Precipitation assimilation at ECMWF

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1 Introduction

The assimilation of observations related to cloud and precipitation has become a very important issue for most operational weather services including ECMWF. Marécal and Mahfouf (2000) developed a 1D-Var method for correcting individual profiles of the model's control variables in order to decrease the discrepancies that may exist between the simulated surface rainfall rates and corresponding retrievals from the Tropical Rainfall Measuring Mission Microwave Imager (TRMM/TMI) or from the Special Sensor Microwave/Imager (SSM/I).

Marécal and Mahfouf (2002) also found that an indirect "1D-Var + 4D-Var" assimilation of TMI derived rainfall rates could improve the quality of humidity, temperature and wind forecasts in the Tropics. In this approach, the background-observation departures on surface rainfall rates are first converted into total column water vapour (TCWV) increments thanks to the 1D-Var, and the corresponding TCWV pseudo-observations are then assimilated in the 4D-Var system. They also showed that this indirect method is more robust than a direct 4D-Var assimilation of the TMI rainfall rates, because of some inconsistencies between the inner and outer loops of 4D-Var. The "1D-Var + 4D-Var" technique therefore seems more appropriate for performing the future assimilation of such data, as long as these inconsistencies are not removed.

Instead of performing the 1D-Var on surface rainfall rates that are derived from multi-channel microwave brightness temperatures (BTs) thanks to various algorithms, the 1D-Var calculations could also very well be applied to the BTs directly. The multiple sensitivities of the BTs to the vertically integrated amounts of rain water and cloud water should provide a stronger constraint on the 1D-Var minimization. Another advantage of this method could result from the better knowledge of observation errors on BTs than on derived rainfall rates.

The potential of applying 1D-Var directly to TMI and SSM/I microwave brightness temperatures has been investigated and its results have been compared with the 1D-Var on derived rainfall rates. The two methods will be referred to as 1D/BT and 1D/RR hereafter. In addition, "1D-Var + 4D-Var" assimilation experiments have been run with the most up-to-date version of ECMWF's forecasting system in order to assess the impact of TMI or SSM/I observations in precipitation areas on 4D-Var analyses and on subsequent forecasts.

2 Modifications of ECMWF's operational convection scheme

Prior to all experiments, some modifications were made to ECMWF's parameterizations of convection and large-scale condensational processes. These changes were expected to increase the level of physical realism of the parameterizations with respect to the very simplified ones used in current 4D-Var. At the same time, the modified schemes were designed such as to behave more linearly when compared to the highly non-linear operational schemes originally designed by Tiedtke (1989, 1993).

The modified convection scheme is still based on the mass-flux approach, but it now features uncoupled equations for the mass-flux and for the updraft characteristics. The total entrainment rate (turbulent and organized) is expressed as 1/(2z), where z denotes the height above the updraft starting level, according to Siebesma and Jakob's recent ideas (personal communication). Detrainment is assumed to be equal to the entrainment rate, except close to cloud top where an enhanced constant value is applied. The vertical evolution of the updraft vertical velocity is parameterized as in Simpson and Wiggert (1969), and the closure of the scheme is based on the relaxation of convective available potential energy for all types of convection.

Tompkins and Janisková (personal communication) have recently developed a new simplified statistical diagnostic cloud-scheme that includes precipitation generation according to Sundqvist (1989) and a new formulation of precipitation evaporation based on the subgrid scale distribution of total water.

3 1D-Var experiments on TMI and SSM/I observations

3.1 Description of the 1D-Var method

The purpose of the unidimensional variational method (1D-Var) is to determine increments that need to be added to the model's control variables so that the difference between a selected output quantity of the model and its observed equivalent becomes minimal in a least-square sense. In the present study, two control variables are considered in the model: temperature and specific humidity.

The selected output quantity to be optimized is either the surface rainfall rate (like in Marécal and Mahfouf 2000) or the multi-channel microwave brightness temperatures. Surface rainfall rate is an output from the model convective and large-scale condensation parameterizations and can also be derived from observed microwave brightness temperatures thanks to a proper retrieval algorithm (see section 2). On the other hand, brightness temperatures can be simulated applying first the parameterizations of moist processes to the model's control variables and then a microwave radiative transfer model.

