QuARL – Quantitative Assessment of the Operational Value of Space-Borne Radar and Lidar Measurements of Cloud and Aerosol Profiles

ESA-ESTEC Contract Nr. 21613/08/NL/CB

EXECUTIVE SUMMARY REPORT

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QuARL

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The QuARL Project Summary Report

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1 Introduction

With the introduction of cloud radar and lidar from space we are entering a new era of cloud and aerosol observation. For the first time a large volume of information on the vertical structure of clouds and aerosols covering all climate regimes is becoming available. Clouds and their interactions have a huge impact on the atmosphere but their representation in large scale models shows substantial uncertainty (e.g. Tompkins *et al.*, 2004), particularly with respect to their vertical structure. The same is true for the representation of aerosols, which play a central role for air quality modeling. Therefore, the new observations are of great potential value to the numerical weather prediction (NWP) community and the purpose of the QuARL project was to explore and demonstrate this by using these data in the context of the ECMWF atmospheric data assimilation and forecasting system. This study investigates potential of the EarthCARE instruments by exploiting CloudSat/CALIPSO data.

2 Observation operator

The work on this project consists of verification, monitoring as well as data assimilation studies, all of which require a forward operator to match model output with observations. The issues of spatial resolution, representativity errors and sub-grid variability also needed to be addressed in this context.

2.1 Operator development

Some already existing forward operators for radar and lidar have been adapted for this project. One of them, the COSP operator (Haynes *et al.*, 2007; Chiriaco *et al.*, 2006) has been mainly used for verification purposes. To meet the requirements of computational efficiency of data assimilation system, the ECMWF radar reflectivity model ZmVar (used previously only for ground-based 14 and 35 GHz radar observations (Benedetti and Janisková, 2004; Janisková, 2004; Lopez *et al.*, 2006)) has been adapted for the CloudSat radar frequency of 94 GHz.

The changes in the ZmVar operator included the attenuation due to gases (Liebe *et al.*, 1992), particle size distributions (PSDs) for liquid (Miles *et al.*, 2000) and ice particles (Marchand *et al.*, 2009) while a Marshall-Palmer PSD has been introduced for rain. Also the particle density of snow has been made variable and is now a function of particle size.

Figure 1 compares the reflectivity-mixing ratio relationships after the modifications described above. One particularly finds that this relationship is close to the measurements published by Hong *et al.* (2008). There is, however, still a difference in the slope of the curves that is probably due to the spherical assumption (Mie theory) used in ZmVar computations.

For representing spatial subgrid variability, the multi-column method of the COSP operator was adopted also for ZmVar. For this each model grid column is split into multiple sub-columns whereby each column conceptually represents an independent radar/lidar shot. The cloud and precipitation profile is then sampled randomly, consistent with NWP model subgrid fraction and overlap assumptions at the respective locations. It was found that such a multi-column approach produces simulated reflectivities closer to CloudSat observations with little additional computational cost.

2.2 Representativity issues

Exploitation of CloudSat and CALIPSO data for model validation and data assimilation requires some knowledge of the error involved with these measurements for which the representativity error related to the small footprint of these instruments plays a crucial role. As it was recognized that

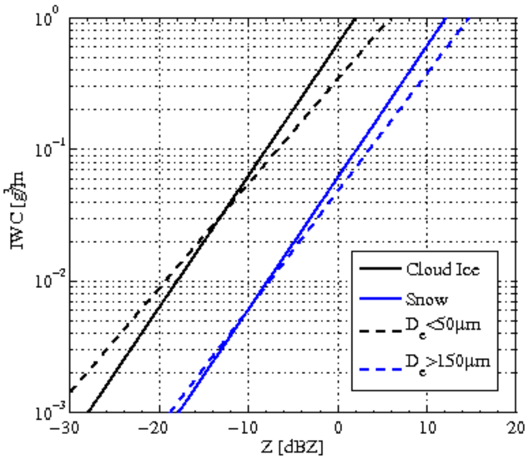

Figure 1: *Relationship between ice water content (IWC) and equivalent radar reflectivity (Z) at 94 GHz for effective particle sizes $D_e < 50\mu m$ (dashed black line) and $D_e > 150\mu m$ (dashed blue line) as obtained by Hong et al. (2008) and compared with ZmVar values for cloud ice (solid black line) and snow (solid blue line).*

the magnitude of this error is strongly dependent on weather regime, a flow dependent error measure has been developed. This has been done by combining a score (i.e., a statistical measure which differentiates weather situations with different representativity-error magnitudes) with synthetic data generated by a stochastic method. These synthetic data (which share some key statistical properties with the observations) are used to establish a quasi-empirical relationship between the score and the representativity error. While, in principle, different types of score measures can be used for this method, the "variogram maximum score" was presented as particularly suitable.

The validity of the method was tested through comparison with observations from scanning satellite instruments (MODIS and TRMM - Tropical Rainfall Measuring Mission) whose horizontal coverage allowed the direct computation of the representativity error. The generally excellent agreement found in validation (Fig. 2) for data with very different statistical properties gives high confidence in the applicability of this method to CloudSat and CALIPSO data.

