar/lidar model are computed by the moist physics parametrizations, the main input variables of which are temperature and humidity fields.

(c) Observations

In our study, measurements of cloud radar reflectivity, converted to $mm^6\ m^{-3}$ (level-1 product), from the CloudSat 94 GHz radar and/or lidar backscatter ($km^{-1}\ sr^{-1}$) due to clouds at 532 nm from CALIPSO are assimilated by the 1D-Var system.

(d) Observation errors

The impact of any type of observation in data assimilation is partly determined by the errors that are assigned to them. These errors take into account the instrument errors, together with forward modelling and representativity errors (due to the narrow field of view). For CloudSat, the instrument random error is used (Di Michele *et al.* 2013a). For CALIPSO, instrument errors are evaluated from level-1 data according to Liu (2006). Forward modelling error is based on evaluation of uncertainty in the microphysical assumption by defining error through the differences between the perturbed state and the reference configuration (Di Michele *et al.* 2013a, b). This is done for the different ranges of temperature. The representativity error used in our experiments provides the flow dependent error estimated based on the structure function maximum according to Stiller (2010) and is defined for the different altitudes and geographical regions.

(e) Bias correction and quality control

For a proper handling of observations in the context of an assimilation system, an appropriate quality control strategy and a scheme for bias correction (Di Michele *et al.* 2013a, 2013b) are required. Based on the statistics of first-guess (FG) departures (differences between the model first guess and observations), the quality control excludes situations when discrepancies between observations and model equivalents are large. Our bias correction scheme is designed using temperature and altitude as predictors, separately for seasons and over geographical regions. By applying correction, a more Gaussian distribution of the FG departures is obtained.

RESULTS FROM 1D-VAR EXPERIMENTS

Using the 1D-Var system, different experiments have been performed using observations of radar reflectivity from CloudSat and lidar backscatter from CALIPSO, either separately or in combination. Observations have been averaged in the grid-box and the full error definition, the quality control and the bias corrections have been applied. The performance of 1D-Var assimilation has been verified against independent observations (i.e. observations which were not assimilated), such as cloud optical depth from MODIS (at the standard reference wavelength of 0.55 μm) or radar reflectivity and lidar backscatter when not assimilated. The results are presented for the period between 2350 UTC on 23 January 2007 and 0026 UTC on 24 January 2007 over the whole Pacific Ocean from 62^{o}N to 62^{o}S, covering a variety of meteorological situations (e.g. tropical convection and an extratropical cyclone in the north).

Figure 1 shows a comparison of the first guess and 1D-Var retrieved radar reflectivity versus CloudSat 94 GHz cloud radar observations over the Pacific Ocean. The 1D-Var analysis is closer to the observations for most of the profiles. However, one can notice that convective clouds between 8^{o}N and 8^{o}S are less modified and remain closer to the first guess values. The latter is due to the larger representativity errors of the observations in areas of convection.