The 1D-Var method searches for the model's state vector **x** that minimizes the following functional:

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x_b})^T \mathbf{B}^{-1}(\mathbf{x} - \mathbf{x_b}) + \frac{1}{2}\left[\frac{H(\mathbf{x}) - Y_{obs}}{\sigma_{obs}}\right]^2$$

where $\mathbf{x_b}$ is the background model state, and $H(\mathbf{x})$ is the non-linear observation operator which permits to convert the model's variables into either surface rainfall rates or microwave brightness temperatures. Y_{obs} denotes the corresponding observed quantity and σ_{obs} is the standard deviation of the observation errors. Matrix **B** contains the model's background error covariances. The result of the 1D-Var is therefore a linear combination of the background term and of the observation term, weighted by the inverse of their respective error statistics.

The minimization of $J(\mathbf{x})$ is performed thanks to the quasi-Newton descent algorithm (M1QN3) developed by Gilbert and Lemaréchal (1989). It involves the jacobian matrix of the nonlinear observation operator $H(\mathbf{x})$ which consists of the modified parameterizations of convection and of large-scale condensation described in section 2. In the case of 1D/BT, the minimization also involves the forward non-linear version and the adjoint version of the radiative transfer model designed by Bauer (2002) and Moreau *et al.* (2002), which takes into account the diffusion of microwave radiation by precipitation.

3.2 Set-up of the 1D-Var experiments

1D-Var experiments have been run on three recent meteorological events: Super-typhoon MITAG near the Philippines at 1200 UTC 5 March 2002, tropical cyclone ZOE close to the Fiji Islands at 1200 UTC 26 December 2002, and an extra-tropical front in the North Atlantic at 1200 UTC 9 January 2002. TMI observations have been used for MITAG and ZOE, SSM/I ones in the mid-latitude frontal case.

In 1D/RR, various algorithms have been tested for retrieving surface rainfall amounts from the multi-channel microwave brightness temperatures observed by either TMI or SSM/I: 2A12-v5 (Kummerow *et al.* 1996), PATER (Bauer 2002), Ferraro (1996) and Bauer-Schluessel (1993). The rainfall retrievals at instrument resolution were then averaged onto the Gaussian grid of the ECMWF model which corresponds to a T511 spectral truncation (grid point resolution of about 40 km), so that observation and model points became co-located. The retrieval errors for PATER have been estimated as in Bauer *et al.* (2002), while the errors derived by L'Ecuyer and Stephens (2002) have been applied to 2A12-v5 retrievals. For the two other algorithms, a constant error of 50% of the rainfall rate has been assumed.

In 1D/BT on TMI observations, the minimization has been applied to seven channels: 10 GHz (V/H), 19 GHz (V/H), 22 GHz (V) and 37 GHz (V/H), where V and H denote the vertical and horizontal polarizations. With SSM/I data, only the 19 GHz (V/H), 22 GHz (V) and 37 GHz (V/H) channels are available. Increasing the number of microwave channels used in the 1D-Var is expected to be beneficial because of their differing sensitivities to temperature, water vapour, cloud water and precipitation. The observed BT at each model grid point has been set equal to its value at the closest TMI pixel, in each microwave channel. For BTs, σ_{obs} has been set to 3 K (resp. 6 K) for the vertically (resp. horizontally) polarized channels. This is assumed to account for both the instrumental errors and the errors of the radiative transfer model.

The model's background fields that enter the 1D-Var have been obtained from 12-hour T511 forecasts with the ECMWF model. The covariance matrix of background errors **B** used in the 1D-Var is taken from the operational ECMWF 4D-Var system (Rabier *et al.* 1997). The temperature and specific humidity errors are assumed to be uncorrelated.

3.3 Summary of the 1D-Var results

As an illustration, Fig.1 displays the results of the 1D-Var calculations on super-typhoon MITAG: the model's background surface rainfall rates are shown in panel (a). The observed rainfall rates as retrieved with the 2A12-v5 algorithm from the TMI BTs appear in panel (b). "Analysed" surface rainfall rates can be simulated using the parameterizations of moist processes after adding the 1D-Var increments to the model's background profiles of temperature and specific humidity. These analysed rainfall rates are shown in panel (c) for 1D/BT and (d) for 1D/RR.

Fig.2 shows the TCWV background field and the corresponding increments from 1D/RR on PATER observations and from 1D/BT.

