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V. Marécal and J-F Mahfouf

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Four Dimensional Variational Assimilation of Total Column Water Vapour in Rainy Areas

VIRGINIE MARÉCAL AND JEAN-FRANÇOIS MAHFOUF
European Centre for Medium-Range Weather Forecasts, Reading, Berkshire, England

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Abstract

This paper studies the impact of assimilating rain-derived information in the European Centre for Medium Range Weather Forecasts (ECMWF) four dimensional variational (4D-Var) system. The approach is based on a one-dimensional variational (1D-Var) method. Firstly, model temperature and humidity profiles are adjusted by assimilating observed surface rainrates in 1D-Var. Secondly, 1D-Var total column water vapor (TCWV) estimates are assimilated in 4D-Var. Observations used are TRMM (Tropical Rainfall Measuring Mission) surface rain rate estimates from TMI (TRMM Microwave imager).

Two assimilation experiments making use of 1D-Var TCWV were run for a 15-day period. "Rain-1"experiment only assimilates 1D-Var retrievals where the observed rain rate is non-zero while "Rain-2" experiment assimilates all 1D-Var TCWV estimates. The period selected includes the hurricane "Bonnie" which was well sampled by TRMM (late August 1998).

Results show a positive impact on the humidity analysis of assimilating 1D-Var TCWV in 4D-Var. The model rainrates at the analysis time are closer to the TRMM observations showing *a posteriori* the consistency of the two-step approach chosen to assimilate rain rate information in 4D-Var. The modification of the humidity analysis induces changes in the wind and pressure analysis. In particular the analysis of the track of Bonnie is noticeably improved for the early stage of the storm development for both "Rain-1" and "Rain-2" experiments. When Bonnie is in a mature stage the influence of the 1D-Var TCWV assimilation is to intensify the hurricane. Comparison with CERES (Clouds and the Earth's Radiant Energy System) measurements also show a slight improvement of the radiative fluxes at the top-of-the atmosphere when using 1D-Var TCWV estimates.

The impact on the forecasts is a slight reduction of the model precipitation spin-down over tropical oceans. Objective scores for the tropics are significantly better particularly for wind and for upper tropospheric temperature.

Analysis and forecast results are generally better for "Rain-2" experiment compared to "Rain-1" implying that the 1D-Var TCWV estimates retrieved where no rain is observed provide a useful information to 4D-Var.

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. 3D-Var systems are currently operational at NCEP (National Centers for Environmental Prediction) and at the United Kingdom Meteorological Office. 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). A 4D-Var system is also operational at Météo-France since June 2000 and developments are in progress at various meteorological centers (NCEP, UKMO, CMC).

The major source of atmospheric observations for assimilation over ocean 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. Numerous research studies have been done on rainfall rate assimilation (e.g. Krishnamurti 1984, Puri and Miller 1990, Heckley *et al.* 1990, Treadon 1996, 1997). Among them, only one 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 and has a positive impact on the tropical wind forecasts, mostly at the 200 hPa level. A more significant improvement of the forecast performances can be expected by assimilating rain rate using a 4D-Var system which can account for the temporal evolution of rainy systems.

A possible way to evaluate the usefulness of any new type of observations in global variational analysis systems at a reasonable cost is to use a one-dimensional variational (1D-Var) approach. In this case the assimilation is performed in two steps. The first step consists of a 1D-Var assimilation of the observed quantity in which 1D-Var seeks for adjusted model variables (e.g. temperature, sea level wind speed) that fit, in the least square sense, the observations within both model and observation errors. The second step is the assimilation of the 1D-Var retrieval products in 3D-Var or 4D-Var. Since 1D-Var products are basic thermodynamic/dynamic model variables, they can be easily introduced in a global data assimilation system without too much technical work and without substantial increase of computing cost. One weakness of this approach is to introduce in the global system correlations between the observations and the model state. However, the one-dimensional framework allows a detailed study of model adjustments related to the assimilation of one particular type of observations. A 1D-Var approach was used operationally at ECMWF for TOVS radiances assimilation in clear air (Eyre *et al.* 1993) from June 1992 to May 1999 and was implemented for SSM/I brightness temperatures assimilation in non-rainy areas in June 1998 (Phalippou 1996, Gérard and Saunders 1999).

The aim of the present paper is to study the impact on analyses and forecasts of the assimilation of TRMM derived rain rates in the ECMWF 4D-Var system. A 1D-Var approach was chosen because it allows the influence of this new type of observation to be evaluated without requiring too much technical developments and computing resources. The 1D-Var method was developed and tested by Marécal and Mahfouf (2000) (noted MM2000 hereafter). It allows the retrieval of adjusted temperature and humidity profiles that provide a model rain rate within both the model and the surface rain rate observation error. Their results showed that 1D-Var is generally able to modify the model temperature and humidity profiles in order to get a rainfall rate close to the observation when the model initially produces rain. In this paper, results of two 4D-Var assimilation experiments are analyzed making use of the total column water vapour (TCWV) retrieved from MM2000's 1D-Var.

A summary of the 1D-Var basis and of MM2000's 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. Analysis and forecast results are discussed in section 4 and 5, respectively. Section 6 shows results of a sensitivity experiment to the rain rate observation error. Concluding remarks are given in section 7.

2. 1D-Var retrieval

2.1 Method

We define R_o an observed surface rain rate 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:

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

where $\mathbf{B}$ is the background error covariance matrix from the ECMWF 4D-Var system (Rabier *et al.* 1997, Derber and Bouttier 1999), σ_o 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 parameterizations of the moist-convective and of the large-scale precipitation processes. The control variable vector contains 63 elements: profiles of temperature T and specific humidity q on 31 model levels and surface pressure P_s. MM2000 used background fields calculated from an ECMWF model version (Cycle 18r3) with spectral truncation T_L319 (corresponding to a 60 km resolution approximately) and 31 vertical levels (up to the 10 hPa level).

2.2 Observations

The rainfall rates used by MM2000 came from the Tropical Rainfall Measuring Mission (TRMM) observations. TRMM's main objective is to measure rainfall and energy exchanges of tropical regions (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 by MM2000 were the instantaneous surface rainfall rates (2A12 product level 4) provided operationally by NASA. They are retrieved from the Kummerow *et al.* (1996)'s algorithm applied to TMI brightness temperatures and are provided at the highest pixel resolution (about 7x5 km^2). Because TMI-2A12 rain estimations are less accurate over land than over sea (Kummerow *et al.* 1996), only observations over ocean were used. To be consistent with the model rain rates which are representative of a much larger area, the observations assimilated in 1D-Var (i.e. R_o) were obtained by averaging the TMI-2A12 rain rates at the model resolution. In MM2000, the observation error σ_o was set to 25% of R_o with a minimum threshold value of 0.01 mm h^{-1}.

2.3 Main results

In their study, MM2000 showed that when precipitation is present in the background field, 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. This weakness was also found by Treadon (1997).

Because there is no objective estimate of σ_o, MM2000 performed sensitivity tests on σ_o value. If σ_o is increased from 25% of R_o to 50% of R_o, this has an impact on 1D-Var results for moderate and heavy rain rates. When the observation error is increased, the 1D-Var provides smaller but non-negligible humidity and temperature changes meaning that an important part of the information contained in the observations is still used.

3. 4D-Var assimilation of TCWV retrievals in rainy areas

3.1 1D-Var configuration

In the present study, the background state $\mathbf{x}^b$ used in 1D-Var comes from fields generated using a more recent ECMWF model version (Cy21r1) with spectral truncation T_L319 and 50 vertical levels (up to the 0.1 hPa level). However, only the 31 lowest model levels are used in the control vector since surface rainfall rate is not influenced by stratospheric levels.

The TMI products selected for the present study are the latest version of the instantaneous surface rainfall rates provided operationally by NASA (2A12 product level 5). As in MM2000, σ_o is set to 25% of R_o with a minimum threshold value of 0.01 mm h^{-1}. The sensitivity of 4D-Var results to the specification of σ_o is discussed in section 6.

3.2 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 (model short-term forecast) and to the observations available over a given time period (currently six 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 parameterizations, 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 parameterizations (Mahfouf 1999).

Because MM2000 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 (i.e. the vertical integral of specific humidity) 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. As shown by Rodgers (1976), the 1D-Var analysis error covariance matrix **A(x)** of the atmospheric state **x** can be approximated by:

$$\mathbf{A}(\mathbf{x}) = \left(\mathbf{B}^{-1} + \frac{1}{\sigma_o^2}\mathbf{R}^T(\mathbf{x})\mathbf{R}(\mathbf{x})\right)^{-1} \quad (2)$$

where **R(x)** is the Jacobian matrix of the partial derivatives of the simulated rain rate with respect to the control variable **x**. The error variance of the analysed TCWV (noted σ_{TCWV}^2) is then obtained by applying the vertical integration operator to the specific humidity elements of the **A** matrix. The elements of the **A** matrix depend on the considered atmospheric state **x** and thus a value of σ_{TCWV} can be computed for each 1D-Var retrieval. A scatter plot of σ_{TCWV} values as a function of 1D-Var analysed TCWVs computed using 3505 retrievals is shown in Fig. 1. There is generally a large spread of the σ_{TCWV} values for a given TCWV. Nevertheless, the global tendency for σ_{TCWV} is to increase until TCWV reaches approximately 50 kg m^{-2} and to decrease for higher TCWV values. This behaviour is modelled by fitting the data with a second order polynomial (see Fig. 1):

$$\sigma_{TCWV} = -1.72 + 0.261 \times \mathrm{TCWV} - 0.00257 \times \mathrm{TCWV}^2 \quad (3)$$

To avoid negative or unrealistic small values for σ_{TCWV}, a minimum threshold of 1 kg m^{-2} is applied to (3).