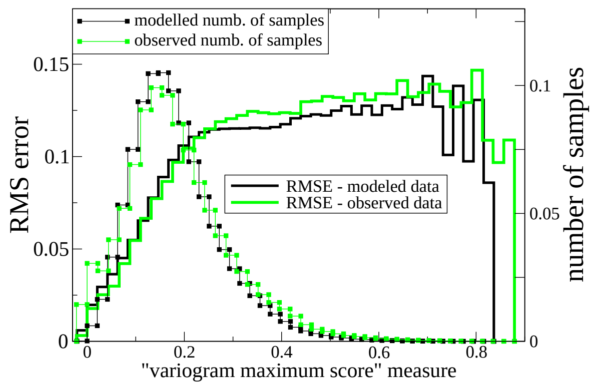

Figure 2: *The dependence of the representativity error (root mean square error, thick lines) on the "variogram maximum score" for real data (green curves, MODIS total cloud fraction) and for synthetic data (black lines). The corresponding number concentrations are given by the thin lines.*

3 Model validation

CloudSat and CALIPSO data offer an extensive and detailed description of the vertical distribution of aerosols, clouds and precipitation across the globe and provide an opportunity to validate the cloud and aerosol parametrizations of atmospheric circulation models.

3.1 Validation of the model clouds

The question of how to evaluate a global NWP model using data from a space-borne radar and lidar, has been explored, to address the problems of different parameters, different spatial scales and limitations/error characteristics of the observations. It is crucial to obtain a fair comparison between model and observations in order to identify real model performance and deficiencies, rather than artefacts of the representativity problem. Two approaches were followed; forward modeling of the observed quantities (radar reflectivity, lidar backscatter), and the alternative method utilising the synergy of the radar and lidar to derive quantities predicted by the model (ice water content, Delanoë and Hogan, 2008). The spatial representativity issue was at least partially addressed by extracting the data from the model close to the observed time along the satellite track with appropriate averaging of the observations to the model grid, or use of the sub-column approach to explicitly represent the model sub-grid variability in cloud and precipitation. Global, regional and regime-based statistical comparisons were used to assess the model and its recent improvements to the representation of physical processes. The global cloud and precipitation occurrence from the model shows good agreement with the observations, but also highlights some deficiencies, particularly the lack of high level cloud in the tropics, the over-prediction of low level cloud at high latitudes and the higher frequency of occurrence of precipitation, the latter which is at least in part due to the representation of precipitation fraction. A comparison of radar reflectivity shows many aspects that agree well, but highlights the over-occurrence of low-level rain from shallow cloud. The ice water content evaluation suggests there is too little ice in the current model, but shows the significant improvement with the new cloud scheme development that changes the representation of snow and mixed-phase ice cloud (Figure 3).

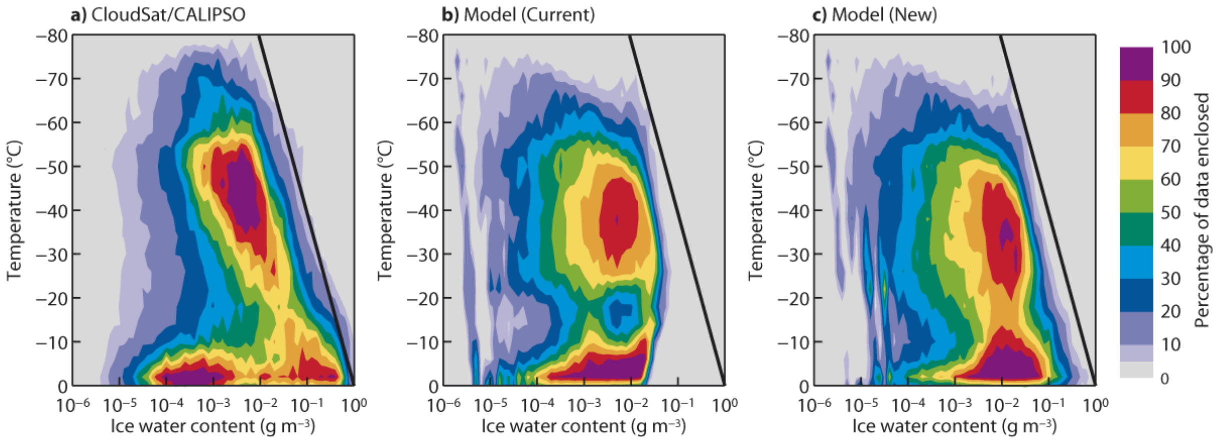

Figure 3: *Comparison of ice water content (IWC) vs. temperature for three weeks in July 2006 for Northern hemisphere mid-latitudes: (a) retrieval from CloudSat/CALIPSO (Delanoë, pers. comm.), (b) the current operational model, (c) model with the new prognostic precipitation variables. The black line indicates the slope of the observed distribution to highlight differences between the current and new model versions.*

An evaluation of the model oceanic trade-cumulus with CALIPSO data was an example for a particular cloud regime, showing the good agreement of the spatial distribution of shallow convection in the model, but differences in the frequency of cloud occurrence and cloud top height. The results also showed the significant improvement of the representation of the cloud top height for the oceanic trade cumulus regime with the new "DualM" parametrization for shallow cumulus (Figure 4) highlighting the value of the observations for validating new model developments.

