4D-VAR ASSIMILATION OF TMI RAINFALL RATES

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Summary

The four-dimensional variational assimilation (4D-Var) of TMI surface rainfall rates is tested using a one-dimensional variational retrieval (1D-Var) approach. Total column water vapour in rainy areas is determined through the 1D-Var assimilation of observed surface rainrates. Observations are the instantaneous surface rainrates from PATER algorithm (EuroTRMM product) applied to TMI brightness temperatures. Results show that the use of 1D-Var TCWV has a positive impact on the humidity and wind analysis. It also improves the wind and temperature forecasts in the tropics. The use of another rainrate estimate from TMI with a different associated error modifies only slightly the global results. But locally the wind and humidity analyses are significantly changed.

1. Introduction

The general problem of assimilation of observations in numerical weather prediction is the definition of the best initial conditions of a forecast model, using all the available information on the atmospheric state in an optimal way. Analysis systems based on three-dimensional (3D-Var) or four-dimensional (4D-Var) variational methods are currently the most promising approaches for global initialisation. Their basis is to minimize an objective function measuring the distance of a model solution to observations available over a given time period (assimilation window) and to a model short-range forecast. The 4D-Var assimilation method, which is the temporal extension of 3D-Var, uses the model dynamics to compare the observations at the appropriate time. In principle, it is possible to assimilate in 3D-Var or 4D-Var systems any type of observations when its corresponding error is known. In practice an accurate observation operator is needed to allow the calculation of the model equivalent of the observed quantity. In a variational context, linearized versions (tangent-linear and adjoint) of observation operators are also necessary. A 4D-Var analysis system based on an incremental formulation (Courtier *et al.* 1994) is operational at ECMWF (European Centre for Medium-range Weather Forecasts) since 25 November 1997 leading to an improvement of ECMWF analysis and forecast skills compared to 3D-Var (Rabier *et al.* 2000, Mahfouf and Rabier 2000, Klinker *et al.* 2000).

The major source of atmospheric observations for assimilation over oceans comes from spaceborne instruments, in particular in the tropics where conventional measurements are scarce. Since November 1997, high resolution estimates of precipitation rates in the tropical belt are provided by the Tropical Rainfall Measuring Mission (TRMM) (Simpson *et al.* 1996, Kummerow *et al.* 1998). Because tropical large-scale rainfall patterns and their associated energy release are known to influence the global circulation, the assimilation of rainfall measurements in the tropics is likely to improve global atmospheric analyses and forecasts. So far, there is only one study on rain assimilation that made use of an operational global variational assimilation system (Treadon 1997). The main reasons are the only recent availability of operational 3D-Var or 4D-Var systems, the technical work needed to develop rain rate assimilation and its computing cost. Treadon (1997) developed and tested the assimilation of satellite derived rainfall rates in the NCEP 3D-Var analysis system. His results showed that rain rate assimilation reduces the precipitation spin-down (model hydrological imbalance) and has a positive impact on the tropical wind forecasts, mostly at the 200 hPa level.

In the study presented here the approach chosen is to use a two step method to perform the assimilation of TRMM-derived surface rainrates in the ECMWF 4D-Var system. The first step consists in a one-dimensional variational (1D-Var) assimilation (Marécal and Mahfouf 2000a) which allows the retrieval of adjusted model temperature and humidity profiles providing a model rain rate within both the model and the rain rate observation error. In the second step the total column water vapour (i.e. the vertical integral of the specific humidity noted TCWV) retrieved from 1D-Var is assimilated in 4D-Var. This means that the rain rate observation is converted into a water vapour information before entering 4D-Var. Since TCWV is a basic model variable, it can be easily introduced in the global data assimilation system without too much technical work. Thus a 1D-Var approach allows the influence of rain rate observations on 4D-Var performances to be evaluated without requiring too much technical developments.

A summary of the 1D-Var basis and of Marécal and Mahfouf (2000a)' main results is given in section 2. Section 3 describes the 4D-Var assimilation experiments designed to test the assimilation of surface rain rate through the 1D-Var approach. This work was done in the framework of the EuroTRMM project (funded by ESA and EC). Rain rate observations used were provided by P. Bauer (from Deutsche Forschungsanstalt für Luft- und Raumfahrt, Germany) who developed a TMI retrieval algorithm (also part of the EuroTRMM project). 4D-Var analysis and forecast results are discussed in section 4. Section 5 shows results of a sensitivity experiment to the rain rate estimate and its associated error. Concluding remarks are given in section 6.

2. 1D-VAR Retrieval

2.1 Method

We define an observed surface rain rate R_0 and $\mathbf{x}$ a vector representing the atmospheric state (or control variable) at the observation location. The 1D-Var retrieval seeks an optimal atmospheric state $\mathbf{x}$ which minimizes a distance between the model and the observed surface rainfall rates, knowing a background constraint provided by a short term forecast profile $\mathbf{x}^b$. When the background and the observation errors are uncorrelated and each has a Gaussian distribution, then the maximum likelihood estimator of the state vector $\mathbf{x}$ is the minimum of the following cost function:

$$J(\mathbf{x}) = \frac{1}{2}\left(\mathbf{x}-\mathbf{x}^b\right)^T \mathbf{B}^{-1}\left(\mathbf{x}-\mathbf{x}^b\right) + \frac{1}{2}\left(\frac{R(\mathbf{x})-R_0}{\sigma_0}\right)^2$$

where $\mathbf{B}$ is the background error covariance matrix from the ECMWF 4D-Var system (Rabier *et al.* 1997, Derber and Bouttier 1999), σ_0 the standard deviation of the observation error. $R(\mathbf{x})$ is an instantaneous surface rain rate obtained from the model atmospheric state $\mathbf{x}$. $R(\mathbf{x})$ is computed using the parametrizations of the moist-convective and of the large-scale precipitation processes. The control variable vector contains the profiles of temperature and specific humidity on model levels and the surface pressure.

2.2 Main results of 1D-Var retrieval

Marécal and Mahfouf (2000a) showed that when precipitation is present in the background field (model short-term forecast), 1D-Var generally provides adjusted profiles of temperature and specific humidity leading to a rain rate close to the observation within the observation error (for 70% to 80% of the profiles). In this case, 1D-Var modifies much more the humidity profiles than the temperature profiles. For background profiles providing no precipitation, 1D-Var is not able to trigger precipitation even if observed.

3. 4D-VAR Assimilation of TCWV Retrievals in Rainy Areas

3.1 Method

The operational ECMWF assimilation system is based on an incremental four-dimensional variational method (Rabier *et al.* 2000, Mahfouf and Rabier 2000, Klinker *et al.* 2000). 4D-Var seeks an optimal balance between observations and the dynamics of the atmosphere by finding a model solution which is as close as possible, in a least-square sense, to the background information and to the observations available over a given time period (six or twelve hours). The incremental formulation of 4D-Var (Courtier *et al.* 1994) consists of computing the background trajectory and the departures (observations minus model) using the full non-linear model at high resolution including a full set of physical parametrizations, and minimizing the cost-function in a low resolution space for the increments at initial time using a tangent linear model and its adjoint at low resolution with a limited set of physical parametrizations (Mahfouf 1999).