Since 1D-Var is not always successful in adjusting the observed rain rates, a quality control was applied to 1D-Var products before entering 4D-Var; only 1D-Var retrievals providing a rain rate fitting the observation within the observation error are selected (as explained more precisely in MM2000). After this quality control, about 1500 to 2000 "1D-Var TCWV observations" can be possibly retained per 4D-Var assimilation cycle.

3.3 Design of the experiments

Three experiments were designed to assess the impact of assimilating 1D-Var TCWV in rainy areas in the ECMWF 4D-Var system using a TL319L50 (Cy21r1) model configuration. The three experiments were run for a 15-day period, between 18 August 1998 at 1200 UTC and 2 September 1998 at 1200 UTC. This period was selected because it includes the whole life time of the tropical cyclone Bonnie which was well sampled by TMI. 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. For each experiment a series of 10-day forecasts was run from the 12 UTC analyses.

The first experiment is the "Control" which only assimilates the operational data set of the considered model version; humidity data used are TEMP specific humidity profiles below 300 hPa, SYNOP relative humidity and SSM/I TCWV in non rainy areas over ocean.

The second experiment (denoted "Rain-1" experiment) is identical to the "Control" except that it includes the assimilation of a reduced number of quality controlled 1D-Var TCWV estimates in 4D-Var; only the 1D-Var retrievals corresponding to a non-zero rain rate observation are selected. The reason for this sorting is that when there is no rain in the observation, 1D-Var seeks the non-rainy state that is the closest to the background state. This retrieved state may differ from the real one since there is a large number of possible atmospheric states that lead to no rain. Moreover, SSM/I TCWV estimates from brightness temperatures are already assimilated operationally in non-rainy areas leading to a possible conflict between the two TCWV estimates.

A third experiment identical to "Rain-1" but including all quality-controlled 1D-Var TCWV estimates was run (denoted "Rain-2" experiment). This experiment was motivated by two reasons. Firstly, TCWV estimates from 1D-Var when no rain is observed can possibly add some useful information to 4D-Var although there is more uncertainty on 1D-Var TCWV than on SSM/I TCWV (when exists) in non-rainy conditions. Secondly, the number of 1D-Var TCWV observations retained for "Rain-1" experiment are around 400 per assimilation cycle. This number, which is about four times smaller than for "Rain-2" experiment, might be too small to lead to a significant impact on 4D-Var analyses and forecasts.

In the three experiments estimates of TCWV from SSM/I brightness temperature observations were used in non-rainy areas (Phalippou 1996, Gérard and Saunders 1999). Because SSM/I TCWV is erroneous when rain is present, a strict rejection procedure was designed to discard SSM/I brightness temperatures in rainy conditions. Rain is identified by applying a regression algorithm (Bauer and Schluessel 1993) to the observed SSM/I brightness temperatures. Note that this modification is now used in the current operational 4D-Var version. This new quality control prevents a possible and undesirable conflict between SSM/I TCWV and 1D-Var TCWV where it rains.

Since TRMM only covers the tropics and the subtropics, results (tables and figures) of these three experiments will be given and discussed for the latitude band sampled by TMI. The term "global" will represent hereafter this latitude band, except in subsection 5c where the full globe will be considered.

4. Impact on analyses

4.1 Statistics of model departures from observations

Figure 2 shows the global mean statistics of the 4D-Var assimilation of 1D-Var TCWV. The background departure is the difference between the observation and the background (short-term forecast). The analysis departure is the difference between the observation and the analysis. The observations considered here are the 1D-Var TCWV estimates. To compute these statistics, the background and analysis fields are converted into TCWV. Because "Rain-1" experiment only uses TCWV estimates when rain is observed, the number of observations used in "Rain-1" experiment (~23 000) is about four times smaller than in "Rain-2" experiment (~103 000). This means that most of 1D-Var retrievals for "Rain-2" experiment correspond to grid points where no rain is observed. This is mainly due to the fact that 1D-Var approach is unable to trigger rain when the model background rain is zero (see MM2000).

For "Rain-2" experiment, the mean background departure exhibits a negative bias of -0.21 kg m^{-2}. On average 1D-Var TCWV observations tend to decrease rainfall rate. This is consistent with the large number of 1D-Var retrievals corresponding to a zero rain observation. A positive bias of 0.56 kg m^{-2} is found for the "Rain-1" experiment meaning that, in this case, 1D-Var TCWV observations tend to increase precipitation by increasing TCWV. For both experiments, the bias is reduced by the analysis indicating that part of the information from 1D-Var TCWV estimates was extracted by the 4D-Var system.

The RMS (root mean square) for “Rain-1” experiment is reduced by the analysis showing a better fit to observations. The slight increase of the RMS for “Rain-2” experiment can be explained by the fact that most of the 1D-Var TCWV observations are assimilated where no precipitation is observed. In this case, a different SSM/I TCWV estimate located close to the 1D-Var TCWV may also be used by the assimilation system. This is reflected in the SSM/I TCWV statistics which show a small deterioration of the RMS analysis for “Rain-2” experiment (not shown).

Compared to SSM/I statistics of model departures, all mean and RMS values for 1D-Var TCWV are smaller than for SSM/I TCWV by a factor two or more. This means that the current experiments only change humidity by small amounts compared to SSM/I.

4.2 Analysis of total column water vapour

The global mean values of 4D-Var analysed TCWV are given in Table 1. The differences between the three experiments are small (< 1%) and are associated with small RMS of background departures (~2 kg m^{-2}) compared to SSM/I (~4.5 kg m^{-2}) and to the low frequency of occurrence of rainy areas within TMI coverage. “Rain-1” experiment provides a slightly moister atmosphere than the control while the opposite result is found in “Rain-2” experiment. This is consistent with the model departure statistics showing that the tendencies for both experiments are, respectively, to increase and to decrease TCWV on average.

The RMS of TCWV increments allows the relative quality of the humidity analysis for the three 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 three experiments are displayed in Fig. 3 and global values are given in Table 1. Both experiments using 1D-Var TCWV provide RMS increments noticeably smaller than the “Control” experiment in most areas thereby showing a positive impact of rain-derived observations. The improvement is more important for “Rain-2” experiment (8%) indicating that the use of all 1D-Var TCWV estimates even where no rain is observed provides a better TCWV analysis. In other words, this means that the information extracted from 1D-Var TCWV estimates where no rain is observed is valuable to 4D-Var although SSM/I TCWV estimates are probably more reliable. It is also important to note that “Rain-1” experiment leads to an improved humidity analysis despite the small number of 1D-Var TCWV retrievals used in 4D-Var.

4.3 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 at the assimilation time closer to the TMI-derived observations. Figure 4 shows the instantaneous surface rain rate at the analysis time for the three experiments together with the observed field on the 25 August 1998 at 1800 UTC. This analysis time was selected because hurricane Bonnie was well sampled by TMI during the corresponding assimilation window. The rain rate fields for “Rain-1” and “Rain-2” experiments show an improvement of both the structure and the intensity of the surface rain rate in the most active parts of the hurricane, “Rain-2” experiment giving better results. Compared to 1D-Var results (see MM2000’s results), the improvement in the 4D-Var context is less important. The main explanation is that 4D-Var uses 1D-Var TCWV estimates together with many other types of observations to modify the analysis in an optimal way.

Global results averaged over the 15-day assimilation period are given in Table 2. Both rain experiments provide 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 differences. "Rain-2" experiment exhibits better results than "Rain-1" experiment. This is consistent with the results obtained for the 4D-Var TCWV analysis.

4.4 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. 5ab, the use of rain-derived observations in 4D-Var improves noticeably the location of the track in the early stages of development of the cyclone. Here again, "Rain-2" experiment provides the best results showing a good consistency between the humidity and the pressure analysis. 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 Bonnie is in a mature stage (from 23 August 1998 to 27 August 1998), all three experiments provide tracks close to the best-track. The small discrepancies between the model and the observed track can be attributed to the 4D-Var minimization which is performed in a low resolution space at the initial time and to the version of 1D-Var which assumes that TMI observations are obtained at the middle of the assimilation window. Figure 5c displays the minimum of mean sea-level pressure in the hurricane for the three experiments. For the early stage, no important differences between the three experiments can be seen. For the mature stage, a much deeper cyclone is analysed in "Rain-1" and "Rain-2" experiments compared to the "Control" experiment with a maximum difference, respectively, of 3 and 5 hPa on the 25 August 1998.

4.5 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 Fig. 6 and 7 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 intensify the hurricane by increasing the maximum horizontal wind and the updraft within the hurricane. "Rain-1" experiment leads to less modifications compared to the "Control" than the "Rain-2" experiment which is consistent with the results of the other analysed fields. 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.

Although the 1D-Var TCWV estimates 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.

