1D-Var tests with TMI and SSM/I observations in rainy areas

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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 often exist between the simulated surface rainfall rates and corresponding retrievals obtained from TMI or SSM/I microwave measurements.

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 the 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 in this study and its results have been compared with the 1D-Var with derived rainfall rates.

Prior to these 1D-Var tests, some modifications were made to the ECMWF's parameterizations of moist processes. These changes were expected to increase the level of physical realism of the parameterizations with respect to the very simplified ones used in the 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.

2. Modifications of ECMWF's operational convection scheme

2.1. Description of the modified convection scheme

Previous studies advocated an improvement of the linearized version of the ECMWF's parameterizations of moist processes, especially convection and the cloud scheme, to be used both in the full 4D-Var and in the simpler 1D-Var algorithm developed by Marécal and Mahfouf (2000). A modified version of the operational convection scheme was therefore developed for the future variational assimilation of cloud and precipitation observations.

This modified mass-flux scheme was designed such as to retain some basic similarities with the original mass-flux scheme from Tiedtke (1989) and at the same time to remove the high degree of complexity of the latter.

All types of convection (shallow, mid-level, and deep) are now treated in a similar way. In particular, the link between the model control variables and the subgrid-scale convective quantities (the so-called *closure assumption*) is expressed through a single formulation that depends on the *release of convective available potential energy* (CAPE) in time.

The equations that describe the vertical evolution of the updraft/downdraft mass-flux M_u and of the updraft/downdraft thermodynamic variables Φ_u are now uncoupled:

$$\frac{\partial \Phi_u}{\partial z} = -\varepsilon\left(\Phi_u - \overline{\Phi}\right) \text{ and } \frac{\partial M_u}{\partial z} = -\left(\varepsilon - \delta\right) M_u \tag{1}$$

This has permitted the removal of the iterative calculations involved in the operational code, thereby leading to an easier development of the adjoint.

The bulk convective updraft is assumed to originate from the surface only if its initial vertical velocity as calculated from the surface heat fluxes is positive. The departures of the updraft from the environment are also assumed to be dependent on the surface heat fluxes. If convection cannot be initiated from the surface, the convective ascent may also originate at higher levels where the atmosphere is close to saturation. The initial vertical velocity of the bulk updraft is then set equal to 1 m/s.

An additional equation permits the determination of the vertical evolution of the updraft kinetic energy, which involves the entrainment of environmental air into the updraft, following Simpson and Wiggert (1969):

$$\frac{\partial w_u^2}{\partial z} = -\alpha\varepsilon w_u^2 + \beta B(z) \tag{2}$$

where α=2/3 and β=1 , B(z) is the buoyancy and w_u is the updraft vertical velocity.

Based on ideas of Siebesma and Jakob (personal communication), the total fractional entrainment rate ε is parameterized as $c_\varepsilon/(z-z_{st})+10^{-5}$, where c_ε=0.5 and z_{st} is the starting altitude of the updraft, while the detrainment rate δ is set equal to the entrainment rate, except close to cloud top where a constant organized detrainment is applied. Convection is assumed to be active only if the updraft vertical velocity remains positive at cloud base.

Simplified calculations of downdrafts and convective momentum transport are also included in the modified parameterization.

2.2. Assessment of the linear behaviour of the modified convection scheme

The sensitivities of the outputs of the modified convection scheme to the input temperature and specific humidity have been computed for a set of several hundred initial atmospheric profiles thanks to the jacobian method. This approach has permitted to efficiently isolate and modify portions of the code that could lead to excessive and thus undesirable sensitivities (*e.g.* dependence of detrainment on updraft vertical velocity). With these modifications, the vertical profiles of the surface rainfall jacobians look much smoother with the modified parameterization than with the operational one. The domain of validity of the linear assumption has also turned out to be broader with the modified convection scheme than with the operational one. Given the more satisfactory behaviour of the modified convection scheme in terms of linearity, its tangent linear and adjoint versions have been coded and tested.

2.3. Validation of the modified convection scheme

The modified convection scheme has first been validated in the single column version of the ECMWF model on several typical cases of deep and shallow convection over both land and ocean. It has then been tested in medium-range (T511 L60) and 4-month long (T95 L60) simulations with the full 3D model.

Observations from ERBE, ISCCP, GPCP, SSM/I and TRMM have been used to validate the radiative and hydrological bugdets of the 4-month long runs. The modified parameterization leads to results that compare rather well with both the operational model and the observations (despite a too narrow Inter-Tropical Convergence Zone in both versions).

