# Physical processes in adjoint models: potential pitfalls and benefits

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**ABSTRACT**

Adjoint models have several applications in the numerical weather prediction (NWP) systems, such as in variational data assimilation, singular vector analysis or sensitivity studies. First the adiabatic linearized models were only used in NWP. Nowadays, the physical processes are progressively included in the linearized models. This paper discusses potential problems with adjoint models containing physical processes and demonstrates the usefulness of linearized physical processes in the different applications.

## 1 Introduction

Adjoint models (transpose of the linearized models) are powerful modeling tools that enable many problems to be solved efficiently. They have several applications such as in the variational data assimilation for efficient determining the optimal solutions, in Ensemble Prediction System (EPS) for computation of the fastest growing modes (singular vectors) or in sensitivity analysis for investigation of the model forecast errors. Though first the adiabatic linearized models were only used in the numerical weather prediction (NWP), it was soon recognized that the use of an adiabatic linear model can be critical especially in the tropics, near the surface, in the planetary boundary layer or the stratosphere, where the description of the atmospheric processes is controlled more essentially by the physics than the dynamics. Therefore a lot of effort was devoted to include physical parametrizations in adjoint models.

Using physical processes in the assimilating model can reduce the so-called spin-up problem, produce an initial atmospheric state more consistent with the physical processes and provide a better agreement between the model and data. Furthermore, it is an important step towards the use of new (satellite) observations in the data assimilation systems (such as rain, clouds, soil moisture). In the case of singular vector computations, using an adjoint with physical processes can help to represent some atmospheric features such as processes in the planetary boundary layer, tropical instabilities or the development of baroclinic instabilities. The diabatic adjoint model should improve the sensitivity analysis thanks to a more consistent description of the atmospheric processes. The adjoint of physical processes can also be used for an efficient determination of the model parameters or for a sensitivity of the parametrization scheme to input parameters.

Some studies have been undertaken to include physical parametrizations in adjoint models (Zou *et al.* 1993, Zupanski and Mesinger 1995, Tsuyuki 1996, Zou 1997, Errico and Reader 1999, Janisková *et al.* 1999, Mahfouf 1999, Laroche *et al.* 2002) with encouraging results. However, these studies have also shown that the linearization of physical parametrization schemes is not straightforward because of the nonlinear and on/off nature of the physical processes. Some strong nonlinearities that could lead to noise problems had to be removed from the models in order to be able to benefit from the physical processes in the linearized models.

## 2 Possible strategy for including physical processes in adjoint models

Due to a presence of thresholds in the physical parametrizations that can reduce the range of validity of the tangent-linear approximation, the best way to include physical processes in tangent-linear models is still matter of debate. For important practical applications (incremental approach of 4D-Var, simplified gradients in 4D-Var, the initial perturbations computed for EPS), the linearized versions of forecast models are run at the lower resolution than the non-linear models. In this case, since the dynamics is already simplified by reducing the resolution, the linearized physics does not need to be the exact tangent-linear version of the full physics. In principle, physical parametrizations can already behave differently between non-linear and tangent-linear models due to the change of resolution. Consequently, some freedom exists to develop a simplified physical package as long as the parametrizations can represent the order of magnitude in intensity and general feedbacks of physical phenomena present in the atmosphere. Simplified approaches can then be a way to include progressively physical processes in the tangent-linear (TL) and adjoint (AD) models. This strategy is used, for instance, in the operational 4D-Var systems of ECMWF (Mahfouf 1999, Mahfouf and Rabier 2000, Rabier *et al.* 2000) and Météo-France (Janisková *et al.* 1999, Geleyn *et al.* 2001).

All modifications in the simplified approaches are done with the aim to have a physical package which is:
- simple - for the linearization of model equations,
- regular- for avoiding strong non-linearities and thresholds otherwise present in the physical processes,
- realistic enough - for keeping the description of atmospheric processes physically sound,
- computationally affordable - for practical and operational applications.

In the numerical weather prediction (NWP), there is a tendency to develop more and more sophisticated physical parametrizations which as a consequence may contain more discontinuities. However for the "perturbation" model, it is more important to describe the basic physical tendencies while avoiding the problem of discontinuities than to aim at having very sophisticated parametrization schemes full of the potential thresholds detrimental for the linearized model.

A level of simplifications or required complexity of the parametrization schemes depends on: which level of improvement is expected (for different variables, vertical and horizontal resolutions) and which type of observations should be assimilated (if adjoint model is to be used in the assimilating model). This will be also influenced by a necessity to remove the threshold processes. There are different ways of simplifications - either a direct development of the simplified physical parametrizations (for instance, gaining from an experience with the simpler parametrization schemes used in history) or applying only part of the linearization (for instance, not taking into account perturbation of exchange coefficients in the vertical diffusion scheme as discussed in Mahfouf *et al.* 1999).

## 3 Problems with adjoint models containing physical processes

There are several problems with including physics in adjoint models. The development requires substantial resources and it is technically very demanding. The validation must be very thorough and it must be done for the non-linear, tangent-linear and adjoint versions of the physical parametrization schemes. The computational cost of the model with physical processes can be very high despite some simplifications applied. One must be also very careful with the non-linear and threshold nature of physical processes which can affect the range of validity of the tangent-linear approximation.