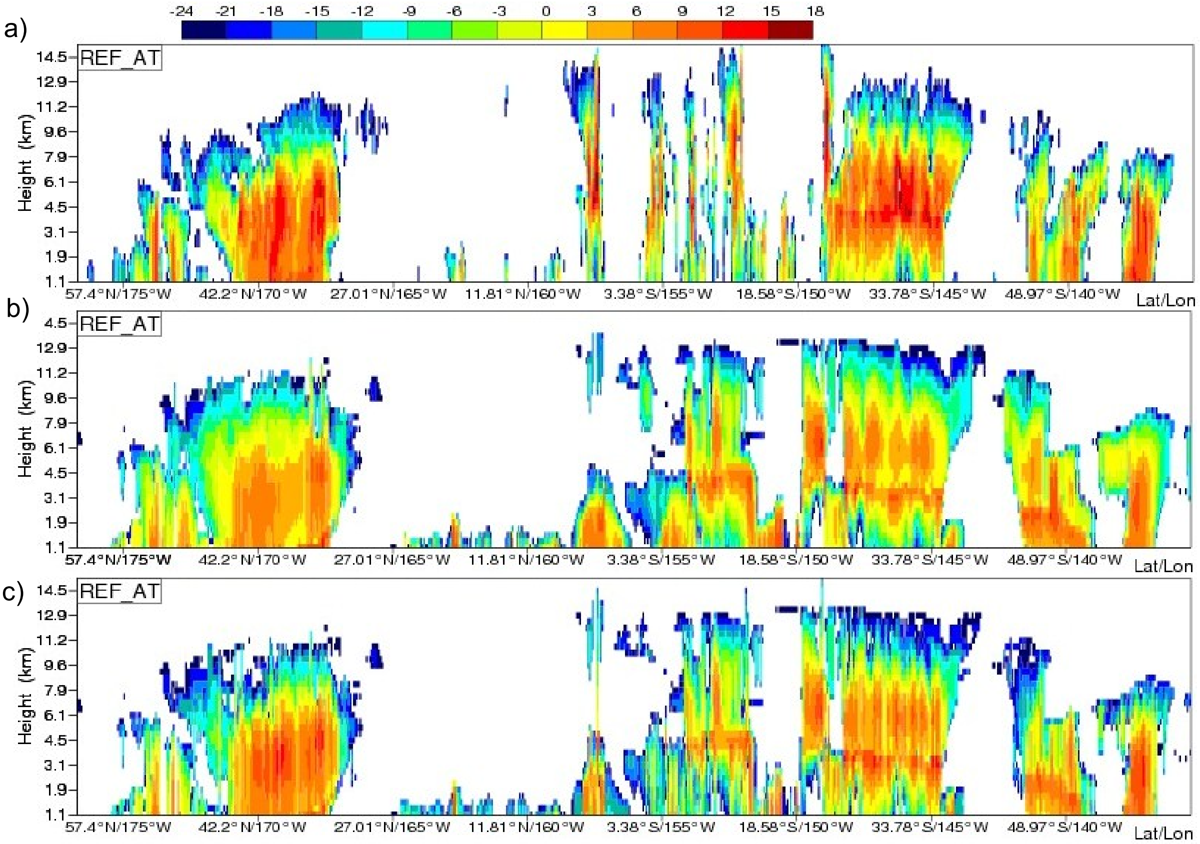

Figure 1: **Cross-section of radar reflectivity (in dBz) on 24 January 2007 over the Pacific Ocean: (a) CloudSat observations from 94 GHz radar, (b) the model first guess and (c) 1D-Var analysis.**

Results from 1D-Var assimilation of CALIPSO lidar observations (Fig. 2), using lidar backscatter due to clouds for the same period, indicate contrary to the radar case that the analysis fit to observations is only marginally better than that for the background. This is partly related to the small observation field of view, which leads to large values of representativity error. These larger errors than reduce the weight given to these observations in analysis.

The performed experiments revealed that the 1D-Var analyses get closer to assimilated observations as well as to independent observations, with the impact of cloud radar reflectivity being larger than of the one of lidar backscatter. This is demonstrated in Fig. 3 displaying the root mean square error (rms) differences between the first-guess (FG) and analysis (AN) departures for both CloudSat radar reflectivity (a) and CALIPSO lidar backscatter (b). A comparison of the background and analysis departures for MODIS cloud optical depth is also shown in Fig. 3c.

Analysis increments of temperature and specific humidity (Fig. 4) have also been evaluated since they can provide information about an impact of the assimilated observations on the control variables of the 1D-Var system. This evaluation revealed that both increments are modified by the assimilation of cloud related observations. Therefore the pseudo-observations of both temperature and specific humidity profiles from the 1D-Var retrievals should be included into the 4D-Var system. Comparing to radar, the lidar increments occur at higher altitudes and are therefore complemenary. At altitudes where both radar and lidar observations are available, the increments are consistent.

