Linearized physics for the assimilation of cloud properties

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1 Introduction

Current operational data assimilation systems do not assimilate observations on clouds available from surface network and satellites. Thus they do not provide a direct analysis of quantities such as cloud fraction, cloud liquid and ice water content. The inclusion of cloud observations in the data assimilation should lead to an improved initial state of the model prognostic variables which could in turn improve the quality of the forecasts (two-metre temperature, cloudiness, precipitation, ...).

The 4D-Var assimilation system has been implemented in November 1997 at ECMWF (Rabier *et al.* 2000, Mahfouf and Rabier 2000). This system is flexible enough to assimilate new types of observations when a proper observation operator exists. The observation operator providing the model counterpart of cloud observations are the linearized versions of both a radiative transfer model and a cloud scheme. Their linearized versions need to be developed for use in variational data assimilation.

A linearized version of a radiation scheme, which enables cloud-radiation interactions, has been developed. The shortwave radiation is based on a linearization of the operational ECMWF code. A combination of artificial neural networks and mean Jacobian matrices has been defined for the linearized longwave radiation scheme to reduce its computational cost. For the time being, the ECMWF diagnostic cloud scheme (used before the implementation of the prognostic one) has been linearized. A simplified linearized prognostic cloud scheme is under development.

The accuracy of the linearization of both radiation and diagnostic cloud schemes are examined. To investigate the potential of radiation and cloud schemes to modify model temperature, humidity and cloud profiles to match better an observation of radiation flux, 1D-Var experiments with simulated observations are presented. Feasibility studies in a 1D-Var framework using data from field experiments providing measurements of both cloud properties and radiative fluxes (e.g. ARM,...) are being started.

2 Development of the linearized radiation and cloud schemes

Current ECMWF operational 4D-Var uses a very simplified linearized radiation code, as radiative transfer is only modelled for the longwave spectrum using a constant emissivity formulation (Mahfouf, 1999). Effective emissivity arrays are stored from the full non-linear radiation scheme. No dependency of radiation on cloudiness is taken into account in this approach. However, a proper consideration of cloud-radiation interactions requires the development of a linearized cloud scheme and a more sophisticated radiation scheme, which enables to take into account cloudiness.

2.1 The shortwave radiation scheme

The ECMWF physical parametrization uses a shortwave radiation scheme (Morcrette, 1989 and 1991) originally developed by Fouquart and Bonnel (1980). The photon-path-distribution method is used to separate the parametrization of the scattering processes from that of molecular absorption. Upward and downward fluxes at a given layer j are obtained from the reflectance and transmittance of the atmospheric layers as

$$F_{sw}^{\downarrow}(j)=F_0\prod_{k=j}^{N}\tau_{bot}(k)$$
$$F_{sw}^{\uparrow}(j)=F_{sw}^{\downarrow}(j)R_{top}(j-1)$$

Computations of the transmittance at the bottom of a layer τ_{bot} start at the top of atmosphere and work downward. Those of the reflectance at the top of the same layer R_{top} start at the surface and work upward. In the presence of cloud in the layer, the final fluxes are computed as a weighted average of the fluxes in the clear sky and in the cloudy fractions of the column as

$$R_{top}=C_{cloud}R_{cloud}+(1-C_{cloud})R_{clear}$$
$$\tau_{bot}=C_{cloud}\tau_{cloud}+(1-C_{cloud})\tau_{clear}$$

In the previous equations, C_{cloud} is the cloud fractional coverage of the layer within the cloudy fraction of the column (depending on cloud-overlap assumption).

This shortwave radiation scheme is less expensive than the ECMWF longwave radiation. Therefore the scheme has been linearized without a priori modifications.

2.2 The longwave radiation scheme

The longwave radiation scheme, operational at ECMWF up to June 2000, is a band emissivity type scheme (Morcrette, 1990). The longwave spectrum from 0 to 2820 cm^{-1} is divided into six spectral regions. Integration of the radiation transfer equation over wavenumber υ within the particular spectral regions gives the upward and downward fluxes. The incorporation of the effects of clouds on the longwave fluxes follows the treatment discussed by Washington and Williamson (1977). The fluxes for the actual atmosphere are derived from a linear combination of the fluxes calculated for a clear-sky atmosphere and those obtained assuming a unique overcast cloud of emissivity unity. In the case of cloud present in several layers, a cloud overlap assumption is defined (Morcrette and Jakob, 2000).