### 3.1 Importance of regularization of the tangent-linear model

As already mentioned, physical processes often have thresholds. Those can be discontinuities of some functions themselves describing the physical processes - some on/off processes (for instance produced by supersaturation, changes between liquid and solid phase), some discontinuities of the derivative of a continuous function (i.e. the derivative can go towards infinity in some points) or some strong non-linearities (for instance created by the transition from unstable to stable regimes in the PBL). In each of these situations an estimation of the derivative close to the discontinuity point will be different between the non-linear model (in finite differences) and the tangent linear model. All of this makes the tangent linear approximation less valid for the model including physical parametrizations than the adiabatic version. To treat the described problems, it is important to regularize, i.e. to apply some smoothing modifications of the parametrized discontinuities in order to have the schemes as much differentiable as possible. It is quite difficult to find a tradeoff between a physically sound description of atmospheric processes and a linear physical parametrization. However, without treatment of most serious threshold processes, the tangent-linear model can become useless. Therefore a lot of effort was devoted by a number of investigators to deal with the discontinuities present in the parametrized processes (Zou *et al.* 1993, Zupanski 1993, Tsuyuki 1996, Errico and Reader 1999, Mahfouf 1999, Janisková *et al.* 1999, Laroche *et al.* 2002).

To illustrate a potential source of the problem in the linearized model, the rain production-function, describing which portion of the cloud water is converted into precipitation, is used as an example (Fig.1). An increase of cloud water mixing ratio by a small amount $dx$ (Fig. 1a) leads to a small change in the precipitation amount $dy_{NL}$ in the case of the non-linear (NL) model, but to a very large one ($dy_{TL}$) in the case of the tangent-linear model. As a possible solution, one can modify the function to make it less steep (dotted line on Fig. 1b ). In this case, the resulting TL increment will be significantly smaller ($dy_{TL_2}$). However, the required modification can be significant and it can deteriorate the quality of the physical parametrization itself. Therefore one must be always careful to keep the balance between linearity and reality of the parametrization schemes. In the future, the better the model will be, the smaller the increments should be and one can hope to have less difficulties with using the linearized physical processes.

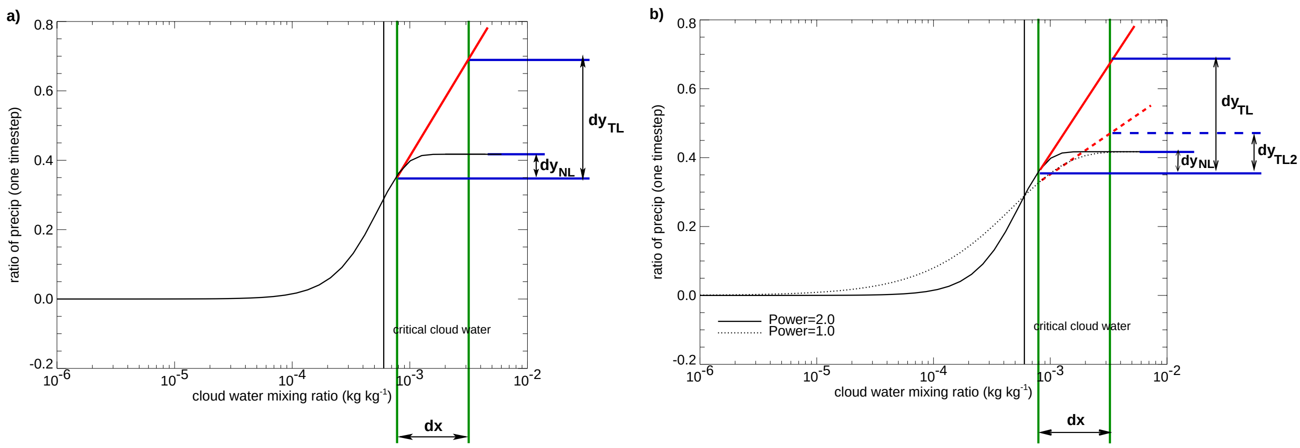


*Figure 1: Autoconversion function of cloud water into precipitation (black solid line) based on Sundqvist et al. (1989). A change in the cloud water by dx results in change of precipitation $dy_{NL}$ in the case of non-linear (NL) model. $dy_{TL}$ is the change in precipitation given by the tangent-linear (TL) model. (b) describes the modified function which is less steep and decreases the TL increments to $dy_{TL_2}$.*

When the most important threshold processes which can affect the range of validity of the tangent linear approximation are removed, the results indicate a clear advantage of the diabatic tangent-linear evolution of errors compared to the adiabatic evolution, as shown in the next section.

### 3.2 Impact of the different physical processes

To demonstrate an impact of the different physical processes in the tangent-linear model, experiments have been performed using the linearized physics of ECMWF, which describes five processes: vertical diffusion, subgrid-scale orographic effects, radiation, deep cumulus convection and large-scale condensation (Mahfouf 1999). In order to prevent spurious unstable perturbations from growing, a number of simplifications have been defined for the schemes. In the operational version of the linearized model, simplified longwave radiation is used. However, improved schemes for shortwave and longwave radiation (Janisková *et al.* 2002a) taking into account cloudiness have already been developed. The simplified deep convection should be soon replaced by a more complex mass flux scheme (Lopez and Moreau 2003) and large-scale condensation by the statistical cloud scheme (Tompkins and Janisková 2003).

For the validation of the tangent-linear approximation, the accuracy of the linearization of a parametrization scheme is studied with respect to pairs of non-linear results. The difference between two non-linear integrations (one starting from a background field $\mathbf{x}^b$ and the other one starting from analysis $\mathbf{x}^a$) run with the full nonlinear model $M$ is compared to the tangent-linear integrations using the TL model $\mathbf{M}$ and propagating in time the analysis increments $(\mathbf{x}^a - \mathbf{x}^b)$ with the trajectory taken from the background field. Computation of singular vectors is also used to find out whether the new schemes do not produce spurious unstable modes.

