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Assimilation of cloud radar and lidar observations towards EarthCARE

Marta Janisková, Peter Bauer

Active satellite instruments provide a three-dimensional characterization of clouds and thus promise new information about the vertical structure of clouds for the benefit of numerical weather prediction (NWP). Observations from CloudSat and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) are already available and new missions, such as EarthCARE (Earth Clouds, Aerosol and Radiation Explorer), will be launched in the near future (Box A). Whether information on clouds extracted from such data can be beneficial for NWP analyses and forecasts has been studied at ECMWF.

Assimilation experiments for cloud radar and lidar observations have been performed at ECMWF using a two-step technique which combines one-dimensional (1D-Var) with four-dimensional variational (4D-Var) data assimilation. The principle of 1D-Var is similar to that of 4D-Var, but only single column model data is used and the time dimension is not included. 1D-Var searches for the optimal model state that fits as closely as possible assimilated observations and the first-guess model data taken from the short-range NWP forecast valid at the time of assimilation. The 1D-Var retrieved model states are then used in a certain form (either as vertically-integrated quantities or vertical profiles themselves) as pseudo-observations to be included in the 4D-Var system together with other regularly assimilated observations.

In this two-step approach (see Box B for more details), 1D-Var assimilation on its own can already provide very useful information about the potential of assimilating new observational data. This was, for instance, demonstrated in preparation for the assimilation of cloud and rain-affected microwave radiometer observations.

Between 2005 and 2009, the 1D+4D-Var technique was used operationally for the assimilation of rain-affected passive microwave observations at ECMWF (*Bauer et al.*, 2006; *Lopez & Bauer*, 2007). Experimentally, it was also applied in first assimilation attempts with space-borne cloud radar observations (*Janisková et al.*, 2012). More recently, this experimentation has been extended to the combination of cloud radar and lidar observations (*Janisková*, 2014).

In this study, pseudo-observations of temperature and specific humidity retrieved from 1D-Var were assimilated in the ECMWF 4D-Var system to assess the impact of radar and lidar observations on the analyses and subsequent forecasts. The results from these experiments have shown that 1D-Var analyses fit both assimilated and independent observations better than the first guess, suggesting that the assimilation is able to produce a more realistic state of atmosphere and clouds when radar and lidar observations are available. However, it was found that the impact of cloud radar reflectivity observations is larger than that of lidar backscatter data since the lidar mostly constrains the cloud top while radar observations provide information on the entire cloud column. The 1D+4D-Var assimilation experiments have indicated a positive impact of the new observations also on the subsequent forecasts. Selected results from this encouraging study are presented here, demonstrating the great potential of this new data.

1D-Var assimilation of cloud radar and lidar observations

A number of 1D-Var experiments have been performed using observations of cloud radar reflectivity from CloudSat and cloud lidar backscatter from CALIPSO, either separately or in combination. Observations have been averaged over model grid-boxes. Observation error definition, quality control and bias corrections have been applied as described in Box B. The performance of 1D-Var has been verified against independent observations which were not assimilated, such as MODIS cloud optical depth retrievals (at reference wavelength of 550 nm) or radar reflectivity and lidar backscatter when these were not assimilated.

Here results are presented for a single satellite track from 23:50 UTC on 23 January to 00:26 UTC on 24 January 2007 crossing the Pacific Ocean from 62°N to 62°S, and for multiple tracks recorded over a 12-hour period from 21:00 UTC on 23 January to 09:00 UTC on 24 January 2007 corresponding to the full length of the 4D-Var assimilation window. The single track covers a variety of meteorological situations (e.g. tropical convection and an extratropical cyclone in the northern hemisphere) while the multiple-track experiment represents global cloud variability.