4.6 Impact on radiative fluxes

Since 1D-Var TCWV assimilation modifies the water variables (water vapour, cloud and rain), an impact on the model radiative fluxes is also expected. In order to evaluate this impact, a comparison with CERES (Cloud and Earth's Radiant Energy System) observations was done. CERES is a three-channel broadband radiometer flying on board the TRMM platform (Weilicki *et al.* 1996) which gives an indirect measure of the longwave and shortwave fluxes at the top of the atmosphere. The model fluxes integrated over 6 hours from the analysis time are compared to the CERES measurements averaged over the same period of time as done in Chevallier and Morcrette (2000). A global comparison of the results for the 15-day period is given in Table 3. The global mean impact of 1D-Var TCWV assimilation is neutral for the "Rain-1" experiment and is slightly positive for the "Rain-2" experiment. These results agree with the improvements found on TCWV and rain rate which are more important for the "Rain-2" experiment. They also show the relatively good consistency in the model between the radiation scheme and the vertical distribution of the humidity related fields (moisture, cloud and precipitation).

5. Impact on forecasts

5.1 Hydrological cycle

The short-range forecast of rainfall rate is affected by the changes in the humidity analysis. Figure 8 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. All the experiments give large rain rates at the beginning of the forecast that decrease rapidly with time. This behavior is known as spin-down. After 48 hours of forecast, the curves reach the model equilibrium for the hydrological cycle.

"Rain-1" and "Control" experiment curves are very close. Although "Rain-1" experiment tends to increase the mean humidity it does not increase the spin-down. It retains slightly more humidity after 24 hours than the control. "Rain-2" experiment reduces noticeably the spin-down because, in this case, the forecast starts from a slightly drier humidity analysis.

5.2 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 leading to an impact on the forecasted tracks. Figures 9a and 10a show the track of the hurricane from observations ("best-track") and forecasted by the model starting on 20 August 1998 at 1200 UTC and on 21 August 1998 at 1200 UTC from the three experiment analyses. Both rain experiments forecast a better track starting on the 20 August 1998 1200 UTC while the opposite is found on the 21 August 1998 1200 UTC. The improvement of the track is not correlated with either an increase or a decrease of the pressure minimum as illustrated by Fig. 9b and 10b. For instance, curves of the pressure minimum for "Rain-1" and "Control" experiments are close while providing different tracks. Note also that there is no direct relation between the quality of the forecasted track and the analysis differences. An ensemble prediction system could be used to diagnose the sensitivity of the forecasted track to different initial conditions. Puri *et al.* (2000) have shown that the trajectory of tropical cyclones is mostly sensitive to modifications of the initial dynamical fields. In the rain experiments, the initial wind field is only slightly modified through TCWV increments.

5.3 Objective scores

In this subsection results are given for the full globe. To evaluate the impact of 1D-Var TCWV assimilation on forecast performances, the RMS error of the geopotential at 500 hPa is calculated. Figure 11 displays the results for the Northern (between +90° and +20° latitude) and the Southern (between -20° and -90° latitude) hemispheres. The impact of the rain assimilation is almost neutral in both hemispheres. In the Northern hemisphere, "Rain-1" experiment provides slightly better scores than the "Control" experiment. This result is significant to the 5% level in the short range. For the Southern hemisphere, "Rain-1" and "Rain-2" experiments provide a small improvement in the short range at a 2% and 5% significance level, respectively.

Figure 12 shows the RMS errors for the tropical wind at 850 hPa and 200 hPa up to day-4. They are computed against their own analysis, as the tropical analyses in the three experiments are significantly different from the operational ones. "Rain-2" experiment performs better than the other two with a 5% level of significance. This is a consequence of the larger modifications to the initial humidity field performed in "Rain-2" 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-2" experiments reduces also significantly the RMS errors of the upper tropospheric temperature at 200 hPa in the tropics (Fig. 13).

6. Sensitivity to rainfall observation error

Because no objective estimate of σ_o (error on the observed rain rate in 1D-Var) is available, the sensitivity of the results to the choice of σ_o values was tested. An assimilation experiment (called hereafter "Test" experiment) using an error of 50% of R_o instead of 25% of R_o in 1D-Var was run for a period of 3 days only, starting on 18 August 1998 at 1200 UTC as for the other three experiments. Since "Rain-2" experiment provides better results than "Rain-1" experiment, the "Test" experiment was run using "Rain-2" configuration which includes all 1D-Var quality controlled TCWV in 4D-Var. Since σ_{TCWV} depends on σ_o (see equation 2), a new relationship between σ_{TCWV} and TCWV was computed using the same samples as used to obtain relation (3). Even though σ_o was doubled, results exhibit very little differences between the new relationship and (3) (not shown). This is due to the dominant role of the background error in the calculation of σ_{TCWV} compared to the rain rate observation error σ_o. Consequently, formula (3) was also used to set σ_{TCWV} in 4D-Var for the Test experiment.

Figure 14 displays the global mean statistics of the 4D-Var assimilation of 1D-Var TCWV for "Rain-2" and "Test" experiments over the 3-day period. Mean background and analysis departures are similar. But RMS of background and analysis departures for "Test" experiment are smaller than for "Rain-2". This means that 1D-Var TCWV is closer to the background for "Test" experiment. This is consistent with the larger σ_o values in

"Test" experiment which lead to generally smaller modifications of TCWV by 1D-Var with respect to the 1D-Var background because of a weaker constraint. It is also important to note that about 600 more 1D-Var TCWV observations are assimilated in 4D-Var for "Test" experiment. This means that more TCWV estimates passed the 1D-Var quality control and thus more information was provided to 4D-Var. This is related to the weaker constraint imposed in 1D-Var for "Test" experiment which allows a larger number of successful retrievals (Marécal and Mahfouf, 2000).

Global results for the TCWV analysis and for the rain rate comparison are given in Tables 4 and 5. No major differences can be found between "Rain-2" and "Test" experiments. They both provide a better humidity analysis as shown by the decrease of the RMS of TCWV increments (see Table 4) and surface rain rates closer to observations (see Table 5). This good behavior of "Test" experiments compared to "Rain-2" experiment can be explained by the increase of the number of TCWV observations assimilated in 4D-Var which counterbalances the decrease in absolute value of TCWV increments. Results for the precipitation spin-down also show that "Test" and "Rain-2" experiments provide very similar global results (not displayed).

7. Conclusion

The aim of this paper was to study the impact of the assimilation of surface rain ate in the ECMWF 4D-Var analysis system. For simplicity, the approach chosen is based on a 1D-Var. Firstly, temperature and humidity profiles are retrieved using MM2000's 1D-Var method constrained by TRMM derived rain rates. Secondly, 1D-Var TCWV estimates are assimilated in 4D-Var. Three assimilation experiments were run for a 15-day period. One is the "Control" and the other two ("Rain-1" and "Rain-2") assimilate 1D-Var TCWV. "Rain-1" considers a limited set of 1D-Var TCWV: only quality controlled 1D-Var profiles corresponding to a non-zero observed rain rate are retained to avoid a possible conflict with SSM/I TCWV assimilation in non-rainy areas. In "Rain-2" experiment all quality controlled 1D-Var TCWV observations are assimilated in 4D-Var.

The global TCWV analysis is only slightly modified by the use of rain-derived data in 4D-Var. This is explained by the small humidity increments provided by 1D-Var to modify precipitation with RMS values around 2 kg m^{-2}. "Rain-2" (resp. "Rain-1") experiment tends to decrease (resp. increase) the humidity because on average a decrease (resp. increase) of precipitation is required. Both rain experiments give a noticeable improvement of the humidity analysis as shown by the global decrease by 3 % for "Rain-1" and by 8% for "Rain-2" of the RMS of TCWV increments. The model surface rain rate at the analysis time is closer to TMI-2A12 observations. This means that the rain rate information from observations is correctly extracted by the assimilation system even though it is done through 1D-Var retrievals. 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-1" and "Rain-2" experiments compared to "Control". This is consistent with the mean sea-level pressure analysis which shows a deeper minimum for both rain experiments. 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 does not lead to better forecasts of the track. Global comparisons with CERES radiative measurements made on board TRMM platform show a slight improvement when rain-derived data are used in 4D-Var.

The impact on the precipitation spin-down is neutral for “Rain-1” experiment even though the global mean humidity is slightly increased. “Rain-2” 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.

The sensitivity of the results to the specification of the errors on TRMM surface rain rates was tested on a 3-day experiment. Results show that by setting the rain rate error to 50% of R_0 instead of 25% of R_0 the global results are only slightly modified. The main reason is that the TCWV error is mostly unchanged when the rain rate error is increased. Moreover the impact of the smaller TCWV increments provided by 1D-Var in the “Test” experiment is counterbalanced by the increased number of quality controlled 1D-Var TCWV (Marécal and Mahfouf 2000).

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. “Rain-2” experiment performs generally better than “Rain-1” experiment. This indicates that the use of 1D-Var TCWV estimates where no rain is observed is useful even though these estimates are likely to be less accurate than TCWV retrievals from SSM/I brightness temperatures. 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. Moreover the use of a one time-slot version of 1D-Var does not allow to take into account the information on the temporal evolution of rainy systems. These limitations 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.