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

$$\varepsilon = \overline{\left|\mathbf{M}(\mathbf{x}^a - \mathbf{x}^b) - \left[M(\mathbf{x}^a) - M(\mathbf{x}^b)\right]\right|} \tag{1}$$

As a reference for the comparisons, an absolute mean error for the tangent-linear model without physics $\varepsilon_{ref}$ is taken. If $\varepsilon_{exp}$ is defined as absolute mean error of the tangent-linear model with the different schemes included, then an improvement coming from including more physics in the tangent-linear model is expressed as $\varepsilon_{exp} < \varepsilon_{ref}$. The relative errors $r_{er}$ and relative improvements $\eta$ are also computed as:

$$r_{er} = \frac{\left|\mathbf{M}(\mathbf{x}^a - \mathbf{x}^b) - \left[M(\mathbf{x}^a) - M(\mathbf{x}^b)\right]\right|}{\left|M(\mathbf{x}^a) - M(\mathbf{x}^b)\right|} \tag{2}$$

$$\eta = \frac{\varepsilon_{exp} - \varepsilon_{ref}}{\varepsilon_{ref}} \tag{3}$$

Figure 2 presents zonal mean of error difference (in terms of fit to the nonlinear model with the full physics) between the tangent-linear model including some parametrization scheme and the adiabatic TL model (i.e. $\varepsilon_{exp} - \varepsilon_{adiab}$). Negative values are associated with an improvement of the model using the parametrization schemes with respect to the adiabatic TL model since they correspond to a reduction of the errors. The operational version of the ECMWF linearized physics has still small negative impact over the tropics between the model levels 34-45 ($\sim$ 300 - 700 hPa) and in the extratropics around the model level 35 ($\sim$ 350 hPa). This is improved by including the new linearized schemes for radiation and clouds. The improvement is significant over the whole tropics and in the lower troposphere. The global relative improvement (in the percentage) coming from progressive including parametrization schemes into the linearized model is shown on Fig. 3 for temperature (a), zonal wind (b) and specific humidity (c). The relative error of the tangent-linear model with respect to the finite differences using the full physics is presented on Fig. 3 (d-f). The largest error is in the case of the adiabatic TL model and the error is reduced (d-f) and improvement increased (a-c) by progressive including physical parametrization schemes.

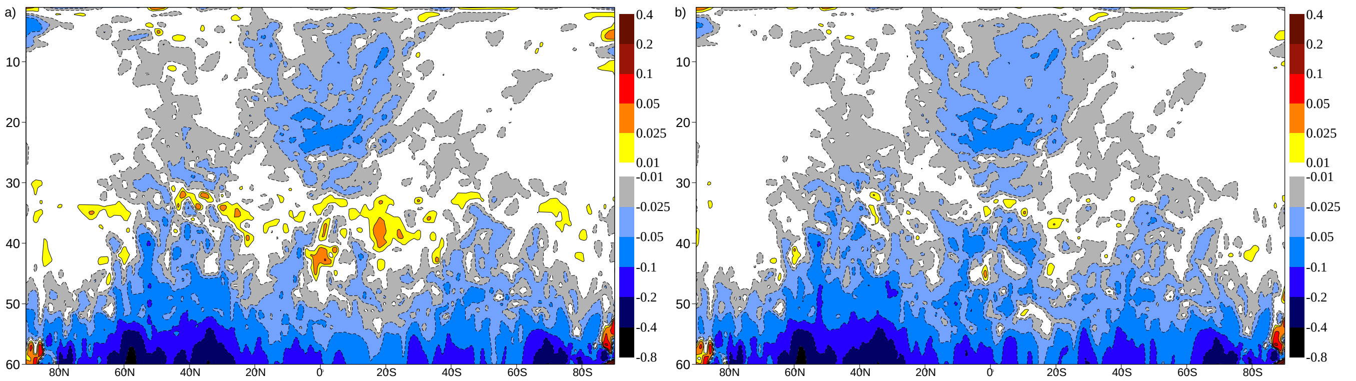

*Figure 2: Impact of the ECMWF operational version of the linearized physics (a) and the improved version with the new radiation and cloud schemes (b) on the evaluation of temperature increments in zonal mean. Results are presented as the error differences (in terms of fit to the nonlinear model with full physics) between the TL model with certain version of the linearized physics and the adiabatic TL model.*

