Preliminary Studies on the Variational Assimilation of Cloud-Radiation Observations Using ARM Observations

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Abstract

A linearized cloud scheme and a radiation scheme including cloud effects have been developed at European Centre for Medium-Range Weather Forecasts (ECMWF) to assimilate cloud properties in the framework of the four-dimensional variational (4D-Var) assimilation system. To investigate the potential of those schemes to modify the model temperature, humidity and cloud profiles and produce a better match to the observed radiation fluxes, one-dimensional variational (1D-Var) assimilation experiments have been carried out using data from the Atmospheric Radiation Measurement (ARM) Program. Observations for both cloud properties and surface radiative fluxes have been used in our feasibility studies. The assimilation of those observations has shown the capability of the 1D-Var to improve the analysis of temperature and specific humidity. Some weaknesses have also been identified, such as the problem of triggering clouds and the need, in some situations, for other observations to complement the surface ones.

Introduction

Current global operational data assimilation systems only account for conventional and satellite observations of pressure, temperature, wind, and water vapour. They do not explicitly include any quantity related to the condensed phase of water as cloud water, cloud ice or rain. As a result, most of the radiances are not used in the analysis because they are diagnosed as cloud- or rain-affected. Recent improvements in the representation of clouds in the models and more flexible data analysis systems (such as variational data assimilation) make investigations towards the use of observations in cloudy situations possible. A linearized cloud scheme and a linearized radiation scheme including cloud effects have been developed at ECMWF to assimilate cloud properties in the framework of the 4D-Var assimilation system (Janisková et al. 2002a). To investigate the potential of the developed schemes to modify the model temperature, humidity and cloud profiles to produce a better match to observations of surface radiative fluxes and cloud properties, 1D-Var assimilation experiments have been carried out using data from the ARM Program (Janisková et al. 2002b).

1D-Var Method

General Description

Let x be the vector representing an atmospheric column described by its temperature T, humidity q and surface pressure p_s (control variables of 1D-Var). The goal of 1D-Var is to define the atmospheric state **x** such that the distance between a background profile (short-term forecast) and observations is minimum. The minimization problem consists in finding an optimum profile **x** which minimizes the objective function:

$$\mathcal{J}(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}^b)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b) + \frac{1}{2}\sum_{i=1}^{n}\left[\frac{F_i(\mathbf{x}) - F_{oi}}{\sigma_{oi}}\right]^2$$

where **B** is the covariance matrix of background errors $\mathbf{x}^b$ is the background vector. F_{oi} represents a set of observations i (I = 1,…, n) with observation errors σ_{oi} (including errors of representativeness). $F_i(\mathbf{x})$ is an observation operator providing the model equivalent of observation F_{oi}, and superscript T is the transpose. In this study, $F_i(\mathbf{x})$ includes the shortwave and longwave radiation schemes together with the diagnostic cloud scheme. The minimum of **J** is obtained using a limited memory quasi-Newton optimization routine, requiring an estimation of the gradient of the objective function at each iteration.

$$\nabla\mathcal{J}(\mathbf{x}) = \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b) + \sum_{i=1}^{n}\mathbf{F}_i^T\left[\frac{F_i(\mathbf{x}) - F_{oi}}{\sigma_{o\,i}^{2}}\right]$$

The transpose of the tangent-linear observation operator, $\mathbf{F}^T$, has been obtained using the adjoint technique.

Observation Operator

For the assimilation of cloud properties and radiation fluxes, the observation operator consists of a cloud scheme and a radiation transfer model. Their tangent-linear (TL) and adjoint (AD) versions have been developed at ECMWF (Janisková et al. 2002a). For the short-wave radiation scheme, they were derived from the original non-linear scheme (Morcrette, 1991) without modifications. The original and much more expensive long-wave scheme is replaced by a combination of artificial neural networks (Chevallier et al. 2000) and pre-computed Jacobians of the long-wave radiation flux with respect to global mean averaged temperature and humidity profiles (Chevallier and Mahfouf 2001). The cloud scheme used here is the diagnostic scheme of Slingo (1987), in which cloud cover is quadratically dependent on relative humidity (RH), and liquid and ice water content (IWC) are proportional to specific humidity at saturation.

