ESA CONTRACT REPORT

Contract Report to the European Space Agency

Support-to-Science-Element (STSE) Study
EarthCARE Assimilation

WP-4000 report: Conclusions and recommendations

February 2014

Authors: M. Janisková, S. Di Michele,
A. Benedetti and S. English

ESA ESTEC contract 4000102816/11/NL/CT

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
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ABSTRACT

Based on the performed studies using CloudSat and CALIPSO observations, data monitoring experiments for cloud radar have suggested that the skill of monitoring system to detect a degradation in the quality of observations is improved when the first guess departures are used compared to using CloudSat observations alone. For lidar, the study has indicated that the monitoring of differences between observations and the equivalent model quantities does not lead to earlier detection. Outcomes from assimilation experiments using cloud radar reflectivity and lidar backscatter, either separately or in combination, have shown that 1D-Var analyses get closer to assimilated and also independent observations. However, impact of the cloud radar reflectivity is larger than that of the lidar backscatter. The performed 1D+4D-Var assimilation experiments have indicated a positive impact of the new observations on the subsequent forecast. Suggested perspectives for the future assimilation are provided together with a brief summary of extensive work required to complete a preparation for possible operational assimilation and monitoring of the EarthCARE radar and lidar cloud observations. Some recommendations for the future technical and scientific developments for lidar aerosol assimilation and data quality monitoring are also supplied. Finally, a short analysis of possible benefits and the required work to assimilate EarthCARE Multi-Spectral Imager is provided.

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1 Introduction

The Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) mission has the basic objective of improving the understanding of cloud-aerosol-radiation interactions by simultaneously measuring the vertical structure and the horizontal distribution of cloud and aerosol fields together with the outgoing radiation over all climate zones. The profiling of clouds will be provided by the combination of a lidar and a cloud radar (ESA, 2004). With the launch in 2006 of the CloudSat (Stephens et al., 2002) and CALIPSO (Winker et al., 2009) missions (as part of the A-Train constellation), observations of clouds from almost coincident space-borne lidar and radar are already available. CloudSat carries the Cloud Profiling Radar (CPR), a 94-GHz nadir-looking radar that measures the power backscattered by clouds with a sensitivity threshold of -26 dBZ (Tanelli et al., 2008). Onboard CALIPSO, CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) is a nadir-viewing, three-channel lidar system (1064 nm and 532 nm parallel and perpendicular) with a 1 m receiving telescope (Hunt et al., 2009). A number of studies, including the ESA funded project Quantitative Assessment of the Operational Value of Space-Borne Radar and Lidar Measurements of Cloud and Aerosol Profiles (QuARL, Janisková et al., 2010), have shown that such observations are useful not only to evaluate the performance of current Numerical Weather Prediction (NWP) models in representing clouds, precipitation and aerosols, but they have also a potential to be assimilated into these models to improve their initial atmospheric state. In order to prepare for the exploitation of radar and lidar observations in data assimilation in the time frame of the EarthCARE mission, the current study (STSE Study - EarthCARE assimilation) developed an off-line system to monitor/assimilate Level-1 data from the CloudSat radar and the CALIPSO lidar in clouds within the NWP model at the European Centre for Medium Range Weather Forecasts (ECMWF).

The monitoring of observational data is a fundamental element of all operational NWP data assimilation systems and the check of the model against observation statistics is a necessary step before the active assimilation of any new data can take place. At ECMWF, every new observation that is brought into the operational analysis system is first monitored for a period of time. Information provided by monitoring provides a unique tool to routinely check for instrument deficiencies using the model as a reference point. As first explained by Hollingsworth et al. (1986), there is a good evidence that the 6-hour forecast error (first-guess error) is quite low, therefore allowing the evaluation of the data quality by comparison with the first-guess. Tracking departures and bias corrections, the monitoring activity helps to identify problems that may be affecting the observations and/or the model. The complementary usage of many different observations in the system permits to separate between model issues and issues in the observations, for example, related to instrument deterioration. Research satellites can also benefit from a monitoring activity: recently Muñoz Sabater et al. (2012) used the ECMWF NWP model to assess the performance of the Soil Moisture and Ocean Salinity (SMOS) mission.

In this project, off-line monitoring systems for observations from the CloudSat radar and the CALIPSO lidar have been prepared. Time series of cloud observations from these instruments and corresponding first-guess departures simulated from the ECMWF model have been generated in order to perform the feasibility studies for monitoring possible problems in the data. Outcomes of those studies are documented in detail in WP-2100 (Di Michele et al., 2014b), WP-2200 (Di Michele et al., 2014a) and WP-3100 (Di Michele and Janisková, 2014).

Improved representation of precipitation and clouds in the global NWP models during the last decade opened new possibilities for improvements of the atmospheric initial state and the model performance itself to be explored through assimilation of data related to clouds. In order to study the impact of the new cloud radar and lidar observations on analyses and subsequent forecast, a technique combining one-dimensional variational (1D-Var) assimilation with four-dimensional variational (4D-Var) data assimilation has been selected. The two-step 1D+4D-Var approach applied in this study was used operationally for assimilation of precipitation related observations (Bauer et al., 2006a,b) at ECMWF from June 2005 to June 2008. Before that, benefits of such method had been demonstrated for rain rate observations by Marécal and Mahfouf (2000, 2002). This technique has also proven to be successful in early implementations of clear-sky infrared radiance assimilation in the past (e.g. Eyre et al., 1993; Phalippou, 2005) and for SSM/I brightness temperatures in clear sky areas (Gérard and Saunders, 1999).

In the experiments performed for this project, the 1D-Var retrieval first runs on the set of CloudSat radar reflectivity and CALIPSO lidar backscatter observations either separately or in combination to produce pseudo-observations of temperature and specific humidity, which are then assimilated in the ECMWF 4D-Var system. The results from assimilation experiments are summarized in WP-3200 (Janisková, 2014).

Section 2 provides conclusions and recommendations from data monitoring experiments for cloud radar and lidar observations. Outcomes from data assimilation experiments for these observations are presented in Section 3 together with the suggested perspectives for the future assimilation of those data. Some recommendations for the future technical and scientific developments for lidar aerosol assimilation and data quality monitoring are supplied by aerosol assimilation experts from ECMWF in Section 4. Section 5 briefly summarizes the extensive work required to complete a preparation for possible operational monitoring and/or assimilation of the EarthCARE radar and lidar cloud observations. Finally, a short analysis of possible benefits and the required work to assimilate EarthCARE Multi-Spectral Imager (MSI) is provided in Section 6.

2 Conclusions and recommendations from data monitoring experiments for radar and lidar

2.1 Performed studies

a) Radar monitoring

During the project, a basic framework for off-line monitoring of radar observations has been established. Time series of CloudSat observations and the first-guess (FG) departures (differences between observed and the model equivalent values) have been evaluated. CloudSat monitoring has been performed constructing time series of mean radar reflectivity (Z) at five reference heights ranging from 2 to 10 km (with 2-km step). The monitoring of cloud-top height (CTH) derived from reflectivity measurements have also been investigated to make the process of monitoring simpler and easier to interpret. For checking only the instrument performance, it would be sufficient to use one piece of information instead of checking the whole vertical profile of measurements. Selected statistics (mean, standard deviation, number of observations) have been calculated over different latitude belts distinguishing between tropical (from 30°N to 30°S) and mid-latitudes cases (above 30°N and below 30°S). This allowed to take into account the different meteorological regimes, which lead to different ranges of variation for observations.

Reflectivity FG departures have been evaluated from the model equivalent reflectivity values obtained by the ZmVar forward operator (Di Michele et al., 2014d) with input atmospheric profiles coming from the ECMWF short-range forecasts matched with CloudSat in location and time. Statistics have been computed using all available data over the ocean, screening for cases likely to be affected by multiple scattering and for cases of large departures as described in Di Michele et al. (2014d,b). Different lengths have been considered for the time window used to build the statistics: a single orbit (or granule), 12 hours (corresponding to the ECMWF 4D-Var assimilation window), 24 hours and a running average over a week (with a one-day stepping) to investigate the sensitivity of the temporal evolution to the size of the accumulated period.