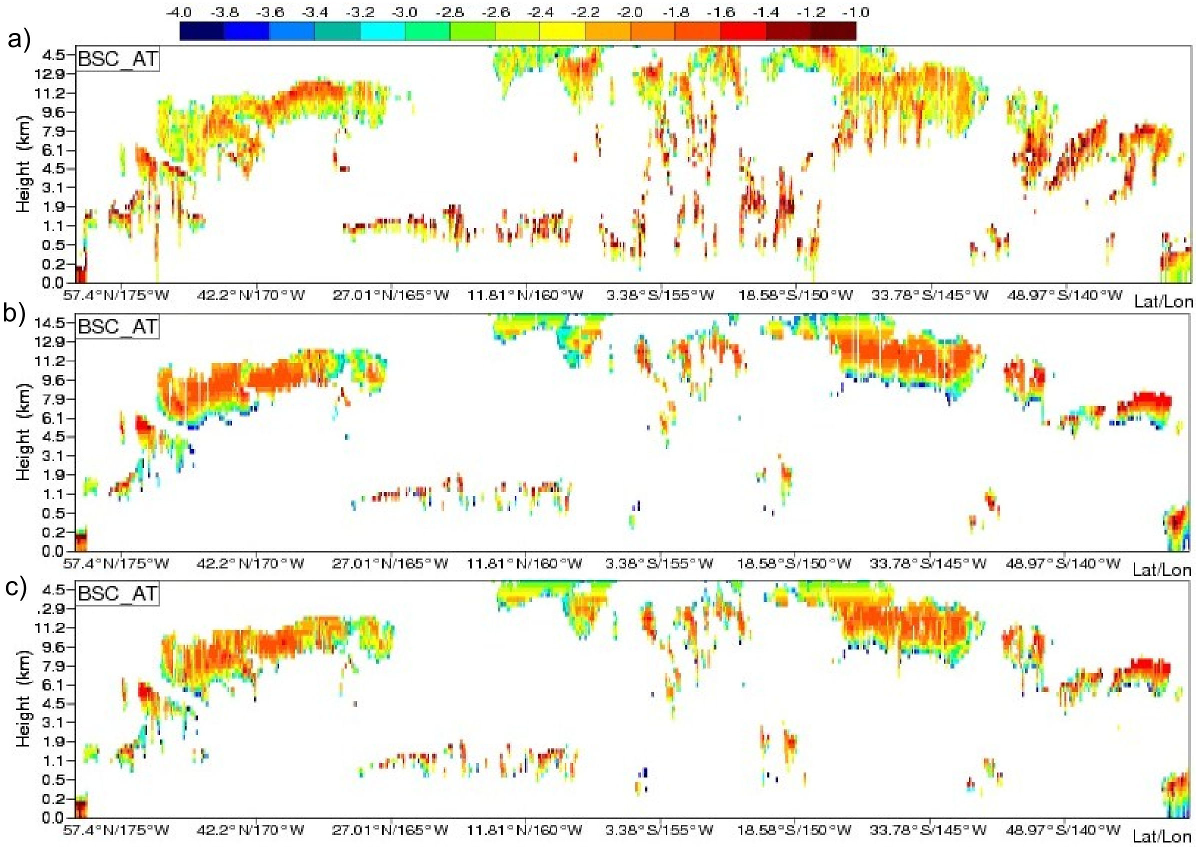

Figure 2: **Cross-section of lidar cloud backscatter (km^{-1} sr^{-1}) for the same situation as in Fig. 1: (a) CALIPSO observations, (b) the model first guess and (c) 1D-Var analysis.**