1D-Var computations includes the forward modeling of cloudy radiation fluxes (F operator) and the corresponding adjoint modeling $\mathbf{F}^T$ operator. In the forward modeling (Figure 1a), from the control variables T, q, and ps the cloud scheme gives the cloud cover (cc), cloud liquid water content (lwc) and cloud ice water content (iwc). All these variables are inputs to the radiation scheme, which includes the definition of cloud optical properties and the maximum-random cloud overlap assumption.

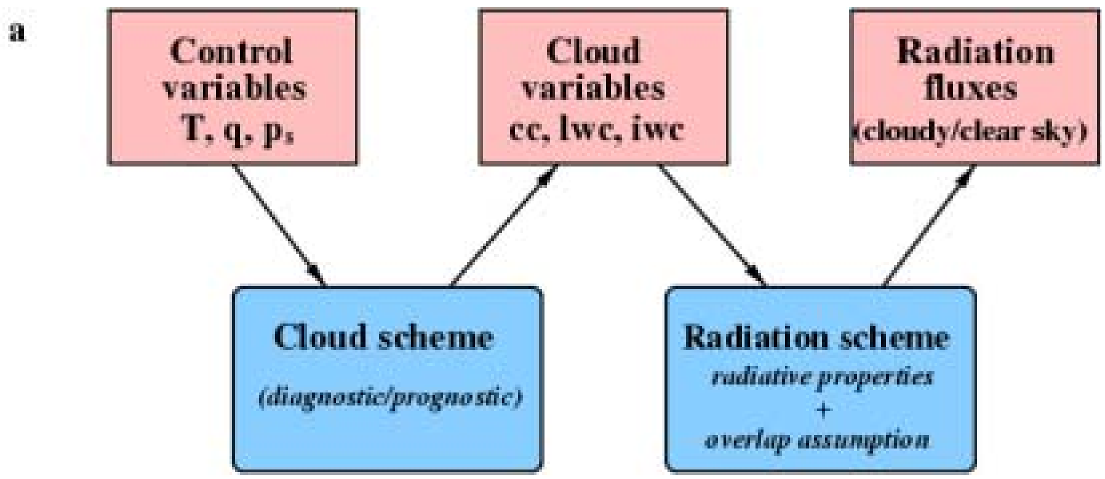


Figure 1a.

Backward computation starts from the departure of cloudy radiation fluxes (the difference between observations and background values) used as inputs to the adjoint of the radiation scheme. Integration of the adjoint scheme gives increments of the cloud variables, used as inputs to the adjoint of the cloud scheme. After its integration, the gradient of the objective function with respect to the control variables is obtained.

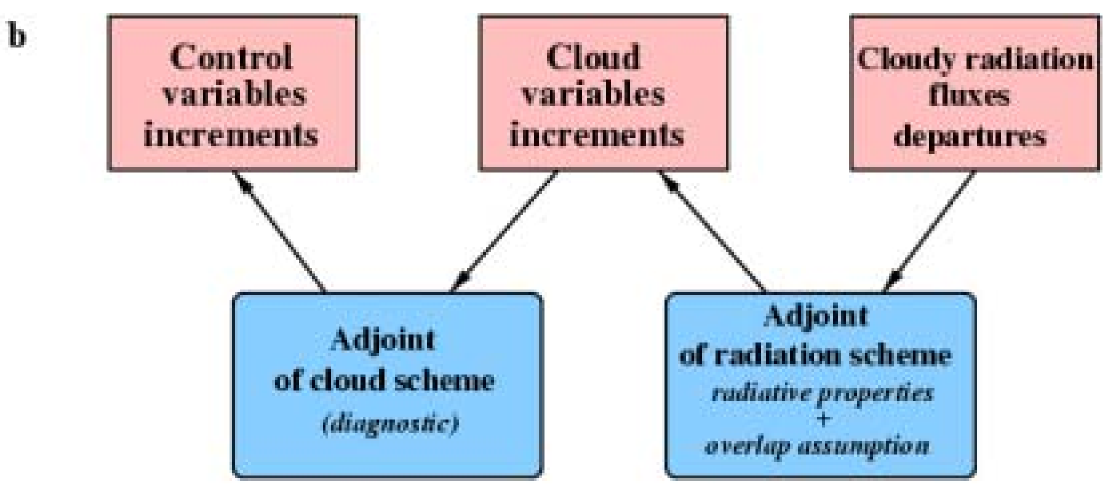


Figure1b.