The final monitoring experiments have been performed for the period of three months from December 2006 to the end of February 2007. In order to understand the skill of this monitoring system to detect a problem in the quality of observations, experiments where CloudSat data were degraded have been performed. Monitoring of stand-alone observations has been compared against monitoring of the FG departures with the aim to investigate whether there are any advantages in considering FG departures compared to using CloudSat observations alone.

b) Lidar monitoring

In a similar way, a lidar monitoring system has been put in place that makes use of CALIOP observations (at 532 nm) in cloudy conditions. The selection of the range gates containing clouds is based on the information contained in the CALIPSO level-2 product called Vertical Feature Mask (Liu et al., 2009). The retained values of cloud backscatter have been averaged onto the closest model grid point to match the horizontal resolution (25 km in our case) of simulated observations. In addition, range bins below 8.3 km have been averaged in couples to get a uniform 60-meter resolution (from the original 30-m) along the vertical. Time series of cloud radar backscatter at six reference heights from 2 to 12 km (with 2-km stepping) as well as cloud-top height derived from the backscatter measurements have been constructed and similar statistics as for the radar monitoring have been computed for the different latitude belts, splitting monitoring to tropical and mid-latitudes cases.

Cloud backscatter FG departures have been evaluated evaluated using the ZmVar lidar operator described in Di Michele et al. (2014c) with the input atmospheric profiles from the ECMWF short-range forecasts matched with the CALIOP data in location and time. Prior to the generation of monitoring statistics of CALIOP-minus-first guess differences, a number of checks have been made to discard cases where the modelling of backscatter would be more difficult. First, having in mind the combined monitoring/assimilation of lidar and radar, cases likely to be affected by radar multiple scattering have been removed based on the screening of situations where the (in-cloud) values of liquid and solid convective precipitation prescribed by the model are respectively larger than 0.02 and 3.0 g m^{-3} (Di Michele et al., 2014d). Then, following the approach described in Di Michele et al. (2014c), a quality check has been applied to remove cases of large departures to guarantee quasi-Gaussian distribution for the FG departures, which is a necessary condition for the assimilation.

Statistics from the CALIOP cloud backscatter and from the corresponding FG departures have been constructed for the different averaging time windows (a single granule, 12 hours or 24 hours). To investigate whether there is any potential in routinely monitoring CALIOP observations against the corresponding quantities derived from the forecast model, the variation range of temporal evolution of the computed statistics has been compared. Finally, experiments for the same three month period as in the case of radar monitoring have been performed using degraded CALIOP observations to assess the skill of monitoring system in detecting observation quality problems.

2.2 Summary of the results

a) Radar monitoring

The analysis of time series of CloudSat observations compared to their model equivalent has shown that, subject to a quality control screening, there is a certain degree of consistency between simulated reflectivity and observations. Investigation of the sensitivity of the temporal evolution to the size of the averaging period revealed, as expected, that time series on the single granule are changing very rapidly because observations in subsequent orbits often correspond to different cloud structures, a consequence of the narrow swath of CloudSat. Variations are decreasing as the averaging time-window increases. At longer averaging windows, it has been noticed that the range of variation for the FG departure is smaller than the monitoring of CloudSat observations alone. This result suggests that the monitoring of CloudSat observations departures from the model FG equivalent values in addition to the monitoring of the observation values would be beneficial for the identification of possible instrument anomalies. The extra information brought by the forecast model can lead to a reduction of the size of minimum anomaly that could be detected through the continuous monitoring of the temporal evolution of prescribed statistical parameters. Similar conclusions can be drawn for using reflectivity-derived CTH as a monitoring variable since the study has shown that there is a remarkable agreement between observed and simulated CTH.

Given the good agreement between the model FG and observations, a warning system has been designed using set of thresholds for the monitoring quantities (as defined in Di Michele et al., 2014b) that could be used as checking limits in a warning system. In order to investigate the ability of the monitoring system to identify glitches in the instrument, experiments from 1 December 2006 to 28 February 2007 with an artificially degraded quality of CloudSat data starting from the second month have been performed. To simulate a drift in the radar constant of 1% every day (as described in Di Michele and Janisková, 2014), an increasing negative bias of 0.05 dBZ (1.5 dBZ after 30 days) has been added to observations daily. The main outcomes from these experiments are summarized in Fig. 2.1 - 2.3.

Figure 2.1 shows time series of daily mean CloudSat reflectivity where dashed lines refer to the monitoring of the untouched daily mean reflectivity (reference), while solid lines are for the experiment where a bias has been added. In addition, blue dots indicate statistical significance of the daily statistics, assuming that values of mean and standard deviation are robust when at least 100 samples are used for their evaluation. The horizontal green lines are the limits for the ordinary range of variation of mean CloudSat Z, defined as 110% of the maximum and minimum values in the first month. Black and red circles indicate when the limits are exceeded, by the original and biased Z, respectively (warning). Second consecutive occurrences are marked with a star symbol (alarm). Both the first warning (6 January 2007) and the first alarm (7 January 2007), occur just at 2 km. More systematic warning and alarm are then observed again at 2 km on 20 January and 21 January 2007, respectively, while there are only few sparse warnings at altitudes above. This better skill is attributed to the lower range of variation of Z at 2 km.

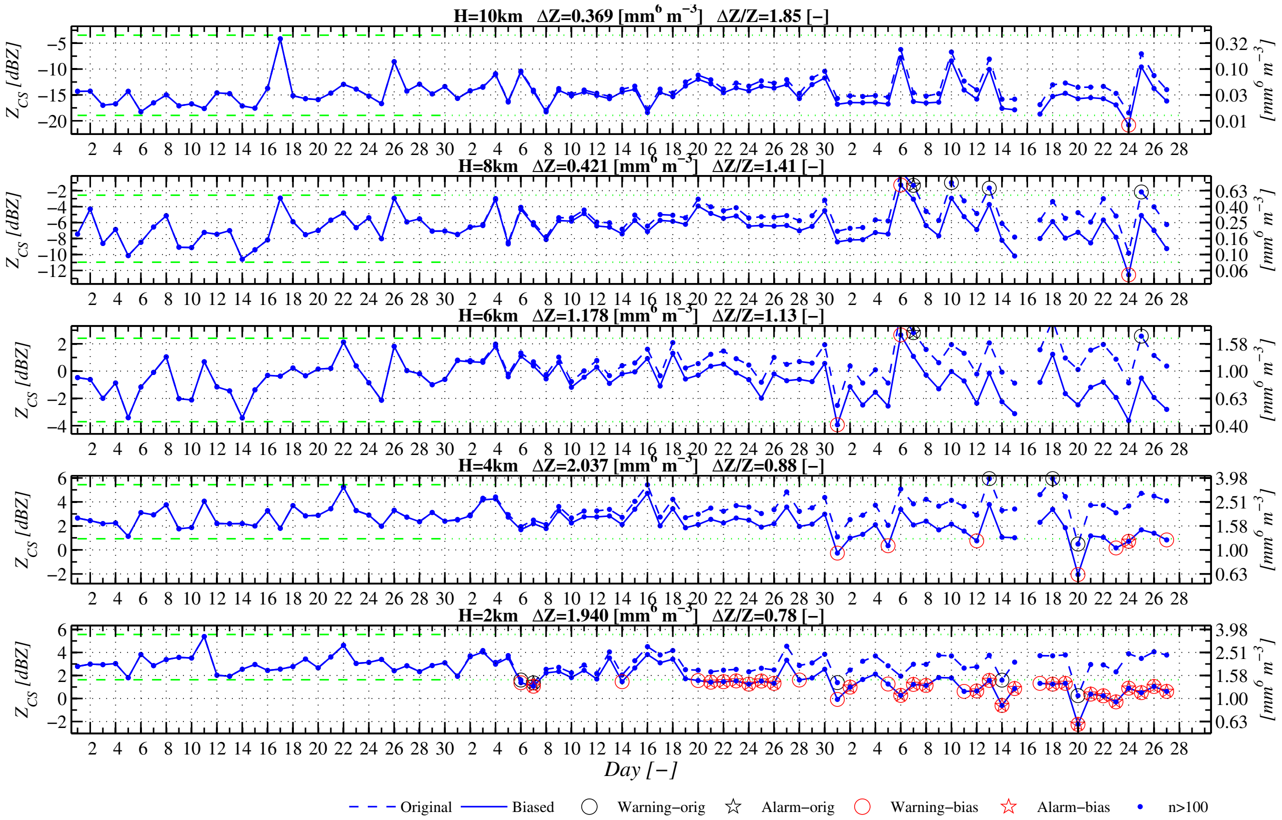

Figure 2.1: Time series of daily mean CloudSat reflectivity for the period between 1 December 2006 and 28 February 2007, considering observations at mid-latitudes South (30°S-60°S). Different panels contain data at the altitude level (H) shown in the title. Blue dashed line is for original observations, while blue solid line is for observations with bias added. Green horizontal lines define the limits for the warning system. See text for more explanation.