3.2 Validation of the model aerosols

Aerosols were first introduced into the ECMWF IFS as part of the GEMS project (Hollingsworth *et al.*, 2008) and an experimental low resolution version of the IFS has run since July 2008. It produces a near-real time analysis followed by a 72-hour forecast of sea-salt, dust, organic and black carbon and sulphate aerosols. The data assimilation system for this IFS suite includes observations of the MODIS optical depth at 550 nm to constrain the model aerosol total optical depth. As part of the original development and on-going verification, comparisons of model optical depth at various

(a) CALIPSO observations (b) Current shallow convection (c) DualM scheme

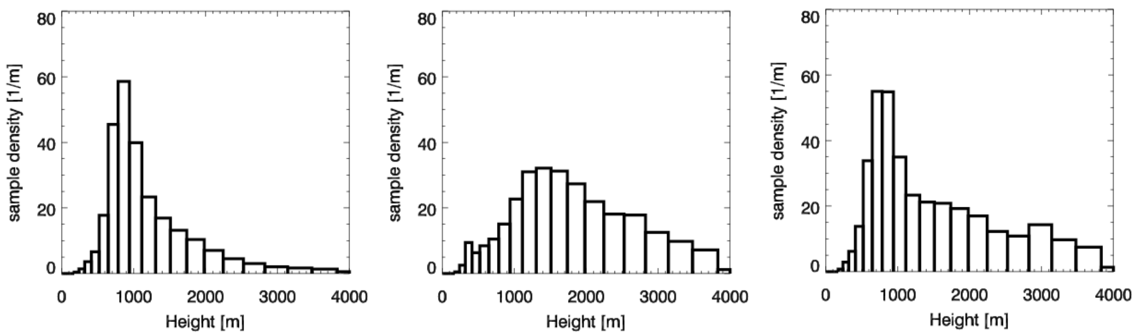

Figure 4: *Cloud top height distributions obtained from (a) CALIPSO, (b) IFS with the current shallow convection scheme and (c) IFS with DualM parametrization. Only trade cumulus clouds with cloud fraction <50% and tops below 4km between 30N and 30S are considered. The vertical axis shows samples per width of bin.*

wavelengths have been carried out against measurements at AERONET ground stations and retrievals from various satellites (MODIS, MISR, AATSR, MERIS and SEVIRI).

Validation of the vertical distribution of the model aerosol has also been performed against the CALIPSO/CloudSat aerosol-cloud mask. The model aerosol was found to generally present a good spatial and temporal horizontal variability, reflecting the quality of the meteorological model into which the representation of aerosols is embedded. The vertical distribution is more uncertain with too much aerosol seemingly transported upward by convection (Fig. 5). Overall, the main deficiency is the often incorrect speciation of aerosols, when the analysis of only one aerosol-related observation correctly modifies the aerosol total optical depth originally produced by the first-guess trajectory but cannot modify the distribution of aerosols between the various types represented by the model. This is usually linked to a poor representation of the aerosol sources, mainly of the anthropogenic components, i.e., organic and black carbon, and sulphate aerosols. Research and development on the aerosol analysis and modeling now continues to address these issues as part of the MACC[1] project.

(a) CALIPSO/CloudSat aerosol-cloud mask (b) Model clouds and aerosols

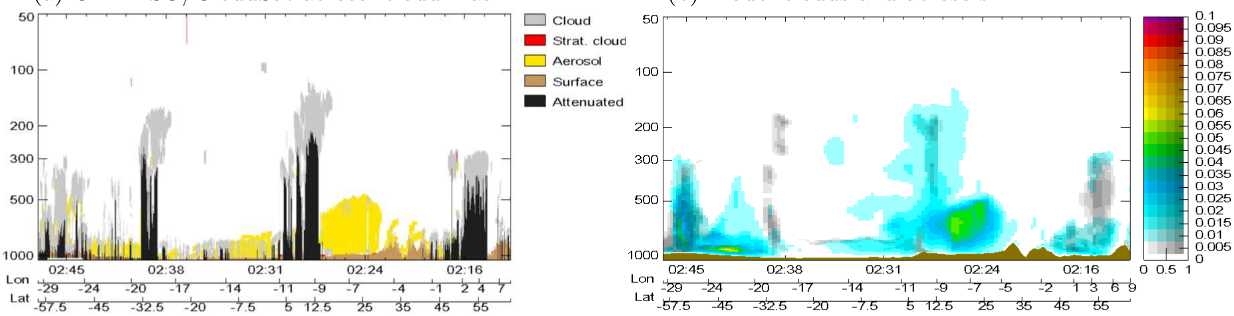

Figure 5: *Model forecast (b) of clouds (grey scale) and aerosols (colour scale) compared to CALIPSO/CloudSat aerosol-cloud mask (a) over orbit on 26 June 2007 between 02:13:14 and 02:47:19 UTC.*