Experimental Framework

The experiments used observations from the ARM South Great Plains (SGP) site over the April and May 1999 period, in particular the surface downward longwave radiation (LWD) measured by pyrgeometers, the total column water vapour (TCWV) from the microwave radiometer (MWR), the cloud liquid water path (LWP) from the MWR. Radiosoundings at Lamont provides humidity information for verification. All observations are averaged over 1 h intervals.

A set of background-temperature and specific humidity profiles and surface pressure are taken from operational 6-hour forecasts with the T_L319 L50 ECMWF forecast model. Surface pressure and the profiles of T and q together with vertical velocity, skin temperature, surface albedo, and soil moisture are used in the observation operator to calculate first the cloud properties (cc, lwc, and iwc) then the corresponding radiation fluxes. In this study, convective clouds are not considered as during the observation period, there was very little convective precipitation. Therefore most of the clouds produced by the diagnostic cloud scheme are of a stratiform nature.

The observation errors are taken as 10 Wm^{-2} for the downward LWD, as defined for the assimilation of SSM/I for the TCWV, and as 50% of the observed value for the LWP.

Results

The improvement/deterioration of the analysis with respect to the first guess after 1D-Var assimilation when using observations of the LWD at the surface (Figure 2), the TCWV (Figure 3), and the LWP (Figure 4) has been assessed over the ARM-SGP site in April and May 1999. The results are presented as differences between the absolute value of the first guess minus observations and absolute value of the analysis minus observations. The positive (negative) values then indicate an improvement (deterioration) of the analysis compared with the first guess with respect to the observations.

Though some deterioration of the analysis appears for short periods, generally 1D-Var is able to retrieve temperature and humidity profiles that provide LWD, TCWV, and LWP closer to the observations.

For an independent validation of the 1D-Var performance, the background, and analyzed profiles of temperature and humidity have been compared against radiosonde observations, which were not used for the assimilation. 1D-Var reduces both the bias and standard deviation for the RH. The results are neutral for temperature. This indicates that mainly the specific humidity representation is improved by the 1D-Var retrieval. Overall, the 1D-Var assimilation of observations from the ARM-SGP site has shown a capability to improve the analysis of temperature and specific humidity through the assimilation of surface observations. However, it has also revealed some weaknesses of 1D-Var (difficulty of triggering clouds when missing in the first-guess [or background]) and of the forward model (particularly the diagnostic cloud scheme). The need for complementary observations in some situations (e.g., profiles of liquid/IWC) has been identified as well.