The monitoring of CloudSat FG departures follows the same approach used for stand-alone observations, with the addition of the screening for large departures (as described in Di Michele et al., 2014b; Di Michele and Janisková, 2014). The time series of the daily mean reflectivity FG departures (Fig. 2.2) show that the negative trend of the biased departures becomes gradually more evident moving towards lower altitudes. At 10 km, the limited number of cases left by the screening (in the first month, only in one day there are more than 100 cases) hampers a reliable monitoring. At lower altitudes, the first warning and alarm messages occur at 6 km, on 4 January 2007 and 6 February 2007, respectively. A lower number of warnings occur below and above 6 km.

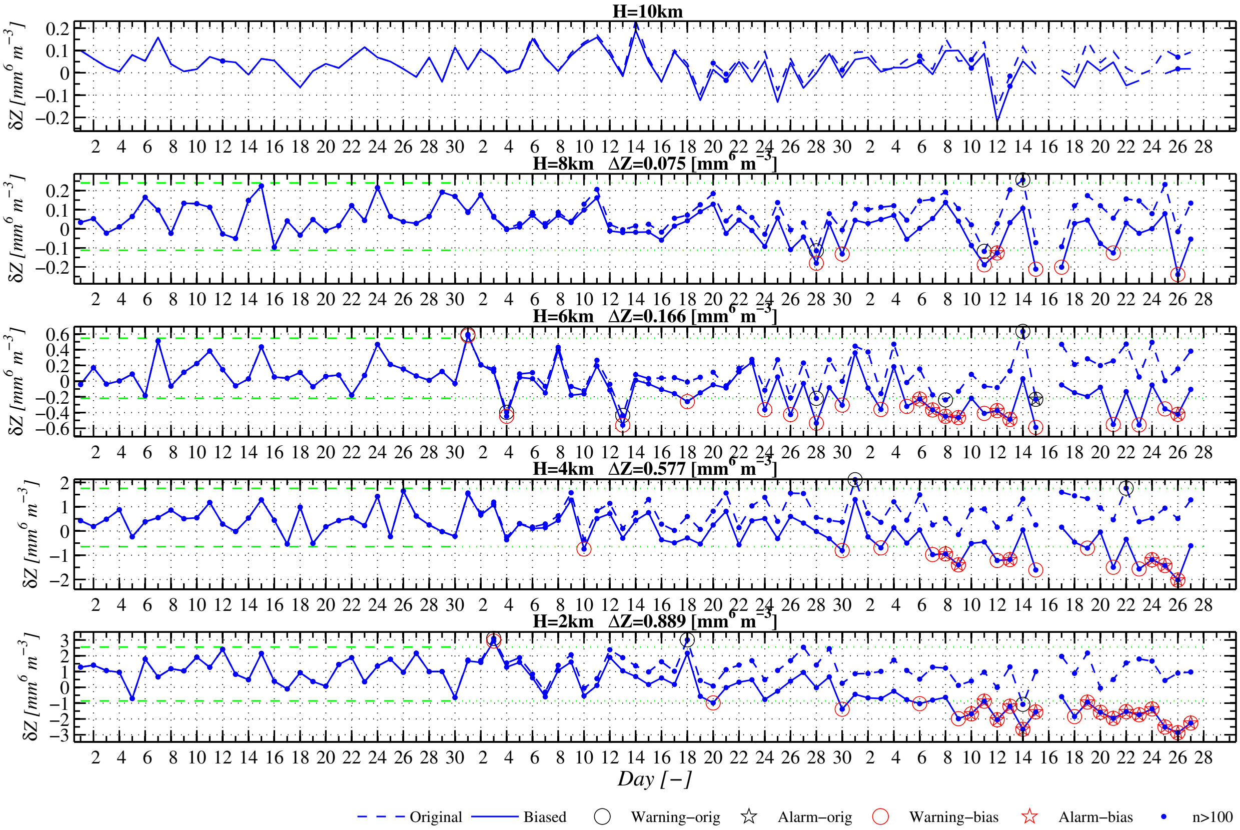

Figure 2.2: Same as in Fig. 2.1, but for time series of mean CloudSat reflectivity FG departures.

The ability of monitoring either CloudSat reflectivity only or the FG departures to identify the bias is summarized in Fig. 2.3, where the number of warning are given on a weekly basis. While Z at 2 km has the advantage in issuing the first warning earlier, the monitoring of the FG departures occur later, but provide a consistent signal across the altitudes which makes this approach more robust.

b) Lidar monitoring

Time series of CALIOP observations have been compared to their model equivalent. Similarly as for the radar monitoring, time evolution of mean/standard deviation of temporary averaged CALIOP observations is very irregular when considering a single granule. The oscillation range of the mean backscatter always decreases as the averaging time window increases. There are large differences in range of variation between the tropical and mid-latitude regions. The fluctuations in backscatter standard deviation are also reduced with increasing time window and they are usually larger in the Tropics. The 12-hour averaging already results in ranges of standard deviation quite stable in time, but with the large differences across altitude levels due to the different magnitude of the backscatter. A better agreement between observations and simulations has been shown when considering backscatter-derived CTH as monitoring variable.

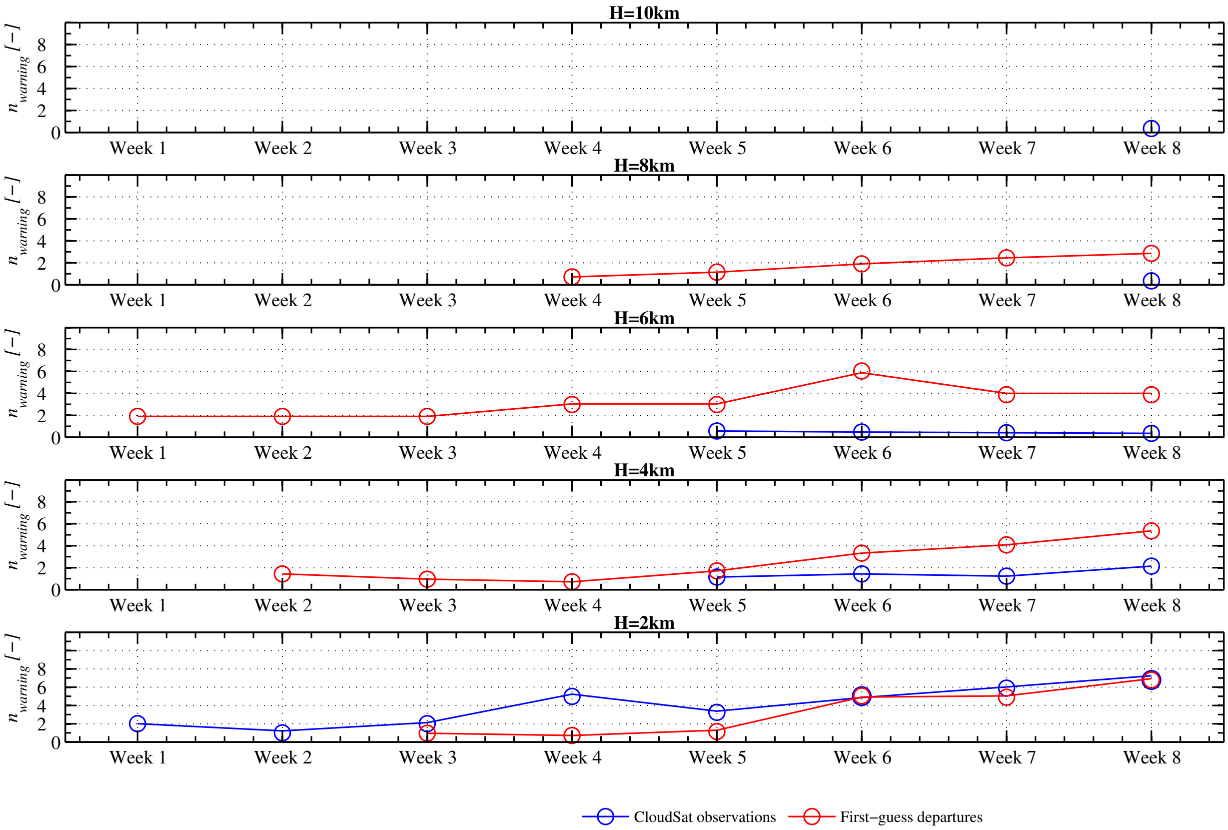

Figure 2.3: Number of days per week with issued warning through monitoring of biased CloudSat observations. Blue line is for stand-alone observations, while red one is for FG departures. Each panels refers to the altitude level (H) shown in the title. Week 1 is the first week with introduced simulated drift.

In the case of time series of mean FG departures, the majority of observations of clouds are rejected at 2 km altitude due to applied screening. Such heavy screening is a consequence of the disagreement between simulated and observed cloud backscatter, which tends to increase at levels below the cloud top. Especially in the tropics, the lidar signal in clouds is considerably affected by attenuation, therefore errors in the attenuation due to inaccuracies in the modelled cloud profile can lead to large differences between the model and the measured attenuated backscatter.