The complexity of the radiation scheme for the longwave part of the spectrum makes accurate computations expensive. In the assimilation framework, simplifications are required to reduce its computational cost.

The longwave radiative fluxes depend upon the prognosed temperature, water vapour, cloud cover and liquid and ice water contents. The design of the scheme allows to separate the contribution of temperature and water vapour from that of cloud parameters. More precisely, the upward and downward longwave fluxes at certain height z_i can be expressed as:

$$F(z_i)=\sum_k a_k(z_i)F_k(z_i)$$

where the coefficients a_k are function of cloudiness and overlap assumptions. A differentiation of the above equation leads to:

$$dF(z_i) = \sum_k [a_k(z_i)\, dF_k(z_i) + F_k(z_i)\, da_k(z_i)]$$

In the proposed approach, the flux perturbation is approximated by:

$$\Delta F(z_i) \cong \sum_k [\underbrace{a_k(z_i)}_{\text{NL model}}\ \underbrace{\Delta F_k(z_i)}_{\text{Jacobian matrices}} + \underbrace{F_k(z_i)}_{\text{NeuroFlux}}\ \underbrace{\Delta a_k(z_i)}_{\text{TL model}}]$$

The coefficients a_k are computed using the non-linear (NL) model (part of the operational radiation code computing cloud optical properties). Perturbations of radiative fluxes $\Delta F_k(z_i)$ with respect to temperature and water vapour are obtained using pre-computed Jacobians averaged globally (Mahfouf *et al.* 1999). Perturbations of radiative fluxes with respect to cloud parameters $\Delta a_k(z_i)$ are computed using a tangent-linear (TL) scheme. The trajectory of radiative fluxes required in tangent-linear and adjoint computations are efficiently estimated from a neural network version (called NeuroFlux) of the ECMWF longwave radiative transfer model (Chevallier *et al.* 2000).

2.3 The cloudiness parametrization scheme

For the time being, the ECMWF diagnostic cloud scheme (Slingo, 1987), used before the implementation of the prognostic scheme, has been linearized to be used with the linearized radiation schemes.

The cloud scheme allows for four cloud types: convective cloud and three types of layer clouds (high, middle and low level).

The convective clouds are parametrized using the scale-averaged precipitation rate ($\overline{P}$) from the model convective scheme. In the linearized version of the scheme, there is a simplification coming from the fact that the current linearized convection scheme does not provide perturbations of precipitation. This leads to zero perturbation of convective cloudiness.

The layer clouds are determined from a function of the layer relative humidity (RH_e) after following adjustment for the presence of convective clouds (C_{conv}) $RH_e = RH - C_{conv}$. The middle level clouds and low level clouds associated with the extra-tropical fronts are modified by a linear transition up to weak ascent using vertical velocity. There are no such clouds in subsidence areas.

Liquid water l_{lwc} and ice water l_{iwc} are proportional to specific humidity at saturation q_{sat}.

In the future, the aim is to use the adjoint of the prognostic cloud scheme (Tiedtke, 1993), in which the time evolution of cloud variables (cloud water content, cloud fraction) is directly linked to the various physical processes. Such developments are necessary not only to account for cloud-radiation interactions, but also to improve the coupling with the convection scheme for the assimilation of precipitation.

2.4 Cloud optical properties

Considering the cloud-radiation interactions, it is not only the cloud fraction or cloud volume, but also cloud optical properties that matter. In the case of shortwave radiation, the cloud radiative properties depend on three different parameters: the optical thickness δ_C, the asymmetry factor g_C and the single scattering albedo

$\overline{\omega}_C$. They are derived from Fouquart (1987) for the water clouds, and Ebert and Curry (1992) for the ice clouds.

Cloud longwave optical properties are represented by the emissivity ε_{cld} related to the condensed water amount and by the condensed water mass absorption coefficient k_{abs} obtained following Smith and Shi (1992) for the water clouds and Ebert and Curry (1992) for the ice clouds.