Because Marécal and Mahfouf (2000a) showed that their 1D-Var retrieval mostly modifies specific humidity to adjust the observed rain rates, a 1D-Var humidity related quantity was chosen for assimilation in 4D-Var. The total column water vapour was preferred to specific humidity profiles because the assimilation of profiles would have enhanced the undesirable correlation between these observations and the model background. The accuracy of 1D-Var TCWV is the 1D-Var analysis error in TCWV that can be estimated objectively following Rodgers (1976) (Marécal and Mahfouf, 2000b).

3.2 Observations

The rainfall rates used come from the Tropical Rainfall Measuring Mission (TRMM) observations (Simpson *et al.* 1996). TRMM carries three instruments that provide independent estimates of precipitation: a radar, a microwave imaging radiometer (TMI) and a visible/infra-red imaging radiometer (Kummerow *et al.* 1998). The TRMM satellite is in a circular orbit at an altitude of about 350 km with a 35° inclination angle resulting in a coverage of the tropics and the sub-tropics only (between -40° to +40° latitude). The TRMM products used here are the instantaneous TMI surface rainfall rates from the PATER algorithm (PR-Adjusted TMI Estimation of Rainfall) developed by P. Bauer in the EuroTRMM project (Bauer 2001, Bauer *et al.* 2001). The PATER algorithm was developed from combined mesoscale cloud model - radiative transfer calculations adjusted to the imaging specifications of the TMI. variability of surfaces (wind speed, sea surface temperature) and viewing geometry (varying zenith and azimuth angles) was included. The technique makes use of co-located TMI-PR observations while conserving the full TMI swath. It consists of an independent passive microwave component which estimates rain liquid water content near the surface. During application, co-located PR estimates of the same quantity are averaged to the TMI product resolution over the common swath (~220 km). Then, a dynamically adjusted calibration as a function of liquid water content is calculated. This is applied to TMI observations over the full swath (~790 km) assuming slowly varying systematic differences between TMI and PR estimates. This approach also allows to calculate remaining standard deviations between both products which, together with an estimate of the PR retrieval error, is taken as a measure of the instantaneous error of the combined retrieval. Note that the PATER rain estimations are only available over oceans. They correspond to a resolution of 27 km by 44 km. To be consistent with the model rain rates, the surface rain rate observations assimilated in 1D-Var (i.e. R_0) were obtained by averaging the TMI-PATER rain rates at the model resolution. The observation error used is that provided with the PATER rain estimates (Bauer *et al.* 2000).

3.3 Design of the experiments

Two periods were selected for the 4D-Var experiments. The first period, noted “Bonnie period”, was from 18/08/1998 at 12UT to 02/09/1998 at 12UTC. It includes the whole life cycle of the tropical cyclone Bonnie. Bonnie reached the state of tropical storm on 20 August 1998 and the state of hurricane on 22 August 1998. Later, it hit the coast of North Carolina on 27 August 1998 and turned into a subtropical cyclone from 29 August 1998. The second period, noted “Christmas 1999 period”, was from 15/12/1999 at 12UTC to 05/01/2000 at 12UTC. It includes the tropical storm Astride that developed in the Indian Ocean between 26/12/1999 and 31/12/1999 and two severe storms over Europe.

For each of the two periods, two experiments were run to assess the impact of assimilating 1D-Var TCWV in rainy areas in the ECMWF 4D-Var system. The first experiment is the "Control" which only assimilates the operational data set of the considered model version. For humidity, data used are: TEMP specific humidity profiles below 300 hPa, SYNOP relative humidity and SSM/I TCWV in non rainy areas over oceans. The second experiment is the “Rain-PATER” that is identical to "Control" but including all quality-controlled 1D-Var TCWV in 4D-Var. For all the experiments the analysis window used was 6 hour long and the model was run with a T_L319 truncation corresponding to a horizontal grid-mesh of about 60 km. The Bonnie and the Christmas 1999 experiments were run with two different model versions: 50 vertical levels for “Bonnie” and 60 for Christmas 1999. For each experiment a series of 10-day forecasts was run from the 12 UTC analyses.

Results have shown that the global impact of assimilating 1D-Var TCWV in 4D-Var is similar for the two periods selected. Thus, to avoid redundancy, results will mostly be discussed using the “Bonnie” experiment outputs. Since TRMM only covers the tropics and the subtropics, results (tables and figures) of these experiments will be given for the latitude band sampled by TMI. The term "global" will represent hereafter this area.

4. Impact of 1D-VAR TCWV on Analyses and Forecasts

4.1 Impact on analyses

4.1.1 Statistics of background departures

Figure 1 shows the global mean statistics of the 4D-Var assimilation of 1D-Var TCWV and SSM/I TCWV for the “Rain-PATER” experiment. The background departure is the difference between the observation and the background (short-term forecast). The observations considered here are the TCWV from TMI in rainy areas and from SSM/I in non-rainy areas (Gérard and Saunders 1999). To compute these statistics, the background fields are converted into TCWV.

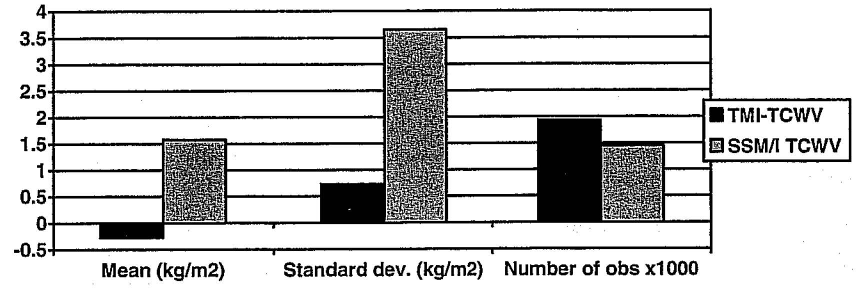

Fig 1: Global mean background departure statistics for TMI TCWV and SSM/I TCWV for the 15-day Bonnie period. Here the background departure is the difference between the TCWV observation and the background TCWV (6-hour model forecast). TMI TCWV are estimated in rainy areas using the 1D-Var method described in this paper and applied to the PATER rainrates. SSM/I TCWV are estimated from SSM/I brightness temperatures in non-rainy areas.

The mean background departure for TMI-TCWV exhibits a slight negative bias of -0.27 kg m^{-2}. This means that on average 1D-Var TCWV observations tend to decrease rainfall rate in the model. This is consistent with the fact that the model tends to trigger more often precipitation than observed. Compared to SSM/I TCWV statistics, 1D-Var TCWVs from TMI are closer to the model. This is because the modification of the model rainfall is very sensitive to changes in humidity leading to small increments needed for rainrate adjustment. The number of observations is smaller for SSM/I TCWV because a thinning (an observation every 250 km is retained) was applied to SSM/I observations in non-rainy areas before being used in the assimilation system. This thinning is applied to avoid assimilating correlated observations (Gérard and Saunders 1999).