3. 1D-Var applications with 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. They are given in the form of individual vertical profiles at a given time.

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 be derived from observed microwave brightness temperatures thanks to a proper retrieval algorithm (see section 3.3). On the other hand, brightness temperatures can be simulated by applying the parameterizations of moist processes to the model's control variables and then a microwave radiative transfer model. The main inputs to the latter model are precipitation contents, cloud water contents, cloud cover, specific humidity and temperature.

In the present study, the 1D-Var method consists of searching for the model's state vector $\mathbf{x}$ that minimizes the following functional:

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x_b})^T \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x_b}) + \frac{1}{2}\left[\frac{H(\mathbf{x})-Y_{obs}}{\sigma_{obs}}\right]^2 \tag{3}$$

where $\mathbf{x_b}$ is the background model state (*i.e.* the model's control vector to be corrected), 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 (see section 3.3). Matrix **B** contains the background error covariances for the model's control variables (temperature and specific humidity). 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 the functional is performed thanks to the quasi-Newton descent algorithm (M1QN3) developed by Gilbert and Lemaréchal (1989). It requires the calculation of the gradient of the functional defined in (3), which writes

$$\nabla J(\mathbf{x}) = \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x_b}) + \mathbf{H}^T \left[\frac{H(\mathbf{x}) - Y_{obs}}{\sigma_{obs}^2} \right] \quad (4)$$

where $\mathbf{H}^T$ is the transpose (or adjoint) of the jacobian matrix of the nonlinear observation operator $H(\mathbf{x})$. In this study, the model consists of the modified parameterization of convection described in section 1.1 as well as of the statistical cloud scheme that has been recently designed by Tompkins and Janisková (personal communication) for the particular purpose of data assimilation in the ECMWF model. In the case of the 1D-Var on brightness temperatures, the simulator also includes 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. Description of the selected meteorological event

The selected meteorological situation focuses on super-typhoon MITAG that developed over the West Pacific at the beginning of March 2002. 5 March 2002 1200 UTC was chosen as the exact date for this 1D-Var test, that is when the super-typhoon has reached his maximum intensity just east of the Philippines (estimated mean-sea-level pressure minimum of 930 hPa located at point 14.2°N/129.9°E). This case involves both convective and stratiform precipitation or, in other words, both the subgrid-scale and large-scale model parameterizations of the model.

3.3. Observations and associated errors

Two different algorithms have been tested for retrieving surface rainfall amounts from the multi-channel microwave brightness temperatures observed by TMI at the instrument spatial resolution: the 2A12-v5 (Kummerow *et al.* 1996) and PATER (Bauer 2002) algorithms. The high-resolution rainfall retrievals were then averaged onto the Gaussian grid of the ECMWF model that corresponds to a T511 spectral truncation (grid point resolution of about 40 km), so that observation and model points are co-localised.

The retrieval errors for PATER were estimated as in Bauer *et al.* (2002). For the 2A12-v5 algorithm, the errors derived by L'Ecuyer and Stephens (2002) have been applied, that is:

$$\frac{\sigma_{obs}}{R_{obs}} = 0.512 - 0.044 \quad R_{obs} + 0.0039 \quad R_{obs}^2 - 0.000054 \quad R_{obs}^3 \quad (5)$$

As regards TMI brightness temperatures, the observed value at each model grid point has been set equal to the 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 and this is assumed to account for both the instrumental errors and the errors of the radiative transfer model.

3.4. Background fields and errors

The model's background fields that enter the 1D-Var have been obtained from a 12-hour T511 integration of the ECMWF model starting at 5 March 2002 0000 UTC. The input fields include the vertical profiles of temperature and water vapour, but also some temperature and humidity tendencies, the surface heat fluxes and the surface momentum stress that are needed for running the modified convection scheme described in section 1.1. Note that the modified convection scheme was used instead of the operational one in these preliminary simulations in order to ensure a better consistency with 1D-Var.

The covariance matrix of background errors **B** is taken from the operational ECMWF 4D-Var system (Rabier *et al.* 1997). The temperature and specific humidity errors are assumed to be uncorrelated.

3.5. Results

3.5.1. 1D-Var on rainfall retrievals

Fig.1 displays the results for the 1D-Var experiments on super-typhoon MITAG: the model 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). The "analysed" surface rainfall rates that are simulated when the 1D-Var analysis increments are added to the model's background profiles of temperature and specific humidity, are shown in panel (c). Panels (d) and (e) display the same quantities, but now when the PATER algorithm is utilized. All fields are expressed in mm h^{-1}.