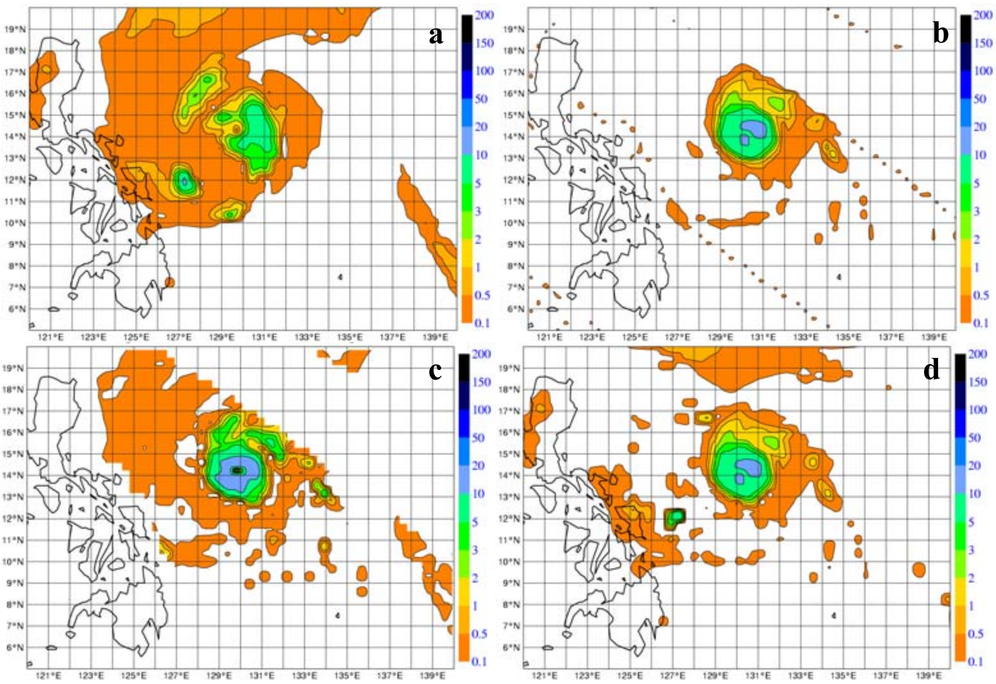

Fig.1. Surface rain rates from model background (a) for the case of super-typhoon MITAG at 1200 UTC 5 March 2002. Corresponding TMI observations from the PATER algorithm (b), and corresponding analysed rainfall rates from 1D/BT (c) and from 1D/RR (d). Units are in mm h^{-1}.

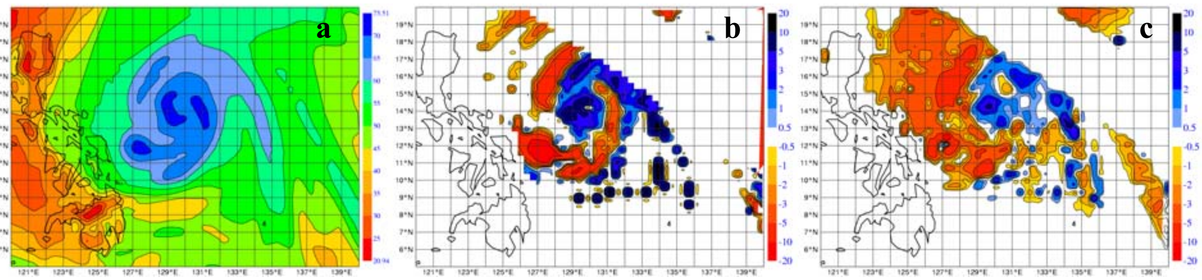

Fig.2. Background TCWV (a) for the case of super-typhoon MITAG at 1200 UTC 5 March 2002. TCWV increments from 1D/BT (b) and from 1D/RR on PATER surface rainfall rates (c). Units are in kg m^{-2}.

Fig.1 clearly demonstrates that both 1D/RR and 1D/BT are able to correct the initial temperature and specific humidity profiles in such way that the model gets closer to the observations. It is noteworthy that in the case of 1D/BT the agreement is all the more remarkable as the PATER rainfall rates provide an *independent* source of validation. The tighter initial screening of points applied in 1D/BT to save computational time explains why the light rain area around the storm is not modified in Fig.1.c. It should also be recalled here that 1D/RR only works at points where the jacobian matrix **R** is non-zero, that is only at rainy points of the model's background. Fig.2 points out the similarity between the patterns of the TCWV increments obtained with the two 1D-Var methods. However, 1D/BT systematically produces increments with a stronger magnitude than 1D/RR, as a result of the multiple sensitivities of microwave brightness temperatures to precipitation but also to cloud condensate and water vapour. All these findings have been confirmed in the two other studied cases (not shown), as well as for the different rainfall rate retrieval algorithms tested.