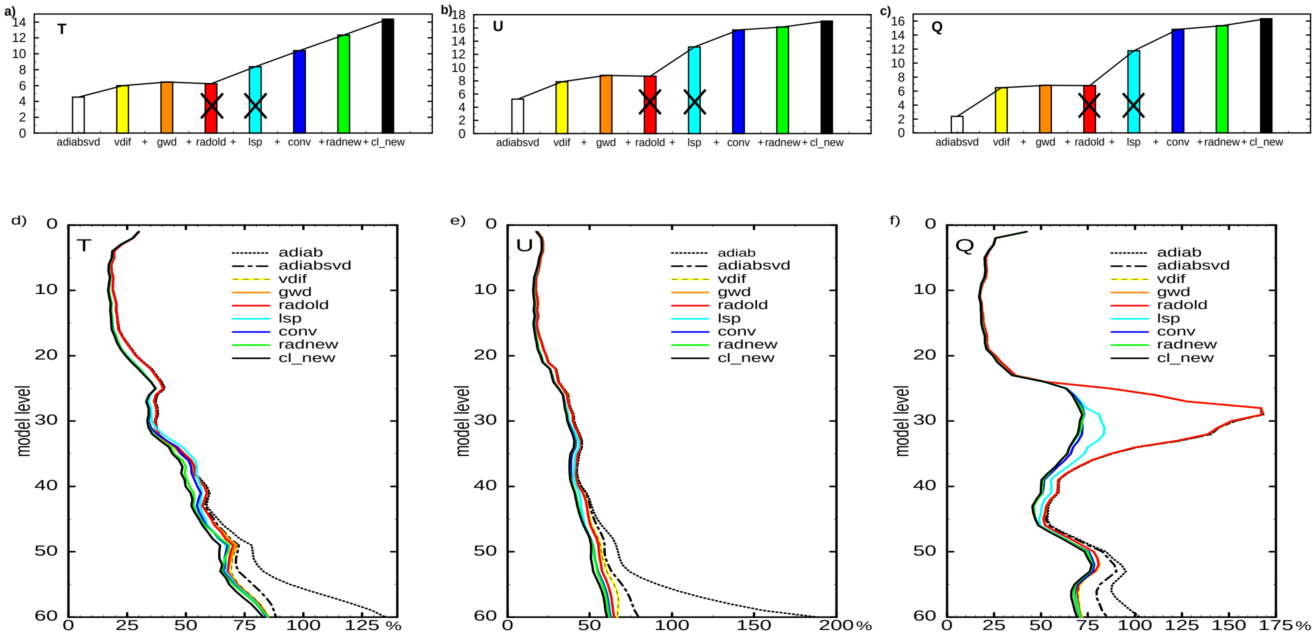

*Figure 3: Global relative improvement (a-c) coming from progressive including parametrization schemes into the ECMWF linearized models (adiabsvd - very simple vertical diffusion of Buizza (1994), vdif - more complex vertical diffusion, gwd - gravity wave drag, radold - operational radiation, lsp - large-scale precipitation, conv - convection, radnew - new improved radiation scheme, cl_new - new statistical cloud scheme). The results are presented as the percentage improvement for (a) temperature, (b) zonal wind and (c) specific humidity. Global relative error of the tangent-linear (TL) model with respect to the finite differences using the full physics is displayed for temperature (d), zonal wind (e) and specific humidity (f) when using the adiabatic (adiab) TL model and the TL model with different physical processes (as in a-c).*

# 4 Benefits from using adjoint models with physical processes

Physical processes can be included in the different applications of linearized models in numerical weather prediction. A benefit from using linearized parametrization schemes in the assimilating model, singular vector computations and sensitivity studies is demonstrated in the following subsections.

### 4.1 Impact of the physics in 4D-Var

Experiments have been performed (Mahfouf and Rabier 2000, Rabier *et al.* 2000) in order to compare two versions of the ECMWF 4D-Var system: one with the linearized physics included (operational version) and another without it. They demonstrated positive impact on the forecast scores coming from inclusion of the linearized physical parametrization schemes in 4D-Var. Using the linearized physics in 4D-Var led to a better consistency between the minimization at high and low resolution. The discontinuity of the objective function imposed by the change of resolution and the change of physical parametrization was smaller with linearized physics. Spin-down in precipitation during the first day of forecasts was significantly reduced with introducing physical processes in 4D-Var, as shown by Mahfouf *et al.* (2000) for the time evolution of total precipitation in the tropical belt (between 30S and 30N).

More recently, 4D-Var experiments have been performed with the linearized physics upgraded by the new linearized radiation schemes accounting for cloudiness (Janisková *et al.* 2002a). As expected from a better description of the cloud-radiation interactions inside 4D-Var, results showed a slight general improvement of the quality of the forecasts in terms of geopotential heights, temperature and wind, with a significant positive impact for some individual cases. An example of impact of these linearized schemes in 4D-Var is shown on the one-day forecast error of 500 hPa geopotential height over the Europe on the 28 August 2001 at 12 UTC. Figure 4a shows a difference between the operational day one forecast and operational analysis, which indicates quite large error of 75 meters. This error is significantly reduced by introducing a more complex radiation scheme in the set of linearized physics (Fig. 4b). Improvement coming from using the new radiation schemes is presented on Fig. 4c. These linearized parametrization schemes are now planned for operational implementation.

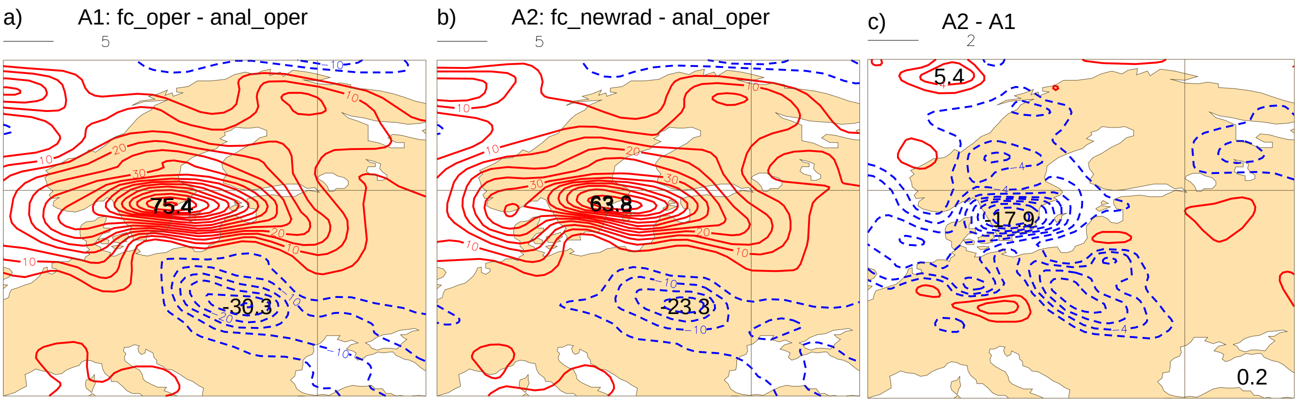


*Figure 4: One-day forecast error (difference between the forecast and analysis) of 500 hPa geopotential height over the Europe on 28 August 2001 at 12UTC for (a) operational system A1 and (b) the system with more complex radiation schemes in the set of linearized physics A2. (c) displays the difference in 500 hPa height between system A2 and A1. The contour interval is 5 m for (a,b) and 2 m for (c).*