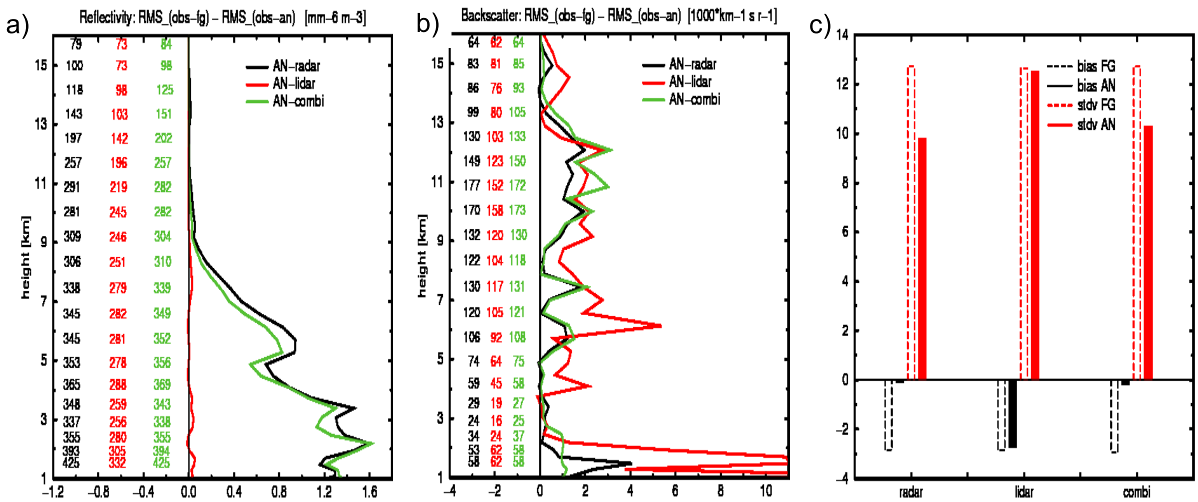

Figure 3: **Difference of (a) CloudSat radar reflectivity rms errors and (b) CALIPSO lidar backscatter rms errors for differences between the first guess (FG) departures and analysis (AN) departures when assimilating observations of cloud radar reflectivity (radar) and lidar backscatter (lidar) separately or in combination (combi) in 1D-Var. Colour number on the left side of (a) and (b) indicates number of observations considered for statistics by the different experiments. (c) Bias and standard deviation of the FG and AN departures from MODIS cloud optical depth for radar, lidar and combi experiments. Results are displayed for the situation on 24 January 2013 over the Pacific Ocean.**