The time series of mean FG departures for both lidar backscatter and CTH clearly show a smaller range of variation than the time series of observations alone. Also for standard deviations, monitoring FG departures is preferable to observations alone since it gives a reduction in the oscillation range, allowing the detection of smaller anomalies. This conclusion is similar to the one obtained in Di Michele et al. (2014b) for the CloudSat and suggests importance of having a model as a reference during monitoring of lidar/radar observations in clouds.

A warning system for the lidar observations has been developed based on the continuous comparison of the monitored statistics against some threshold values. The most appropriate thresholds values have been defined from the analysis of the time series (as described in Di Michele et al., 2014a; Di Michele and Janisková, 2014), distinguishing between geographical regions and seasons.

To understand if the monitoring of backscatter FG departures has some advantages in identifying glitches in the instrument compared to the observation alone, experiments have been performed for the period of three month starting on 1 December 2006 where the quality of CALIOP data has been degraded by imposing a drift in the value of the lidar calibration coefficient, decreasing it by 1% every day from 1 January 2007. A sample of the

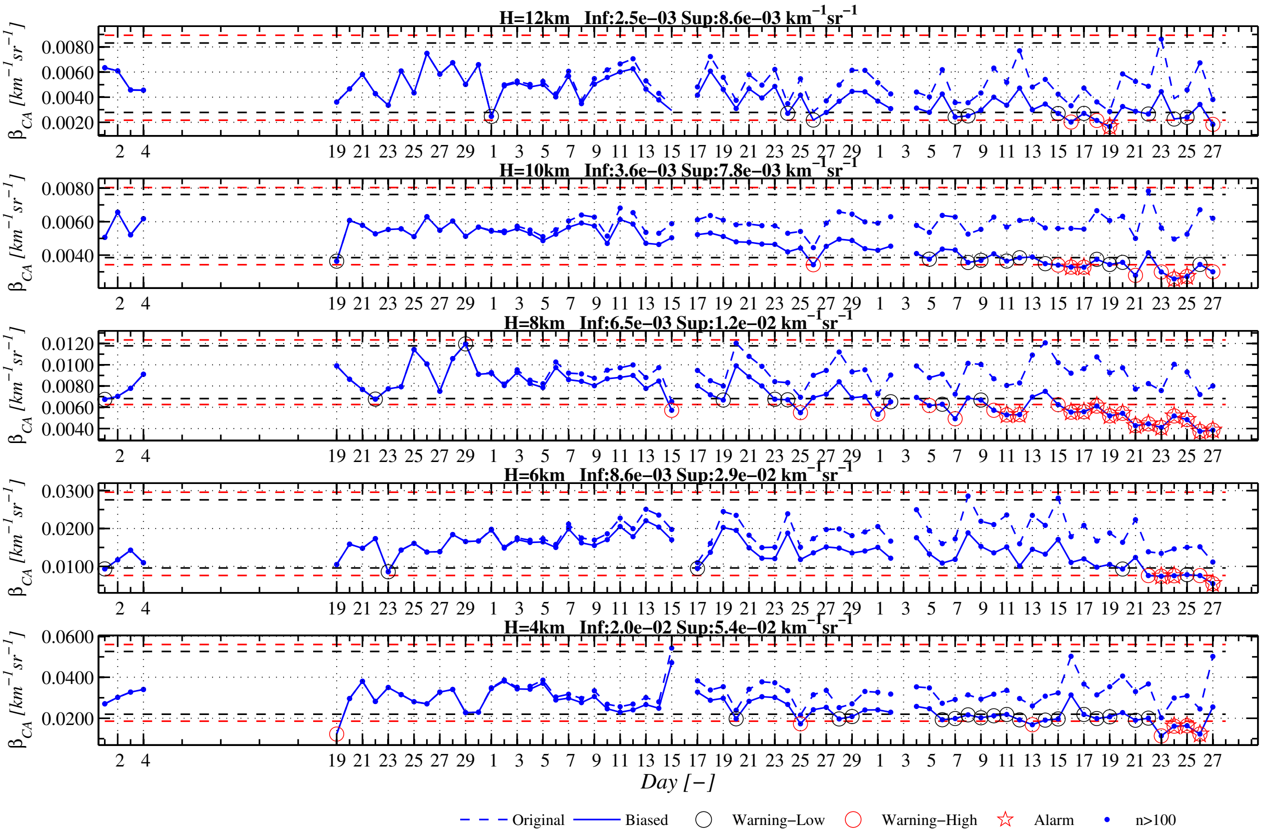

Figure 2.4: Time series of daily mean CALIOP cloud backscatter at 532 nm for the period between 1 December 2006 and 28 February 2007, considering observations at mid-latitudes South (30°S-60°S). Different panels contains data at the altitude level (H) shown in the title. Blue dashed line is for original observations, while blue solid line is for observations with artificial bias added. Horizontal lines define the limits used as warning system. See text for more explanation.

results from these experiments for Southern mid-latitudes (30°S - 60°S) is presented in Fig. 2.4 - 2.5.

Cloud backscatter monitored at five different heights, from 4 km to 12 km (every 2 km) displayed in Fig. 2.4 indicates a more pronounced drift at higher altitudes, where the backscatter usually reaches larger values. The first alarm (11 February 2007) occurs at 8 km because at this altitude the backscatter exhibits a range of variation smaller than the one at other levels. Based on time series of the mean cloud backscatter departures (Fig. 2.5), the effect of imposed bias on the CALIOP backscatter is most evident at 8 km and 10 km. Below and above this altitude range, the analysis is compromised by the low number of samples. Comparing to the corresponding time series of daily mean cloud backscatter values, there is no obvious advantage in the FG monitoring despite the fact that the FG departures from CALIOP backscatter observations have a smaller range of variation.

2.3 Conclusions and perspectives

In the radar case, the performed studies to investigate the skill of monitoring system to detect a degradation in the quality of observations have indicated that statistics of CloudSat observations are stable so that their time-monitoring can provide indications of possible drifts. The coupling with a forecast model allows for earlier automatic detection. The monitoring of CTH FG departures is less efficient than reflectivity in identifying trends. The results from radar monitoring studies therefore suggest that monitoring of radar data can benefit from extra information brought by the forecast model when monitoring the departures of observations from the model first guess equivalent rather than observations alone.

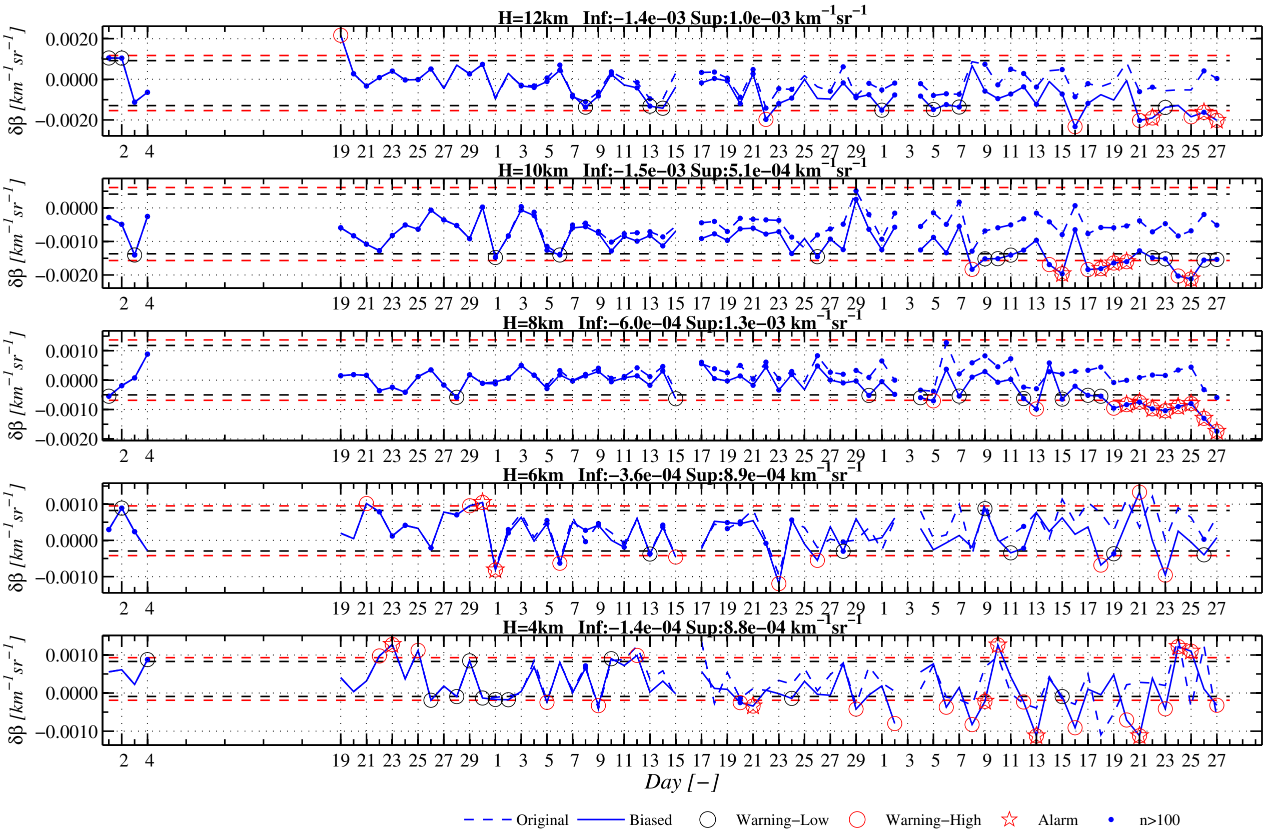

Figure 2.5: Same as Fig. 2.4, but for time series of CALIOP cloud backscatter mean first-guess departures considering observations at mid-latitudes South (30° S-60° S).