### 4.2 1D-Var assimilation of observations related to the physical processes

One-dimensional variational (1D-Var) assimilation technique can be used to assimilate some observed quantities related to the model physics, e.g. precipitation or radiances from microwave satellite channels. The goal of 1D-Var is to define the atmospheric state $\mathbf{x}$ such that the distance between a background profile (short-term forecast) and observations $\mathbf{y}^o$ is minimum taking into account information about background and observation errors. Then the minimization problem consists in finding an optimum profile $\mathbf{x}$ which minimizes the objective function:

$$\mathscr{J}(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}^b)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b) + \frac{1}{2}(H(\mathbf{x})-\mathbf{y}^o)^T\mathbf{R}^{-1}(H(\mathbf{x})-\mathbf{y}^o) \tag{4}$$

where $\mathbf{B}$ is the covariance matrix of the background error for the model control variables, $\mathbf{x}^b$ is the background vector and $\mathbf{R}$ represents observation and representativeness error covariance matrix. $H$ is the observation operator providing a model equivalent of the observations from the model variable $\mathbf{x}$. It can employ physical parametrization schemes, microwave radiative transfer model, reflectivity model, depending on which type of observations will be assimilated.

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

$$\nabla\mathscr{J}(\mathbf{x}) = \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b) + \mathbf{H}^T\mathbf{R}^{-1}(H(\mathbf{x})-\mathbf{y}^o) \tag{5}$$

The transpose of the observation operator $\mathbf{H}^T$ can be obtained explicitly through the Jacobian matrix computed in finite differences by a perturbation method (affordable due to the low dimension of the control vector in 1D-Var). Using the adjoint technique for the computation of $\mathbf{H}^T$ reduces significantly the computational cost.

### 4.2.1 Assimilation of precipitation observations

Work on the precipitation assimilation at ECMWF was initiated by Marécal and Mahfouf (2000). In their first experiments, they used a 1D-Var technique to assimilate rainfall rates (RR) from the TMI (TRMM Microwave Imager, TRMM - Tropical Rainfall Measuring Mission) and SSM/I (Special Sensor Microwave/Imager) to correct individual profiles of the model control variables in order to match better rainfall observations. Later Marécal and Mahfouf (2002) combined 1D-Var with 4D-Var for assimilation of TMI derived rainfall rates. They showed that indirect "1D-Var+4D-Var" assimilation of rainfall rates is more robust than the direct 4D-Var assimilation and is able not only to improve humidity, but also the dynamics in the forecasts.

More recently, new simplified convection (Lopez and Moreau 2003) and statistical cloud (Tompkins and Janisková 2003) schemes were developed. The microwave radiative transfer model (Bauer *et al.* 2002) was also derived to allow microwave radiances to be simulated in rain-affected column of the atmosphere. 1D-Var calculations can then directly deal with the brightness temperatures (TBs) instead of performing the 1D-Var retrievals on surface rainfall rates that are derived from multi-channel microwave TBs through various algorithms. This would homogenize the approach and could even provide more accurate retrievals, since TBs are sensitive not only to rain, but also to cloud water and water vapour (Moreau *et al.* 2003a). Assimilation experiments of direct measurements from TRMM and SSM/I instead of indirect retrievals of rainfall rates are also being performed in a "1D-Var+4D-Var" framework.

Two methods are now under investigation at ECMWF to be used for an assimilation of observations related to precipitation. In the first method, TMI and SSM/I microwave brightness temperatures or TRMM precipitation radar reflectivities are used as observations. In the other method, surface rain-rates are retrieved using different algorithms from the raw brightness temperatures. The high resolution observations are scaled to the model resolution. After some screening of the data, the observations are entering to 1D-Var system. In the first case, the moist physics and a radiative transfer model are used to obtain a model counterpart to the observations. In the second case, only the moist physics schemes are needed. The outputs of 1D-Var are modified profiles of temperature and humidity, which are used for the computation of the total column water vapour (TCWV) to be included as a pseudo-observation to the 4D-Var system.

An example of 1D-Var results for assimilation of precipitation related observations is taken from the study by Moreau *et al.* (2003b). Figure 5 displays the tropical cyclone ZOE (26 December 2002). The background surface rain rates and a surface rain-rate retrieved by PATER (Precipitation radar Adjustment TMI Estimation of Rainfall, Bauer *et al.* 2001) algorithm are on the top panels (a,b). The bottom panels (c,d) show analyzed values of rainfall rates obtained using the two different methods described above. One can see that the 1D-Var improves the location and intensity of precipitation patterns in the both methods. The shape of the cyclone and the northern rainband in the analysis agree well with the PATER retrieval.