4.1.2 Analysis of TCWV

The global mean values of 4D-Var analysed TCWV are given in Table 1. The differences between the two experiments are small (< 1%) and are associated with small standard deviations of background departures (~1 kg m^{-2}) compared to SSM/I (~3-4 kg m^{-2}) and to the low frequency of occurrence of rainy areas within TMI coverage. "Rain-PATER" experiment provides a slightly drier atmosphere than the "Control" experiment. This is consistent with the background departure statistics showing that the tendency is to decrease TCWV on average.

The root mean square (RMS) of TCWV increments allows the relative quality of the humidity analysis for the "Control" and "Rain-PATER" experiments to be evaluated. These increments are the departure in TCWV between the background and the analysis. A reduction of the RMS in regions where humidity observations are assimilated means that short-range forecasts are closer to the observations and that smaller corrections are necessary for the assimilation. RMS of TCWV increments for the "Bonnie" experiments are displayed in Figure 2 and global values are given in Table 1. The "Rain-PATER" experiment provides RMS increments noticeably smaller (8%) than the "Control" experiment in most areas thereby showing a positive impact of rain-derived observations.

	Control experiment	Rain-PATER experiment	Rain-2A12 experiment
Mean analysed TCWV	35.98	35.92	35.92
RMS of TCWV increments	1.81	1.65	1.66

Table 1: Global mean values in kg m^{-2} of analysed TCWV and RMS of TCWV increments averaged over the 15-day Bonnie period.

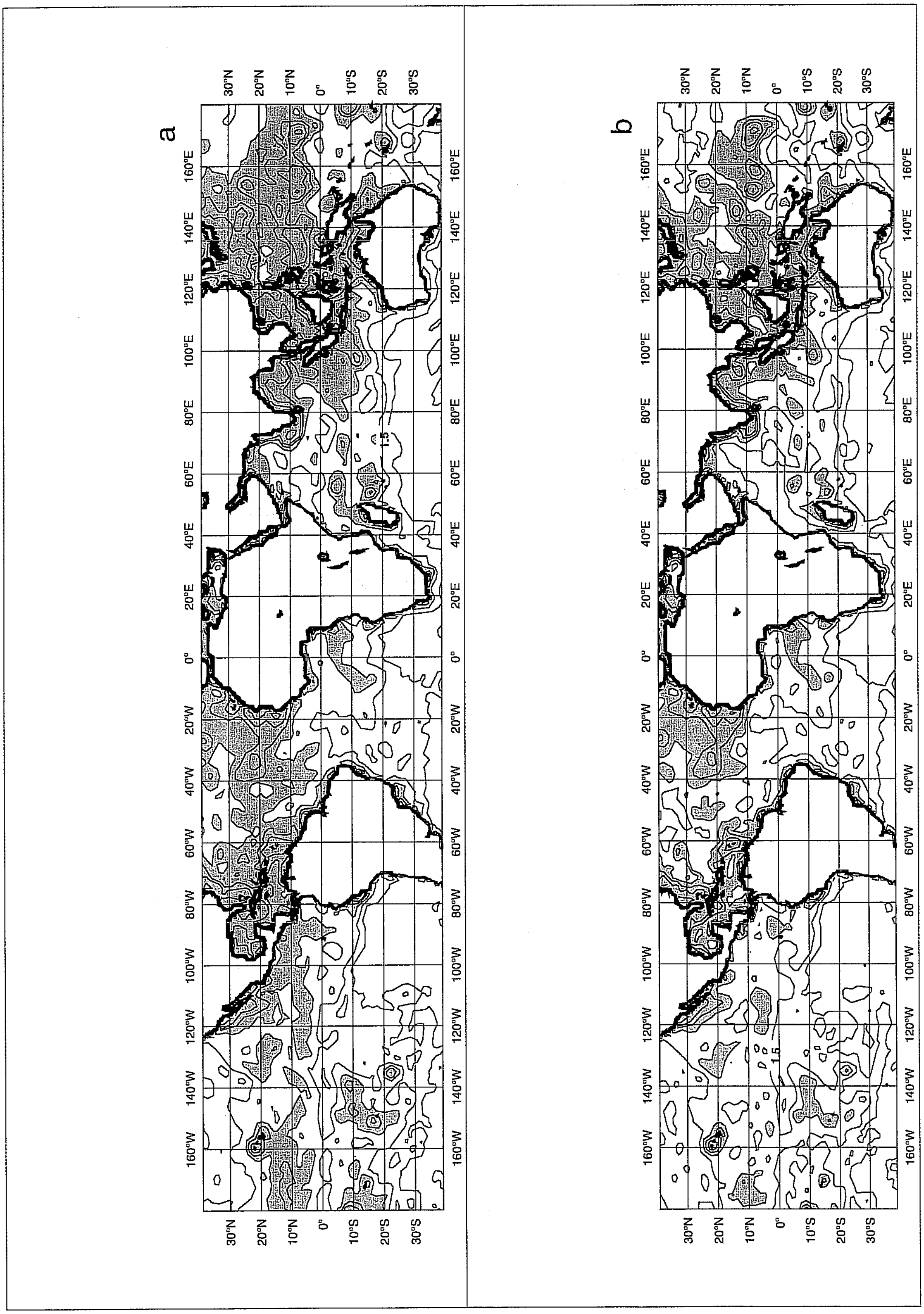

Fig 2: Root mean square of TCWV increments in kg m^{-2} averaged over the 15-day Bonnie period. (a) "Control" and (b) "Rain-PATER". Contours are every 0.5 kg m^{-2} and grey shading starts at 2 kg m^{-2}.

4.1.3 *Impact on rainfall rates*

The modifications of the humidity analysis induced by the assimilation of 1D-Var TCWV in 4D-Var aim at producing a model surface rainfall rate closer to the TMI-derived observations. Global results averaged over the 15-day assimilation period for Bonnie are given in Table 2. “Rain-PATER” experiment provides a surface rain rate closer to TMI observations than the "Control" as shown by the increase of the correlation coefficient and by a reduction of the RMS.

	Control experiment	Rain-PATER experiment
Correlation with TMI observations	0.378	0.396
RMS (model – observations)	8.5	7.3

Table 2: Global comparison for the 15-day Bonnie period of the model instantaneous rainrate with TMI rainrate estimates (PATER) used in 1D-Var. The RMS is the root mean square of the difference between the model values and the observations in mm day^{-1}.

4.1.4 *Trajectory of hurricane Bonnie*

The ECMWF 4D-Var humidity analysis assumes that the background humidity errors are not correlated with other model variables such as temperature. Nevertheless, since 4D-Var takes into account the temporal evolution of any variable within the assimilation window, a modification of the analysed humidity induces a modification of the global solution and consequently of the thermodynamical and dynamical fields. A way to evaluate the impact of 1D-Var TCWV assimilation on the analysed pressure field is to compare the hurricane track provided by the model to the "best-track" derived from observations (obtained from the National Hurricane Center, National Oceanic and Atmospheric Administration). The model tracking algorithm locates the cyclone by determining the position of the minimum mean sea level pressure.