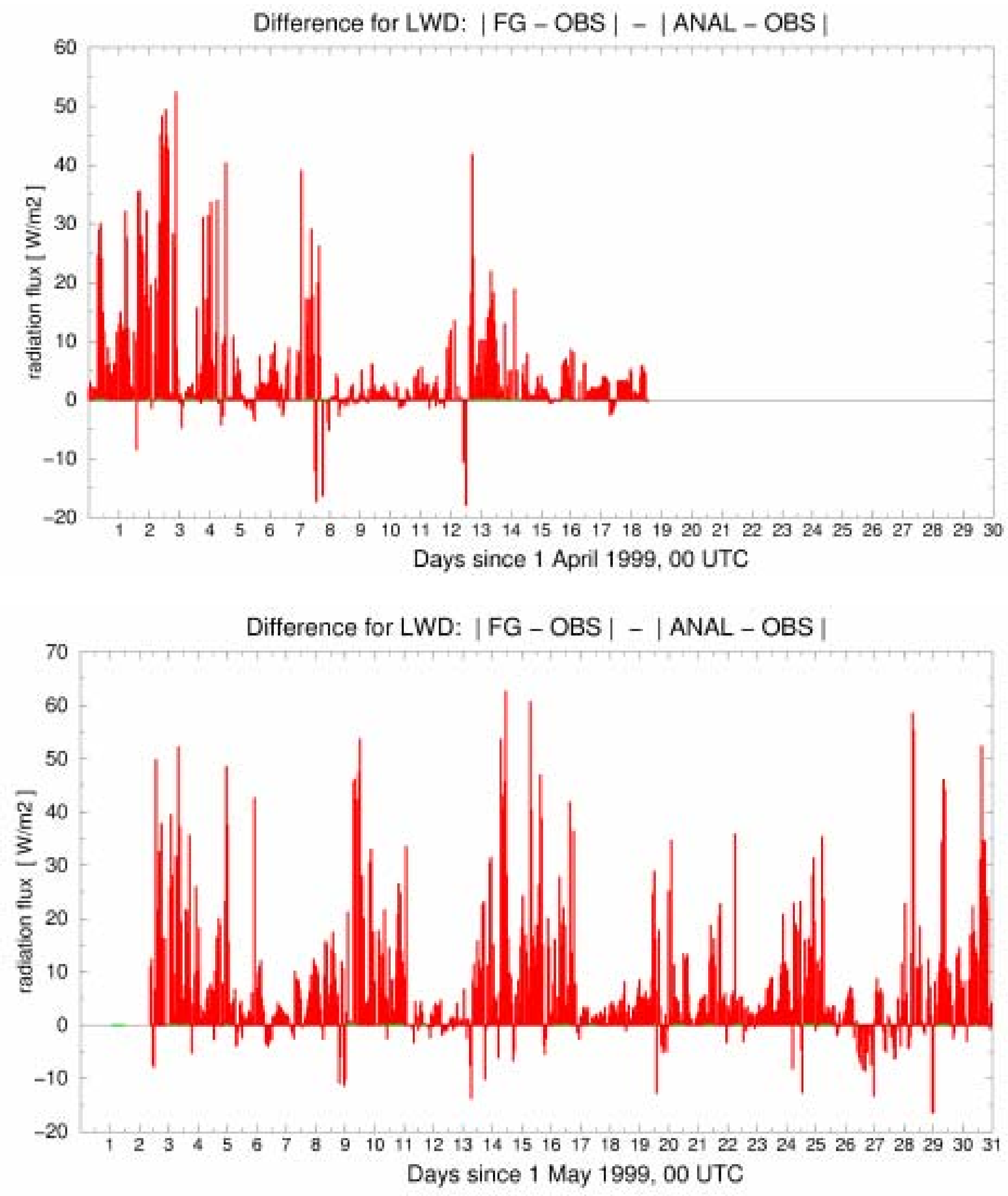
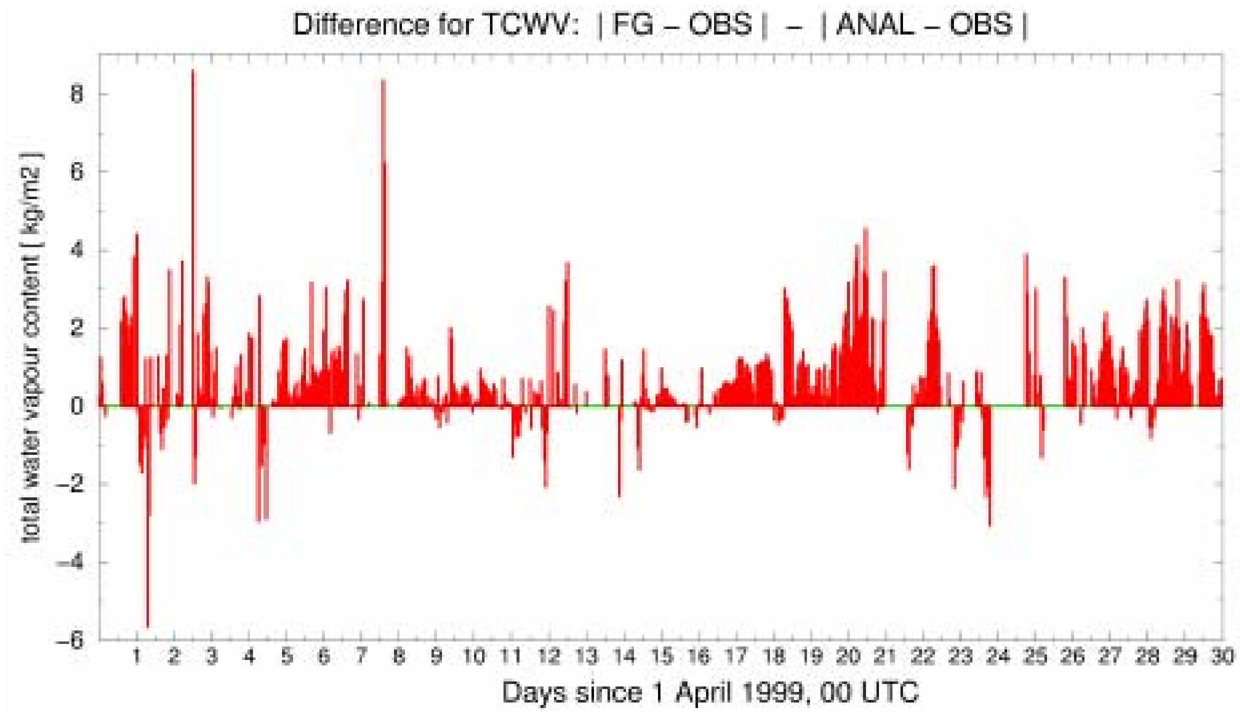