3 Validation of the linearized model including cloud-radiation processes

The validation of the developed linearized schemes has been done. The classical verification of the correctness of the tangent-linear model is done through the Taylor formula:

$$\lim_{\lambda \to 0} \frac{M(\mathbf{x}+\lambda\delta\mathbf{x})-M(\mathbf{x})}{M'(\lambda\delta\mathbf{x})}=1,$$

where M is a discretized primitive equation model of the atmosphere, M' is the tangent-linear model of M and $\mathbf{x}$ represents a model state at certain time. For the verification of the adjoint, one tests the identity between inner products for given $\mathbf{x}$ and $\mathbf{y}$ vectors, as

$$\forall\mathbf{x},\forall\mathbf{y} \qquad \langle M'.\,\mathbf{x},\mathbf{y}\rangle=\langle\mathbf{x},M^{*}.\mathbf{y}\rangle$$

In the above equation, the linear operator M^* is the adjoint of the linear operator M'.

Then the accuracy of the linearization of both radiation and diagnostic cloud schemes has been studied with respect to pairs of non-linear results. The tangent-linear integrations propagating in time analysis increments have been performed with the trajectory computed using either the diagnostic cloud scheme (as it was used in 4D-Var) or the prognostic cloud scheme (now operational in 4D-Var).

Singular vector computation has also been done to verify that the new schemes do not produce spurious unstable modes (Janisková *et al.* 2000).

3.1 Experimental framework

To evaluate the impact of including radiation and cloud schemes to existing linearized parametrizations, set of experiments has been done for different dates with integrations up to 24 hours using model resolution T63L31. The radiation and cloud schemes have been used at each time step and at every grid point. In the operational ECMWF model, the full radiation computations are presently done on a reduced horizontal grid (1 point out of 4 in the longitudinal direction is used) and not at each time step (Morcrette, 2000). However, the assimilation of cloud properties will require calling the linearized radiation more often and at the full spatial resolution for an improved description of cloud-radiation interactions.

In the validation experiments, the difference between two non-linear integrations (one starting from a background field $\mathbf{x}_{fg}$ and the other one starting from an analysis $\mathbf{x}_{an}$) is computed using the full physics. This difference is then used as the standard reference of the tangent-linear integrations which propagate in time the analysis increments $\delta\mathbf{x} = \mathbf{x}_{an} - \mathbf{x}_{fg}$ with the trajectory taken from the background field (Janisková *et al.* 1999, Mahfouf 1999).

For a quantitative evaluation of the impact of the cloud and radiation schemes, their relative importance is evaluated using mean absolute errors between tangent-linear and non-linear integrations as

$$\varepsilon = \overline{\left| \left[M(\mathbf{x}_{an}) - M(\mathbf{x}_{fg}) \right] - M'(\mathbf{x}_{an} - \mathbf{x}_{fg}) \right|}$$

where M is the forecast model starting from different initial conditions:

$\mathbf{x}_{an}$ - from analysis,

$\mathbf{x}_{fg}$ - from the first guess,

M' is the tangent-linear model starting from the initial conditions ($\mathbf{x}_{an}$ - $\mathbf{x}_{fg}$), $\overline{(...)}$ represents the mean over a particular domain.

As a reference for the comparisons, an absolute mean error for the tangent-linear model without any radiation, resp. with old radiation ε_{ref} is taken. ε_i represents an absolute mean error for the tangent-linear model with new shortwave, longwave radiation and cloud schemes included with respect to pairs of non-linear integrations with the full physics. Then an improvement coming from including more physics in the tangent-linear model should be expressed by:

$$\varepsilon_i < \varepsilon_{ref}$$

The impact of including new radiation and cloudiness schemes has been evaluated studying the time evolution of analysis increments at different model levels and using the zonal mean diagnostics of mean absolute errors.

3.2 Impact of including the new schemes within the existing linearized parametrizations

The relative importance of the different tangent-linear radiation schemes has been evaluated. For that purpose, zonal mean absolute errors between non-linear and tangent-linear integrations have been computed. The results of our experiments have shown that the inclusion of more sophisticated radiation improves the fit to the nonlinear model. However, the impact of the linearized diagnostic cloud scheme is small (Janisková *et al.* 2000).