3.3 Assessing the quality of height assignments from other satellite instruments

Cloud detection and screening is a fundamental means of satellite observation quality control. The active instrument measurements from CloudSat/CALIPSO provide the opportunity to cross-validate cloud detection algorithms for the passive satellite instruments which are used in the ECMWF data assimilation system. In the QuARL project, three height assignment methods have been compared against corresponding values obtained from co-located CALIPSO measurements. These are the cloud-top height (CTH) derived from the AIRS cloud detection algorithm, the CTH also derived from AIRS but for assimilation of cloudy radiances, and the height assignment (HA) for Atmospheric Motion Vectors (AMVs) derived from geostationary cloudy radiances. The performed inter-comparison has

[1] http://www.gmes-atmosphere.eu/

shown an overall tendency of height assignments for AMVs to produce CTHs lower than CALIPSO particularly for high clouds.

Generally, a large scatter was found when comparing passive and active CTHs. However, the discrepancies could be strongly reduced by applying adequate screening conditions to the co-located measurements. Figure 6 shows an example where estimates of CTH from AIRS cloud detection have been restricted to (a) cases over ocean, (b) cases matched with more than 10 (out of maximum 15) CALIPSO shots within the AIRS field of view (FOV) and (c) cases where all CALIPSO shots see a cloud. Comparing the red and black symbols one finds that the errors in the vertical height can be further reduced by looking only at those cases where CALIPSO shots in the AIRS FOV are fully attenuated. Apparently the opaque/transparent distinction of CALIPSO observations highlighted those most difficult situations which can not be easily retrieved from passive instruments.

CloudSat products have been also used to validate the assimilation of microwave (MW) radiances in cloudy regions. For this study the use of CloudSat measurements had to be restricted to regions where the representativity problem is less severe. The investigation showed that CloudSat provides useful information about the impact of cloud and precipitation affected passive MW observations in the assimilation system. The validation also revealed that the geographical patterns of AMSR-E first guess (FG) departures (first guess minus observations) agreed well with the differences between the cloud liquid first guess and CloudSat products. These results indicate the potential of CloudSat to be used as a diagnostic and independent validation tool for monitoring the cloud and rain affected radiance assimilation.

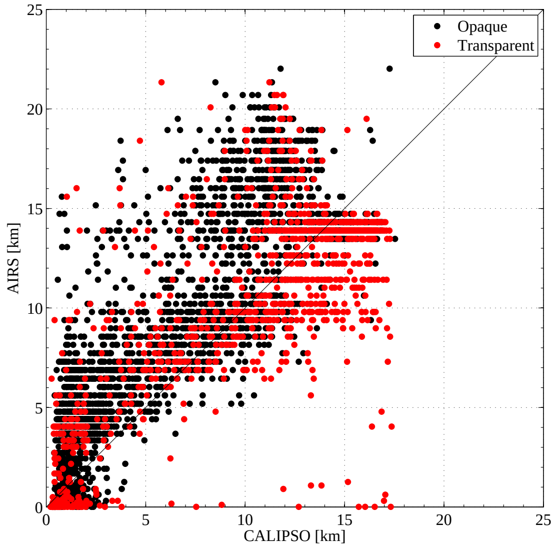

Figure 6: *CTH from AIRS cloud detection algorithm vs. CTH from coincident CALIPSO Level-2 Layer Product (averaged to AIRS resolution). Screening criteria have been applied as explained in the text. Black and red dots respectively indicate opaque and transparent occurrences.*

4 Data assimilation experiments

In order to develop strategies for radar and lidar data assimilation, feasibility studies have been performed. As for the introduction of other new observation types in the past, the so-called 1D+4D-Var approach (Moreau *et al.*, 2004; Bauer *et al.*, 2006ba) has been chosen in which a 1D-Var (one-dimensional variational) retrieval of the observations is fed into the full 4D-Var (four-dimensional variational) assimilation system. This approach allows an additional level of quality control and a better understanding of how the observations are assimilated.

4.1 1D-Var retrievals

Two 1D-Var systems have been set up, one assimilating cloud information from CloudSat, the other assimilating aerosol information from CALIPSO clear sky measurements.

4.1.1 Cloud retrieval

For the CloudSat retrievals, the 1D-Var operator consists of two simplified parametrizations of moist atmospheric processes: a convection scheme (Lopez and Moreau, 2005) and a cloud scheme simulating large-scale condensation and precipitation processes (Tompkins and Janisková, 2004). The assimilation of cloud radar reflectivity observations further requires a radar forward operator to convert model fields into reflectivities. The ZmVar operator (described in section 2.1) has been used in the assimilation studies. Its tangent-linear and adjoint versions have been coded to reduce the computational cost of the 1D-Var experimentation.