For lidar, monitoring experiments have shown that a systematic change in the lidar calibration coefficient can be detected through analysis of the temporal evolution of lidar cloud backscatter. The study has also indicated that the monitoring of the differences between observations and the equivalent quantities derived from the ECMWF forecast model does not improve the detection skill. This result can be explained with the discrepancies that the simulated cloud backscatter has compared to the CALIOP observations. Planned improvements in the description of clouds in the model and refinements to the lidar forward operator could reduce such discrepancies, thus leading to more important value of the monitoring of FG departures for data quality in the future.

3 Conclusions and recommendations from data assimilation experiments for radar and lidar

3.1 Performed studies

In order to study the impact of such new observations as cloud radar reflectivity and lidar backscatter on analyses and subsequent forecast, a technique combining 1D-Var assimilation with 4D-Var 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. The 1D-Var retrieval first run on the set of CloudSat radar reflectivity and CALIPSO lidar backscatter observations either separately or in combination to produce pseudo-observations of temperature and specific humidity, which have been then assimilated in the ECMWF 4D-Var system.

The background values have been taken from the 12-hour forecast of the ECMWF model with T799 spectral truncation (corresponding to a grid resolution of approximately 25 km) and 91 vertical levels. The forecast results have been stored every half an hour in order to use observations in 1D-Var in a similar way as in the operational 4D-Var system where all observations are split into half-hour time slots. 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 for the selected situations have been averaged to the model resolution mentioned above before being assimilated by the 1D-Var system (Janisková, 2014).

Several 1D-Var experiments have been run with different setups to study the impact of the complex observation error definition, bias correction and quality control on the performance of 1D-Var assimilation. 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. Analysis increments of temperature and specific humidity have also been evaluated since they can provide information about the impact of assimilated observations on the control variables of 1D-Var system.

Several 1D+4D-Var experiments have been run over one assimilation cycle of 12-hours (i.e. the current length of 4D-Var assimilation window at ECMWF) assimilating T and q pseudo-observations retrieved from the 1D-Var with cloud radar reflectivity and lidar backscatter either separately or in combination. These pseudo-observations have been added to the full system of regularly assimilated observations by the ECMWF system. Only profiles with non-zero increments of temperature and specific humidity obtained from 1D-Var assimilation have been used in 4D-Var. Impact of added observations on 4D-Var analyses has been investigated by comparing the first-guess departures (differences between observations and the model FG) against the analysis departures (differences between observations and analysis). Verification of the performed assimilation runs has also been carried out against other assimilated observation types in 4D-Var.

From obtained 4D-Var analyses, 10 day forecasts have been run to study the impact of these new observations also on the subsequent forecasts. The comparisons have been concentrated on the forecast of specific humidity, temperature and wind.

3.2 Summary of the results

a) 1D-Var experiments

The results from 1D-Var assimilation experiments (Janisková, 2014) performed using observations of cloud radar reflectivity (**R**) and lidar backscatter (**L**), either separately or in combination (**C**), have indicated that the 1D-Var analyses get closer not only to assimilated (Fig. 3.1), but also to independent observations (Fig. 3.2).

The impact of cloud radar reflectivity is significantly larger than the impact of lidar backscatter due to clouds. Such difference in impact is obvious from Fig. 3.1 displaying differences between the root-mean square (rms) errors of the first guess departures and the rms of the analysis departures for the CloudSat radar reflectivity and the CALIPSO lidar backscatter. The largest improvement (i.e. smallest rms errors of the analysis departures) for the lidar backscatter is achieved by assimilation of the combined radar and lidar observations indicated by the positive values in Fig. 3.1b. For the radar reflectivity observations, above 13 km assimilation of the combined radar and lidar observations provides better results than using the radar reflectivity alone, below that altitude there are very small differences between these two experiments.

A general error reduction of the analysis departures with respect to the first-guess departures for all assimilated experiments is also demonstrated when using MODIS cloud optical depths as validation data. Figure 3.2 shows that the 1D-Var analyses get closer to these independent observations, though the impact of lidar backscatter is small.

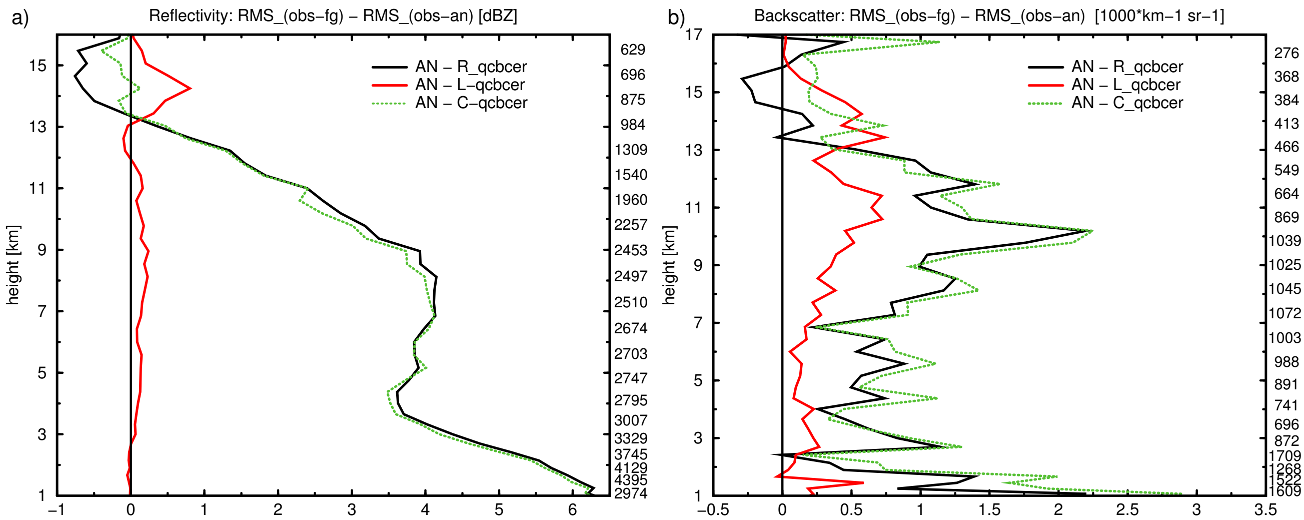

*Figure 3.1: Difference of (a) CloudSat radar reflectivity rms errors (in dBZ) and (b) CALIPSO lidar backscatter rms errors (in 1000 km^{-1} sr^{-1}) for differences between the first guess (FG) departures and analysis (AN) departures when assimilating cloud radar reflectivity (**R**, black solid line) or lidar backscatter (**L**, red solid line) either separately, or in combination (**C**, green dotted line). Numbers on the right side of (a) and (b) indicate an average number of observations considered for statistics by the different experiments for 12-hour period from 23 January 2007 21:00 UTC to 24 January 2007 09:00 UTC.*

The performed experiments have also indicated how important it is to apply an appropriate quality control, bias correction and error estimate to the used observations for an optimal 1D-Var performance. In the case of 1D-Var with the lidar backscatter, the analysis only got closer to the independent CloudSat radar reflectivity observations with a proper treatment of lidar observations.

The evaluation of temperature and specific humidity analysis increments has revealed that both increments are modified by the assimilation of cloud radar reflectivity and/or lidar backscatter. Therefore the pseudo-observations of both temperature and specific humidity profiles from 1D-Var retrievals need to be included into the 4D-Var system. Comparing to radar, the lidar increments occur at higher altitudes and are therefore complimentary. At altitudes where both radar and lidar observations are available, the increments are consistent.