As shown in Fig. 3a, the use of rain-derived observations in 4D-Var generally improves the location of the track in the early stages of development of the cyclone. It is important to note that the improvement of the cyclone track is more important for the assimilation windows that include a good sampling of Bonnie by TMI (for instance on the 20 August 1998 at 1800 UTC). This means that there is, at least locally, a real benefit on the analysis in using rain-derived information when available. When hurricane Bonnie is in a mature stage (from 23 August 1998 to 27 August 1998), “Rain-PATER” and “Control” experiments provide a track close to the best-track. The small discrepancies between the model and the observed track can be attributed to the 4D-Var minimisation which is performed in a low resolution space at the initial time. Figure 3b displays the minimum of mean sea-level pressure in the hurricane for the two experiments. For the early stage, no important differences between the two experiments are found. For the mature stage, a much deeper cyclone is analysed in "Rain-PATER" experiment compared to "Control" experiment with a maximum difference of 5 hPa on the 25 August 1998.

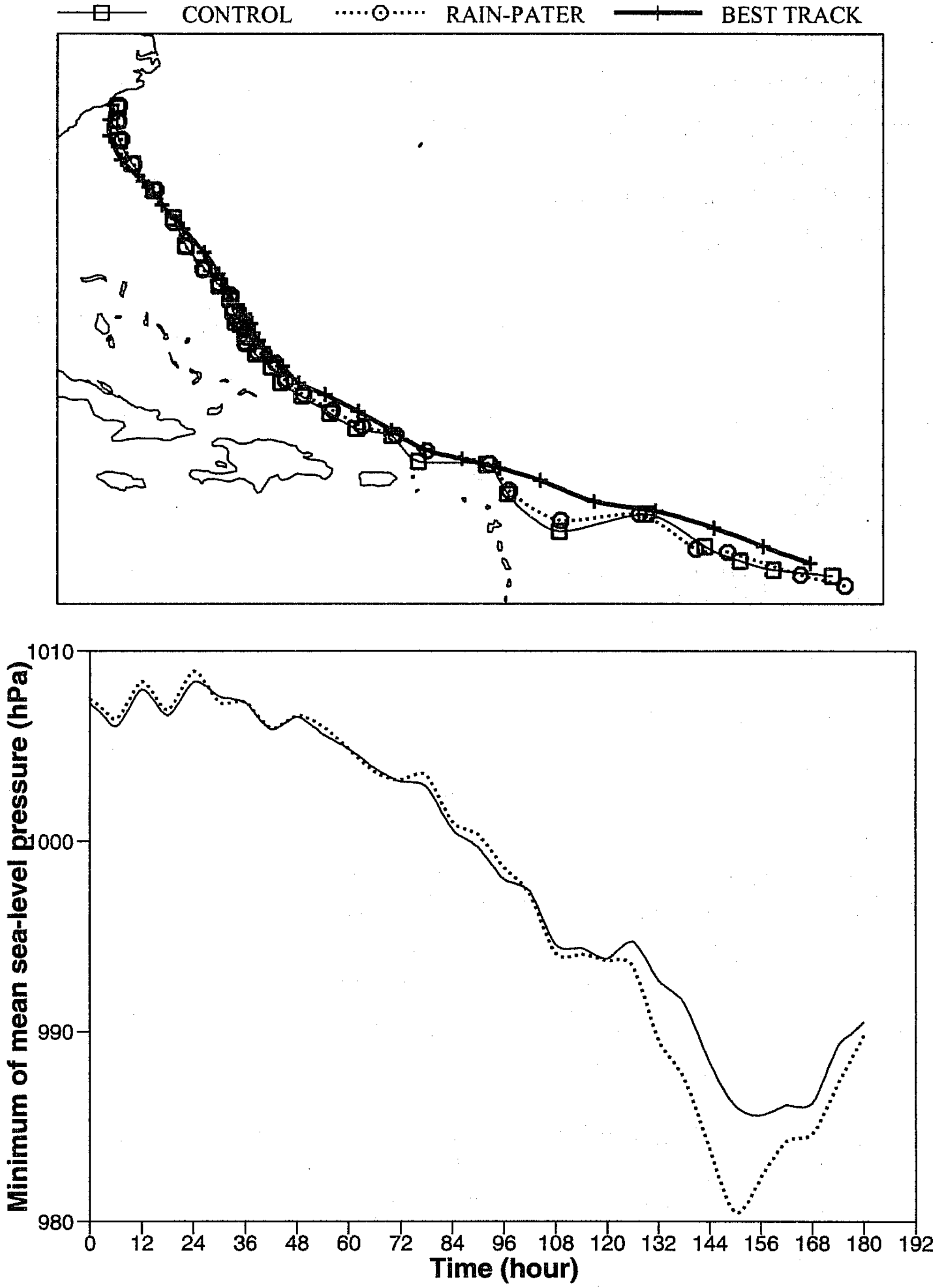

Fig 3: Analysed track of hurricane Bonnie. (Top panel) Location from 19 August 1998 at 1200 UTC to 27 August 1998 at 0000 UTC. (Bottom panel) Temporal evolution of the minimum of mean sea level pressure (hPa) in the hurricane (initial time corresponds to 19 August 1998 at 1200 UTC). Symbols are every 6 hours.

4.1.5 Analysis of wind field

The impact on the global mean analysed wind field (not shown) is small (< 0.5%) for two reasons: the low occurrence of TMI observations in rainy areas over oceans and the use in 4D-Var of many sources of wind data. Nevertheless, locally the wind field can be significantly modified by the assimilation of 1D-Var TCWV. This is illustrated in Figure 4 showing the analysed horizontal and vertical velocity fields at 700 hPa for hurricane Bonnie on the 25 August 1998 at 1800 UTC. The impact of the 1D-Var TCWV assimilation is to noticeably intensify the hurricane by increasing the maximum horizontal wind and the updraft within the hurricane. The impact on wind analysis in the early stage of development of the hurricane is much smaller than in the mature stage (not shown). In the early stage, the rain assimilation acts more on the location of the hurricane than on its intensity. All these results are consistent with the analysis of surface pressure discussed in the previous subsection.