Figure 1 shows the comparisons done for the tangent-linear (TL) integrations propagating in time the analysis increments with the trajectory computed either using diagnostic cloud scheme (as it was used in 4D-Var) or prognostic cloud scheme (as it is now used in 4D-Var). The TL models using the whole physics with old radiation scheme and with new radiation and cloud schemes are compared to the TL model without any radiation (reference TL model). Negative values (resp. positive values) correspond to an improvement (resp. deterioration) of the investigated TL model with respect to the reference one. When using the diagnostic cloud scheme in the trajectory computations, one can see that the old longwave radiation scheme (Fig. 1a) only gives a slight global improvement of 0.31 %. Negative impacts appear in the middle of atmosphere. The problems come from over-simplifications in this linearized radiation scheme, which uses the constant emissivity approach, which is not appropriate in the stratosphere. The new longwave and shortwave radiation schemes (Fig. 1b) give a global improvement of 4.71 %. There are only few places with some small negative impact.

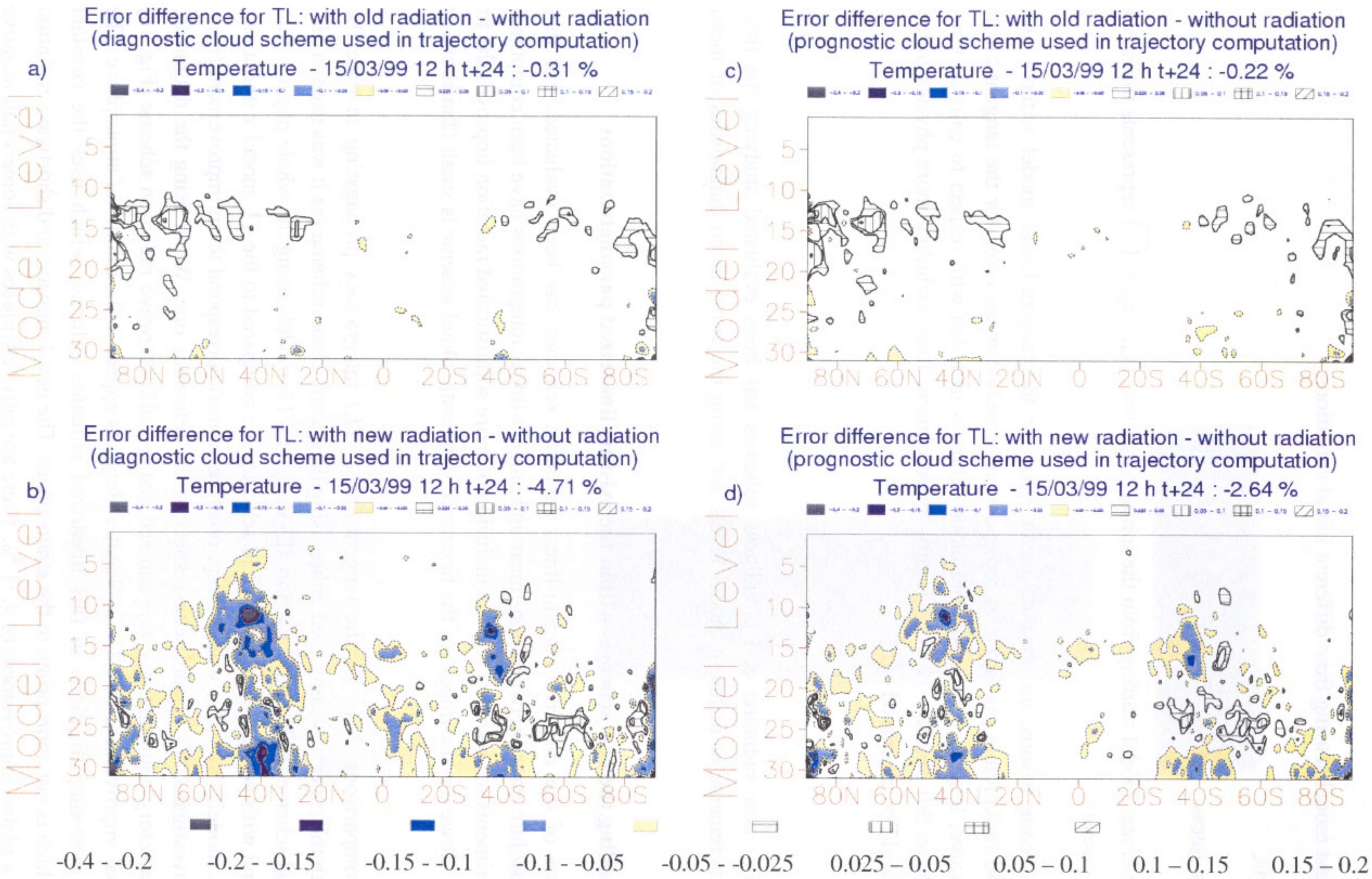


Fig 1: Influence of the different tangent-linear radiation schemes on the evolution of temperature increments with the trajectory computed using either diagnostic cloud scheme (a, b) or prognostic cloud scheme (c, d). Results are presented as the error differences (in terms of fit to the nonlinear model with full physics) between the tangent-linear (TL) model including operational linearized physics (old radiation) and the TL model without any radiation (a, c). (b) and (d) present the same, but for the TL model containing new radiation scheme with the simplified diagnostic cloud scheme. (24-hour forecast for the situation of 15 March 1999 12 UTC, units: K)

When the prognostic cloud scheme is used in trajectory computations, the run with old radiation scheme (Fig. 1c) is only slightly influenced, since effective emissivity arrays are stored from the full non-linear radiation scheme. Therefore the arrays used in the TL model are obtained from the non-linear integration with the prognostic cloud scheme. It means that there is a consistency between non-linear and tangent-linear integrations. However, when the TL model containing the new radiation and diagnostic cloud scheme uses the trajectory computed with the prognostic cloud scheme (Fig. 1d), results are worse than in the run with the trajectory obtained using the diagnostic cloud scheme (Fig. 1b). In this case, different cloud schemes are used in the trajectory computation and in the linearized model, therefore having an influence on the accuracy of the TL approximation. One of the reasons to aim for using a simplified version of the prognostic cloud scheme is to avoid such discrepancy.