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. Moreover data are only used over oceans and where the model first-guess provides non zero rain rates leading to a reduced number of rain-derived observations that can possibly be assimilated by the 4D-Var. A way to increase this number would be to use the SSM/I (Special sensor Microwave/ Imager) on board DMSP (Defence Meteorological Satellite Program) satellites which 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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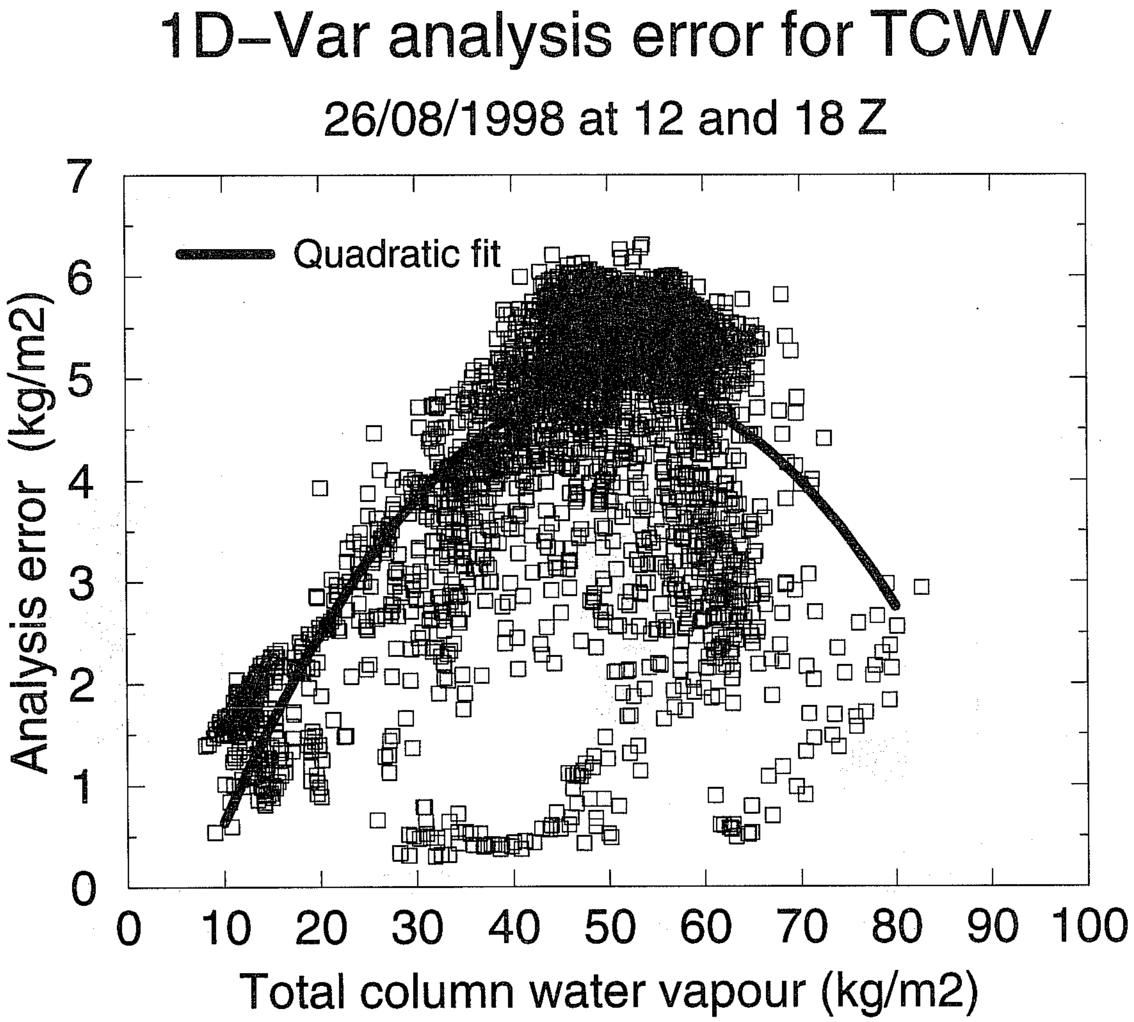

Figure 1: Scatter plot of 1D-Var analysis error on TCWV (σ_{TCWV}) in kg m^{-2} as a function of TCWV in kg m^{-2}. The number of TCWV retrievals used is 3505. The solid line corresponds to the best fit by second order power law. Coefficients of the quadratic fit are given in (3).

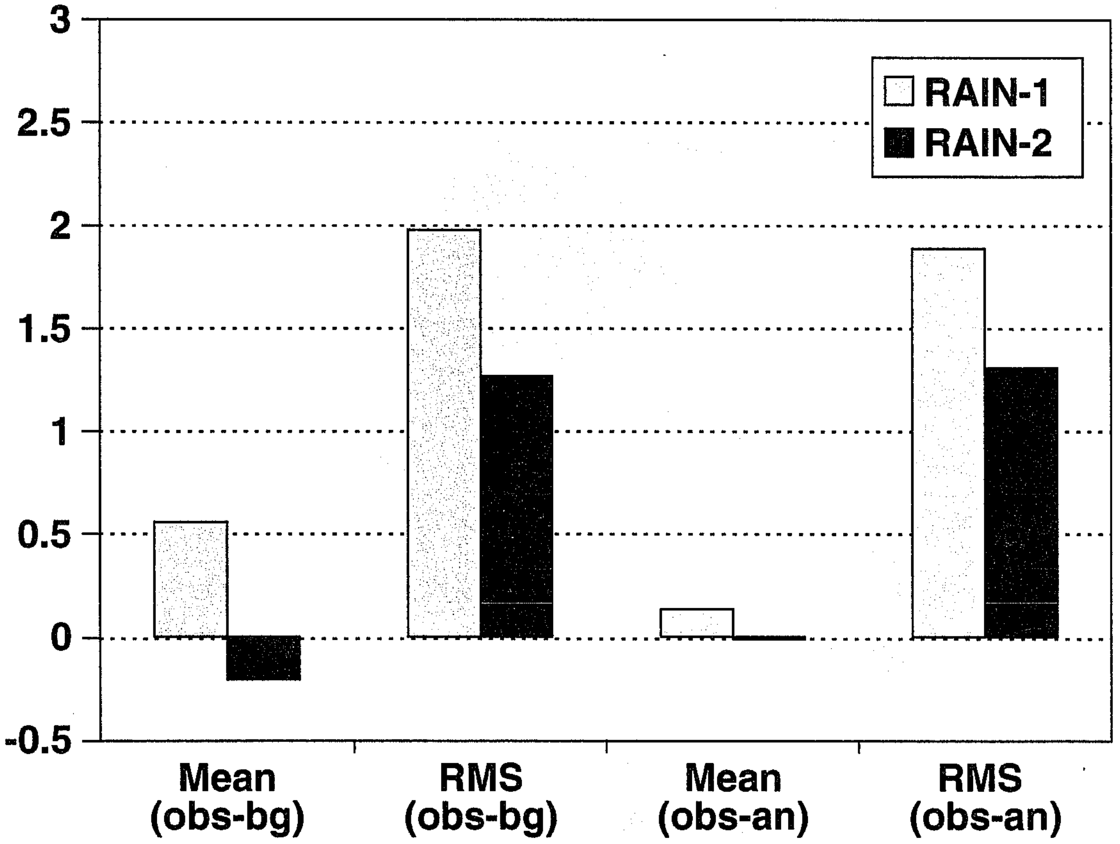

Figure 2: Global mean statistics of the 1D-Var TCWV used in 4D-Var for the 15-day period. Units are in kg m^{-2}. The background departure is the "1D-Var TCWV retrieval" minus the background TCWV (6-hour model forecast). The analysis departure is the "1D-Var TCWV retrieval" minus the 4D-Var analysed TCWV. The number of observations used to compute the statistics is 23058 for "Rain-1" experiment and 103097 for "Rain-2" experiment.