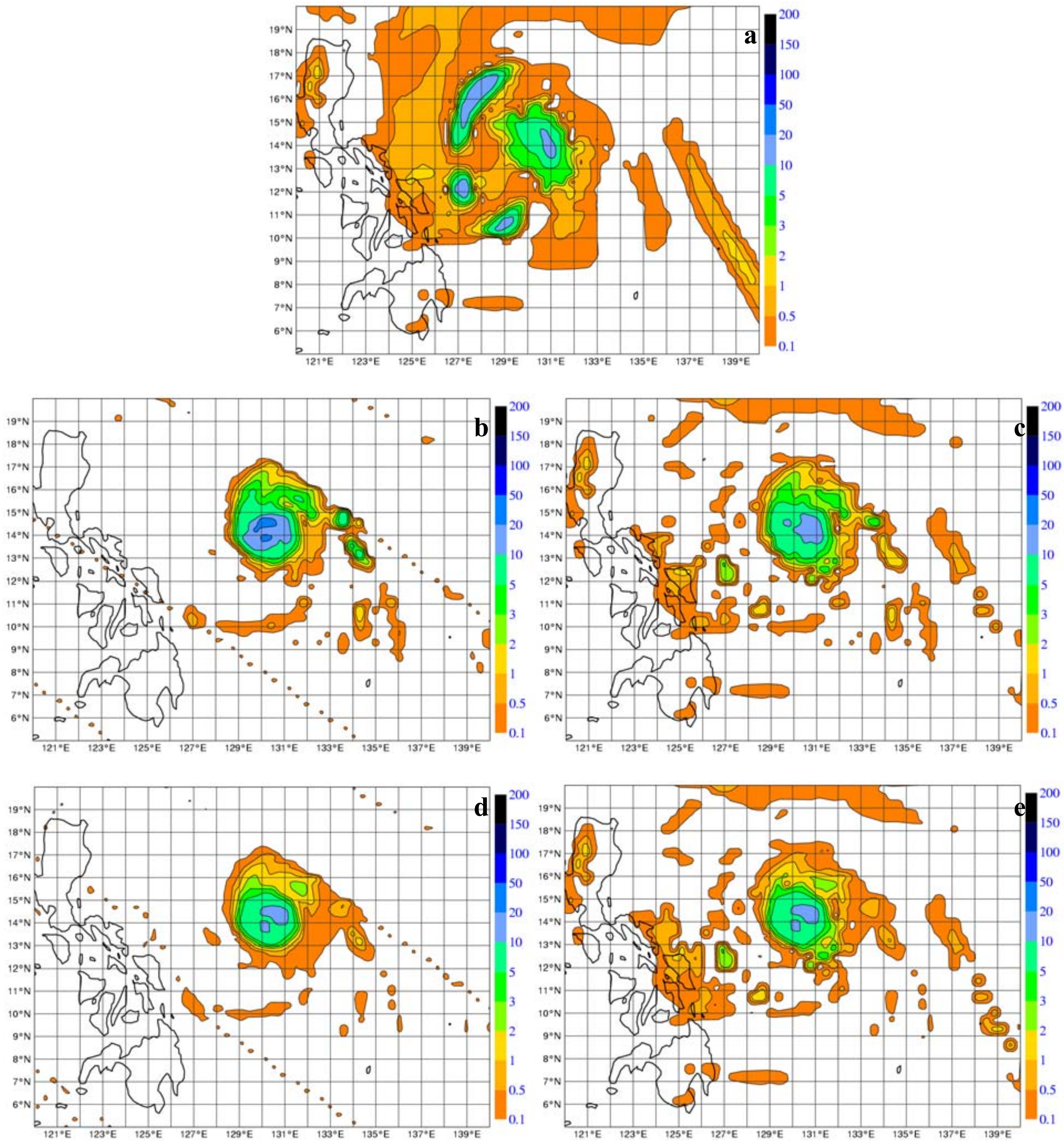

Fig.1. 1D-Var on TMI derived surface rainfall rates for the case of super-typhoon MITAG at 5 March 2002 1200 UTC: Rain rates from model background (a) from 2A12-v5 (b) and as in the corresponding 1D-Var analysis (c) from PATER (d) and as in the corresponding 1D-Var analysis (e). Units are in mm h^{-1}.

Although some heavy rain is correctly simulated by the model in the vicinity of the typhoon's core, panel (a) indicates that the background clearly differs from the observations in the western periphery of the storm. Indeed, three regions with heavy precipitation which do not appear in the TMI observations are simulated by the model.