According to our experiments, the improvement coming from the new radiation scheme with respect to the old one represents up to 10 % of the perturbation value. It can reach locally several Kelvins in some specific situations (not shown here).

4 Perspectives in improvement of the cloud parametrization for the linearized model

Preliminary results have shown some weaknesses of the current linearized diagnostic cloud scheme (no explicit link with moist convection, inconsistencies with the operational prognostic cloud scheme). Therefore, as it was already mentioned, it is planned to develop a simplified version of the ECMWF prognostic cloud scheme for linearization purposes.

The current scheme is too complex to be used as such in data assimilation. It contains many thresholds which can degrade the validity of the tangent-linear approximation and its prognostic variables (cloud fraction, cloud liquid and ice water contents) cannot be initialized without major changes to the current data assimilation system. Moreover, the development of a linearized prognostic cloud scheme will also require a revision of the linearized mass-flux convection scheme in order to improve the coupling with convection.

Without having an explicit coding of tangent-linear and adjoint versions of an improved cloud scheme, it is possible to investigate some of its potential in a one-dimensional variational context using a Jacobian approach. Some one-dimensional assimilation experiments have been undertaken using simulated observations to demonstrate the usefulness of the linearized schemes already developed. The 1D-Var tool can also be used for identification of the most important (sensitive) processes to be included in the linearization of the cloud scheme.

5 1D-Var sensitivity studies

To investigate the potential of the developed radiation and cloud schemes to modify model temperature, humidity and cloud profiles to produce a better match to the observations of radiation fluxes, preliminary 1D-Var experiments with simulated observations have been carried out.

5.1 Description of the system

Let **x** be the vector representing an atmospheric state described by 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 a distance between the model variables and the observations is minimum. The model is constrained to fit the observations by adjusting its initial conditions. Then the minimization problem consists in finding optimum profile **x** which minimizes the objective function:

$$J(\mathbf{x})=\frac{1}{2}(\mathbf{x}-\mathbf{x}^b)^T\ \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b)+\frac{1}{2}\left[\frac{F(\mathbf{x})-F_o}{\sigma_o}\right]^2$$

where $\mathbf{B}$ is the covariance matrix of background error and $\mathbf{x}^b$ is the background vector (short term forecast profile). F_o represents a simulated observation of radiation flux with its observation error σ_o. In our experiments, the observation operator $F(\mathbf{x})$ includes the shortwave and longwave radiation together with the cloud scheme.