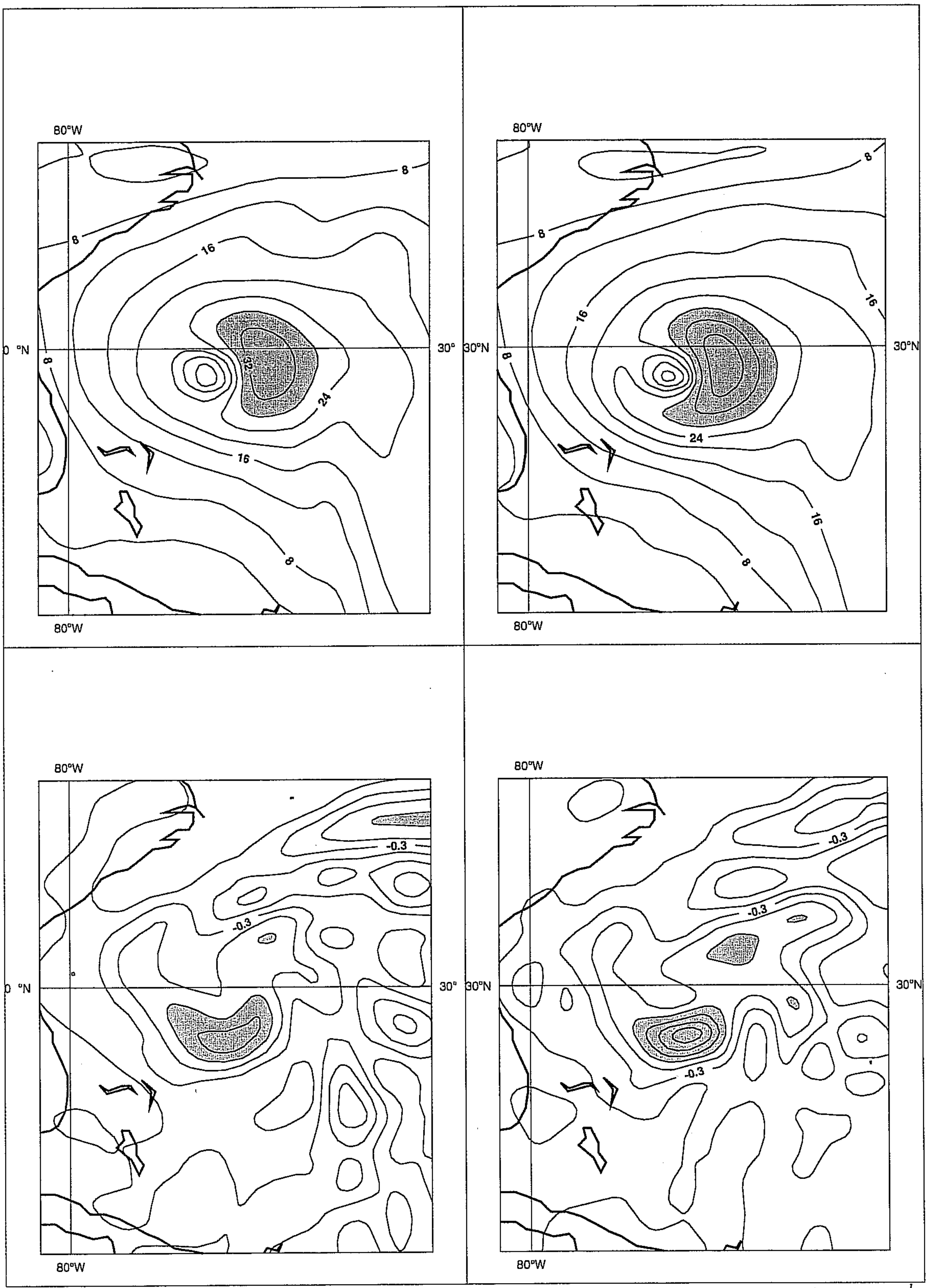

Fig 4: Wind velocity at 700 hPa on 25 August 1998 at 1800 UT. Top panels are for the horizontal wind velocity in m s^{-1} and bottom panels are for the vertical wind velocity in Pa s^{-1}. "Control" and "Rain-PATER" experiments are displayed, respectively, on the left-hand side and right-hand side. Grey shading starts at 28 m s^{-1} for horizontal wind and below –0.9 m s^{-1} for vertical wind.

Although the 1D-Var TCWV retrievals induce small modifications to the humidity analysis compared to SSM/I, the impact on wind analysis is large where TMI observations are available. This means that the analysed dynamics is very sensitive to modifications of the precipitation and cloud fields. This is because latent heat exchanges which take place in rainy areas have a major impact on the horizontal and vertical energy distribution and consequently on the dynamics.

4.2 Impact on forecasts

4.2.1 Hydrological cycle

The short-range forecast of rainfall rate is affected by the changes in the humidity analysis. Figure 5 shows the global surface rain rate over oceans accumulated over the 12 past hours as a function of the forecast range for the three experiments. The "zigzag" shape of the curves reflects the diurnal cycle. The two experiments give large rain rates at the beginning of the forecast that decrease rapidly with time. This behaviour is known as spin-down. After 48 hours of forecast, the curves reach the model equilibrium for the hydrological cycle. "Rain-PATER" experiment provides an improvement compared to the spin-down. This is because the "Rain-PATER" forecast starts from a slightly drier humidity analysis. "Control" by reducing noticeably the spin-down. This is because the "Rain-PATER" forecast starts from a slightly drier humidity analysis.

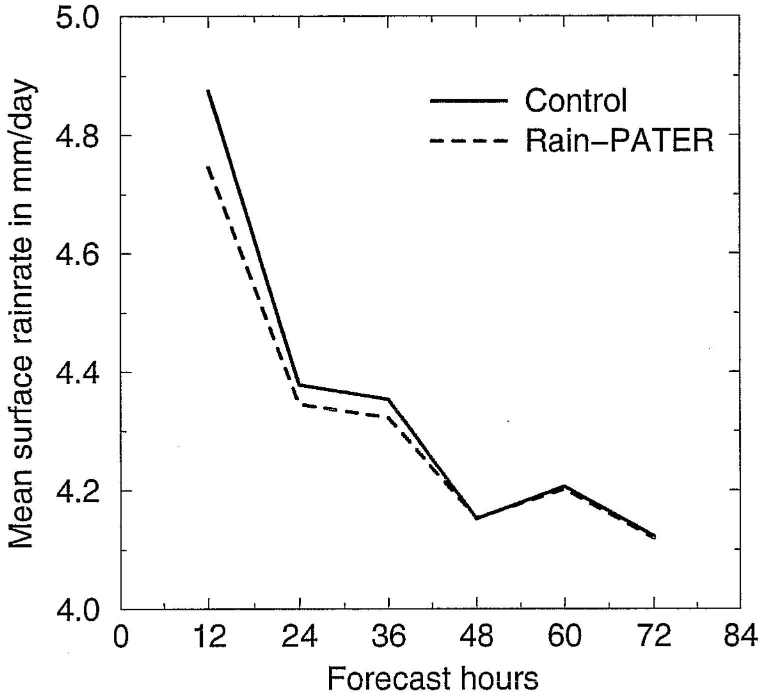

Fig 5: Mean surface rainfall rate over tropical oceans as a function of forecast range in hours. The surface rain rate is here the accumulated rain rate between T-12 hours and T, T being the forecast time.