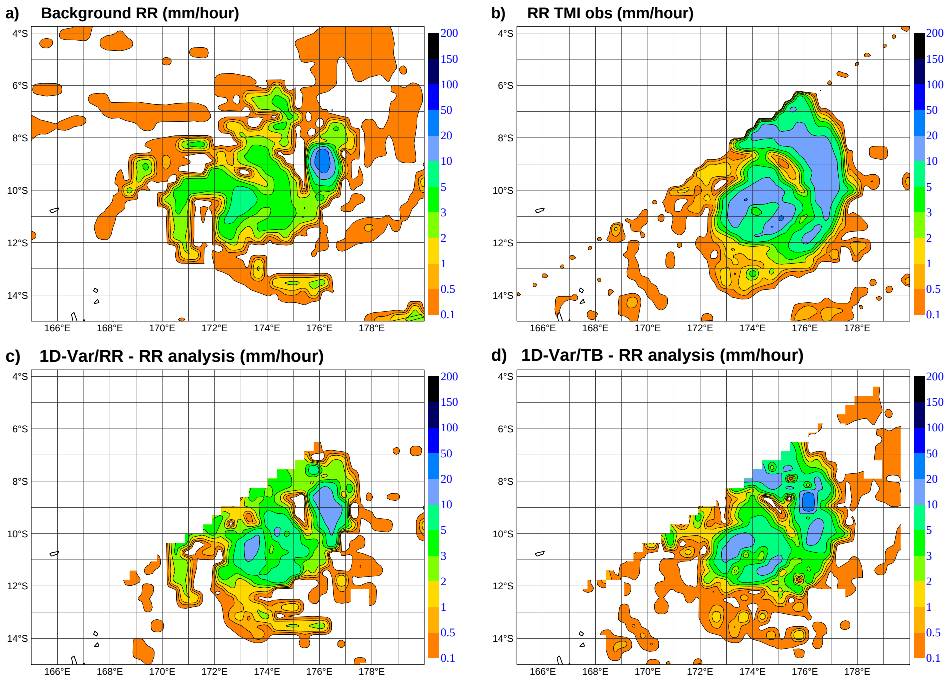


*Figure 5: 1D-Var of precipitation related observations for the tropical cyclone Zoe at 12UTC 26 December 2002. Rain rates (RR) from the model background (a), RR retrieved from TMI using PATER algorithm (b), analyzed RR obtained using 1D-Var assimilation of RR (c) and of brightness temperatures TBs (d). Units are mm.h$^{-1}$.*

### 4.2.2 Assimilation of cloud and radiation related observations

Feasibility studies in a 1D-Var framework using cloud-radiation data have also been done to investigate the potential of the radiation and cloud schemes to modify the model profiles of temperature, humidity and cloudiness to produce a better match to the observations of the radiation fluxes (Janisková *et al.* 2002b). Measurements from the site of the Atmospheric Radiation Measurement (ARM) Program located at the South Great Plains (SGP, Oklahoma) used in the experiments are the surface downward shortwave (SWD) and longwave (LWD) radiation, the total column water vapour (TCWV) and cloud liquid water path (LWP). The observation operator providing a model equivalent of the data contains the shortwave and longwave radiation schemes together with the cloud scheme in this case.

Improvement, resp. deterioration of the analysis with respect to the first guess after 1D-Var assimilation of the ARM observations are summarized for May 1999 on Fig. 6. Since the results are presented as the differences between the absolute value of the first guess minus observation and the absolute value of the analysis minus observation, the positive values indicate an improvement of the analysis compared to the first guess with respect to the observations. Though some deterioration of the analysis appears at some hours, generally 1D-Var is able to retrieve temperature and humidity profiles that provide LWD, TCWV (Fig. 6a,b) and LWP (not shown) closer to the observations. For the shortwave radiation, the number of cases with an improvement only slightly dominates over the deterioration of SWD (not shown).

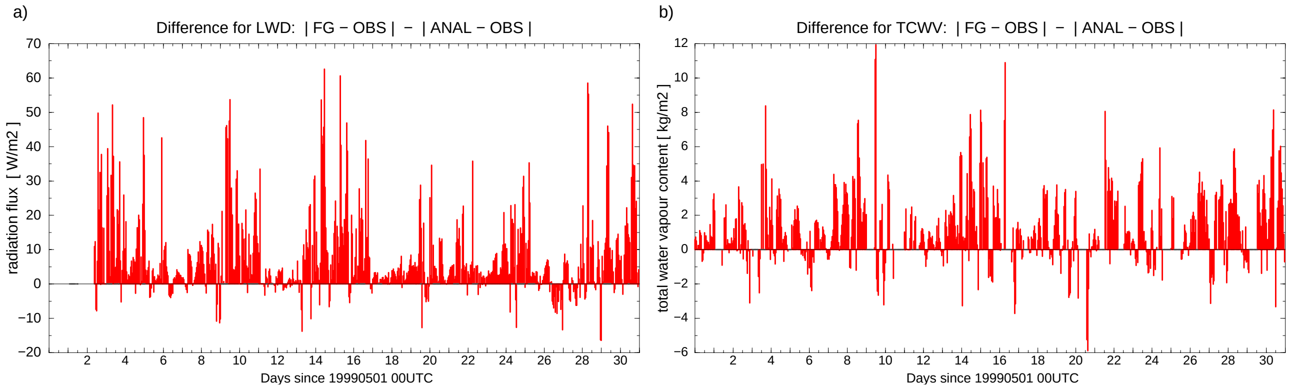


*Figure 6: Improvement/deterioration of the analysis with respect to the first-guess after 1D-Var assimilation of the ARM observations over the SGP site in May 1999. The results are presented as difference between absolute value of the first-guess minus observation and absolute value of the analysis minus observations for the downward radiation at the surface (a) and the total column water vapour (b).*

Some studies have been done to investigate the capability of 4D-Var systems to assimilate cloud-affected satellite infrared radiances (Chevallier *et al.* 2003). 4D-Var assumes that the forward operator is linear in the vicinity of the background. Observations for which significant non-linearities affect the forward model are discarded. Therefore infrared satellite radiances are currently not assimilated in the presence of clouds. At ECMWF, an observation operator has been developed that computes cloud-affected satellite brightness temperatures from some control variables (profiles of temperature and specific humidity). It contains a diagnostic cloud scheme with a representation of large-scale and convective processes and a radiation model. The possibility of using this operator to assimilate cloud-affected infrared radiances from the narrow-band Advanced Infrared Sounder (AIRS) has been assessed. The study showed that there is a potential benefit in assimilating some of the upper tropospheric channels at 4.5, 6.3 and 14.3 $\mu$m in the presence of clouds directly in 4D-Var. The developed observation operator has also been used for 1D-Var retrievals. In the performed experiments, observations of AIRS brightness temperature from 35 upper tropospheric channels are used. The retrievals are performed only if clouds are detected in more than 13 channels. Figure 7 (provided by Chevallier, ECMWF 2003) shows the comparison of the retrieved relative humidity against European radiosondes for the period of November 2002 to February 2003. Using 1D-Var of AIRS observations, the root mean square error of relative humidity is reduced.