The minimization requires an estimation of the gradient of the objective function:

$$\nabla J(\mathbf{x})=\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b)+\mathbf{F}^T\left[\frac{F(\mathbf{x})-F_o}{\sigma_o}\right]$$

The transpose of the tangent-linear observation operator $\mathbf{F}^T$ can be obtained explicitly through the Jacobian matrix computed using finite differences by a perturbation method. Such approach is affordable due to the low dimension of the control vector in 1D-Var. Using adjoint of the tangent-linear physical processes to compute $\mathbf{F}^T$ can significantly reduce the computational cost.

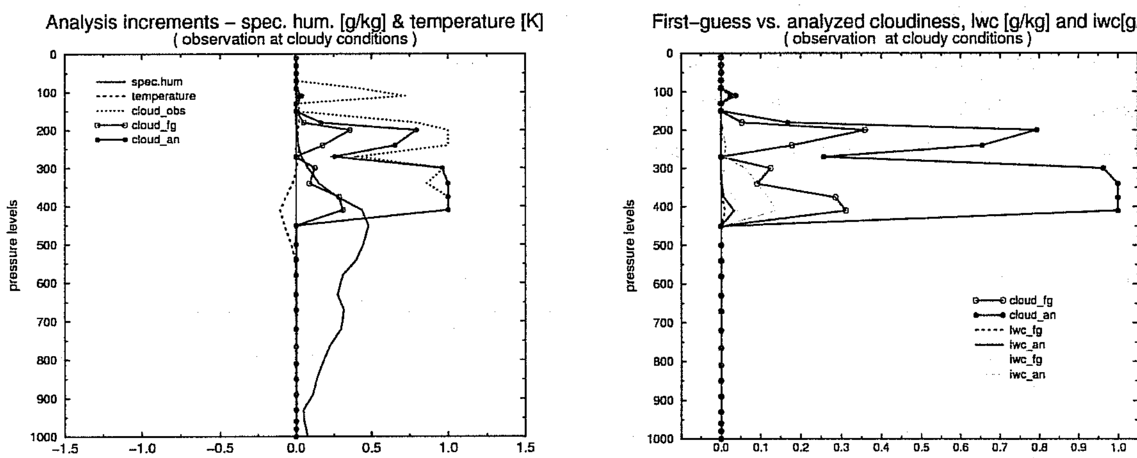
1D-Var computations contain forward modelling of cloudy radiation fluxes (F operator) and corresponding adjoint modelling ($\mathbf{F}^T$ operator). In the case of forward modelling, the computation starts from the control variables T, q, p_S, which are input variables for the cloud scheme. The outputs of the cloud scheme are cloud variables as cloud cover, cloud liquid water and ice water contents. Those variables together with the control variables are entering the radiation scheme. The cloud-radiation interactions are taken into account there. The incorporation of the effects of clouds on radiation fluxes is achieved through cloud optical properties and effective cloud cover computed using the maximum-random overlap assumption. Then from the radiation scheme, one can get cloudy (or clear sky) radiation fluxes. Backward computation of the cloudy radiation fluxes starts from the departure of cloudy radiation fluxes, which are entering the adjoint of the radiation scheme. Integration of the adjoint scheme gives increments of the cloud variables. Those are used as input for the adjoint of the cloud scheme (for the time being, there is only adjoint of the diagnostic cloud scheme). After its integration, one can get increments of the control variables.

5.2 The assimilation experiments

1D-Var experiments have been undertaken using simulated observations. In those experiments, the first-guess data are taken from 3D-model integrations. The simulated observations are obtained from a 1D-model integration (over one time step) of cloud and radiation schemes by modifying the vertical profiles of temperature and humidity. The observation operator can be obtained explicitly through Jacobian matrix in the case of the finite-differences approach or it can be obtained using the adjoint technique. Several experiments have been done using simulated observations of the longwave downward radiation flux at the surface, longwave upward radiation flux at the top of atmosphere, shortwave downward radiation flux at the surface or the combination of all those fluxes. The profiles of temperature and specific humidity have been used in some experiments as well.

One of the questions, which we tried to answer in our experiments, was whether it is possible to modify significantly cloud cover when using 1D-Var to improve the agreement in terms of radiative fluxes. To answer this question, experiments have been run for different model profiles simulating a nearly clear sky or cloudy "observed" atmosphere, while the first-guess was describing the opposite situation.