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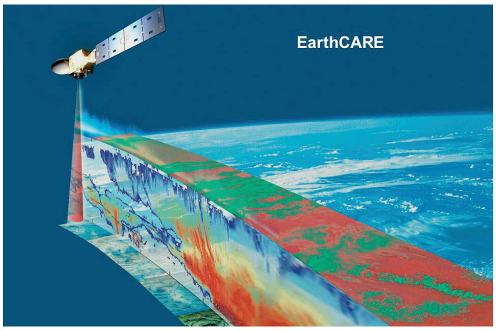
From CloudSat and CALIPSO to EarthCARE

A

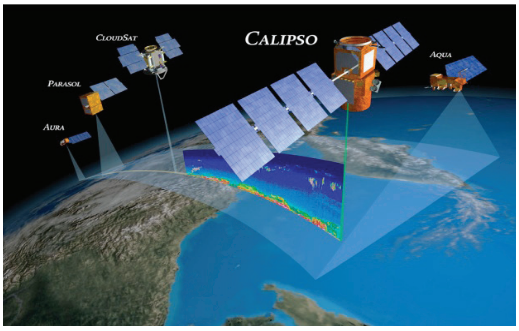
The objective of the joint ESA-JAXA EarthCARE mission is to make global observations of clouds, aerosols and radiation. Cloud and aerosol processes play a crucial role in the global energy budget and their accurate representation in models is one of the top priorities in climate change prediction. The satellite will carry two active instruments, namely a high-resolution atmospheric lidar (ATLID) and a Doppler radar (cloud-profiling radar, CPR), and two passive instruments, a scanning multispectral imager (MSI) and a broadband radiometer (BBR).

For EarthCARE, vertical profiles of aerosol and thin cloud properties will be derived from lidar observations while profiles of thicker clouds and precipitations will be obtained from the radar. A multispectral imager will provide cloud and aerosol information in the direction perpendicular to the lidar and radar measurements, and a broadband radiometer will measure the outgoing reflected solar radiation and the emitted thermal radiation from Earth. The great asset of the EarthCARE mission is that the combination of these observations will permit cloud and aerosol properties to be quantitatively linked to radiation. EarthCARE is planned for launch in early 2018 with a three-year nominal lifetime.

The enormous benefit of combined lidar and radar observations from space has been demonstrated by the US CloudSat and CALIPSO missions, which are part of the so-called A-train with its core satellite Aqua launched in 2002. The A-train comprises several satellites that fly in a sequence to provide quasi-collocated observations of the atmosphere. Among these are the CloudSat 94 GHz cloud-profiling radar (CPR) and the CALIPSO 532 and 1064 nm lidar that are hosted on different platforms separated by 15 seconds. Both were launched in 2006 and are still functional today. Other cloud-related observations can be derived from A-train instruments such as AMSR2 (microwave imager onboard GCOM-W1) and MODIS (visible/infrared imager onboard Aqua).



EarthCARE (courtesy of ESA).



A-train including CloudSAT and CALIPSO (courtesy of NASA).

A comparison was made between the simulated radar reflectivity using first-guess and 1D-Var analysis profiles with CloudSat radar observations over the Pacific Ocean. The 1D-Var analysis (Figure 1c) is closer than the model first guess (Figure 1b) to the observations (Figure 1a) for most of the profiles. However, one can notice that convective clouds between 8°N and 8°S are only weakly modified and remain close to the first guess. This is due to large representativity errors assigned to the observations in areas of convection since the observations only sample a small sub-set of cloud variability.

Results from the 1D-Var assimilation of CALIPSO lidar observations (Figure 2c) for the same track indicate that the analysis fit to observations (Figure 2a) is only marginally better than that of the first guess (Figure 2b). This is partly related to the small observed field of view, which again produces large representativity errors reducing the weight given to these observations in the analysis. When a combination of cloud radar reflectivity and lidar backscatter data is used in 1D-Var (Figure 2d) the analysis also has a better fit with cloud lidar backscatter observations, indicating that the lidar data alone provides a weaker constraint on the analysis than the combined observations.