Figure 2. Improvement/deterioration of the analysis with respect to the first guess for the LWD.



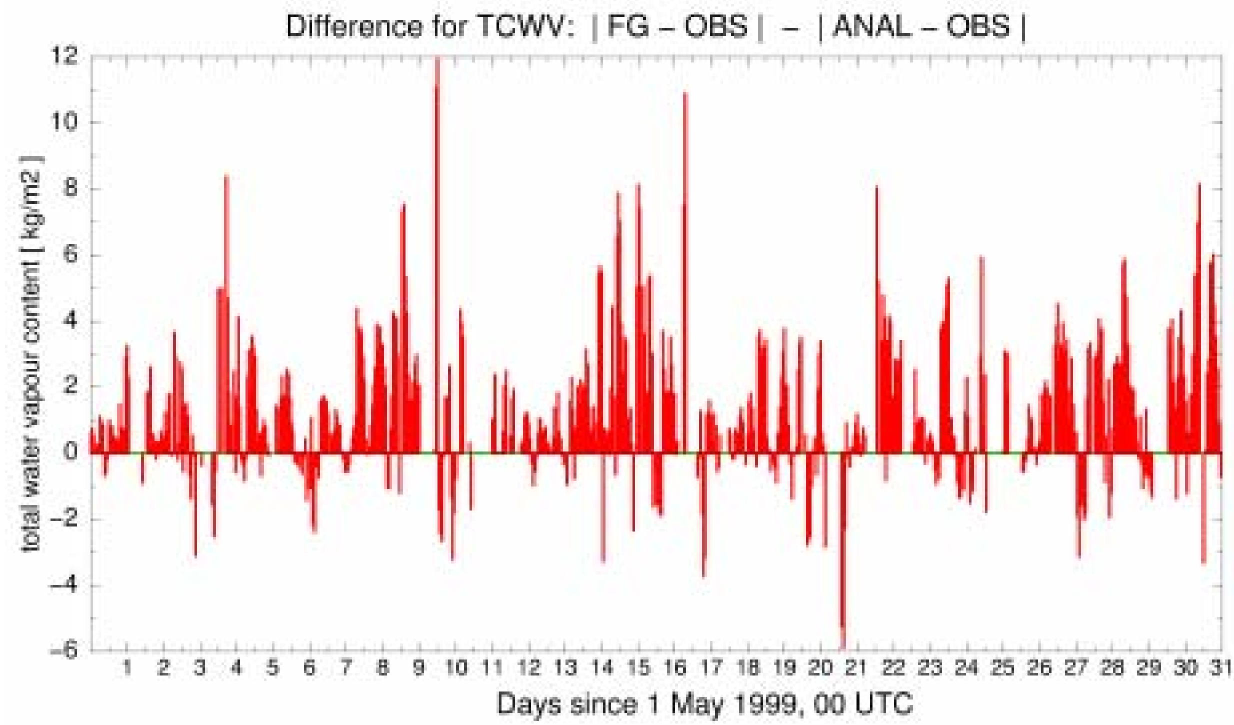


Figure 3. Improvement/deterioration of the analysis with respect to the first guess for the TCWV.