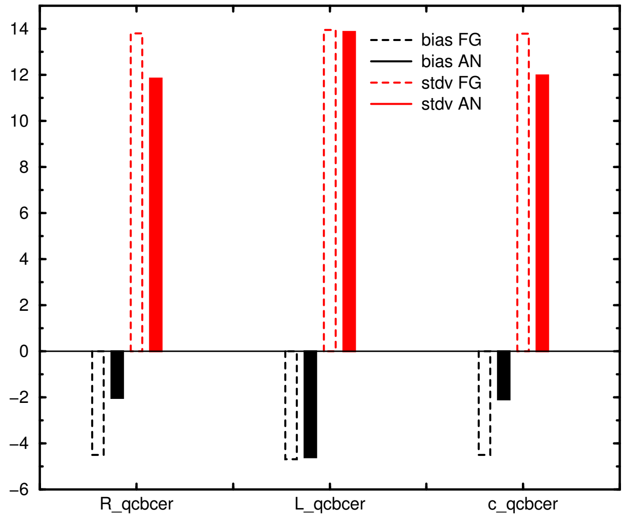

Figure 3.2: Bias (in black) and standard deviation (in red) of the FG (dashed bar) and AN (solid filled bar) departures from MODIS cloud optical depth for the same 1D-Var experiments as in Fig. 3.1. 12-hour period from 23 January 2007 21:00 UTC to 24 January 2007 09:00 UTC.

b) 1D+4D-Var experiments

The performed 1D+4D-Var experiments have shown that 1D+4D-Var reduces analysis departures for q pseudo-observations and provides analysis departures closer to T pseudo-observations than would be obtained if temperature pseudo-observations were not used. Verification of the performed assimilation runs has also been carried out against other assimilated observation types in 4D-Var. The results indicated that mainly for conventional observations (such as TEMP radiosonde, PILOT or AIREP observations) standard deviations of the analysis departures are systematically larger in the experimental runs compared to the reference run not using pseudo-observations, while bias of these departures is more comparable. This indicates that the new cloud related observations bring more variability into the system which may be related to the fact that clouds often represent small scale features. Small, but systematic improvements coming from the lidar observations when combined with the radar have also been noticed. For all other types of observations assimilated in 4D-Var, no significant changes have appeared when considering observation-minus-background and observation-minus-analysis departure statistics. It should be mentioned that achieving a significant improvement between the experimental runs and the reference run over a domain well covered by a large amount of other measurements is not easy. Therefore any improvement is encouraging since it indicates a potential benefit from assimilating cloud information.

The impact on the subsequent forecasts started from the 1D+4D-Var analyses obtained by assimilating pseudo-observations retrieved from the cloud radar and lidar observations over the whole 12-hour assimilation window has also been assessed. An evaluation has been done by considering differences in rms between experimental forecast errors and the reference forecast errors with respect to the operational analysis. The experimental forecasts start from analysis created by 4D-Var assimilation of T and q retrieved from the 1D-Var of either cloud radar reflectivity separately or in combination with the lidar backscatter. The reference forecasts start from the operational analysis. Zonal means of these rms error differences (i.e. *rms(FC_exp - AN_oper) - rms(FC_ref - AN_oper)*, where *exp* indicates experimental run, *ref* reference run and *oper* indicates operational analysis) have been assessed. The comparisons have been done for specific humidity, temperature and wind. The zonal mean of error differences from the experimental run with the radar are presented for 12- and 24-hour forecasts in Fig. 3.3 to show how the signal of reduced, resp. increased, rms errors from the experimental run with the radar propagates in time. Generally, rms errors are reduced in the experimental runs compared to the reference run. They are mainly reduced in the zonal band between 30°N and 30°S for specific humidity and temperature, while error reductions for wind are more scattered in space and time. The rms error reduction is also demonstrated in Table 3.1 providing rms errors over the whole globe for the forecasts up to 48 hours from the reference and from the experimental runs using T and q pseudo-observations over 12-hour assimilation window coming from 1D-Var of the cloud radar reflectivity alone or combined with the lidar backscatter. Even though the positive impact of the new assimilated observations on the subsequent forecast decreases in time, it is still noticeable up to 48-hour forecast. This indicates a potential benefit from the assimilation of cloud information in a 4D-Var system.

	specific humidity			temperature			wind		
	T+12	T+24	T+48	T+12	T+24	T+48	T+12	T+24	T+48
RMS (FC_ref - AN)	0.6392	0.7692	0.8684	1.8305	2.3053	2.8800	5.3078	7.0468	8.6276
RMS (FC_R - AN)	0.6313	0.7627	0.8630	1.8113	2.2975	2.8833	5.2866	7.0325	8.6296
RMS (FC_C - AN)	0.6307	0.7629	0.8631	1.8087	2.2963	2.8832	5.2863	7.0299	8.6271

*Table 3.1: Rms errors for the differences: (***ref***) between the forecast starting from the reference analysis and the operational analysis, (***R***) or (***C***) between the forecast starting from the experimental 4D-Var assimilation using T and q pseudo-observations over the whole 12-hour assimilation window coming from 1D-Var of cloud radar reflectivity separately or in combination with the lidar backscatter and the operational analysis. Statistics is computed over 12-, 24- and 48-hour forecasts over the whole globe.*

3.3 Perspectives

The performed studies have provided indications on a potential which assimilation of cloud information from active sensors could offer. The feasibility to assimilate such observations has been demonstrated. One should mentioned that it was not obvious at the beginning that it would ever be possible to use such observations, ever less so to already hint at real benefit doing so. The achieved results triggered the desirability to use these new type of cloud observations for assimilation. Though the results are encouraging and the project provided the necessary developments and experimentation prior to the future pre-operational assimilation/monitoring of EarthCARE observation, to achieve full benefit from these observations in the operational context will still require a substantial amount of work. More experiments and statistical evaluation of the model equivalents to the observations need to be done for different situations to refine data quality control, bias correction and error definition usage. The 1D+4D-Var approach used in this project requires to define errors for pseudo-observations retrieved from 1D-Var, which are computed from the 1D-Var analysis covariance matrix. This is quite expensive for profiling observations and only affordable for non-operational application. Therefore for any future operational implementation, the use of a direct 4D-Var assimilation of cloud related observations should be considered.

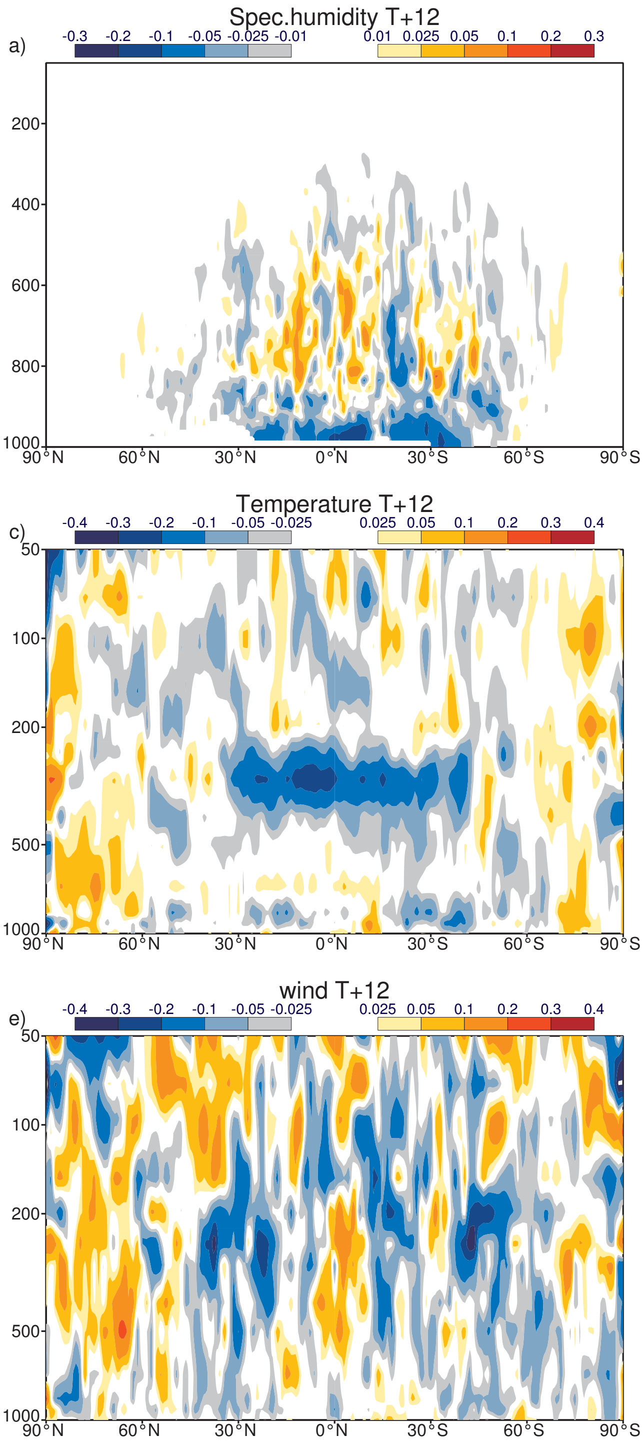

Figure 3.3: Zonal mean of differences of (a,b) specific humidity (in g.kg^{-1}), (c,d) temperature (in K) and (e,f) wind rms errors for the differences between the forecasts starting from analysis created by 4D-Var assimilation of T and q pseudo-observations retrieved from 1D-Var of cloud radar reflectivity and the operational analysis and between the forecast starting from the reference analysis and the operational analysis. (a,c,e) 12-hour and (b,d,f) 24-hour forecasts. Reduction (resp. increase) of rms errors for the experimental run is shown with blue (resp. red) shadings.