By looking at the other cases, it has also been evidenced that 1D/RR performs better at points where the background precipitation originates from the large-scale condensation scheme and not from the convective parameterization which involves more non-linearities. This was clearly seen in the case of tropical cyclone ZOE for which 1D/BT was more successful than 1D/RR in the presence of intense deep convection in the model.

A statistical cross-comparison of 1D/RR with 1D/BT has pointed out that the reduction of the model-observation errors on BTs with 1D/RR is more systematic than the reduction of the model-observation errors on rainfall rates with 1D/BT. Furthermore, the 1D-Var outputs have been validated against independent measurements from the TRMM precipitation radar (both in terms of rainfall rates and reflectivities) and from the NOAA AMSU-B instrument.

4 "1D-Var + 4D-Var" assimilation of TMI observations in rainy areas

After running 1D/RR and 1D/BT on TMI observations over the region of tropical cyclone ZOE, pseudo-observations of TCWV have been obtained by vertical integration of the 1D-Var increments of specific humidity and adding the result to the background TCWV. These TCWV pseudo-observations have been assimilated inside ECMWF's 4D-Var in order to study their impact on 4D-Var analyses and on subsequent forecasts. Three experiments have been run: a "control" 4D-Var assimilation of all available routinely used observations, a 4D-Var assimilation of the same data plus the 1D/RR TCWV pseudo-observations, and a similar experiment with 1D/BT TCWV pseudo-observations.

These tests have permitted to find 1) that 4D-Var can properly handle the 1D-Var/TMI TCWV pseudo-observations, 2) that significant increments can be seen on the humidity field but also on the dynamics in the vicinity of the storm, and 3) that the amplitude of these increments remain significant in the forecasts started from the new analyses. These findings confirm earlier results from Marécal and Mahfouf (2000) obtained with an older set-up of ECMWF's model.

As an illustration, Fig.3 displays differences of TCWV and 850 hPa winds between 12-hour forecasts issued from the new analysis and from the control analysis, when using 1D/RR (a) and 1D/BT (b) TCWV pseudo-observations.

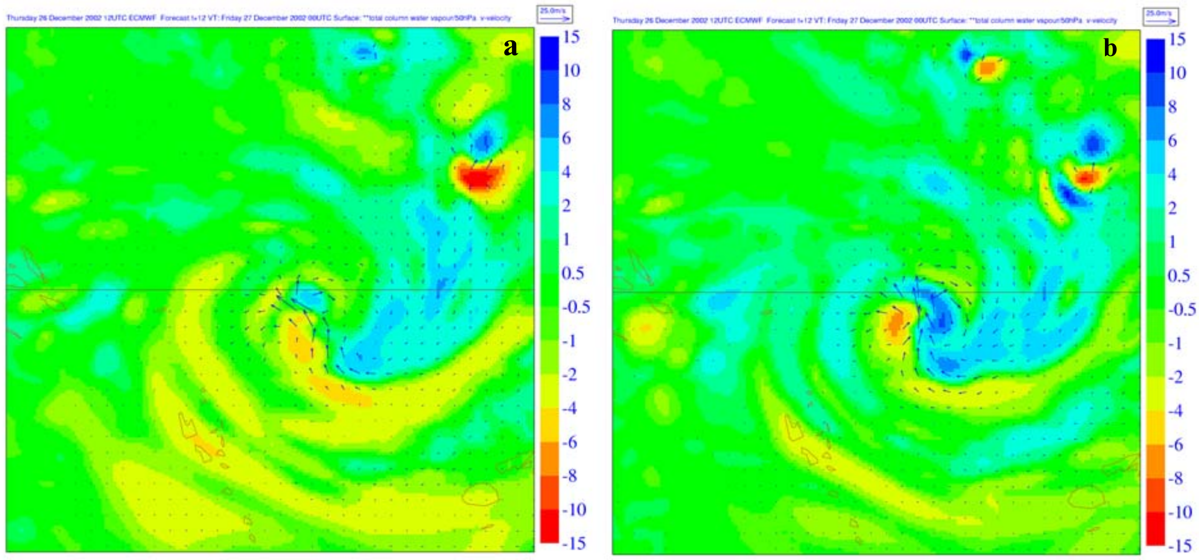

Fig.3. Differences between 12-hour forecasts started from the 4D-Var analysis with TMI observations and from the control 4D-Var analysis, when using 1D/RR (a) and 1D/BT (b). Differences of TCWV are displayed in colors and differences of 850 hPa winds are plotted as arrows. At this time (0000 UTC 27 December 2002), tropical cyclone ZOE is centered at the middle of the plotted domain. Units for TCWV are in kg m^{-2}, while for wind differences the longest arrow corresponds to 25 m s^{-1}.