Panels (c) and (e) clearly demonstrate that the 1D-Var procedure is able to correct the initial temperature and specific humidity profiles in such way that the "analysed" rain field gets rather close to the observations. This improvement on the picture of the simulated typhoon results from both the increase and the decrease of precipitation at places where the observed value is higher, respectively lower, than the model's background value. However, it should be emphasized that the 1D-Var based on rainfall rates is efficient only at points where the background precipitation is non-zero. At locations where the initial simulated rainfall rate is zero, the jacobian matrix **R** is zero, which implies that the minimization is ineffective. In the present case, the 1D-Var on rainfall rates work well because the rain produced by Tompkins and Janisková's large-scale condensation scheme spreads over a wide area around the storm. Earlier 1D-Var tests run with another parameterization that generated more confined precipitation, led to much less satisfactory analysed surface rain rates.

The convergence of the minimization is usually satisfactory, except at a few grid points, for which the analyzed rainfall rates remain far from the observations due to non-linearities or problematic jacobians.

One should also note that the observed TMI rainfall rates from PATER are substantially weaker than the ones obtained from 2A12-v5. Such difference was already evidenced by Marécal *et al.* (2002). Besides, the agreement of the "analysed" rainfall rates with the corresponding observed values is better when using the PATER retrievals than the 2A12-v5 data, which can be explained by the fact that the initial departures between the background and the observations are usually smaller in the PATER case.

Fig.2 shows the vertical profiles of the temperature and specific humidity increments that are generated by the 1D-Var, averaged over the geographical domain of Fig.1, with a distinction between points for which the background rainfall rate is either larger or lower than the TMI observed value. These profiles clearly indicate that the reduction (resp. the increase) of the model surface rainfall by the 1D-Var is achieved through a drying and a heating (resp. a moistening and a cooling) of the troposphere below 300 hPa. This latter result can be readily explained by the fact that these increments are mainly obtained by activating the large-scale condensation scheme, not the convective parameterization. A simple conversion of the temperature increments into equivalent increments of saturation specific humidity also points out that the 1D-Var corrections on temperature are approximately four times weaker than the corrections on specific humidity at all levels, which confirms the previous findings of Marécal and Mahfouf (2000). However, this conclusion is likely to depend on the type of parameterizations used for describing moist processes.

Since the specific humidity increments largely exceed the temperature ones, the global impact of the 1D-Var procedure on the model state can be synthesized in Fig.3 which shows the TCWV background field and the corresponding increments for the 2A12-v5 and PATER experiments. This figure clearly points out that, in both cases, positive increments reaching 5 kg m^{-2} (resp. negative increments down to -10 kg m^{-2}) are required to increase (resp. decrease) the background surface rainfall rates towards the observed values. The larger positive increments needed with 2A12-v5 are consistent with the higher observed rainfall rates that are retrieved with this algorithm at the centre of the storm (see Fig.1).