4 Recommendations for future technical and scientific developments of lidar aerosol monitoring and assimilation

4.1 Background

In the context of the project Monitoring Atmospheric Composition and Climate - Interim Implementation (MACC-II, Peuch and Engelen, 2012), there have been developments toward assimilation of aerosol lidar backscatter data from the CALIPSO satellite. The CALIPSO team, lead by Dave Winker, has made available a specific product for assimilation, called Expedited Aerosol Backscatter (Level 1.5). This product is available in quasi near real time (NRT) thanks to an expedited calibration which can be done shortly after the download of data. The lidar data are processed at 1-km resolution to take away the cloud signal, and are then averaged at a resolution of 20km which is suitable for assimilation. The standard deviation is also computed and is used as a proxy for the observation error. The native vertical resolution of the data is 60m. Initial assimilation/monitoring tests at ECMWF have lead to further processing of the data. The data currently used in the ECMWF/MACC-II 4D-Var system have a vertical resolution of 300m. Horizontal thinning is also applied, and only every other profile is considered.

The lidar forward operator is based on new more general and flexible software which has been recently developed and included within the ECMWF IFS. This code is flexible and can simulate lidar signals at the wavelengths commonly used by lidar systems (355, 532 and 1064 nm) and that is applicable to both, to ground based and space borne measurements. In the work presented here, the operator is only used for the CALIPSO 532 nm channel. The backscatter coefficients for the eleven prognostic aerosol variables included in the GEMS/MACC version of the ECMWF IFS (Morcrette et al., 2009) have been computed with a standard Mie code (Morcrette, personal communication). The lidar signal (LS) is then simulated according to Huneeus and Boucher (2007), from the mass mixing ratios of these eleven prognostic aerosols. The species included in the current version of the aerosol system are sea salt (three size bins), desert dust (three size bins), organic and black carbon in their hydrophilic and hydrophobic types, and sulphate. The tangent linear and adjoint of the observation operator for aerosol lidar backscatter (required when variational assimilation technique is used) was developed by Olaf Stiller in the context of the ESA-funded project QuARL (Janisková et al., 2010). The aerosol system also includes assimilation of Aerosol Optical Depth (AOD) from the MODIS Dark Target AOD retrievals at 550 nm (Benedetti et al., 2009). Tests have been performed to asses the impact of the joint assimilation of profiling data from CALIPSO and MODIS data. A brief description of the results is provided below.

4.2 Results of the assimilation tests

The ingestion of the lidar data in the ECMWF's 4D-Var system has required several technical changes. This included the vertical interpolation of the aerosol model data to the lidar levels which was a new development with respect to the assimilation of AOD which is a column-integrated quantity. Existing software has been adapted for the purpose. Initial test with the ECMWF model showed that the model was strongly biased with respect to the observed aerosol lidar backscatter. Improvements in the aerosol model, particularly those related to the dust parameterization and a correction for the lack of molecular backscattering contribution in the observation operator, have dramatically reduced this bias. The reduction in bias and standard deviation can be seen from Fig. 4.1 which shows first-guess and analysis departures (observations minus model) of aerosol lidar backscatter for two lidar experiments with the old and the new model cycle. Besides model changes, more specific assimilation changes were also implemented: (*i*) the vertical averaging of the lidar data to 300 m vertical resolution; (*ii*) the screening of the data at upper levels when the bias is large, possibly due to model inaccuracies in the molecular backscatter and/or in stratospheric aerosol representation; (*iii*) a preliminary level-by-level bias correction, based on the first guess departures and computed using the online estimator available in the ECMWF's 4D-VAR; and (*iv*) the implementation of a simple parameterization for the representativeness error as a function of height with increasing error toward the surface to express that the CALIPSO data are less representative due to the increase in attenuation by the atmospheric column. No provision for the horizontal representativeness error was made in the current test experiments.

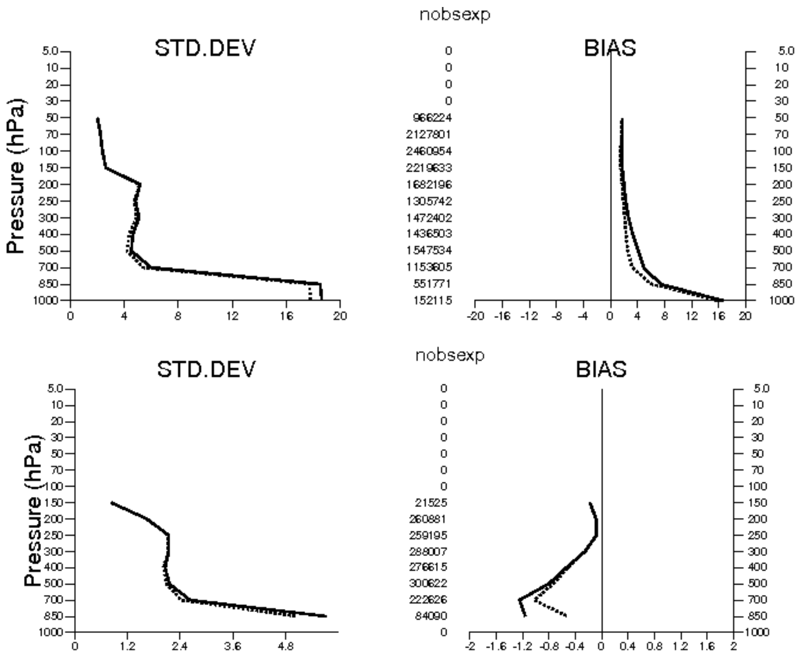

Figure 4.1: First guess (solid line) and analysis (dotted line) departures of aerosol lidar backscatter for the old model cycle (upper panel) and the new model cycle (lower panel). The units are $sr^{-1}km^{-1}$ multiplied by a factor of 10^7. Departures shown here are time-averaged over 10 days from March 22 to April 2, and spatially averaged over the Southern Hemisphere.

Preliminary verification of the impact of the lidar data on the aerosol system has been performed using global ground-based observations of AOD from the AERONET stations, and the MPLNET ground-based lidar at Sede Boker. The control experiment assimilates MODIS only, while the lidar experiment also assimilates CALIPSO measurements. Verification with AERONET AOD data only shows a benefit of the lidar data in areas such as deserts, where MODIS Dark Target data are lacking, while globally the experiment with MODIS only data performs better. However, the aerosol extinction profiles are in better agreement with the ground-based lidar observations for the experiment which included also the lidar data as shown in Fig. 4.2 and 4.3. This result is, at the moment, qualitative, as more statistics from different sites are needed to assess the impact of the CALIPSO data on the aerosol profiles in a significant manner.

4.3 Preliminary conclusions and recommendations

The technical implementation of the aerosol lidar assimilation in the ECMWF/MACC-II system has been demonstrated using CALIPSO aerosol level 1.5 data. From the scientific point of view many open questions still remain, related in particular to the error characterization of the lidar operator (representativeness error) and of the CALIPSO level 1.5 observations. More attention is also needed for the bias correction. Finally model improvements are also needed to ensure that the first-guess bias with respect to the observations is minimal. It is therefore recommended that more effort be devoted to the aerosol assimilation activities, especially in preparation for the upcoming ESA lidar missions Aeolus and EarthCARE.