## 4.3 Impact of physical processes on singular vector analysis

The adjoint models can be used not only for the data assimilation, but they have also application in singular vector analysis. Impact of including physical processes in adjoint models is demonstrated on the probabilistic forecast using the tropical singular vectors. Figure 8 (provided by Leutbecher and Van Der Grijn, ECMWF 2003) shows the strike probability maps, i.e. probability that the cyclone Kalunde will pass within 120 km radius during the next 120 hours. Numbers represent a real position of the cyclone at the certain hour. The green line is a control forecast (unperturbed member of ensemble) and the blue lines are different ensemble member forecasts. The left panel (a) shows the results obtained by EPS using the tropical singular vectors with very simple vertical diffusion (Buizza 1994), the right one (b) with the whole set of linearized physics developed at ECMWF (Mahfouf 1999). The strike probability maps show that the cyclone moves too slowly when only a simple diffusion scheme is used. In the case of tropical singular vectors with a more sophisticated description of physical processes, there are few ensemble members which follow the real track of cyclone.

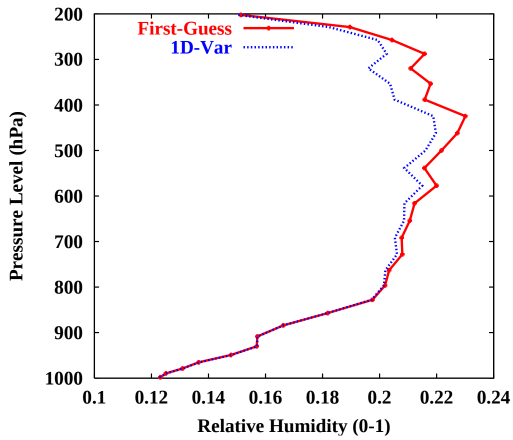


*Figure 7: Comparison of the first-guess (red) and retrieved (blue) relative humidity using 1D-Var of AIRS observations against European radiosondes for the period of November 2002 to February 2003. Results are presented as root mean square errors.*

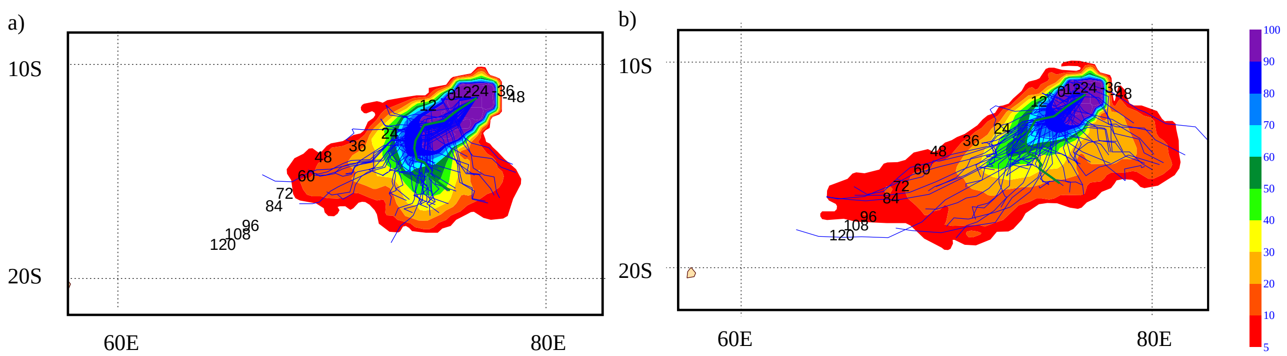


*Figure 8: Strike probability maps for the cyclone Kalunde (6 March 2003, 12UTC), obtained by EPS using the tropical singular vectors with very simple vertical diffusion (a) and with the whole set of linearized physics (b). See text for details.*

### 4.4 Using adjoint technique for sensitivity of the parametrization scheme to input parameters

The adjoint models can also be used for sensitivity studies since they allow to compute the gradient of one output parameter of a numerical model with respect to all input parameters. When such technique is applied to a particular physical parametrization scheme, it can provide information on the meteorological variables to which the parametrization scheme is the most sensitive. From a data assimilation point of view, it can give some indications related to the importance and efficiency of particular types of observations. Given the definition of the adjoint, adjoint( $\mathbf{F}^T$) of the linear operator $\mathbf{F}$ provides the gradient of an objective function $\mathscr{J}$ with respect to $\mathbf{x}$ (input variables) given the gradient of $\mathscr{J}$ with respect to $\mathbf{y}$ (output variables) as:

$$\frac{\partial \mathscr{J}}{\partial \mathbf{x}} = \mathbf{F}_{\mathbf{x}}^T . \frac{\partial \mathscr{J}}{\partial \mathbf{y}} \quad \text{or} \quad \nabla_{\mathbf{x}} \mathscr{J} = \mathbf{F}_{\mathbf{x}}^T . \nabla_{\mathbf{y}} \mathscr{J} \tag{6}$$

As an example of such sensitivity, the gradient with respect to $\mathbf{y}$ of unity size (i.e. perturbation of some of the radiation fluxes) is provided to the adjoint of the radiation schemes in order to get the sensitivity of this scheme with respect to its input variables, i.e. temperature, specific humidity and cloud characteristics (cloud fraction, cloud liquid and ice water contents).