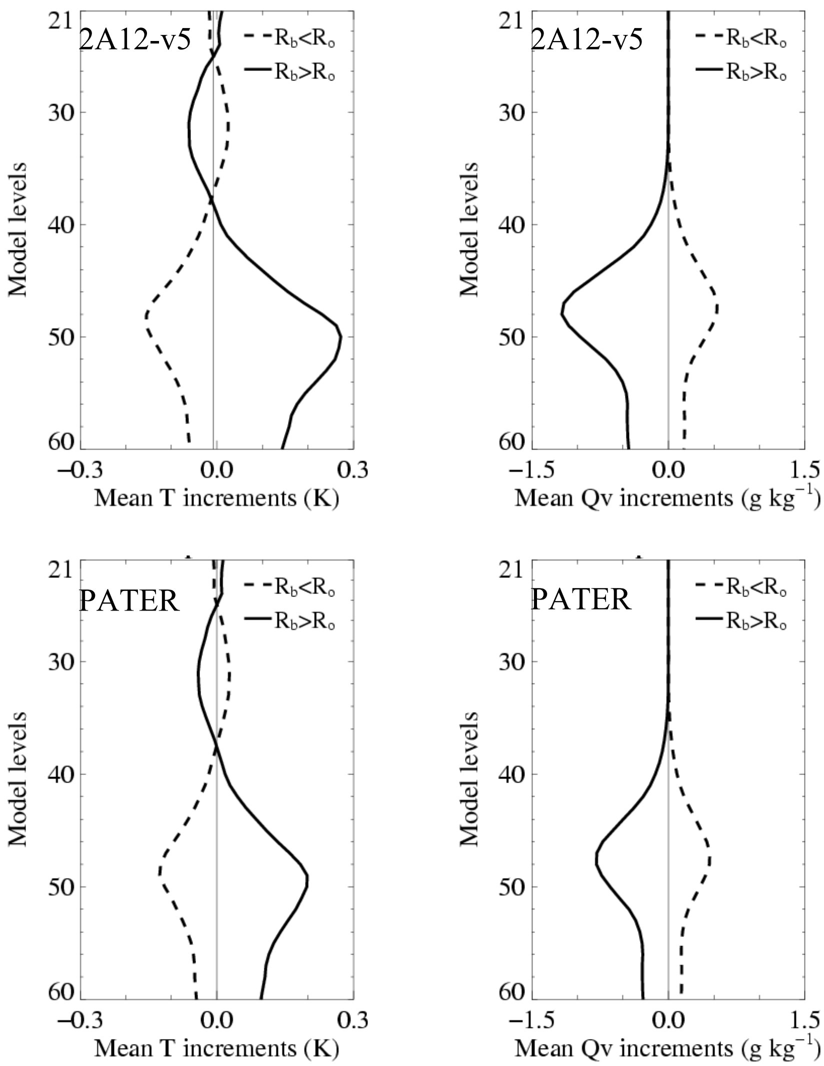

Fig.2. 1D-Var on TMI derived surface rainfall rates for the case of super-typhoon MITAG at 5 March 2002 1200 UTC: Mean vertical profiles of the increments in temperature (left panel) and specific humidity (right panel) when using rainfall observations from 2A12-v5 (top) and from PATER (bottom). Cases for which the background rainfall rate needs to be increased (resp. decreased) are plotted with a dashed line (resp. solid line). Model level 60 is close to the surface and model level 21 roughly corresponds to 50 hPa.