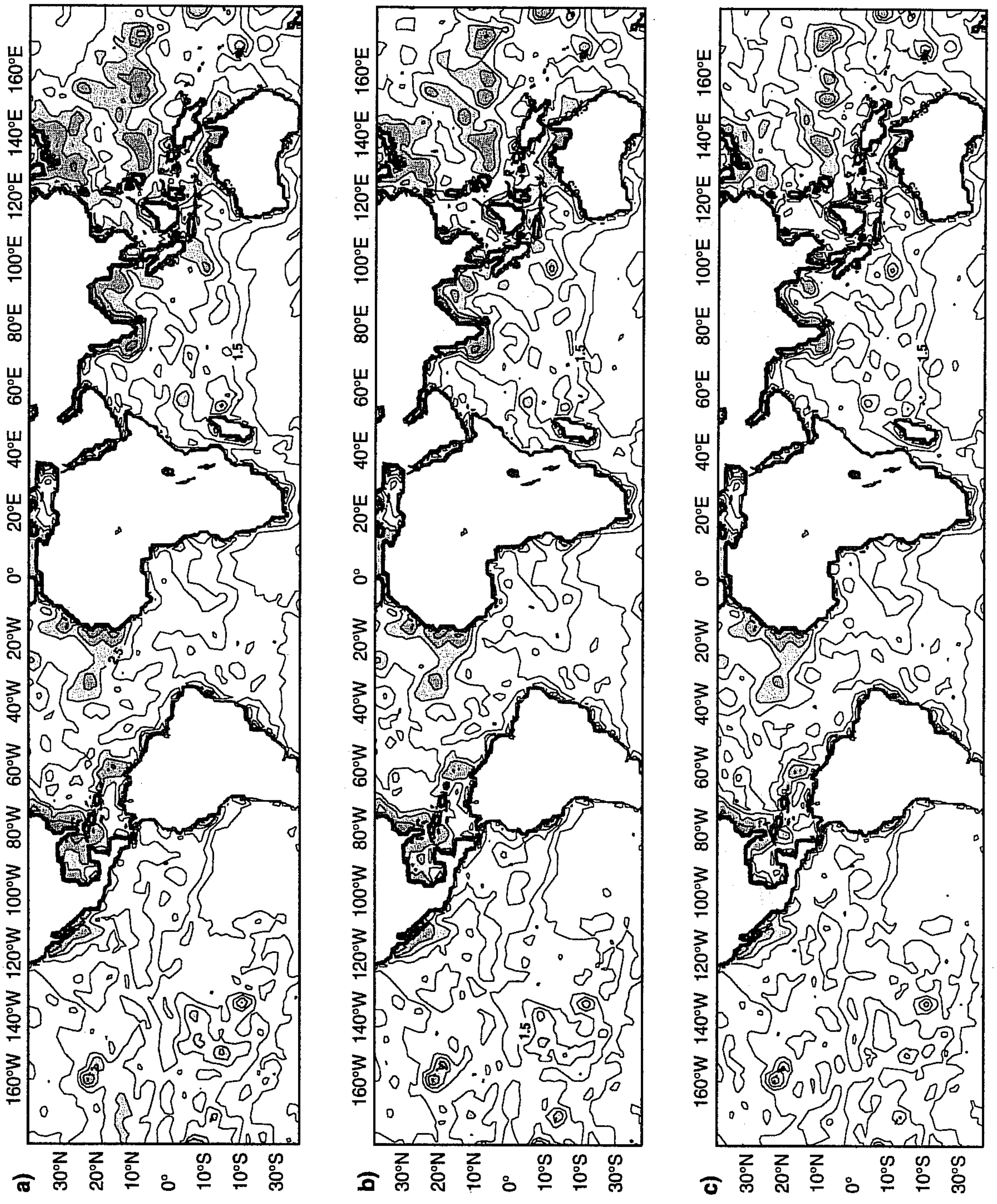

Figure 3: Root mean square of TCWV increments in kg m^{-2} averaged over the 15-day period. The increment field is obtained by computing analysed field minus background field (6-hour model forecast). (a) "Control" experiment, (b) "Rain-1" experiment and (c) "Rain-2" experiment. Contours are every 0.5 kg m^{-2} and grey shading starts at 2 kg m^{-2}.

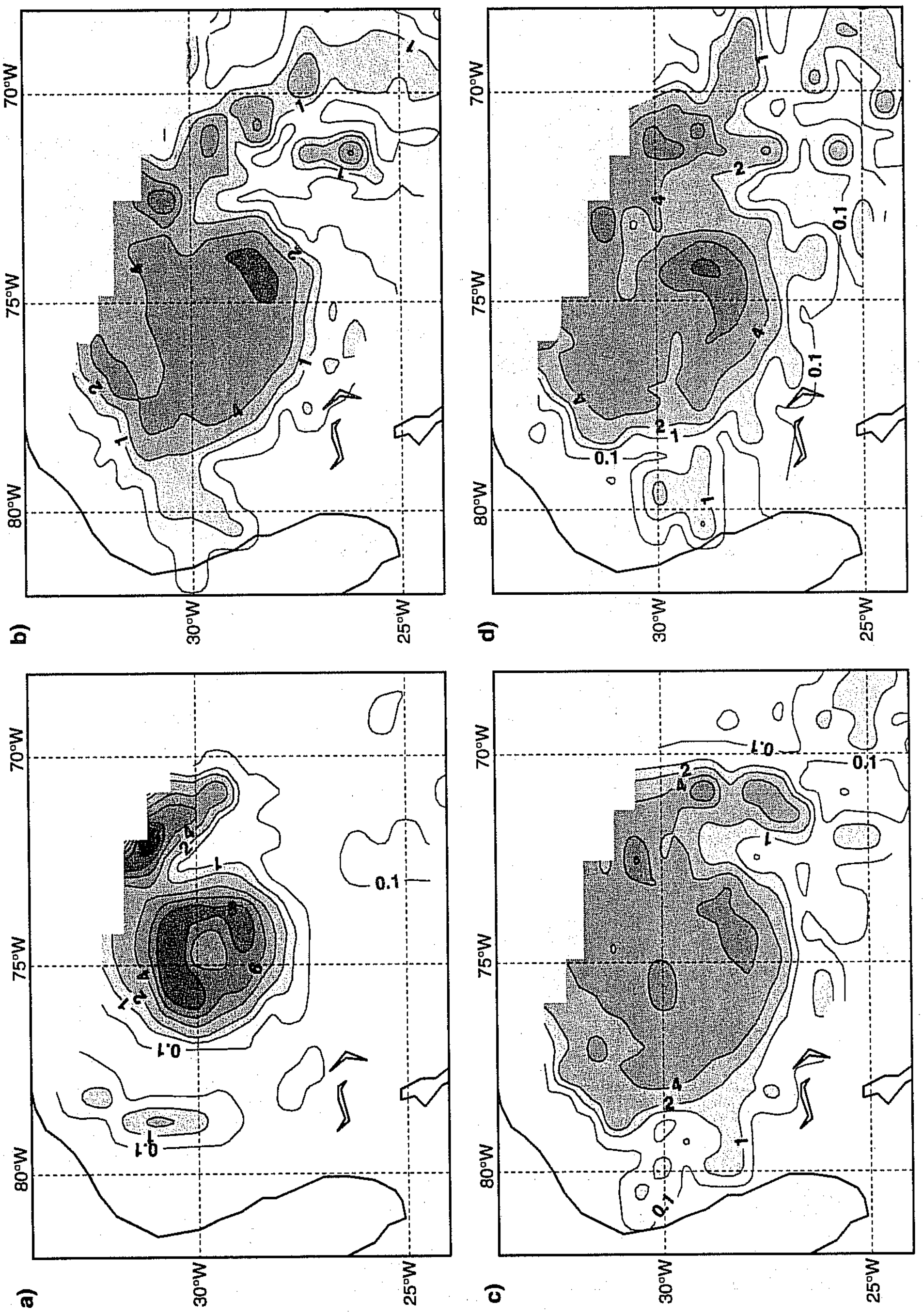

Figure 4: Surface rainfall rate in mm h^{-1} on 25 August 1998 at 1800 UTC. (a) from TMI 2A12 observations, (b) from "Control" experiment analysis, (c) from "Rain-1" experiment analysis and (d) from "Rain-2" experiment analysis. Model results are only displayed along the TMI swath.

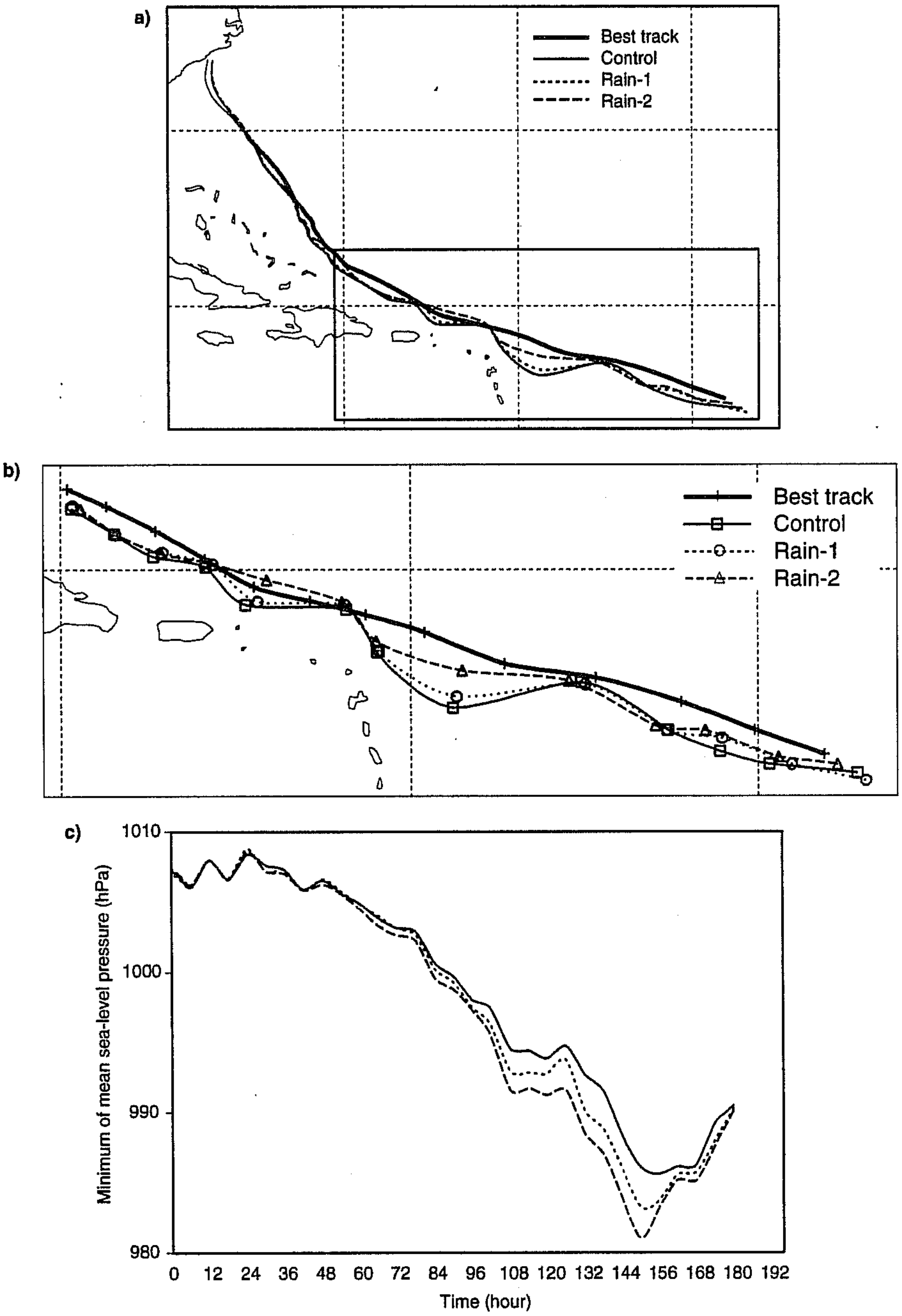

Figure 5: Analysed track of hurricane Bonnie. (a) location from 19 August 1998 at 1200 UTC to 27 August 1998 at 0000 UTC. (b) Zoom of the location from 19 August 1998 at 1200 UTC to 22 August 1998 at 1200 UTC (c) Temporal evolution of the minimum of mean sea level pressure in the hurricane (initial time corresponds to 19 August 1998 at 1200 UTC). Symbols are every 6 hours.