The 1D-Var assimilation performance shows that the analyses also produce a better fit to independent observations. Again, the impact of lidar backscatter data is smaller than that of cloud radar reflectivity. This is shown by comparing the root-mean-square (rms) error differences between the first-guess and analysis departures for both CloudSat radar reflectivity (Figure 3a) and CALIPSO lidar backscatter (Figure 3b) for the

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full 12-hour period. A comparison of the first-guess and analysis departures for independent MODIS cloud optical depth data is shown in Figure 3c, indicating that the analyses get closer to these observations for all assimilated experiments with the smallest improvement when assimilating cloud lidar backscatter alone.

Analysis increments for temperature and specific humidity have been evaluated because they can provide information about the impact of the assimilated observations on the variables that control the 1D-Var system. Generally, increments from lidar data assimilation occur at higher altitudes than those from radar assimilation and point at the complementarity of both instruments. At altitudes where both radar and lidar observations are available the increments are consistent. Both temperature and specific humidity are modified by the assimilation of cloud radar reflectivity and/or lidar backscatter data since the analysis not only modifies cloud condensates but also the related thermodynamic state. Therefore both profiles obtained from the 1D-Var retrievals need to be included in the 4D-Var system as pseudo-observations. This is an extension of the formerly operational 1D+4D-Var rain assimilation where only pseudo-observations of total column water vapour were used (*Bauer et al.*, 2006).

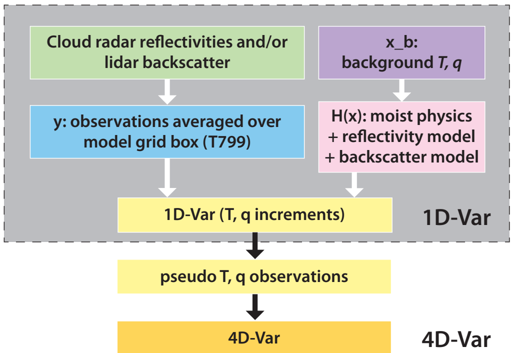
Description of the 1D+4D-Var approach

B

The diagram illustrates the work flow of the 1D+4D-Var assimilation method. In the first step, a 1D-Var retrieval is used to assimilate radar reflectivity from the CloudSat 94 GHz radar and/or 532 nm lidar backscatter from CALIPSO in order to adjust temperature and humidity profiles obtained from model short-range forecasts. To provide model equivalent to the observations, the observation operator *H* employs the physical parametrization schemes for moist processes (convection scheme and cloud scheme simulating large-scale condensation and precipitation processes – *Janisková & Lopez,* 2013) and a fast cloud radar reflectivity and lidar backscatter (*Di Michele et al.*, 2014a,b) simulator.

For a proper handling of observations in the context of an assimilation system, the definition of observation errors, an appropriate quality control methodology and a bias correction scheme are essential (*Di Michele et al.*, 2014a,b). Particularly for highly variable cloud observations observed by instruments with a narrow field of view, a suitable representativity error definition is important. This representativity error needs to be state dependent and uses a statistical approach based on probability distributions (*Stiller,* 2010).

The bias correction scheme uses temperature and altitude as predictors, and it includes dependence on geographical location and on seasons to account for the cloud variability associated with different weather regimes and cloud types.



The second step of the 1D+4D-Var approach performs the 4D-Var assimilation of specific humidity (q) and temperature (T) profiles retrieved from 1D-Var. In 4D-Var these retrievals are treated like radiosonde or dropsonde observations of the same quantities. However, they have their own error definition and quality control, but are not bias corrected. This second step allows the study of the impact of the new observations on global analysis and subsequent forecast. The observation errors for T and q retrievals (pseudo-observations) correspond to the 1D-Var retrieval errors which depend on the background error assumed for the 1D-Var control variables, the observation errors (either for reflectivity or for backscatter) and the accuracy of the observation operator used in the 1D-Var. As in *Bauer et al.* (2006), *Lopez & Bauer* (2007) or *Janisková et al.* (2012) the retrieval errors are calculated from the 1D-Var analysis error covariance matrix.