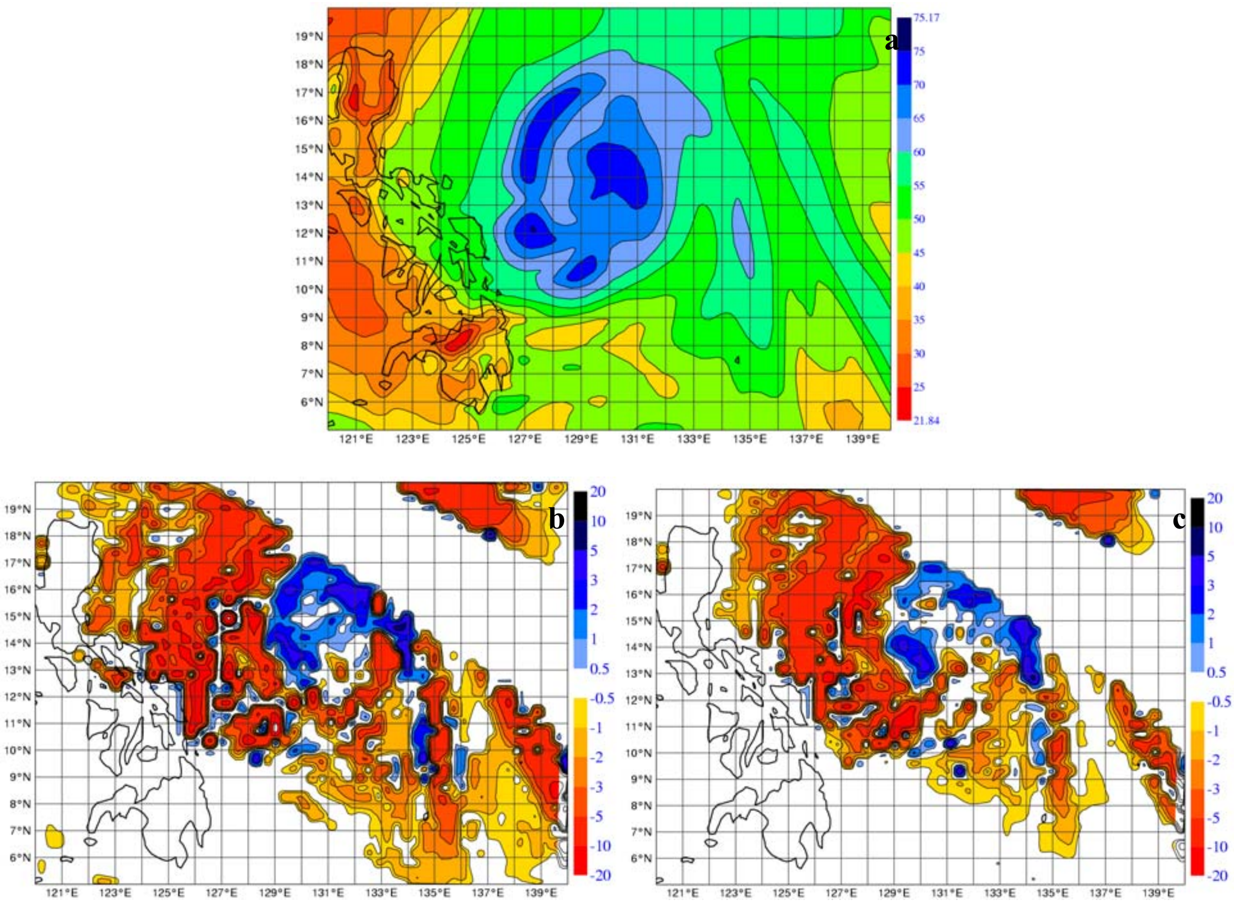

Fig.3. 1D-Var on TMI derived surface rainfall rates for the case of super-typhoon MITAG at 5 March 2002 1200 UTC: Background field of TCWV (a) and TCWV increments when using surface rainfall rates from 2A12-v5 (b) and from PATER (c). Units are in kg m^{-2}.

3.5.2. 1D-Var on microwave brightness temperatures

Fig.4 displays the surface rainfall rates that are obtained after adding the 1D-Var increments to the background temperature and specific humidity when the minimization is directly performed on the TMI brightness temperatures in three channels (panel (a): 19V, 19H, 22V) and seven channels (panel (b): 10V, 10H, 19V, 19H, 22V, 37V, 37H). Increasing the number of microwave channels used in the 1D-Var was expected to be beneficial because of their differing sensitivities to temperature, water vapour, cloud water and precipitation. For instance, the use of the 10 GHz BTs, which are particularly sensitive to the rain content, permits to avoid the saturation of the signal (*i.e.* the weak sensitivities) that occurs in other channels in heavy rain regions. However, adding channels also implies that more constraints are imposed during the minimization, which may lead to additional problems of convergence. Also note that the 85 GHz channel has been disregarded for the time being due to its strong sensitivity to ice for which the radiative transfer calculations may not be as accurate as for the liquid phase.

Fig.4 illustrates the fact that the 1D-Var performed on brightness temperatures is able to generate temperature and specific humidity increments that lead to a substantial improvement on the simulated surface rainfall rates with respect to the rainfall retrievals in Fig.1.b and d. The discrepancies between these data and the "analysed" rainfall rates are however larger with the BT approach than with the method based on rainfall retrievals. This is due to the fact that the temperature and specific humidity increments now result from simultaneous corrections applied to the rain profiles but also to the profiles of cloud water.

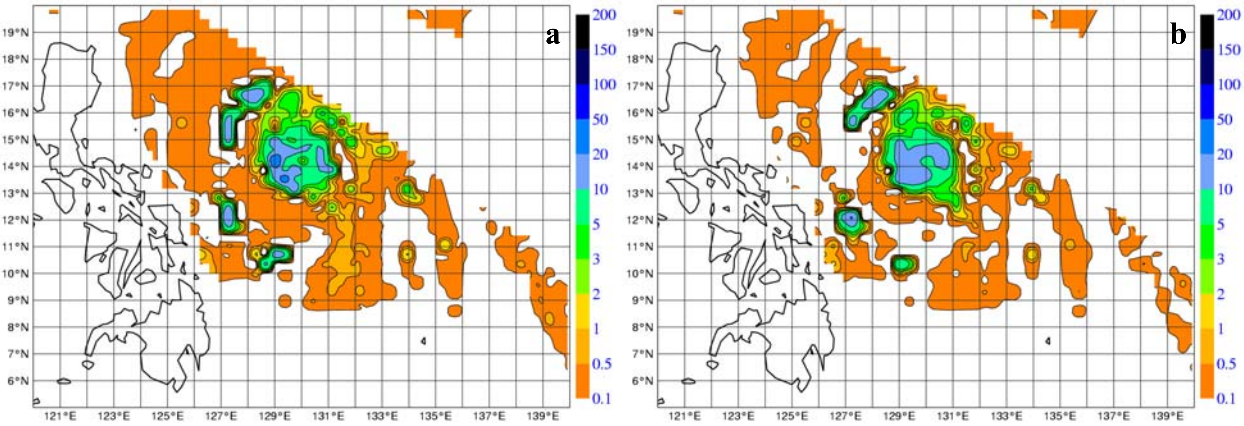

Fig.4. 1D-Var on TMI microwave brightness temperatures for the case of super-typhoon MITAG at 5 March 2002 1200 UTC: "Analysed" surface rainfall rates obtained when using the 19V, 19H and 22V channels (a) and the 10H, 10V, 19H, 19V, 22V, 37H and 37V channels (b). Units are in mm h^{-1}.