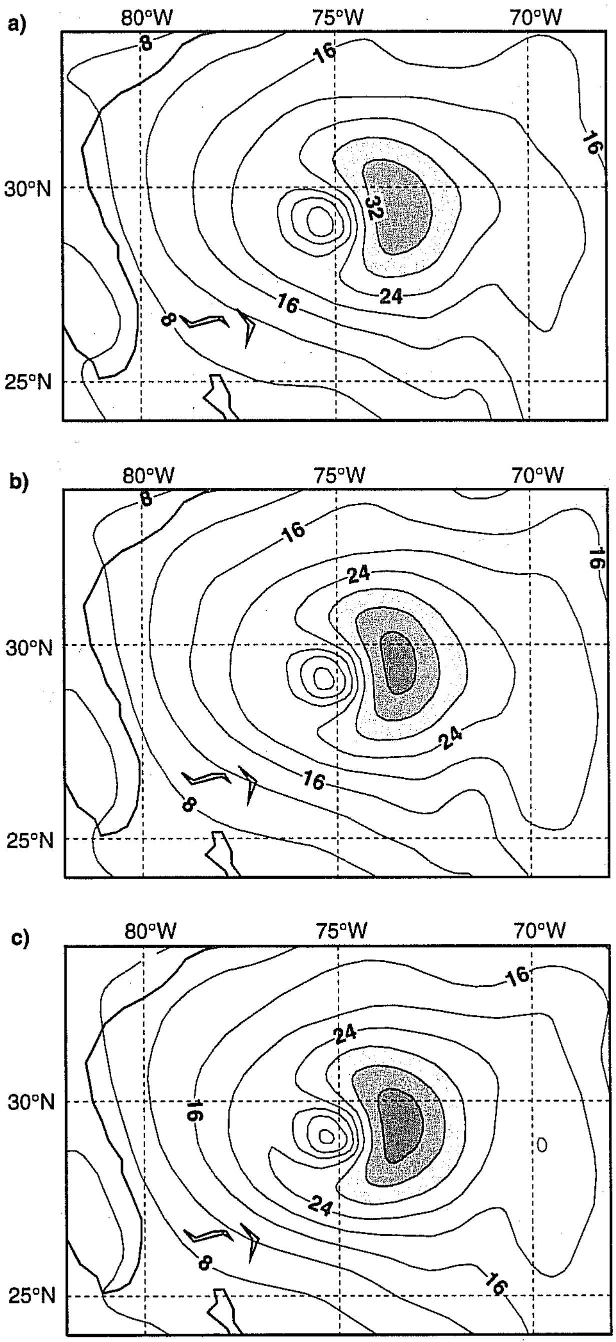

Figure 6: Horizontal wind velocity in m s^{-1} at 700 hPa on 25 August 1998 at 1800 UTC from (a) "Control" experiment, (b) "Rain-1" experiment and (c) "Rain-2" experiment. Grey shading starts at 28 m s^{-1}.

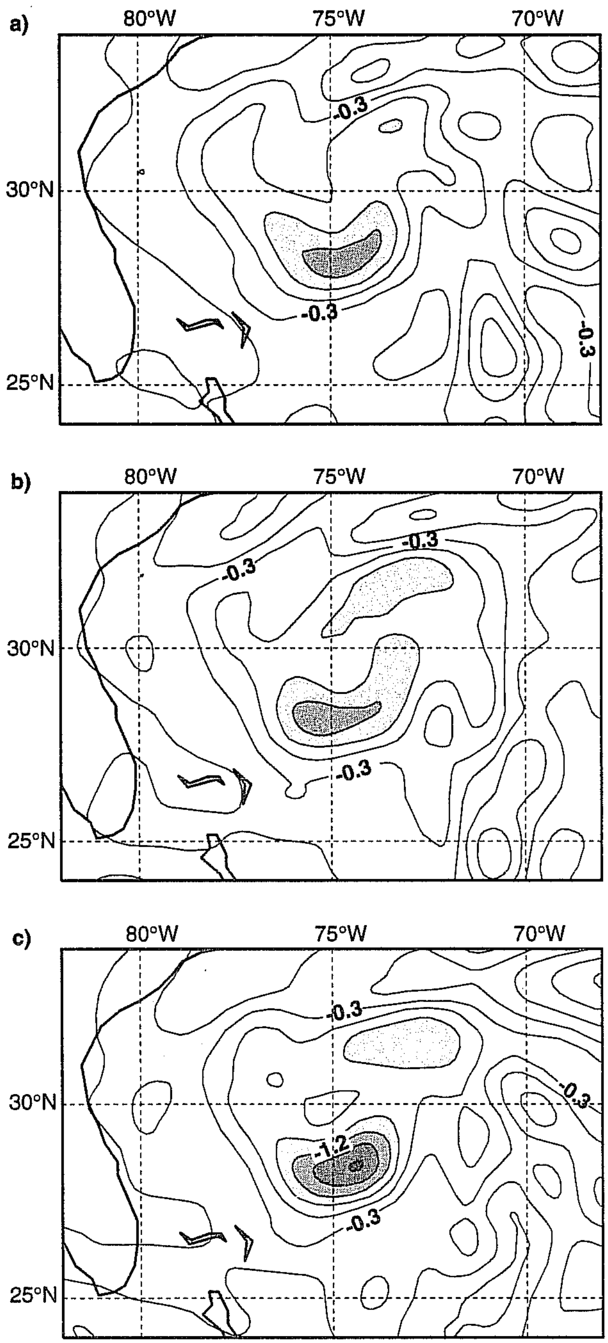

Figure 7: Same as Fig. 6 but for the vertical velocity (in Pa s^{-1}*) at 700 hPa. Grey shading starts below -0.9 Pa* s^{-1}*.*

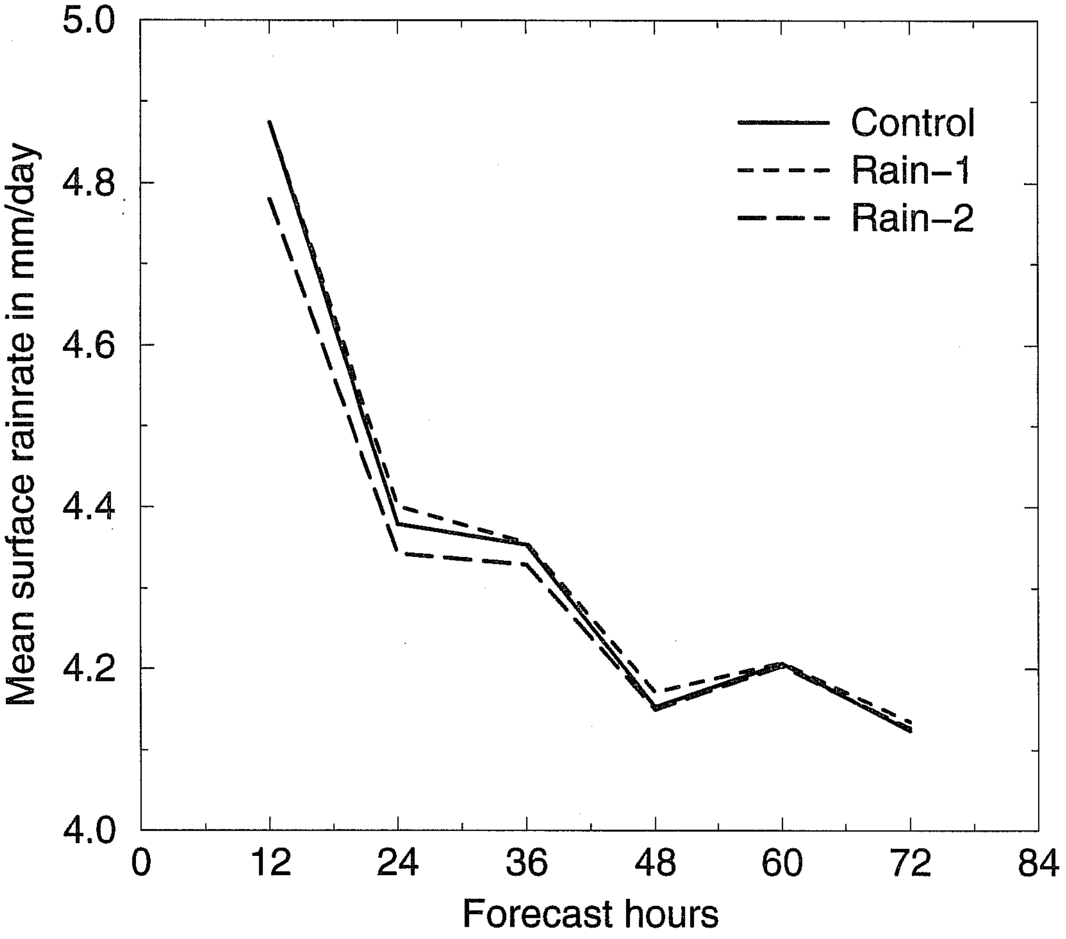

Figure 8: Mean surface rainfall rate over tropical oceans as a function of forecast range in hours. The surface rain rate is here the accumulated rain rate between T-12 hours and T, T being the forecast time.