In order to test the suitability of different data types, CloudSat reflectivities (level-1 products) as well as retrieved cloud liquid and ice water contents (level-2 products) have been explored. These profile observations have also been combined with MODIS cloud optical depth providing a column integrated measurement with larger spatial coverage. This combination has been tested as a possible way to eliminate a possible representativity problem when using measurements with very limited spatial coverage as provided by CloudSat. The 1D-Var assimilation is performed with the aim of adjusting the model temperature and specific humidity profiles. Experiments have been done for several selected situations and they showed that the analyses obtained by assimilating either level-1 (Fig. 7) or level-2 (not shown) products get closer not only to the assimilated, but also to independent observations. This indicates that the analysis (AN) could benefit from the assimilation of these types of observations and therefore efforts should be made to further explore the possibilities of their use in the assimilation system of NWP models.

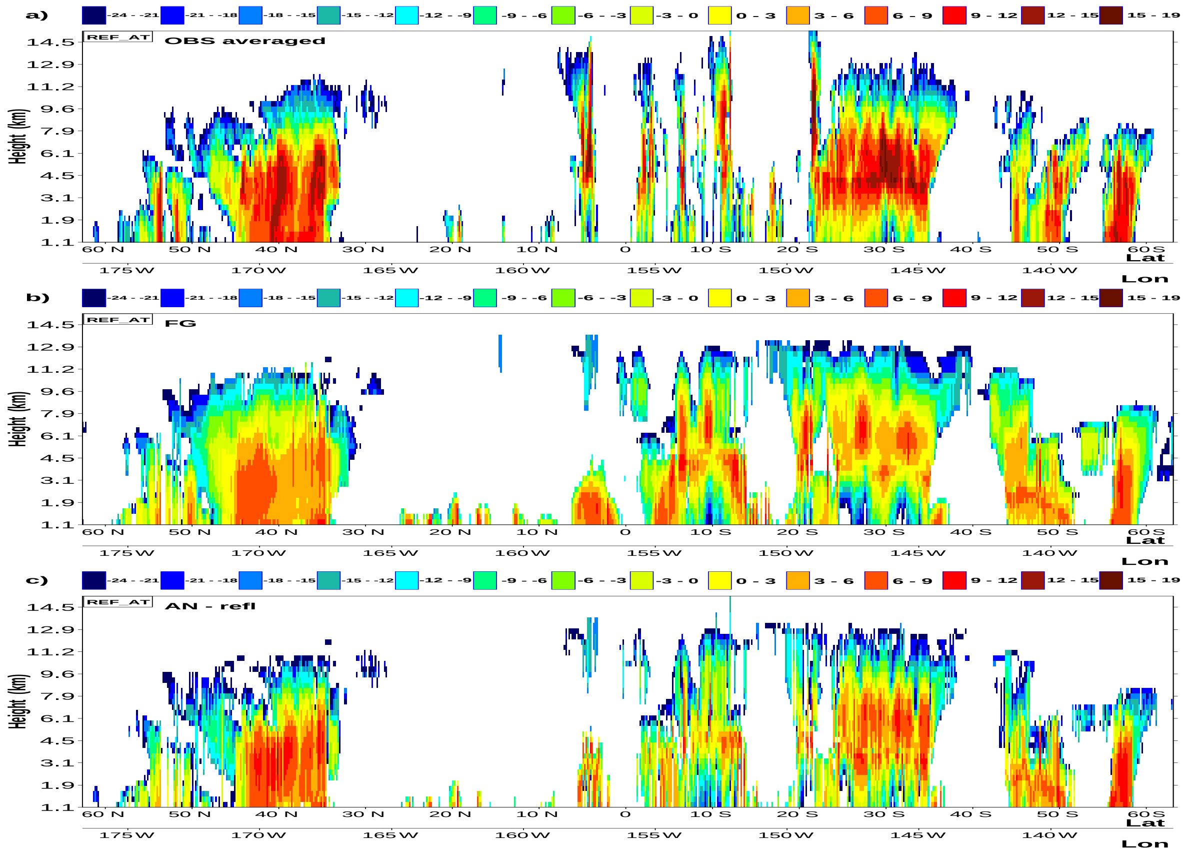

Figure 7: *Cloud radar reflectivity (in dBZ) for a situation on 23 January 2007 - (a) CloudSat observations from 94 GHz radar averaged over the model grid-box, (b) model background (FG) and (c) 1D-Var retrieval using averaged cloud reflectivity (AN - refl).*

4.1.2 Aerosol retrievals

The clear sky aerosol retrievals were based on a newly developed forward operator (Morcrette *et al.*, 2009) which considers extinction and backscatter from 11 aerosol species, gaseous extinctions as well as the temperature and pressure dependencies of these processes. However, in the 1D-Var system only the sensitivities with respect to the aerosol field are considered as these are dominant and aerosols have a great uncertainty in the first guess. Since only one aerosol related observation was assimilated, only one aerosol field (the total aerosol mixing ratio) has been retrieved, while the partitioning into different aerosol species was entirely determined by the first guess.

Cloud screening was necessary due to the dominant impact of clouds (when present). For this purpose the cloud-top heights from the CALIPSO level-2 5km cloud-layer product have been used and no aerosols were assimilated below the highest cloud top.