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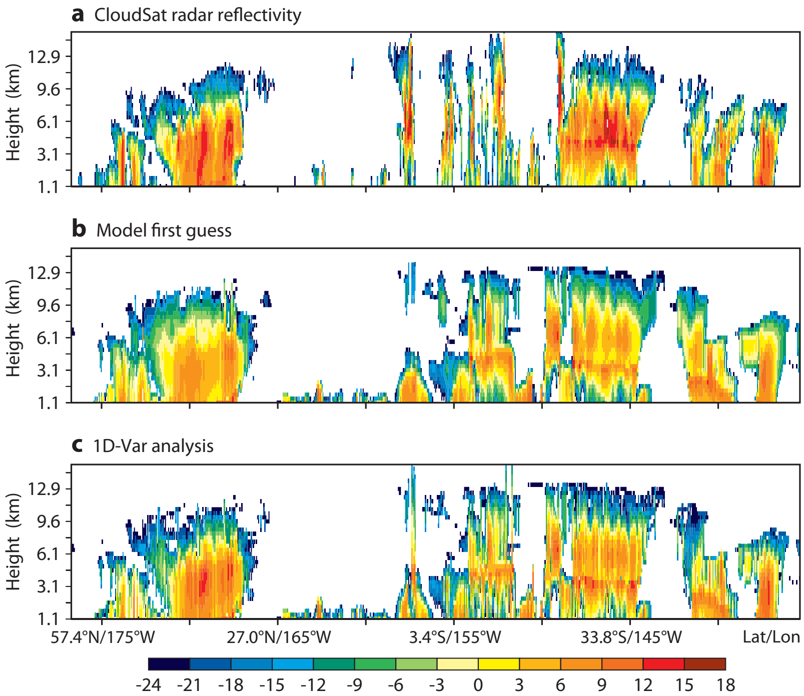


Figure 1 Cross-section of radar reflectivity (in dBZ) on 24 January 2007 over the Pacific Ocean: (a) CloudSat observations from 94 GHz radar, (b) model first guess and (c) 1D-Var analysis.