4.2.2 The trajectory of hurricane Bonnie

In the early stage of the development of Bonnie, the analysed track is improved by the use of rain-derived information. This leads to an impact on the forecasted tracks that is slightly positive or slightly negative depending on the starting date/time of the forecast as shown in Marécal and Mahfouf (2000b).

4.2.3 Objective scores

Figure 6 shows the RMS errors for the tropical wind (between –20° and +20° latitude) at 850 hPa and 200 hPa up to day-4. They are computed against their own analysis, as the tropical analyses in the two experiments are significantly different from the operational ones. The two periods, Bonnie and Christmas 1999, were used to calculate these statistics. Figure 6 shows that the "Rain-PATER" experiments perform better than the "Control" with a 2% level of significance for both levels considered. This is a consequence of the modifications to the initial humidity field performed in "Rain-PATER" experiment and of the strong dependency of tropical circulation to the diabatic heating by convection. The modification of the intensity of the hydrological cycle in "Rain-PATER" experiments also reduces significantly the RMS errors of the upper tropospheric temperature at 200 hPa in the tropics (as shown in Marécal and Mahfouf 2000b).

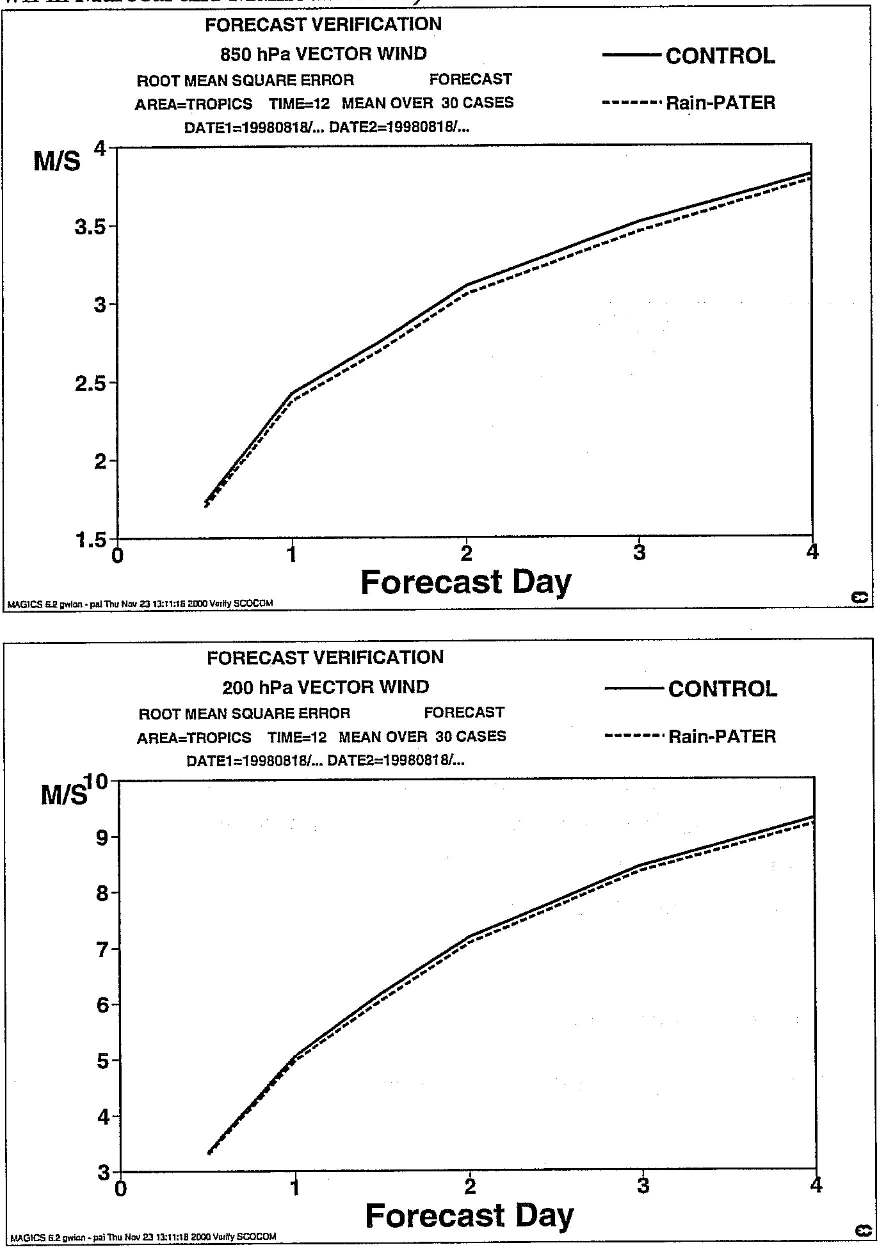

Fig 6: Root mean square forecast error for tropical winds verified against its own analysis at 850 hPa (top panel) and 200 hPa (bottom panel).

5. Sensitivity to rainrate estimates and associated errors

Because 1D-Var makes use of both the rainrate estimates and their associated error, the sensitivity of the assimilation results to these two parameters should be addressed. In this section, another TMI rainrate estimate is tested: the 2A12 (level 5) surface rainrate product provided operationally by NASA (Kummerow *et al.* 1996). Note that the 2A12 rainrates were averaged using the same procedure as for the PATER product. Two analysis/forecast experiments similar to "Rain-PATER" ones were run with the 2A12 rain rates (noted "Rain-2A12" experiments): one for Bonnie period and one for Christmas 1999 period.

5.1 Comparison between PATER and 2A12 products

Before evaluating the assimilation/forecasts performances of 2A12 product compared to PATER, it is important to first compare 2A12 and PATER rainrate estimates. Results are given in Table 3. Even if the correlation between 2A12 and PATER is high, the RMS of the difference between the two rainrates is fairly large showing significant discrepancies between the two products. Compared to the ECMWF model, PATER product is closer than 2A12 with a higher correlation and a much smaller RMS.

	TMI 2A12	TMI PATER	ECMWF model
TMI 2A12	▨	▨	▨
TMI PATER	0.93 / 4.1	▨	▨
ECMWF model	0.27 / 16.6	0.38 / 8.5	▨

Table 3: Comparison between TMI rainrates from 2A12 and from PATER products and the ECMWF model rainrates. The numbers given on the left and right hand sides are, respectively, the correlation and the root mean square of the difference in mm day^{-1}. Statistics were obtained on the 15-day Bonnie period.

No estimate of the rain rate error is provided with the 2A12 product. In agreement with scientists in charge of the 2A12 algorithm a simple relation was used for the rain rate error (σ_0) as a function of the rain rate (R_0). This is illustrated in Figure 7. Most of the observed rain rates (at model resolution) are found between 0.5 and 8 mm h^{-1}. Thus the error chosen for 2A12 product is generally smaller than the one for PATER.