Figure 2 shows the results for one of the vertical profiles from the study of the 1D-Var ability to create clouds. In that experiment, the simulated observations indicate larger amount of clouds than given by the first-guess. Three types of observations were used: longwave downward radiation flux at the surface (LWDs), longwave upward radiation flux at the top of atmosphere (LWUPtoa) and shortwave downward radiation flux at the surface (SWDs). The observations were assumed to be nearly perfect, since the observation error σ_o was set up to 2 W.m^{-2}. The values of observed, first-guess and analyzed radiation fluxes are written below Fig. 2. Analysis increments of specific humidity (solid line) and temperature (dashed line) together with the cloud profiles (observed, first-guess and analyzed) are on the left panel (a) of the figure. This figure shows that the analyzed cloud cover is much larger than the first-guess. Except for the higher model levels, it nearly reaches the amount of observed clouds. This result is presented in more details on the right panel (Fig. 2b), which also shows information about cloud liquid water and ice water contents. At the same time, analyzed radiation fluxes are close to the observed ones. Our experiments have shown (not presented here) that the clouds can be created even when they were completely missing in the first-guess. However, in this case the atmospheric state must be close to the state of cloud formation.

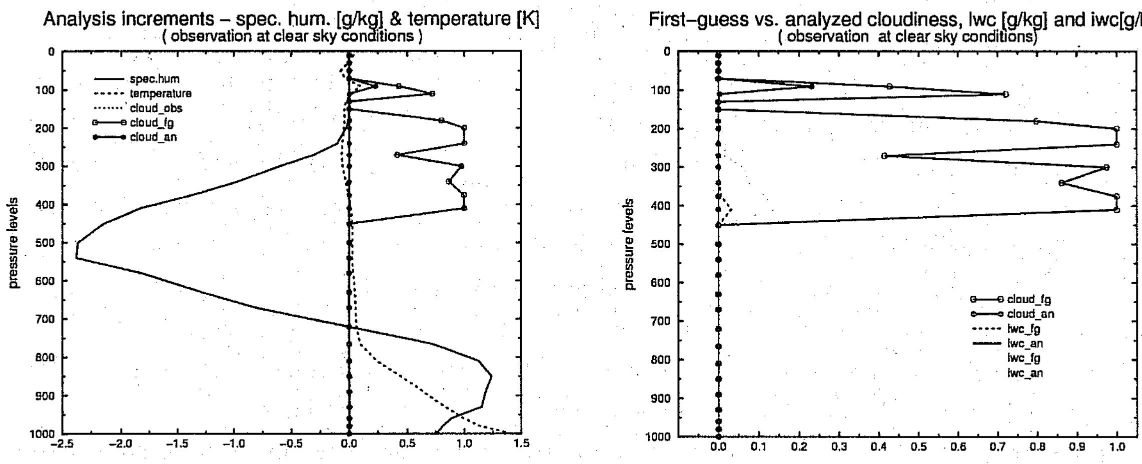


a) b)

	LWDs	LWUPtoa	SWSDs
Obs:	422.72 W.m^{-2}	-181.62 W.m^{-2}	227.68 W.m^{-2}
Fg:	409.49 W.m^{-2}	-242.15 W.m^{-2}	409.87 W.m^{-2}
anal:	423.23 W.m^{-2}	-183.94 W.m^{-2}	227.52 W.m^{-2}

Fig 2: 1D-Var ability to increase/create clouds. (a) Analysis increments for specific humidity (solid line) and temperature (dashed line) together with the cloud profiles (observed – dotted line, first-guess – solid line with empty circles and analyzed – solid line with filled circles). (b) Cloud liquid water content (first-guess – black dashed line, analysis – black solid line) and cloud ice water content (grey lines). Values of observed, first-guess and analyzed radiation fluxes are also given.