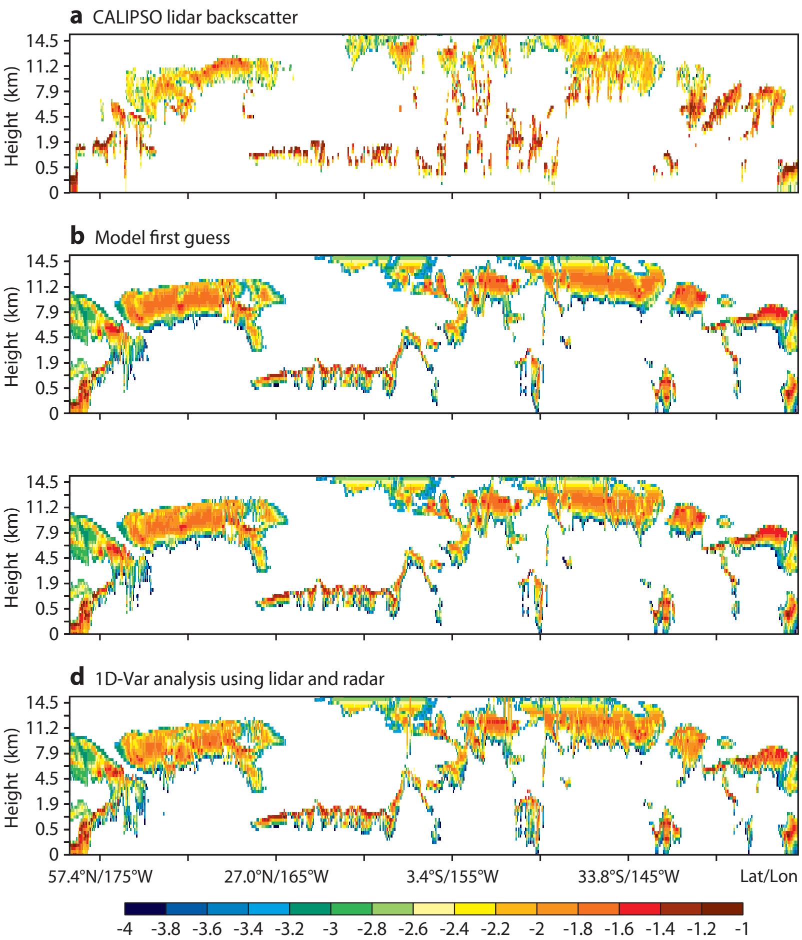
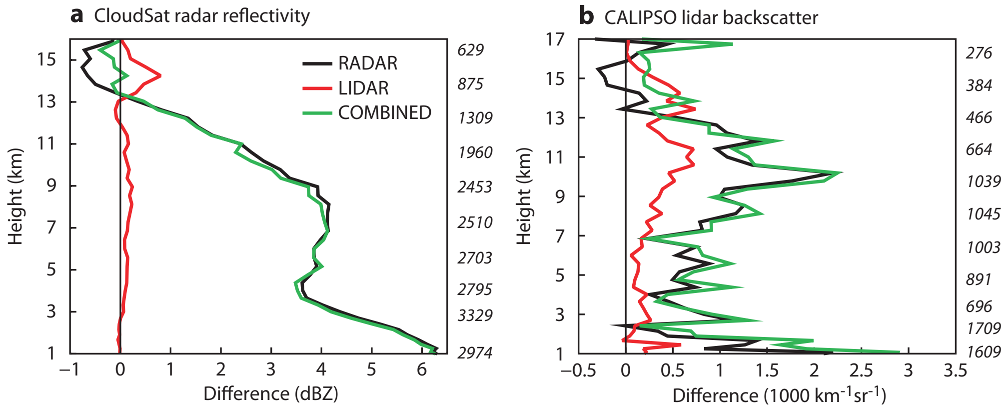


Figure 2 Cross-section of lidar cloud backscatter (in km^{-1} sr^{-1} using logarithmic scale) for the same situation as in Figure 1: (a) CALIPSO observations, (b) model first guess, (c) 1D-Var analysis using cloud lidar backscatter alone, and (d) the 1D-Var analysis using a combination of cloud lidar backscatter and radar reflectivity.



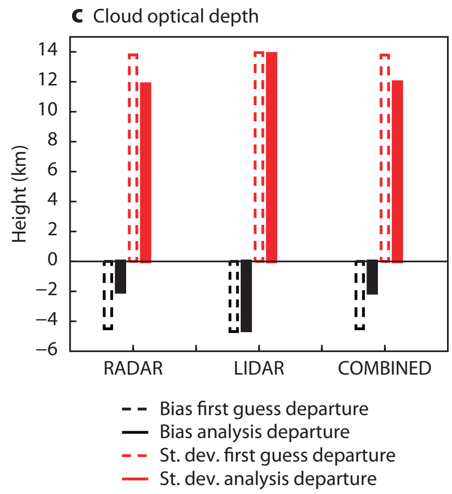


Figure 3 Difference between rms of observation minus first guess and observation minus analysis for (a) CloudSat radar reflectivity (in dBZ) and (b) CALIPSO lidar backscatter (in 1000 km^{-1} sr^{-1}) when assimilating cloud radar reflectivity (labelled RADAR) and lidar backscatter either separately (labelled LIDAR), or in combination (labelled COMBINED). Numbers on the right side of (a) and (b) indicate the average number of observations included in the statistics. (c) Bias (in black) and standard deviation (in red) of the first guess (dashed bar) and analysis (solid filled bar) departures from MODIS cloud optical depth. Results are displayed for the 12-hour period from 21 UTC on 23 January to 09 UTC on 24 January 2007.