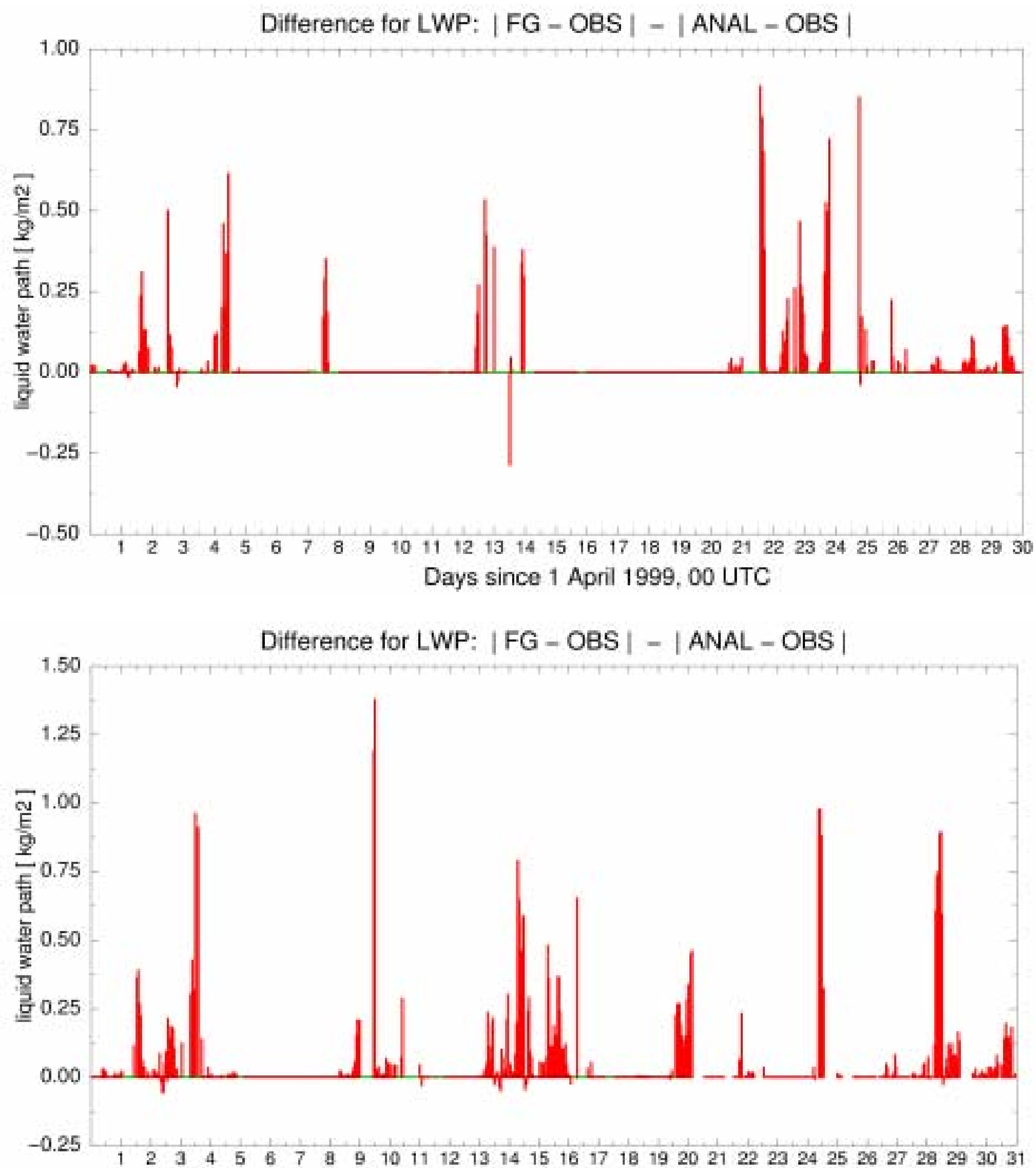


Figure 4. Improvement/deterioration of the analysis with respect to the first guess for the total cloud water.