In both cases, the impact on the TCWV and wind fields is still large after 12-hours, but is even stronger when using 1D/BT, despite a smaller number of TCWV observations because of differences in the 1D-Var screening. This is due to the fact that the 4D-Var analysis increments (not shown) are already larger when using 1D/BT.

In addition, Fig.4 illustrates the clear improvement of the track forecast for tropical cyclone ZOE in the "1D/RR+4D-Var" and "1D/BT +4D-Var" experiments compared to the control experiment and to observations.

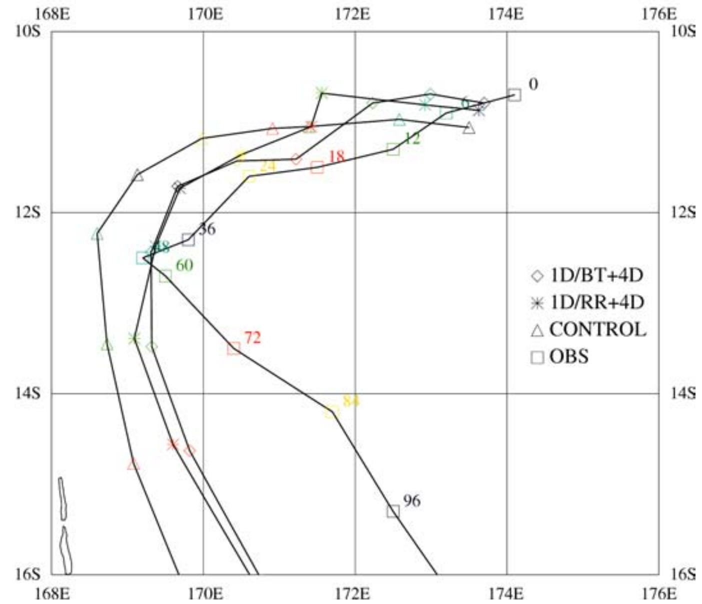

Fig.4. Comparison of the tracks of tropical cyclone ZOE as from observations (squares), from control 4D-Var (triangles), from '1D/TMI-RR + 4D-Var' (stars), and from '1D/TMI-BT + 4D-Var' (diamonds). Forecast times in hours are indicated along the observed track, and similar colors correspond to similar forecast times in the experiments. Time 0 corresponds to the analysis.

5 Conclusions

1D-Var experiments based on retrieved surface rainfall rates as observed from TMI and SSM/I have been compared to 1D-Var experiments directly performed on the TMI and SSM/I brightness temperatures, for three tropical and mid-latitude cases. These runs include simplified versions of ECMWF's operational parameterizations of moist processes. Both 1D-Var methods are successful in producing reasonable and consistent temperature and specific humidity increments that permit to correct either the model's surface rainfall rates or the simulated BTs towards their observed equivalents. Besides, specific humidity increments dominate and are generally larger with 1D/BT than with 1D/RR.

The 1D-Var on rainfall rates has the main advantage of being computationally cheaper than the 1D-Var on BTs. The two major drawbacks of the former lies in its total inefficiency wherever the background rainfall rate is zero and in the necessity of choosing the proper retrieval algorithm for converting microwave BTs into surface rainfall rates. On the other hand, two advantages of the brightness temperature approach can be listed: firstly, the error statistics are better known for BTs than for derived surface rain rates that depend on the retrieval algorithm used. Secondly, the fact that microwave BTs are sensitive not only to precipitation but also to water vapour and cloud water, make it possible to correct the model's control variables outside non-rainy areas of the background.

Preliminary 4D-Var assimilation of pseudo-observations of TCWV obtained from the 1D-Var on TMI rainfall rates or BTs in rainy areas around tropical cyclone ZOE have shown that these extra observations can lead to significant thermodynamic and dynamical changes in the 4D-Var analyses and the subsequent forecasts. The changes in 4D-Var obtained with 1D/BT TCWV observations are clearly larger than with 1D/RR. A clear improvement is also found in the track forecast of the studied storm.

Global monthly experiments currently in progress will help determine whether the assimilation of TMI and SSM/I observations can lead to a systematic improvement of both analyses and forecast scores.

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