Impact of 1D+4D-Var assimilation on analyses and subsequent forecasts

Several 1D+4D-Var experiments have been run over a single assimilation cycle of 12 hours by assimilating pseudo-observations of temperature and specific humidity retrieved with 1D-Var. These pseudo-observations have been added to the full system of regularly assimilated observations at ECMWF. From the resulting 4D-Var analyses, 10-day forecasts have been run to study the impact of these observations on subsequent forecasts.

Verification of the assimilation runs has been carried out against other assimilated observation types used in 4D-Var. The results indicate (not shown here) that, when compared against conventional observations (such as TEMP radiosonde, PILOT or AIREP observations), there is some reduction in bias of the analysis departures while standard deviations are systematically larger when CloudSat and CALIPSO data is assimilated. This indicates that the new cloud-related observations introduce variability into the system which is associated with the observations constraining the small-scale features. The small but systematic bias reduction obtained from combined lidar-radar data assimilation suggests an additional improvement of the mean model state. No significant changes were found in the statistics of satellite data departures. Achieving significant improvements with new observations over a domain well covered by a large amount of other measurements is always a big challenge. Therefore a small but beneficial impact is encouraging since it indicates an area of potential for the future role of cloud observations in NWP.

The impact on the subsequent forecasts has also been assessed. The evaluation has been performed for temperature, specific humidity and wind by considering differences in rms forecast errors between experiments and a reference run (without new observations) computed with respect to the operational analysis. Zonal means of the rms-error differences for temperature and specific humidity are shown in Figures 4a and 4c for 24-hour forecasts. Generally, errors are reduced when cloud data is assimilated. Even though this positive impact decreases quickly with time, it is still noticeable for 48-hour forecasts (Figures 4b and 4d). Assimilating data related to moist variables tends to produce little impact in the medium range because moist physical processes act on short time scales and the model effectively diffuses the initial state information.

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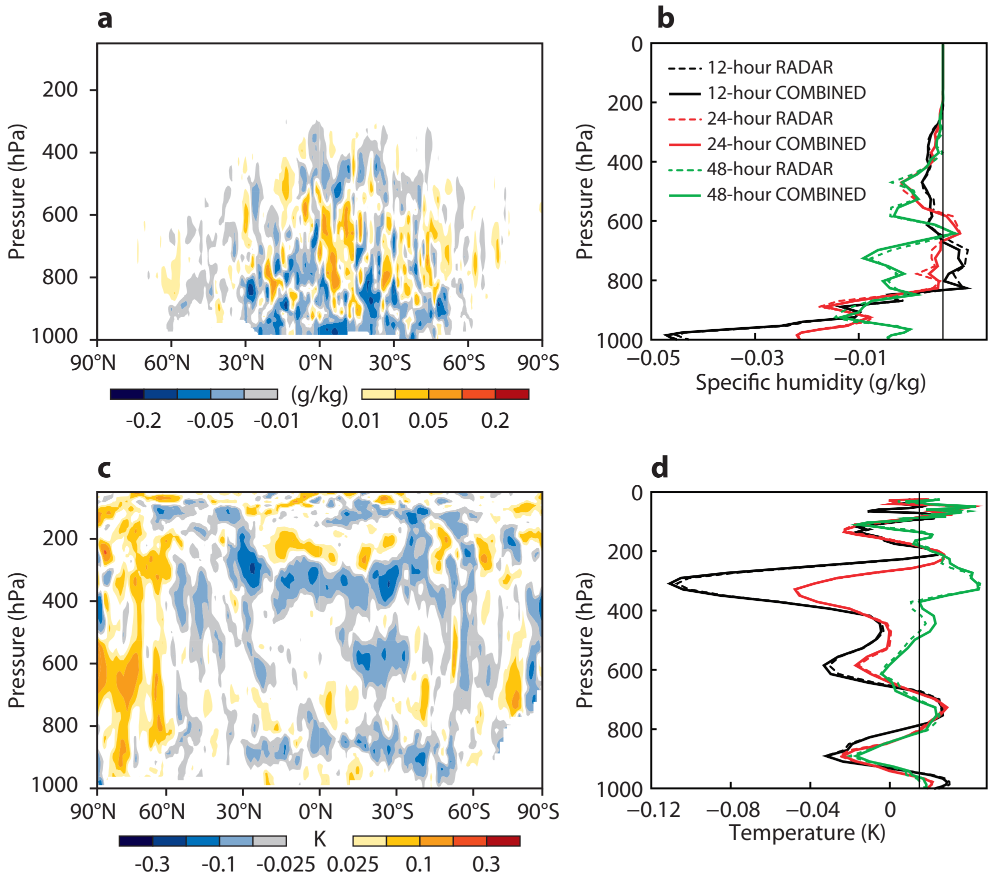