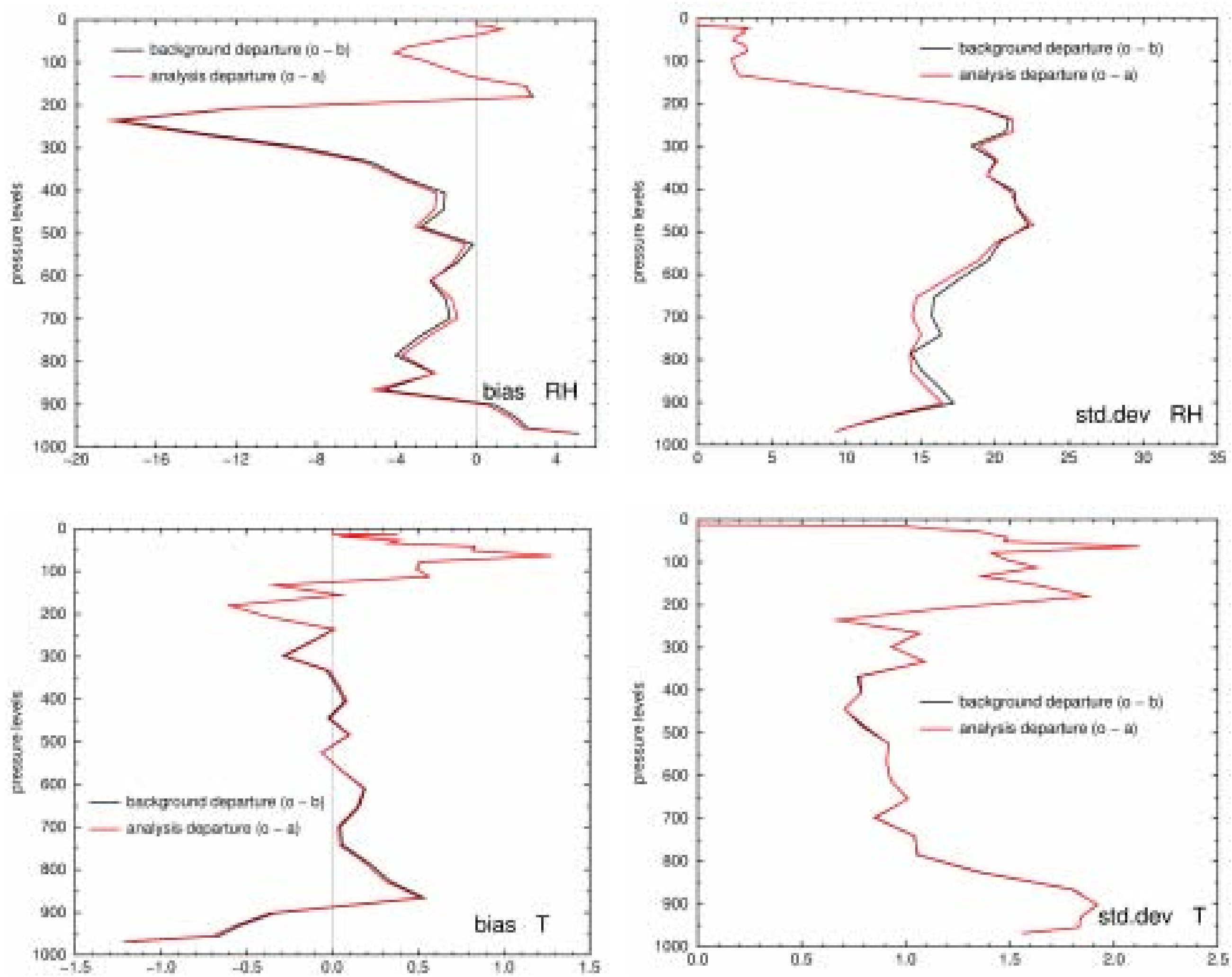


Figure 5. Mean (left panels) and standard deviation (right panels) of the difference between the background (black) or analyzed (red) RH (%) (top panels) and temperature T (K) (bottom panels) and the corresponding observations at the ARM-SGP for April 1999.

Conclusions and Perspectives

One of the questions to be answered in this study was whether it is possible to modify cloud cover significantly using the 1D-Var approach to improve the fit of the model to radiative fluxes. The assimilation demonstrated the capability of 1D-Var to improve the analysis of temperature and specific humidity. The cloud cove is improved consistently with improved radiation, TCWV and LWP.

The linearized version of the diagnostic cloud scheme used in this study has some weaknesses since there is no direct relationship between diagnosed cloud cover, water/ice and precipitation generation.