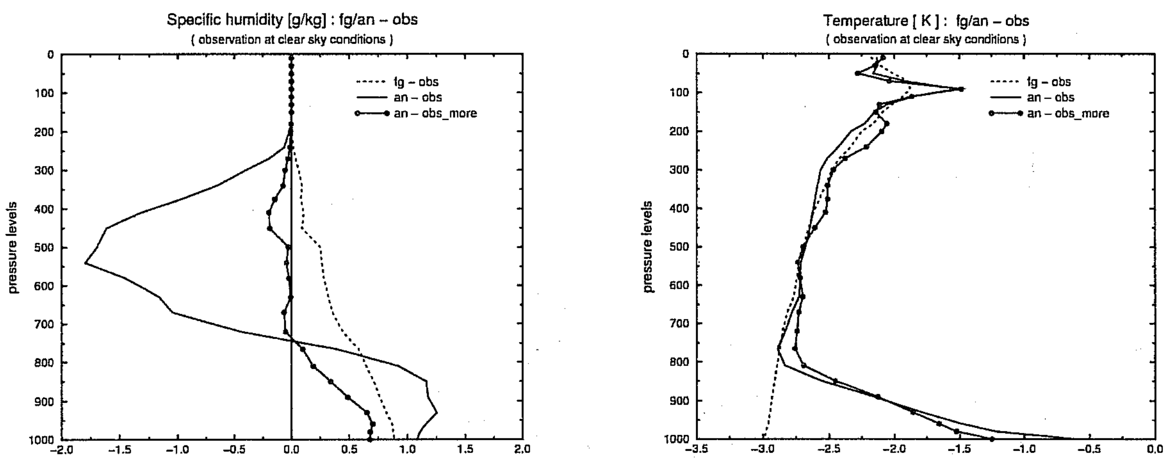
The results from the experiment studying whether 1D-Var is able to remove the clouds are presented in Fig. 3. The same types of information as in the previous figure are included there. In this case, the first-guess indicates significant amount of clouds and the simulated observation is clear-sky one. One can see that analyzed cloud cover is significantly reduced and the analyzed radiation fluxes are adjusted to the observed ones.



a) b)

	LWDs	LWUPtoa	SWSDs
Obs:	413.82 W.m^{-2}	-281.04 W.m^{-2}	493.17 W.m^{-2}
Fg:	422.48 W.m^{-2}	-182.52 W.m^{-2}	228.49 W.m^{-2}
anal:	412.20 W.m^{-2}	-278.41 W.m^{-2}	493.23 W.m^{-2}

Fig 3: Same as Fig. 2, but for 1D-Var ability to remove clouds.



a) b)

Fig 4: Comparisons of the first-guess (dashed line) and analyzed (solid line) vertical profiles of specific humidity (a) and temperature (b) against observations corresponding to the situation presented in Fig. 3. The differences between improved analysis and observations when using observations on vertical levels for temperature and humidity are presented as solid line with symbols.

Our experiments have shown that 1D-Var is able to modify the temperature and humidity profiles (analysis increments of temperature and humidity are presented in Fig. 2a and 3a) in order to reduce or increase cloud cover. However, in several cases, it is possible to adjust the model state to the observed fluxes with very different profiles than the reference ones. An example of such situation is presented in Fig. 4. This figure shows comparisons of the first-guess (dashed line) and analyzed (solid line) vertical profiles of specific humidity (a) and temperature (b) against observations from the previous study when reducing cloud cover. Though the cloud cover is reduced using 1D-Var, one cannot be satisfied with retrieved temperature and humidity profiles. Especially for specific humidity, the difference between analysis and observations is increased compared to the difference between first-guess and observations, whereas one would rather expect to obtain opposite results after the performed analysis. This demonstrates the ambiguity of the surface or top of atmosphere fluxes on the retrievals. Experiments have shown that using some observations on vertical profiles helps to retrieve more accurate profiles. The differences between improved analysis and observations when using observations on vertical profiles for temperature and humidity are displayed in Fig. 4 (solid line with symbols).

6 Conclusion

The linearized radiation and cloud schemes have been developed for variational data assimilation of cloud observations. The results of our validation experiments have shown that the inclusion of more sophisticated radiation to the existing linearized parametrizations improves the fit to the nonlinear model. However, impact of the linearized diagnostic cloud scheme is small. It is planned to develop a simplified version of the ECMWF prognostic cloud scheme for linearization purposes in order to improve cloud-radiation interactions and the coupling with the convection scheme.

Feasibility studies in a 1D-Var framework will continue using data from field experiments (e.g. ARM, CLARE) where measurements of both cloud properties and radiative fluxes are available. One of the objectives of those experiments will be to investigate the usefulness of linearized parametrization schemes for both radiation and clouds. Another objective will be to assess the importance of cloud observations together with radiative measurements, as well as to investigate the relative importance of the various control variables.

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