Sensitivity of the shortwave upward radiation flux at the top of atmosphere (TOA) with respect to specific humidity at clear sky conditions is shown on Fig. 9 for the winter (a) and summer (b) cases. The results are presented as zonal means. The shortwave radiation is the most sensitive to humidity at high latitudes in the summer hemisphere, while the tropics is an insensitive region. This latitude dependent features are linked to the surface albedo. Since the tropical surface is characterized by oceans with large darkness, the atmosphere and surface system almost fully absorb the radiation. By contrast, the surface at high latitudes is characterized by snow or ice cover with large brightness. Indeed, the sensitivity structure at 700 hPa (Fig. 10), which corresponds to the maximum absorption height, illustrates the predominant linkage to the surface albedo. One can see a large sensitivity over the summer polar area and lands with a large albedo. Similar results were obtained by Li and Navon (1998) in their study of adjoint sensitivity of the Earth's radiation budget to cloud cover, water vapour, atmospheric temperature and surface temperature in the National Centers for Environmental Prediction (NCEP).

Compared with the standard approaches for evaluation of physical parametrization schemes (sensitivity of all the outputs to a given input quantity), the adjoint is a complementary and very efficient approach for sensitivity studies. Using a single integration when perturbing one output parameter by unity size perturbation, it is possible to get sensitivity to all input parameters.

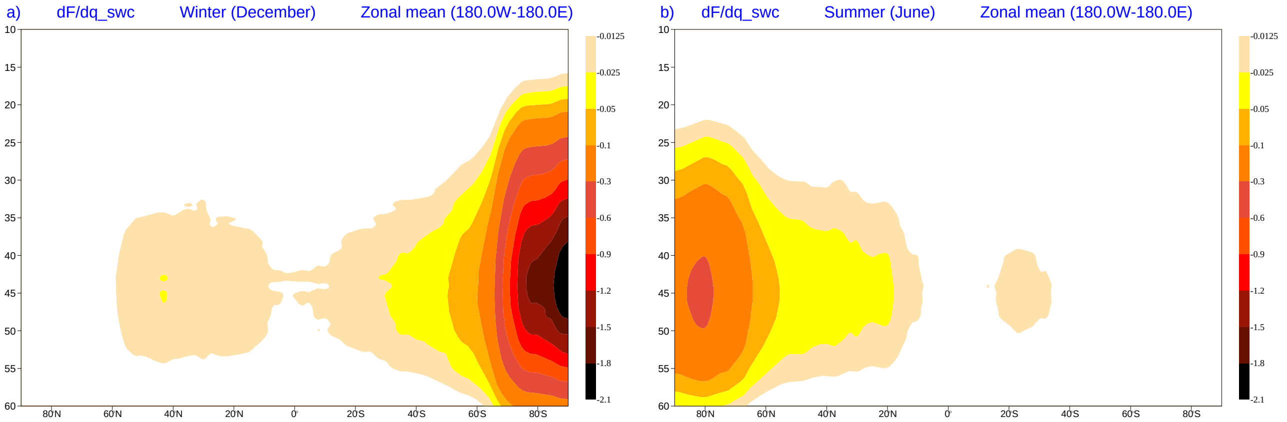


*Figure 9: The zonally averaged sensitivity of the shortwave upward radiation flux at the top of atmosphere (TOA) to specific humidity for (a) December and (b) June cases. The colour contour intervals are in* $Wm^{-2}g^{-1}kg$.

## 5 Conclusions

A positive impact from including linearized physical parametrization schemes into the assimilating model and singular vector computations has been demonstrated in the experimental and operational runs. The adjoint of physical processes can also be used for sensitivity studies and for model parameter estimations.

Physical parametrizations become more and more important components in recent variational data assimilation systems. To benefit from including the physical processes in the linearized models, it is important to be always careful whether the linearized parametrization schemes are not too nonlinear or discontinuous and to apply some regularizations/simplifications when necessary. This caution is particularly relevant for the assimilation of observations related to moist processes (precipitation, clouds and soil moisture), to which a lot of effort is currently devoted at ECMWF. Development of adjoint code is technically demanding and time-consuming.

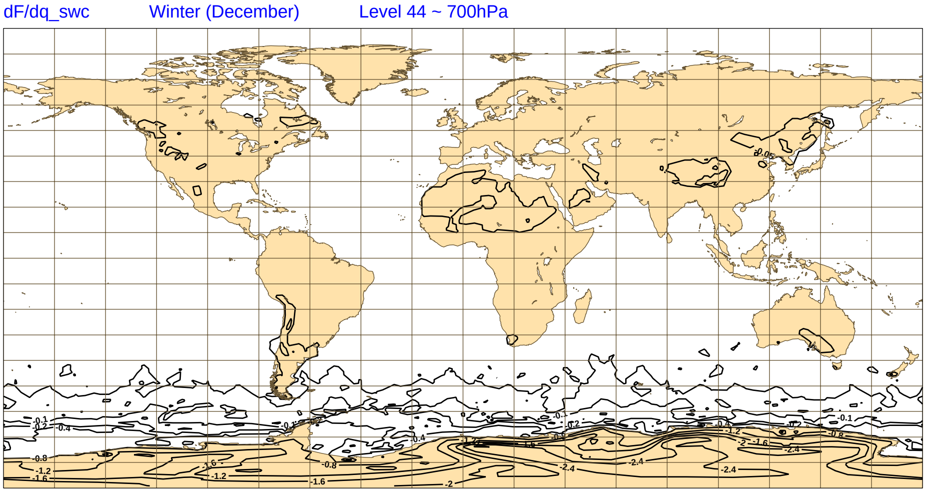


*Figure 10: Sensitivity of the shortwave upward radiation flux at the TOA to specific humidity for winter and for the model level close to 700 hPa. The contour interval is 0.2 $W m^{-2} g^{-1} kg$.*

Therefore, a reliable automatic tool for adjoint coding, which provides correct and computationally efficient adjoint code, would be useful.

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