5.2 Statistics of background departures

Figure 8 shows the global mean statistics of the 4D-Var assimilation of 1D-Var TCWV for the "Rain-PATER" and "Rain-2A12" experiments. Both experiments exhibit a negative bias, "Rain-PATER" providing the largest. This is because the PATER rain rates are smaller on average than 2A12 ones. The standard deviation for "Rain-2A12" experiment is much larger than for "Rain-PATER" while the number of TCWV observations used in 4D-Var is significantly smaller for "Rain-2A12". This shows that 1D-Var retrieval is less successful in adjusting temperature and humidity when 2A12 rain rates are used but provides larger increments in TCWV. This is because 2A12 rain rates are further from the model rain rates than PATER ones. Moreover the error on 2A12 observations is generally smaller leading to more constraint from the observation term in the 1D-Var minimisation.

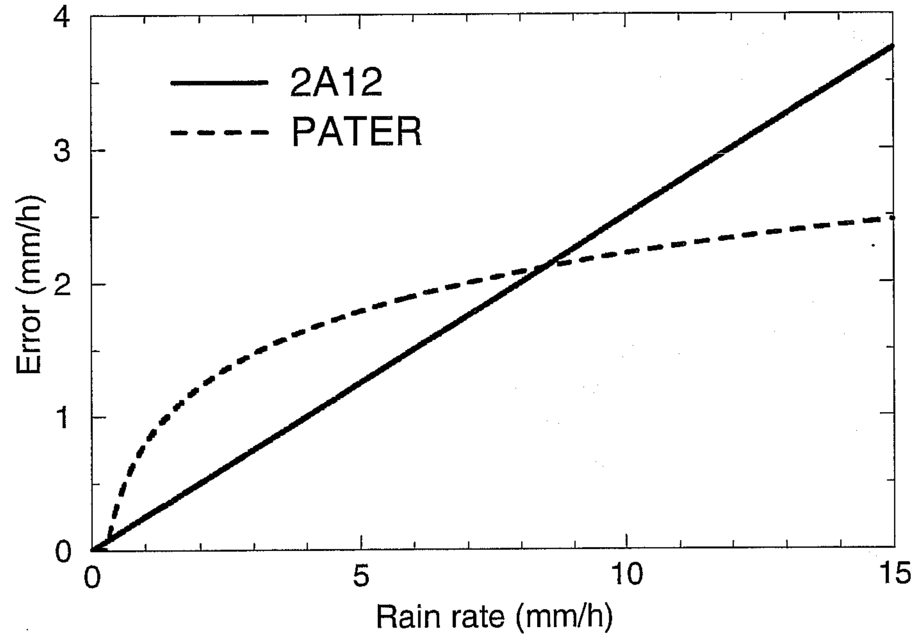

Fig 7: TMI rainrate error (σ_0) as a function of the rainrate (R_0) in mm h^{-1} for the 2A12 and the PATER products.

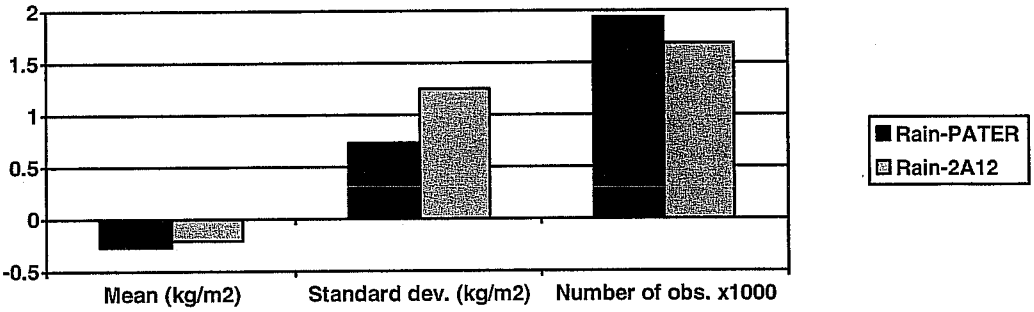

Fig 8: Global mean background departure statistics for TMI-TCWV for the 15-day Bonnie period calculated from the "Rain-PATER" and "Rain-2A12" assimilation experiments.

5.3 TCWV analysis and statistics

Global results on the humidity analysis for the Bonnie period are given in Table 1. They show that on average "Rain-PATER" and "Rain-2A12" experiments provide similar humidity analysis with the same mean TCWV. The mean of the RMS of TCWV increments is also very close for the two experiments. Thus on average the effect of having less TCWV observations used in the "Rain-2A12" experiment is counterbalanced by larger TCWV increments.

5.4 Wind analysis

Even if no significant differences are found on global mean results, some should be found locally because of the different behaviour of 2A12 and PATER products in 1D-Var. This is illustrated by the horizontal wind field displayed in Figure 9 for 24/08/1998 at 1200 UT and for 25/08/1998 at 1800 UT. These two analyses include an overpass of TRMM over hurricane Bonnie. For both dates the wind structure of the hurricane is slightly different for "Rain-PATER" and "Rain-2A12" experiments. On the 24/08/1998 at 1200 UT the "Rain-2A12" experiment exhibits stronger maximum wind (30 m s^{-1}) compared to "Rain-PATER" experiment (28 m s^{-1}), The contrary is found on the 25/08/19998 at 1800 UT with a difference of 2 m s^{-1}.

6. Conclusion and perspectives

The aim of this work was to study the impact of the assimilation of surface rain rate in the ECMWF 4D-Var analysis system. For simplicity, the approach chosen was based on a 1D-Var retrieval. Firstly, temperature and humidity profiles were retrieved using Marécal and Mahfouf (2000a)' 1D-Var method constrained by TRMM derived rain rates (EuroTRMM product: PATER). Secondly, 1D-Var TCWV estimates were assimilated in 4D-Var. Assimilation experiments were run, firstly, for a period of 15 days including hurricane Bonnie and, secondly, for a period around Christmas 1999. For each period were run a "Control" experiment and a Rain-PATER" experiment that assimilates 1D-Var TCWV. Both periods give consistent results.

The global TCWV analysis is slightly drier by the use of rain-derived data in 4D-Var. This is because the model tends to trigger more often precipitation than observed. "Rain-PATER" experiment gives a noticeable improvement of the humidity analysis as shown by the global decrease by 8% of the RMS of TCWV increments. The model surface rain rate is closer to TMI-PATER observations. This means that the rain rate information from observations is correctly extracted by the assimilation system even though it is done through a 1D-Var retrieval. It justifies a posteriori the use of a 1D-Var approach to test the impact of rain assimilation in the ECMWF forecasting system.

The global mean wind analysis is only slightly modified by the rain assimilation. The main reason is the low occurrence of TRMM data in rainy areas within 6 hours. Nevertheless, there is a local impact of assimilating rain-derived products on the wind field within and in the vicinity of rainy areas. In particular, an intensification of hurricane Bonnie has been noticed between 23 August 1998 and 27 August 1998 for "Rain-PATER" experiment compared to "Control". This is consistent with the mean sea-level pressure analysis that shows a deeper minimum. Before 23 August 1998 (i.e. in the early stages of the storm development), assimilating rain-derived data allows a better analysis of the track of hurricane Bonnie. Nevertheless, this improvement has a neutral impact on the forecasted track. "Rain-PATER" experiment provides a more balanced model hydrological cycle as shown by the noticeable decrease of the precipitation spin-down. The global forecast performance is mainly improved for winds and upper tropospheric temperature in the tropics.