Figure 4 (a) Zonal mean of rms error difference for 24-hour forecasts of specific humidity from experiments with cloud radar reflectivity alone (reduction/increase of rms errors for the experimental run is shown with blue/red shadings). (b) The rms error difference presented as global values for 12-, 24- and 48-hour forecasts of specific humidity from experiments with cloud radar reflectivity alone (labelled RADAR) or in combination with lidar backscatter (labelled COMBINED). (c), (d) As (a), (b) but for temperature. Shown are the differences between the rms error of forecasts starting from the analysis created by 4D-Var assimilation of pseudo-observations and the rms error of forecasts starting from the reference analysis (i.e. without the pseudo-observations). The rms errors are computed with respect to the operational analysis.

Summary and perspectives

The studies described here have demonstrated the potential offered by the assimilation of cloud observations from space-borne radar and lidar instruments. Information retrieved from these observations combined with spaceborne Doppler-lidar observations could further enhance analysis quality in the tropics indicated by wind lidar observations (*ECMWF Newsletter No.137*, *Horányi et al.*, 2013). Although the feasibility of assimilating cloud radar and lidar observations has been proven but is by no means easy to accomplish. The first and foremost condition is to have a good short-range forecast of clouds which provides the first guess. The experiments suggest that the model physics used in the Integrated Forecasting System (IFS) represents clouds well enough to be able to exploit observations with spatial and physical detailed cloud information. However, there are a number of other requirements that need to be fulfilled in order to succeed. One of them is the availability of sufficiently accurate observation operators, i.e. models that enable the comparison of equivalent model fields with observations. Another requirement is the linearity and regularity of the observation operator used in the variational assimilation which is based on the strong assumption that the analysis is performed in a quasi-linear framework. Without the proper handling of threshold processes, the linearized model required for variational data assimilation can produce erroneous results as demonstrated by Janisková & Lopez (2013). In addition, for the safe handling of observations, an appropriate quality control strategy and a bias correction scheme are required. This is particularly difficult for cloud observations due to the very large dynamic range of the observations as a function of cloud states. An important aspect is that the observation error definition needs to account for the spatial representativity of radar and lidar observations with their rather narrow horizontal field-of-view.

The first results from cloud radar and lidar assimilation have been encouraging. To achieve the full benefit from these observations in an operational context, a substantial amount of work is still required.

- More experiments and statistical evaluations of the model simulations of reflectivity and backscatter need to be performed for a wider range of situations to refine data quality control and error definition.
- The 1D+4D-Var assimilation method also needs to calculate 1D-Var retrieval errors that serve as observation errors in the second stage when retrieved temperature and humidity profiles are assimilated in 4D-Var. Their computation from the 1D-Var analysis covariance matrix is expensive for profiling observations and only affordable in non-operational applications. Therefore, for any future operational implementation, the direct 4D-Var assimilation of cloud related observations will be considered.
- The observational data handling in the described experiments employed an off-line route. The next stage of these developments will therefore aim at integrating data flow and pre-processing in the path used for all operationally assimilated data. Implementing these changes means that experiments for long data assimilation periods can be performed in preparation for the future operational assimilation of cloud radar and lidar data. The completion of this step will mark the readiness level for the eagerly expected availability of EarthCARE observations.

Further reading

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