Two case studies including different weather types as well as different surface conditions have been performed. As seen in Fig. 8 the assimilation process drew the backscatter profile from the first guess strongly towards the observations. In both cases, the aerosol distribution (though not the intensity) of the first guess seemed quite close to the observations, which is remarkable particularly as these distributions were taken from a one month trial in which the aerosol field was spun up from zero without assimilation of any aerosol-specific observations (only the presence of physically and geographically determined sources and sinks).

The encouraging success of these retrievals suggests that the ECMWF aerosol system is in a state where it could greatly benefit from lidar aerosol observations provided they are available in near real time.

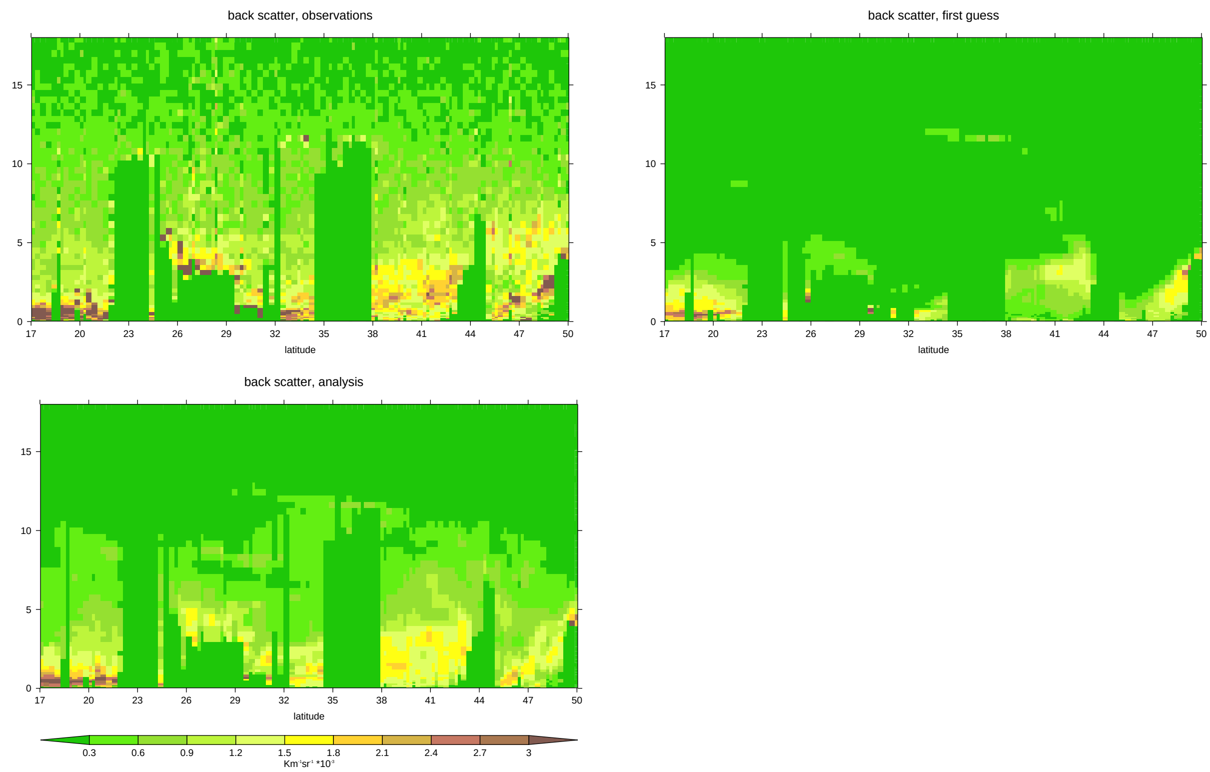

Figure 8: *Cloud-screened backscatter data obtained from CALIPSO (top left) with the corresponding model equivalent for the first guess (right) and the 1D-Var analysis (bottom).*

4.2 1D+4D-Var experimentation

To study the impact of observations related to clouds on 4D-Var analyses and subsequent forecasts, a 1D+4D-Var technique has been selected. This two step approach has been used operationally for assimilation of precipitation observations at ECMWF in the past years (Bauer *et al.*, 2006a,b). In the first step, a 1D-Var assimilation technique is used to assimilate CloudSat reflectivities (level-1 products) or retrieved cloud liquid and ice water contents (level-2 products). The CloudSat observations are averaged over the model grid-box with T799 spectral resolution (corresponding to approximately 25 km). An evaluation of specific humidity and temperature analysis increments performed in 1D-Var studies has shown that both variables are modified by the assimilation of cloud related observations and therefore pseudo-observations of specific humidity and temperature profiles from 1D-Var retrievals should be used instead of the total column water vapour (TCWV) used in the 1D-Var+4D-Var approach for precipitation observations. The second step consists of the assimilation of these 1D-Var retrieval products into the 4D-Var system as pseudo-observations.