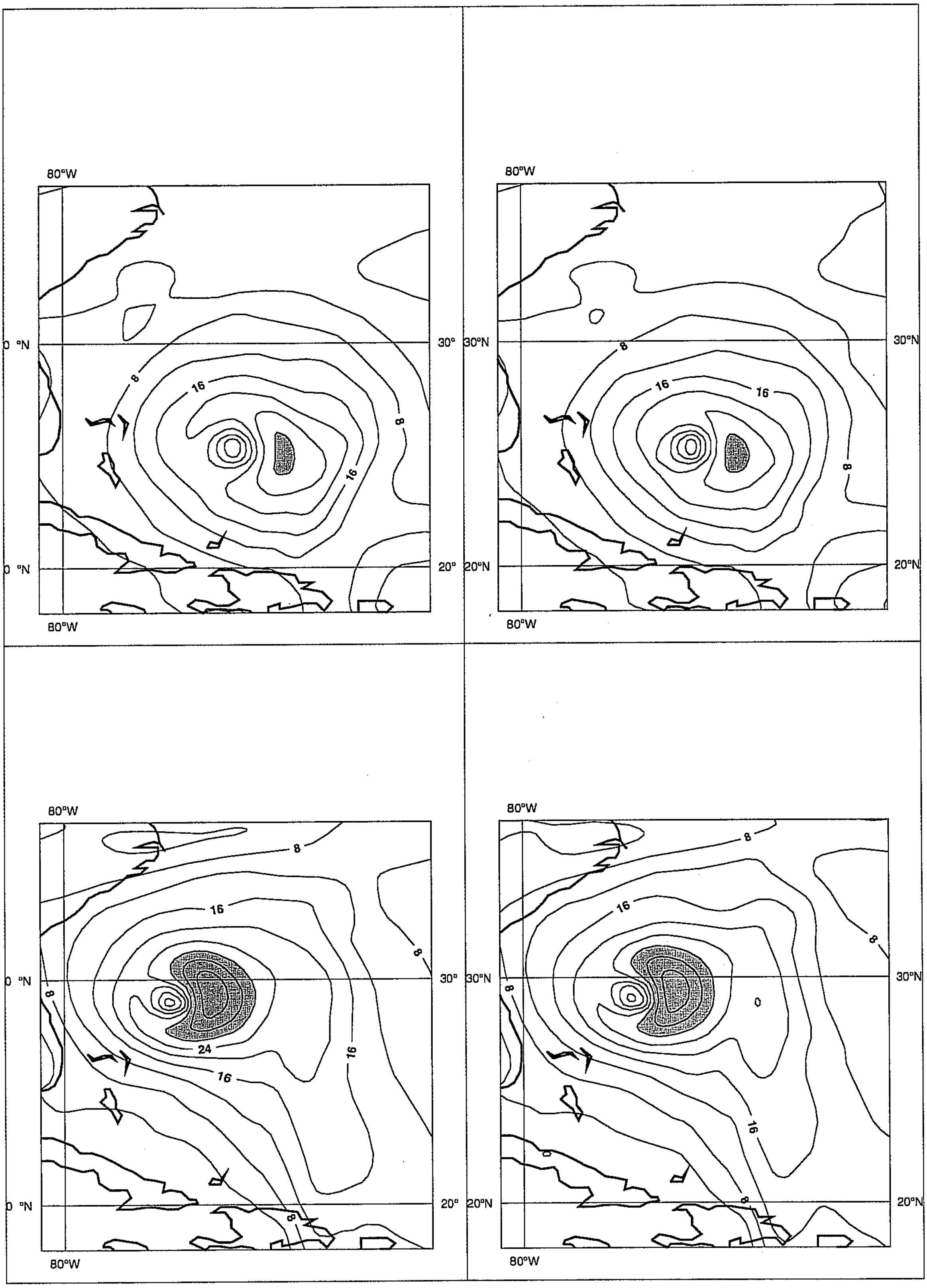

Fig 9: Horizontal wind velocity in m s^{-1} at 700 hPa. Top panels are for 24/08/1998 at 1200 UTC and bottom panels are for the 25/08/1998 at 1800 UTC. "Rain-PATER" and "Rain-2A12" experiments are displayed, respectively, on the left-hand side and right-hand side. Contours are every 4 m s^{-1} and grey shading starts at 28 m s^{-1}.

The sensitivity of the results to the specification of the surface rain rate estimate from TMI and to its corresponding accuracy was tested. Results show that using 2A12 rain rate with a different error only slightly modify the global results. 1D-Var TCWV increments for "Rain-2A12" experiment are larger than for "Rain-PATER" experiment. This is counterbalanced by a decrease of the number of quality controlled 1D-Var in the "Rain-2A12" experiment. Nevertheless, there is locally a significant impact on winds in rainy areas of using 2A12 instead of PATER.

All these results show that there is a positive impact on the ECMWF analyses and forecasts of using rain-derived information in the 4D-Var. The two-step approach for rain rate assimilation gives satisfactory results. Nevertheless, it tends to filter the information contained in the rain rate observations before entering 4D-Var This limitation of the 1D-Var approach together with the positive impact found in this study motivate the on-going development of a direct 4D-Var assimilation of surface rain rates. It is planned to assimilate operationally at ECMWF satellite-derived rain rates within two years using either a 1D-Var approach or a direct 4D-Var depending on the performances of the direct 4D-Var approach. Nevertheless, several issues have to be addressed to make an efficient use of rain observation directly in 4D-Var. Concerning the assimilation, an improvement of the statistics of forecast error for humidity has to achieved to account for the differences between rainy and non-rainy areas and for the correlation between humidity and other 4D-Var control variables such as temperature and humidity. Also to be mentioned is the non-linearity of the observation operator (here convection and large scale condensation parametrizations) which might cause problems in 4D-Var if not treated properly, the incremental formulation assumes the validity of the tangent-linear hypothesis. On the observation side, the horizontal correlation of the rain rate observations has to be taken into account in 4D-Var. Note also that the direct 4D-Var assimilation approach will be more sensitive to the rain rate estimate and to its associated error than the 1D-Var approach. This implies that a rain rate product too far from the model estimates or too accurate will not be possibly assimilated in 4D-Var directly

Another issue concerns the number of 1D-Var observations used per assimilation cycle. Rain only occurs sparsely and TRMM provides a limited coverage of the globe within 6 hours. To increase this number we plan to test the use the SSM/I (Special sensor Microwave/ Imager) on board DMSP (Defence Meteorological Satellite Program) satellites that sample larger areas than TRMM. Even if SSM/I radiometer has less channels than TMI, on-going studies based on TRMM data should provide improved algorithms to compute the surface rain rate from SSM/I brightness temperatures.

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