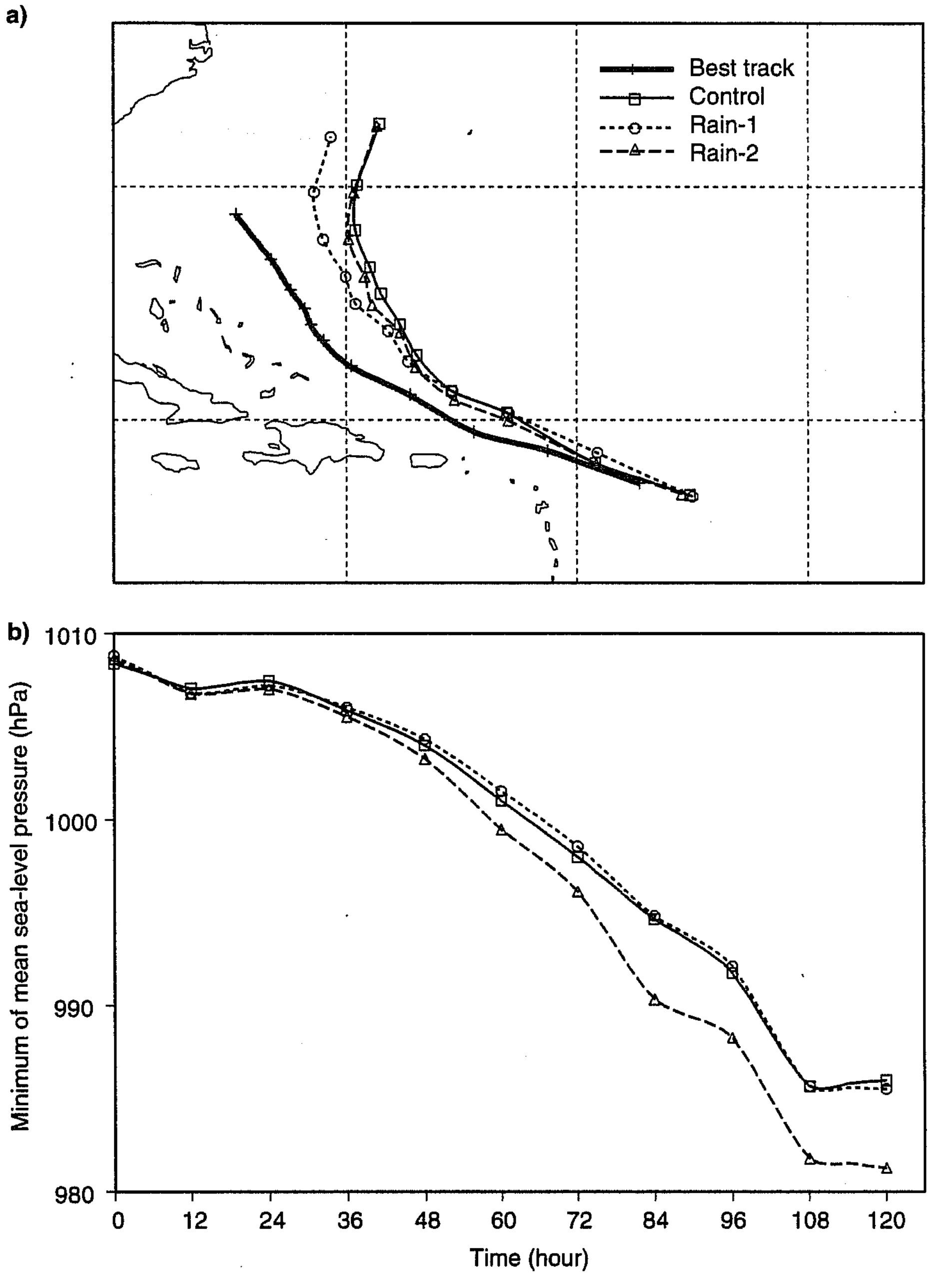

Figure 9: Forecast tracks of hurricane Bonnie. (a) Tracks from 5-day forecasts starting on 20 August 1998 at 1200 UTC based on the three experiment analyses together with the best-track from observations. (b) Temporal evolution of the minimum of mean sea level pressure in the hurricane (initial time corresponds to 20 August 1998 at 1200 UTC). Symbols are every 12 hours.

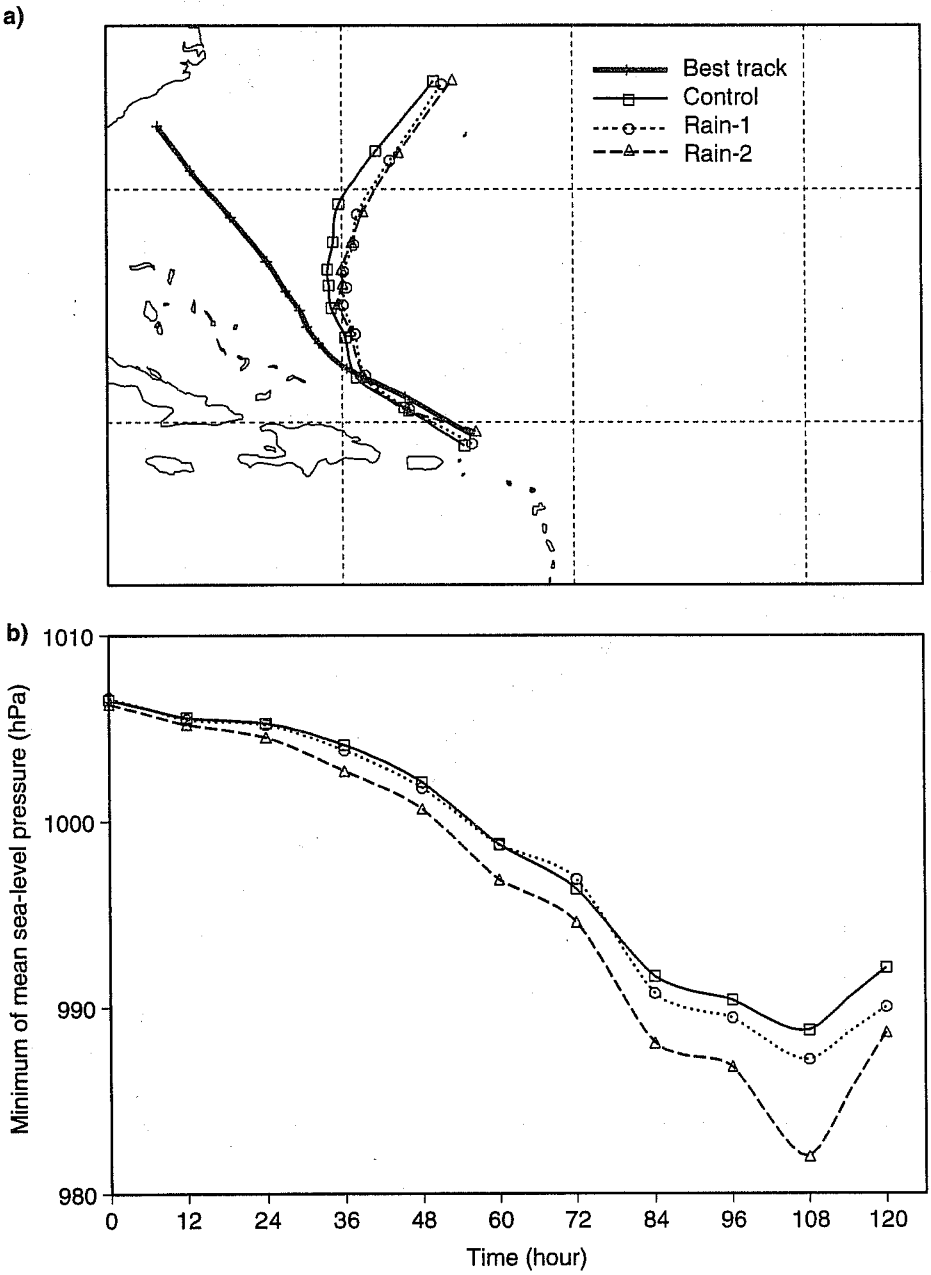

Figure 10: Same as Fig. 9 but for the forecasts starting on 21 August 1998 at 1200 UTC.