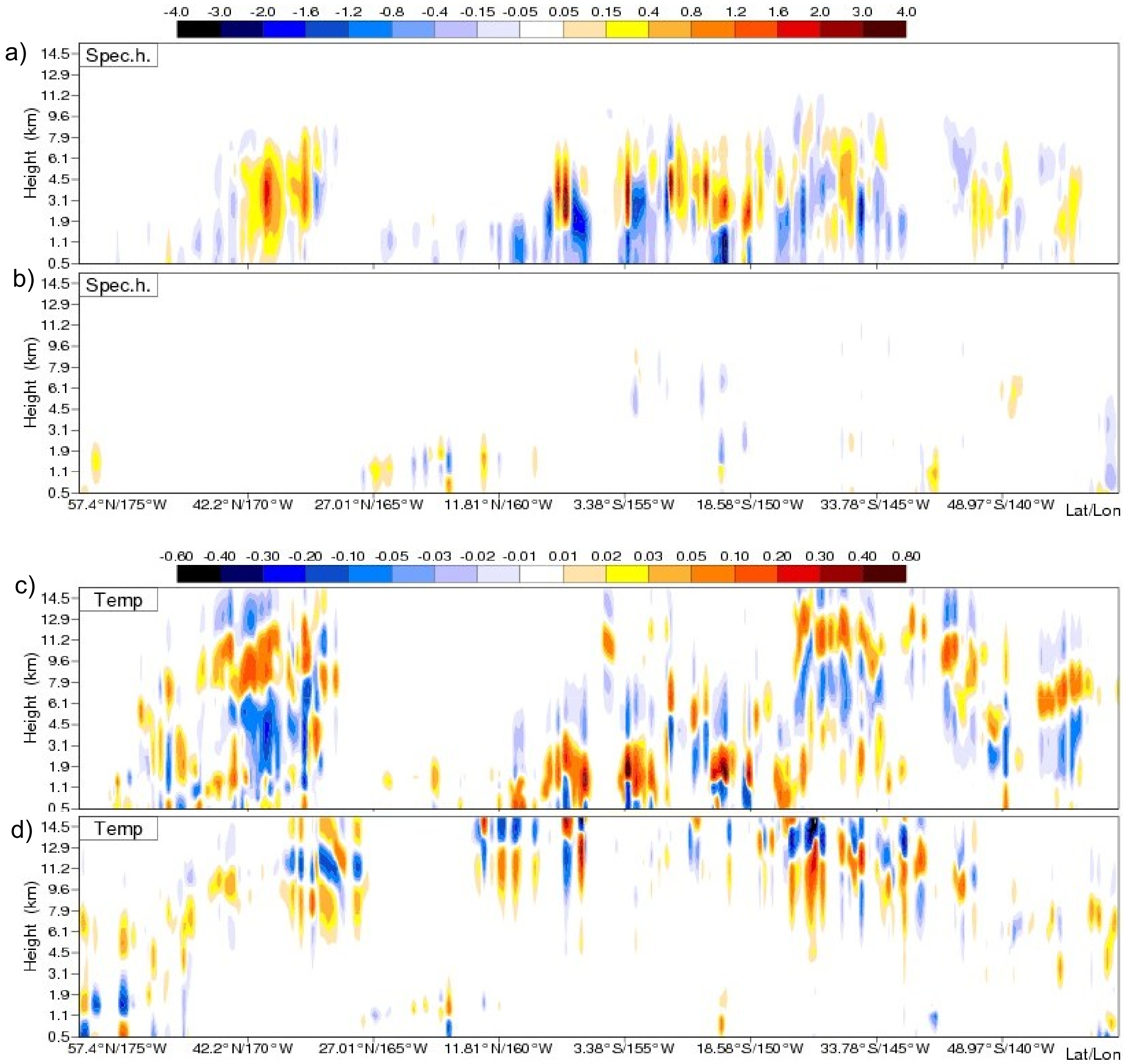

Figure 4: **Analysis increments for specific humidity in g/kg (a, b) and temperature in K (c, d) from 1D-Var assimilation of: (a, c) CloudSat reflectivity shown in Fig. 1 and ((b, d) CALIPSO lidar backscatter shown in Fig. 2. Situation over the Pacific Ocean on 24 January 2007.**

1D+4D-VAR ASSIMILATION

In the past years, a 1D+4D-Var approach has been developed for assimilation of rain affected observations at ECMWF (Bauer *et al.* 2006b, Lopez and Bauer 2007). This technique has also been used in the study of Janisková *et al.* (2012) which demonstrated the positive impact that the 4D-Var assimilation of temperature and humidity pseudo-observations derived from CloudSat has on the analysis and forecast of temperature, humidity and winds. An extension of this study is currently on-going where lidar observations or combined radar/lidar observations are used in the 1D-Var for definition of the pseudo-observations.

(a) Methodology

The simple diagram (Fig. 5) provides the schematic description for 1D+4D-Var assimilation. Specific humidity (*q*) and temperature (*T*) profiles retrieved from offline 1D-Var assimilation of radar and/or lidar data are used as pseudo-observations to be included in the 4D-Var system in order to study the impact of the new observations on 4D-Var analyses and subsequent forecasts.