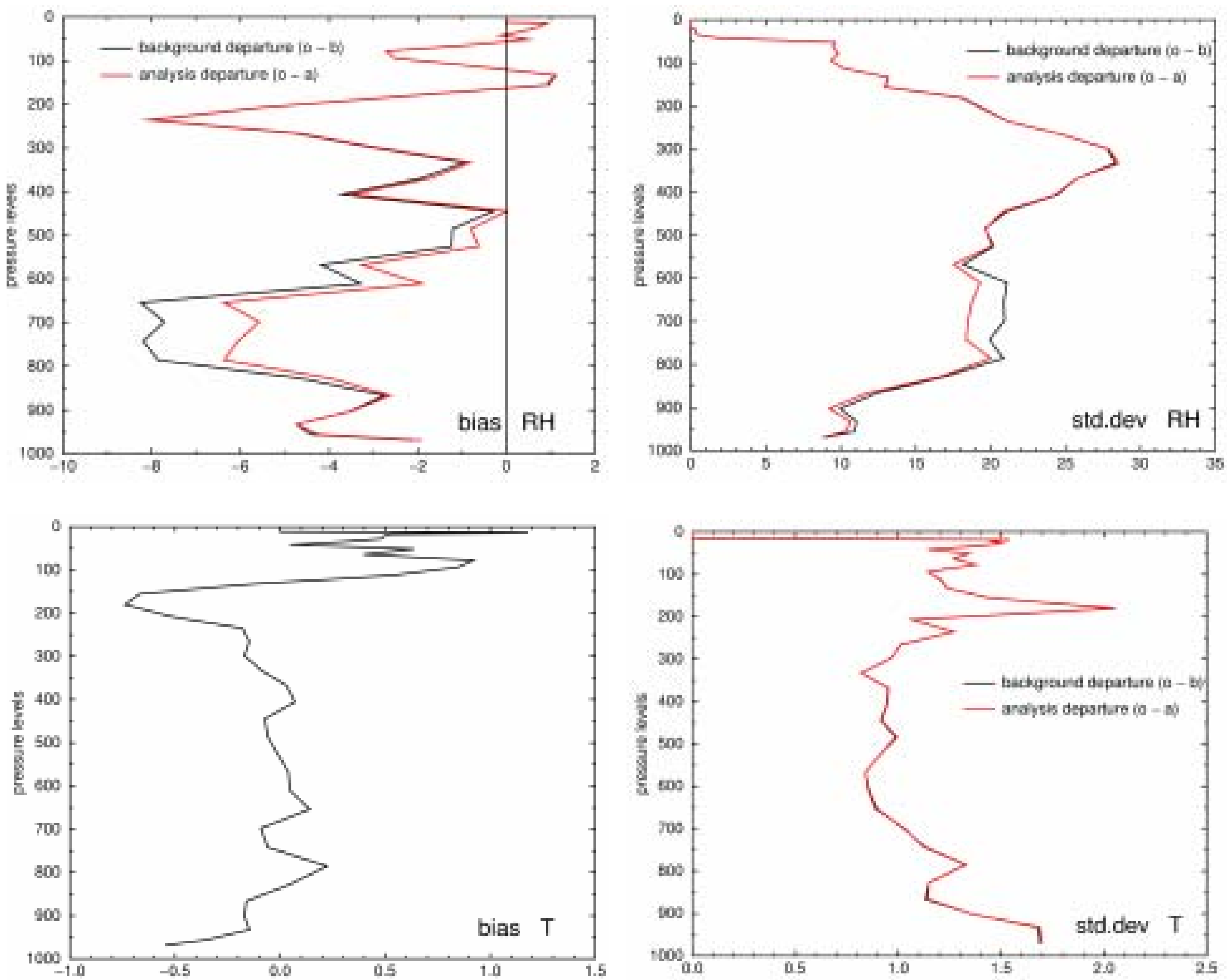


Figure 6. Same as in Figure 5, but for May 1999.

Recently, a new cloud scheme for the linearized model has been developed, which addresses these weaknesses. The scheme is based on prognostic humidity and temperature variables and a diagnostic assumption concerning subgrid variability is used to derive cloud water, ice and cover characteristics.

Feasibility studies in a 1D-Var framework are going on for situations where convective clouds are dominant. The top of the atmosphere radiation fluxes derived from geostationary satellite data (GOES-8 over ARM-SGP, GMS-5 over Manus and Nauru in the Tropical West Pacific) will also be used to further assess how cloud and radiation observations can be used for analysis purposes.

1D-Var assimilation experiments, using either observations from field experiments or from satellites represent preparatory studies for the future 4D-Var assimilation of cloud-radiation observations.

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