The addition of the 10 GHz and 37 GHz channels in panel (b) leads to a slight increase of the surface rainfall rates inside the storm and to a further decrease in its vicinity. With three or seven channels, the minimization fails to converge at a few isolated points but also in the northwest periphery of the super-typhoon's core. There, the departures between simulated and observed BTs reach such high values that the minimization problem becomes highly non-linear so that no reasonable analysis increment can lead to the expected decrease of the simulated surface rainfall rates.

Fig.5 shows the vertical profiles of temperature and specific humidity increments produced by the 1D-Var on BTs. In terms of shape, they look rather similar to the profiles obtained with the 1D-Var on rainfall rates in Fig.2. In terms of magnitude however, temperature increments tend to be smaller with the BT approach and the maximum increment at level 50 that was seen in Fig.2 (left panels) is not present in Fig.5 (left panels). On the other hand, the specific humidity increments, which again dominate, are higher when BTs are directly involved in the minimization instead of surface rain rates.

Fig.6 displays maps of the TCWV increments obtained from the 1D-Var with BTs when three and seven channels are selected (panels (a) and (b), respectively). Their spatial distribution looks very similar to the one shown in Fig.3 for the 1D-Var on surface rain rates, with positive TCWV corrections in the core of the storm, and negative values around it. However, their magnitude is clearly much stronger since extreme absolute values exceed 20 kg m^{-2} locally. As already underlined, these larger TCWV increments can be explained by the fact that when working with BTs it is not only the amount of rain that is corrected, but also the amounts of water vapour and cloud water themselves. It is though very reassuring that two different 1D-Var methods lead to similar increment patterns.