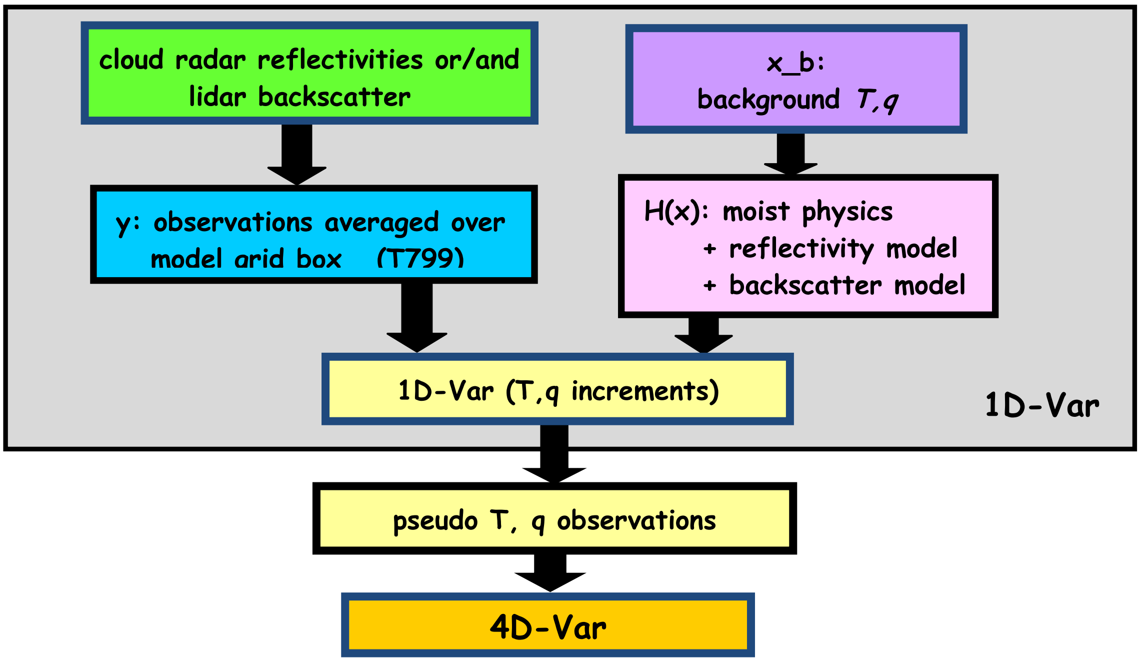

Figure 5: **Schematic description of 1D+4D-Var system for assimilation of cloud related observations.**

(b) Observations errors

Observation errors for *T* and *q* are directly derived from 1D-Var analysis covariance matrix, **A**, as

$$\mathbf{A} = \left[\mathbf{B}^{-1} + \mathbf{K}^{T}(\mathbf{x})\ \mathbf{R}^{-1}\ \mathbf{K}(\mathbf{x})\right]^{-1}$$

where $\mathbf{K} = \left[\frac{\partial H(\mathbf{x})}{\partial \mathbf{x}}\right]$ represents the Jacobian matrix of the partial derivatives of the 1D-Var observation operator, H, with respect to the control variable, $\mathbf{x}$. This error computation could be influenced by the problem of possible non-linearity of the observations operator. However, based on the convergence performance of 1D-Var system, it seems that the linearity of the observation operator is ensured for the majority cases. Experiments have also been performed with the errors twice as large as computed in order to have errors closer to those for radiosonde *T* and *q* measurements.

RESULTS FROM 1D+4D-VAR EXPERIMENTS

1D+4D-Var assimilation experiments with CloudSat and CALIPSO observations have been run over one assimilation cycle followed by 10 day forecasts. The results are presented for the same situation as for 1D-Var runs.

The statistical evaluation of the 1D+4D-Var performance shows that generally the probability distribution functions (PDFs) of analysis departures become more narrow compared to the PDFs of FG departures (Fig. 6) indicating that the analyses are getting closer to these observations. This is also confirmed by the vertical profiles of differences between rms of the FG departures and rms of the analysis departures (Fig. 7). The results are shown for the experiments when assimilating T and q pseudo-observations retrieved from 1D-Var with cloud radar reflectivity separately or in combination with lidar. Small additional improvement coming from lidar is noticeable on these profiles.

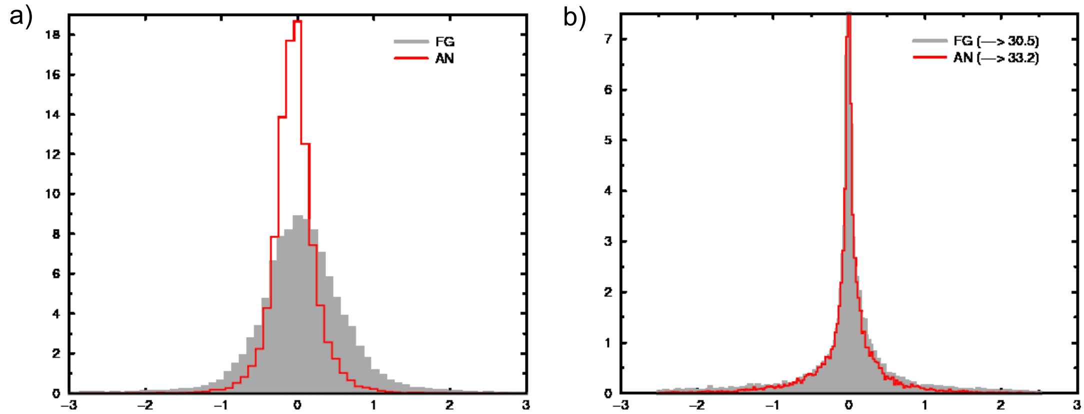

Figure 6: **Probability distribution function (PDF) of the first-guess (grey shading) and analysis (red line) departures for (a) temperature [K] and (b) specific humidity [g/kg] from 4D-Var experiments assimilating T and q pseudo-observations retrieved from 1D-Var with cloud radar reflectivity, using observation errors twice as large as the computed ones. Situation on 24 January 2007.**