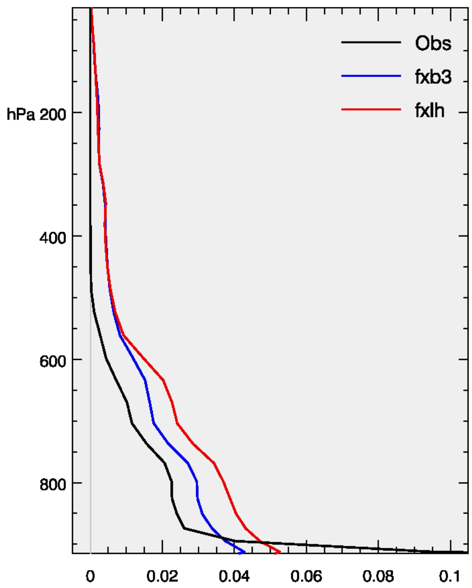

Figure 4.2: Monthly average for April 2012 of aerosol lidar extinction from the model and the observations. The control experiment with only MODIS data is denoted in red, the experiment with assimilated MODIS and CALIPSO data is denoted in blue and the observations are in black. Units are km^{-1}.

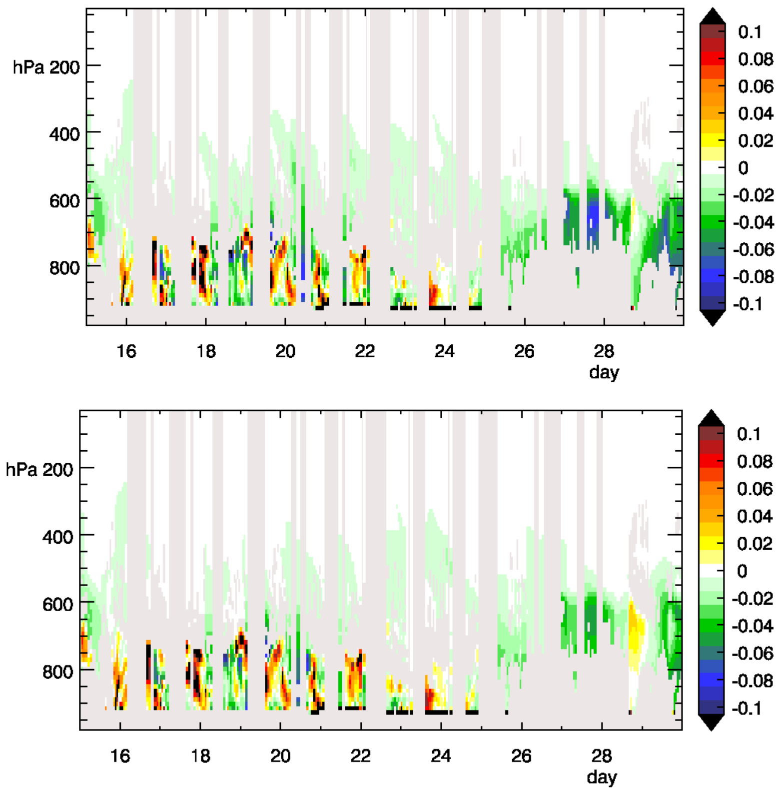

Figure 4.3: Difference between aerosol extinction from the MPLNET lidar and: the MODIS baseline (top panel) or MODIS+CALIPSO (bottom panel) experiments for the month of April 2012 at Sede Boker, Israel.

5 Summary of required work for possible operational monitoring/assimilation of EarthCARE radar and lidar observations

During the current project, whose main outcomes are summarized in Sections 2 and 3, the focus was concentrated on preparing off-line data assimilation and monitoring systems to exploit combined space-borne lidar and radar cloud observations for their assimilation in NWP models. The project thus provided necessary developments and experimentations important for further work towards preparation for the future pre-operational assimilation/monitoring of the EarthCARE observations. The future activities should focus on direct (in-line) data assimilation and monitoring systems.

As suggested by conclusions from the performed assimilation experiments (WP-3200, Janisková, 2014), direct assimilation of the radar and lidar cloud observations into 4D-Var should be developed. A beneficial additional activity would be a quality monitoring system against a global NWP model, which is an important step before any observations are assimilated into 4D-Var. This will require adjustments of assimilation related tools previously developed, such as quality control, data screening, bias correction and observation error definitions (namely, representativity and forward operator errors). A brief summary of the work required to prepare the system for the direct assimilation/monitoring of cloud radar and lidar data include:

- basic data handling, i.e. conversion of data to BUFR format used generally for assimilation/monitoring of observations;
- preparation of observation database (ODB) for the new observation types;
- first guess check and quality control;
- incorporating observation operators for radar reflectivity and lidar backscatter in the system of the global model;
- technical testing of the above development;
- bias correction built in the system;
- refining statistics for error definition;
- including observation error definition in the system;
- basic scientific testing of correctness of the system.

6 Brief analysis of possible benefits and required work for assimilation of EarthCARE MSI observations

The Multi-Spectral Imager (MSI) instrument has seven spectral bands: one visible (VIS), one near-IR (NIR), two short-wave IR (SWIR) and three thermal IR (TIR). It has a swath width of 150 km with a pixel resolution of 500m. The purpose of the MSI on EarthCARE is to provide information on the horizontal variability of the atmospheric conditions. In the context of data assimilation of the lidar and radar observations this could potentially allow characterisation of the representativity error. Representativity error arises because the NWP model can not resolve all the scales being observed by the instruments. The unresolved scales appear to the assimilation system to be an observation error, even though in reality they are not. This problem can be partially solved by scale matching, but for the EarthCARE radar and lidar this can only be done in the along track direction. The MSI can, in principle, give a more accurate assessment of the 2D variability along and across track. This would allow the assimilation system to give EarthCARE observations less weight when the 2D variability was high. In very high resolution NWP it may also be possible to assimilate the MSI observations alongside the radar and lidar. When EarthCARE radar and lidar are assimilated the information is spread by the assimilation system in four dimensions, according to the description of background error and the evolution of the linearised model. If MSI observations clearly show that there are cloud-free regions close to the EarthCARE sub-satellite track, but the radar and lidar observations are cloudy, then the MSI assimilation could constrain the assimilation system not to spread the cloud increments into the cloud-free regions. It should be noted however that the assimilation of TIR and SWIR channels for cloudy scenes is at an early stage of development, and for VIS and NIR it is even less mature. Therefore to assimilate MSI observations would require significant new development, both in radiative transfer and assimilation capability. One aspect in favour of MSI assimilation is the very small pixel size. This will provide a larger return of completely clear and completely cloudy fields of view compared to, for example, TIR and SWIR sounders with a resolution of around 10km. Research with the larger pixel size instruments has shown that it is much easier to assimilate observations where cloud cover is 0 or 100% than partly cloudy scenes. Therefore assimilation of these observations may not prove too difficult to accomplish. However radiative transfer models designed for data assimilation, such as RTTOV and CRTM, do not yet have the capability to simulate the NIR (by day) and VIS channels. Therefore these spectral bands would require substantial effort.

Acknowledgements

The NASA CloudSat Project is kindly 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. Thanks are due to Anton Beljaars for review of this document.

List of Acronyms

1D-Var	One-Dimensional Variational Assimilation
4D-Var	Four-Dimensional Variational Assimilation
AIREP	AIRcraft Weather REPort
AERONET	Aerosol Robotic Network
ATLID	ATmospheric LIDar
AOD	Aerosol Optical Depth
BUFR	Binary Universal Form for the representation of meteorological data
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CloudSat	NASA's cloud radar mission
CPR	Cloud Profiling Radar
CRTM	Community Radiative Transfer Model
CTH	Cloud Top Height
EarthCARE	Earth, Clouds, Aerosols and Radiation Explorer
ECMWF	European Centre for Medium Range Weather Forecasts
ESA	European Space Agency
FG	First Guess
GCM	Global Circulation Model
GEMS	Global Environment Monitoring System
IFS	Integrated Forecasting System of ECMWF
IR	infrared
LS	Lidar Signal
MACC-II	Monitoring Atmospheric Composition and Climate - Interim Implementation
MODIS	Moderate Resolution Imaging Spectroradiometer
MPLNET	Micro-Pulse Lidar Network
MSI	Multi-Spectral Imager
NASA	National Aeronautics and Space Administration
NIR	near-IR
NRT	Near Real Time
NWP	Numerical Weather Prediction
ODB	Observation DataBase
PDF	Probability density function
QuARL	Quantitative Assessment of the operational value of space-borne Radar and Lidar measurements of cloud and aerosol profiles
rms	root-mean square error
RTTOV	Radiative Transfer model for TIROS Operational Vertical Sounder
SMOS	Soil Moisture and Ocean Salinity mission
SWIR	short-wave IR
stdv	standard deviation
STSE	Support-to-Science-Element
TIR	thermal IR
TIROS	Television Infrared Orbiting Satellite
VIS	visible
Z	Radar reflectivity
ZmVar	Z (reflectivity) Model for Variational assimilation of ECMWF

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