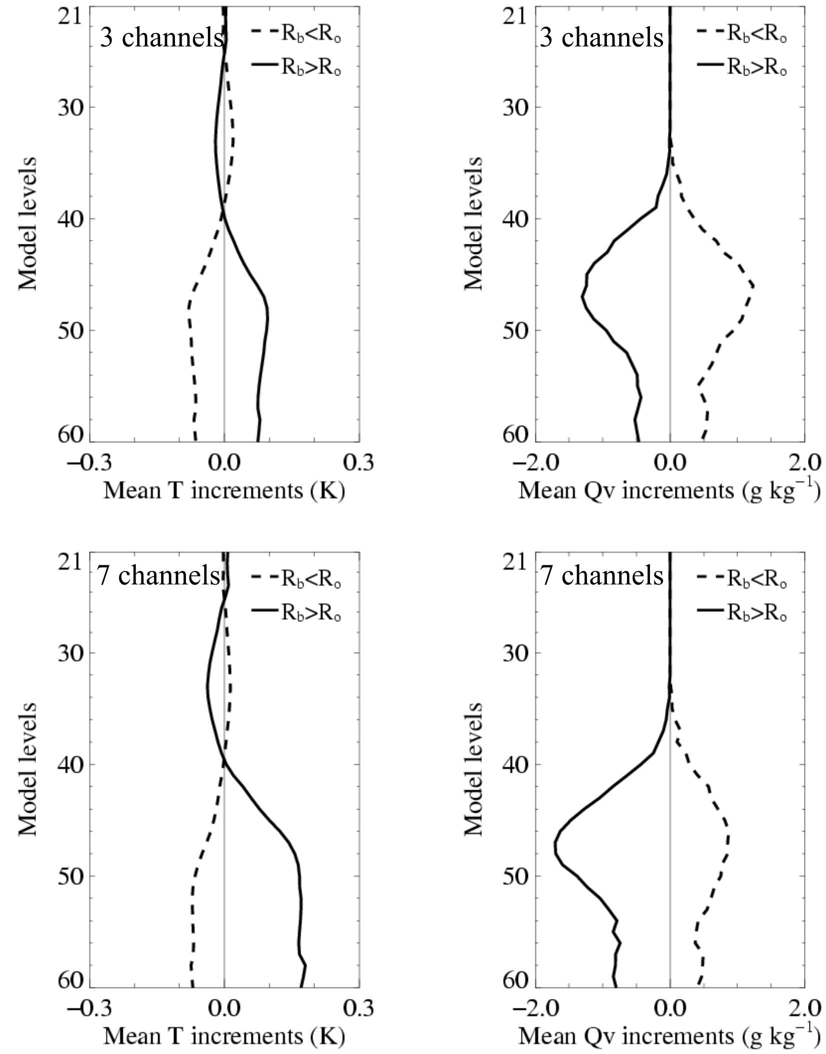

Fig.5. 1D-Var on TMI microwave brightness temperatures for the case of super-typhoon MITAG at 5 March 2002 1200 UTC: Mean vertical profiles of the increments in temperature (left panel) and specific humidity (right panel) when using 3 TMI channels (top) and 7 TMI channels (bottom). Cases for which the background rainfall rate needs to be increased (resp. decreased) are plotted with a dashed line (resp. solid line). See text for more details.

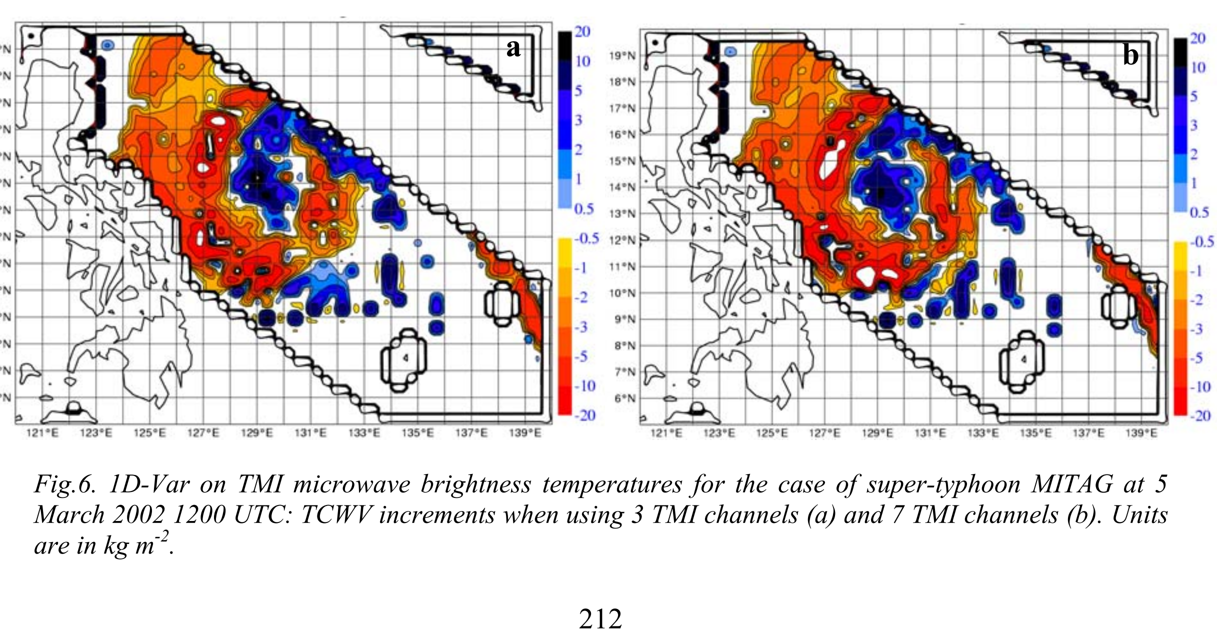

Fig.6. 1D-Var on TMI microwave brightness temperatures for the case of super-typhoon MITAG at 5 March 2002 1200 UTC: TCWV increments when using 3 TMI channels (a) and 7 TMI channels (b). Units are in kg m^{-2}.

4. Conclusions

In this study, 1D-Var experiments based on retrieved surface rainfall rates as observed from TMI have been compared to 1D-Var experiments directly performed on the TMI brightness temperatures, for the case of super-typhoon MITAG in March 2002. These runs include a modified and more linear version of Tiedtke's convective parameterization operationally used at ECMWF, as well as a new simplified cloud scheme designed by Tompkins and Janisková. Both 1D-Var methods have succeeded in producing reasonable and coherent temperature and specific humidity increments that permit to correct either the model's surface rainfall rates or the simulated BTs towards the equivalent TMI observations.

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.

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. On the other hand, the main drawback of the 1D-Var with BTs is the additional computational cost of the radiative transfer model.

The actual differences between the two 1D-Var methods and their respective potential for the future operational assimilation of precipitation at ECMWF will be further investigated in some indirect '1D-Var + 4D-Var' experiments (Marécal and Mahfouf 2002), in which pseudo-observations of TCWV produced by the 1D-Var are assimilated in the ECMWF 4D-Var.

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