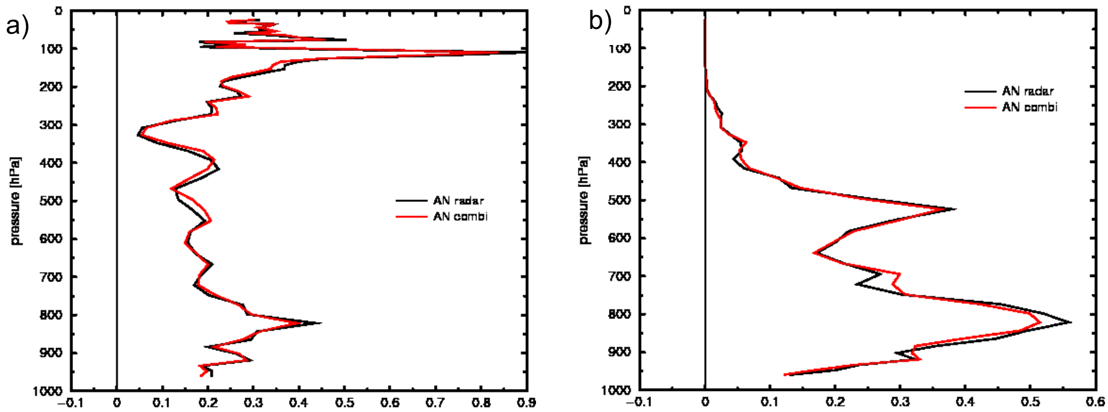

Figure 7: **Vertical profiles of differences between rms of the FG departures and rms of the analysis departures for (a) temperature [K] and (b) specific humidity [g/kg]. The results are shown for the experiments when assimilating T and q pseudo-observations retrieved from 1D-Var with cloud radar reflectivity separately (in black) or in combination with lidar (in red). Situation on 24 January 2007.**

Verification of the assimilation runs has also been done against other assimilated observation types for the domain over the Pacific Ocean. Generally, no significant changes have appeared when considering observation-minus-background and observation-minus-analysis departure statistics for all types of observations assimilated in 4D-Var. There was just a noticeable improvement (not shown) in zonal wind in the experimental assimilation runs when verified against conventional aircraft weather report (AIREP) as well as for the surface pressure verified against SYNOP observations. It should be mentioned that achieving a significant improvement between experimental runs and the reference run over a domain well covered by a large amount of other measurements is not easy, so any improvement is encouraging since it indicates a potential benefit from assimilating cloud information.

CONCLUSIONS AND PERSPECTIVES

1D-Var assimilation experiments have been performed using observation of cloud radar reflectivity and lidar backscatter, either separately or in combination. The obtained results have indicated that the 1D-Var analysis get closer not only to assimilated, but also to independent observations. However, the impact of lidar backscatter due to clouds is smaller than of cloud radar reflectivity.

Information on temperature and specific humidity retrieved from 1D-Var have been used as pseudo-observations in the 4D-Var system. 1D+4D-Var assimilation runs have shown that the analysis departures for these pseudo-observations are reduced. However, their impact on the first guess and analysis departure statistics when verified against other observation types assimilated in 4D-Var is small. Getting more impact from the new data would require tuning carefully their usage in the assimilation system. Therefore more experiments need to be performed for different situations to enhance data impact through possible improvements in data control, bias correction and error definition.

Acknowledgements

The authors would like to thank Anton Beljaars and Steven English for their valuable advice and feedback concerning this study. The CloudSat Data Processing Center at the Coopeartive Institute for Research in the Atmosphere at Colorado State University is acknowledged for providing the CloudSat data. The authors are also grateful to the NASA Langley Research Center - Atmospheric Science Data Center for making the CALIPSO data available and to the Goddard Earth Sciences Data and Information Center (GES DISC) for providing MODIS data. The contribution to this study by the last two authors was funded by the European Space Agency under the project Support to Science Element - EarthCARE Assimilation (ESTEC contract A0/1-6441/10/NL/CB).

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