Several 4D-Var experiments have been run for a couple of selected meteorological situations and an evaluation of the obtained analysis and the subsequent forecasts (mainly short range) has been done. When comparing the first guess and analysis against assimilated observations, generally, analyses are getting closer to these observations. Information about the vertical structure of the model departures from assimilated observations is provided in Fig. 9 in terms of standard deviation for one of the 4D-Var experiments assimilating T and q pseudo-observations retrieved from 1D-Var with cloud radar reflectivity. This comparison shows that the fit of analysis to the observations is improved over the whole vertical profile.

The results from the 1D+4D-Var experiments have shown that information on specific humidity and temperature retrieved from 1D-Var of cloud radar data and assimilated as pseudo-observations into the 4D-Var system can lead to improved initial conditions and partially better forecast for the selected cases. The performed feasibility study provides some hints of what one could expect from assimilating cloud information from active sensors. However, real assimilation of such measurements would still require a substantial amount of work to fully benefit from these observations.

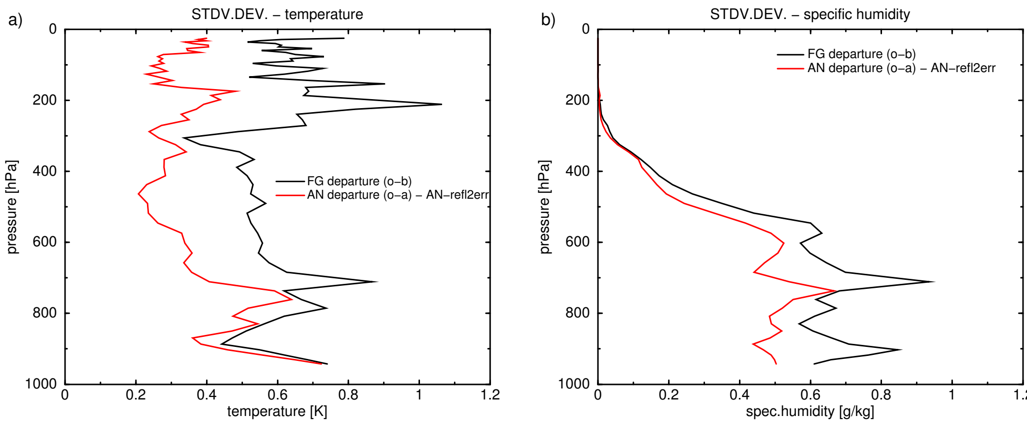

Figure 9: *Profiles of (a) temperature (in K) and (b) specific humidity (in g kg^{-1}) standard deviation for the first guess (black solid line) and analysis departures (red solid line) from 4D-Var experiment assimilating T and q pseudo-observations retrieved from 1D-Var with cloud radar reflectivity. Case of 24 April 2008 over the USA.*

4.3 Demonstration of monitoring

In the context of this project, a basic framework for monitoring CloudSat observations has been established. To investigate the possibility of identifying problems with CloudSat data, the temporal evolution of reflectivity FG departures has been evaluated along a 20-day study period. Reflectivity FG departures are calculated comparing CloudSat observations with the output from the forward operator for reflectivities ZmVar (Di Michele *et al.*, 2009) applied to short-range forecast fields. Time series of departures have been evaluated also adding Gaussian noise to CloudSat measurements over 5 consecutive days of the study period. Two types of noise have been considered: the first with a large (5 dBZ-negative) mean and a small (1 dBZ) standard deviation and the second unbiased, but with a large (5 dBZ) standard deviation. This was done with the aim to simulate an instrument calibration issue and a partial instrument failure. Time series of mean and standard deviation of FG departures together with the number of used samples are given in Fig. 10 considering reflectivities around 6 km height for mid latitudes south observations (30°S-60°S). These statistics are calculated grouping CloudSat data into 12-hour time slots, similarly to what is done in the 4D-Var assimilation at ECMWF. When considering the untouched data (black curves), the most important feature is that both mean and standard deviation are quite stable in time (top and mid panels). The mean departure for the biased noise (top panel, red curve) shows a clear drop during the failure period, while in case of unbiased noise with strong variance the departures standard deviation shows a sharp change (mid panel, blue curve). Fig. 10 also shows that the number of observations (bottom panel) always decreases because when noise is added more cases fall outside the limit set for the maximum allowed departure (±9 dBZ). Interestingly, when the biased noise is applied, we see a reduction in the standard deviation of departures (mid panel, red curve) because the strong (negative) bias creates a narrower distribution, skewed toward the lower limit of -9 dBZ for FG departures. In summary, this example shows that anomalous glitches in reflectivity measurements can be identified if they lead to appreciable changes in the time trends of FG departures. With these observations within a fully-fledged real-time monitoring system, this kind of anomalies could be instantaneously detected.

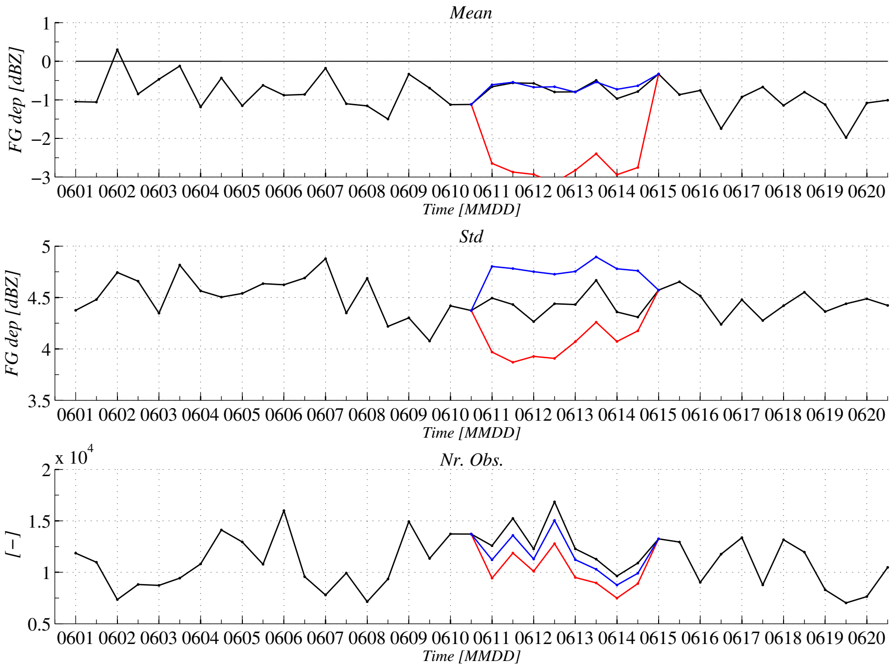

Figure 10: *Time series of first guess departures for CloudSat reflectivity between 1st and 20th of June 2008. Only observations around 6 km and at mid latitudes South (30S-60S) are considered. From top to bottom: mean, standard deviation and number of samples. Black lines refer to untouched CloudSat measurements, while blue and red are relative to the experiments where CloudSat measurements are perturbed with an unbiased noise and a biased one, respectively.*

5 Conclusions

In this project, different ways of exploiting the new wealth of information about the vertical distribution of clouds and aerosols obtained from the new space-borne radar and lidar instruments have been explored. The performed studies have shown a number of areas in NWP system that benefit from these observations.

The comparisons between data from the ECMWF model and observations from the new instruments helped to identify some apparent weaknesses of the forecast model. This has given guidance for current model developments and, as a consequence, some of the discrepancies between model and observations could already be reduced. There is therefore significant potential that the global datasets with high resolution vertical profiles of aerosol and cloud-related information (such as that from CloudSat/CALIPSO and EarthCARE) will provide an invaluable source of data to inspire and validate model parametrization schemes.

Generally, the work on assimilating the new observations has shown great potential. While, so far, the improvements found in the 1D+4D-Var assimilations performed for this project were relatively small, strong benefits of the new data could be demonstrated in the context of the 1D-Var retrievals. The successful use of the new data by the 1D-Var system is the basis for future progress and shows that these data can be correctly interpreted in the form of model relevant parameters. The impact of such information on the whole data assimilation system (as tested in the 1D+4D-Var studies) is, however, a much broader issue. The question of the extent to which global data assimilation systems in their current form can exploit highly resolved cloud and aerosol information is not trivial and a subject of ongoing research. This will require improvements in several areas, such as building a suitable bias correction for these data, better screening of observations and improved observation error definition (including representativity error).

Results from monitoring studies suggest that potential problems with cloud radar observations can be identified when first guess departures are brought outside their typical range of variation in the time trends. This could provide a basis for a future alert system.

The work carried out for this project has not only demonstrated the usefulness of the new data types (through validation and data assimilation studies), but it has also helped in laying the technical and conceptual foundations for their future operational exploitation.

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List of acronyms

1D-/4D-Var	One-/Four-Dimensional Variational assimilation
AATSR	Advanced Along-Track Scanning Radiometer
AERONET	Aerosol Robotic Network
AIRS	Atmospheric Infrared Sounder
AMSR-E	Advanced Microwave Scanning Radiometer for the Earth Observing System
AMV	Atmospheric Motion Vector
AN	analysis
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CloudSat	NASA's cloud radar mission
COSP	CFMIP Observation Simulator Package
CTH	Cloud Top Height
EarthCARE	Earth, Clouds, Aerosols and Radiation Explorer
ECMWF	European Centre for Medium Range Weather Forecasts
FG	First Guess
FOV	Field Of View
GEMS	Global and regional Earth-system (Atmosphere) Monitoring using Satellite and in-situ data
HA	Height Assignment
IFS	Integrated Forecasting System
MACC	Monitoring Atmospheric Composition and Climate
MISR	Multi-angle Imaging SpectroRadiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MW	Microwave
NWP	Numerical Weather Prediction
PSD	Particle Size Distribution
SEVIRI	Spinning Enhanced Visible and Infra-Red Imager
TCWV	total column water vapour
TRMM	Tropical Rainfall Measuring Mission
ZmVar	Z (reflectivity) Model for Variational assimilation of ECMWF