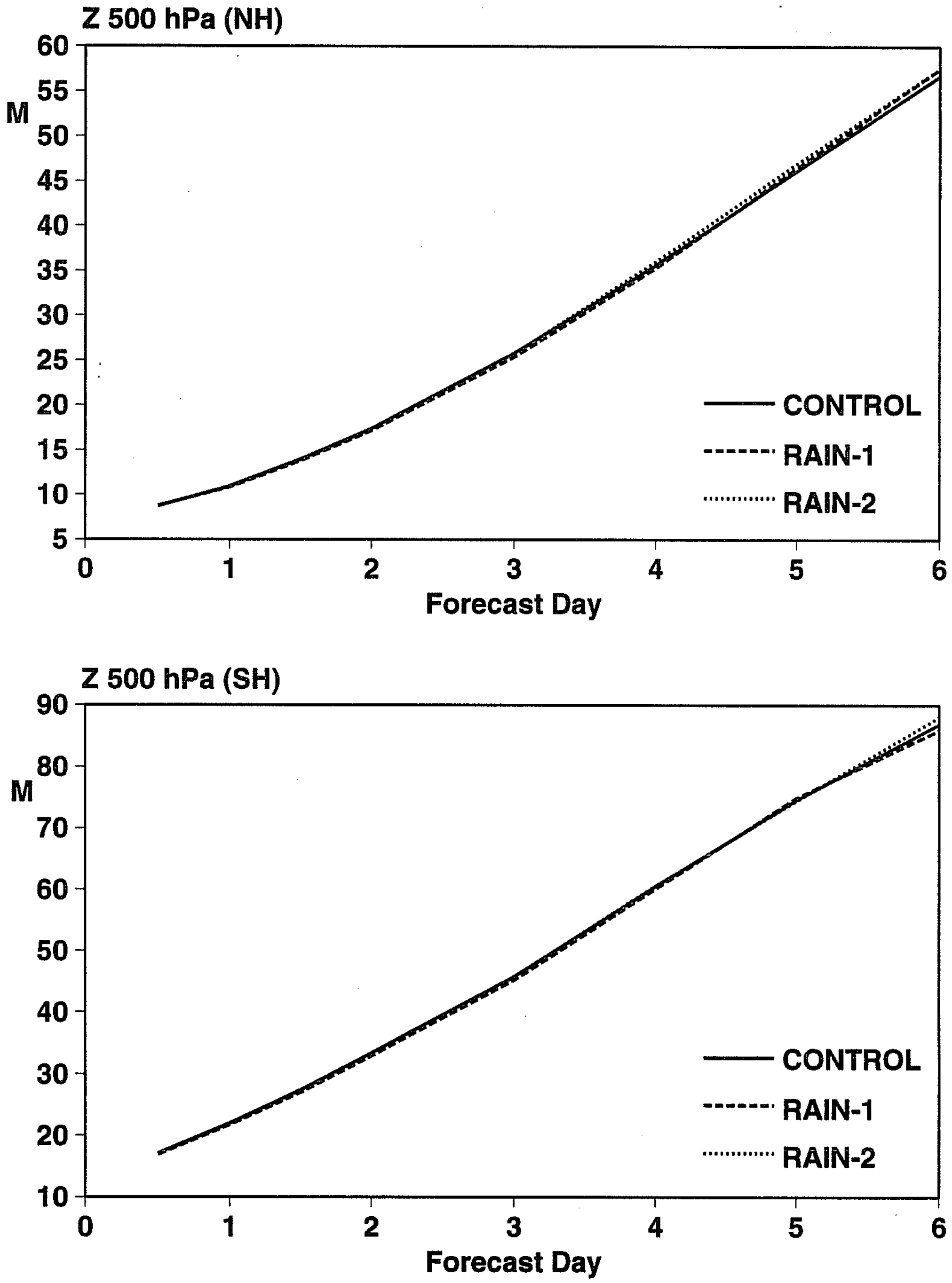

Figure 11: Root-mean square forecast errors of the geopotential at 500 hPa for the averaged over 16 cases (18 August 1998 to 2 September 1998) over the Northern Hemisphere (top panel) and the Southern Hemisphere (bottom panel).

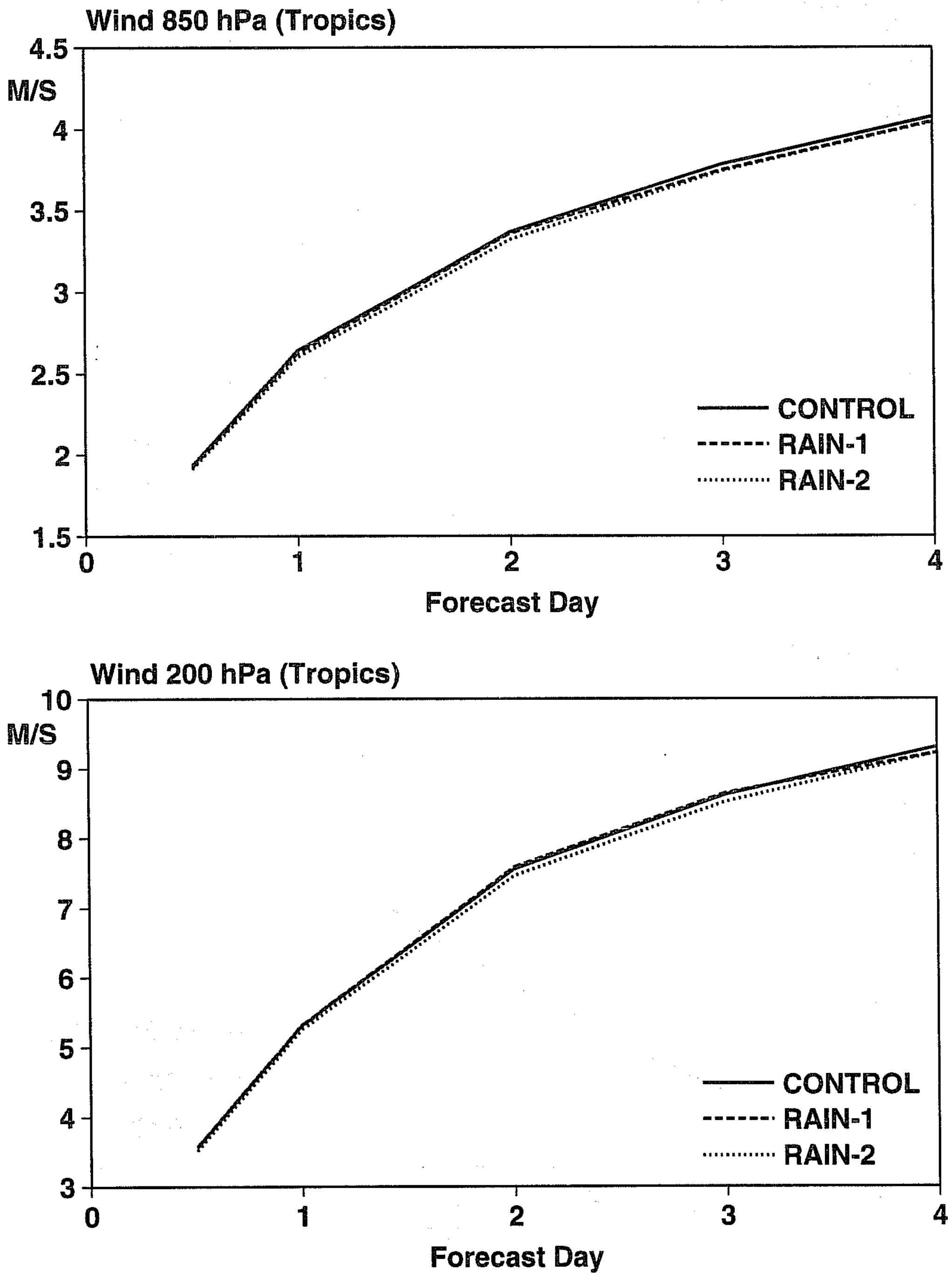

Figure 12: Root-mean square forecast errors for tropical winds verified against its own analysis at 850 hPa (top panel) and 200 hPa (bottom panel) averaged over 12 cases.

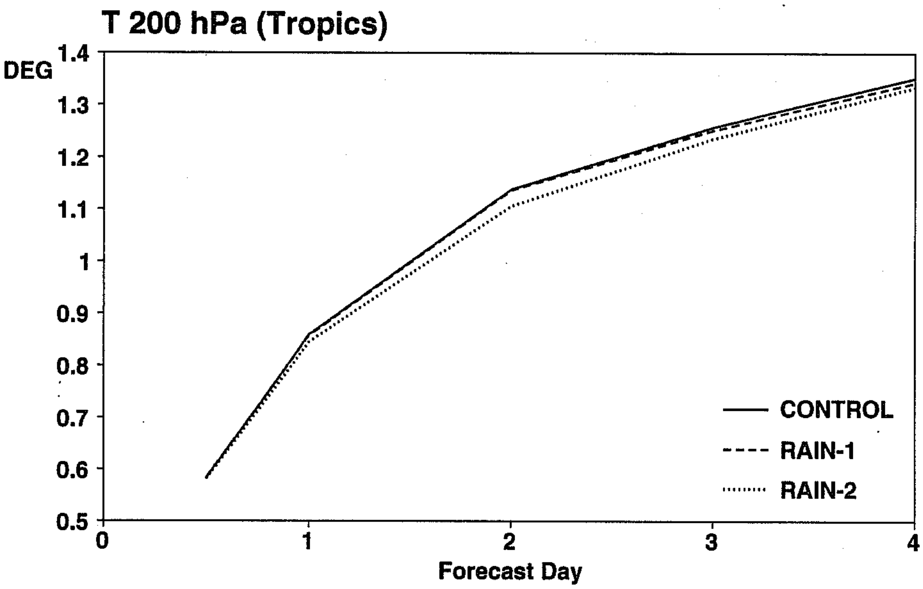

Figure 13: Root-mean square forecast errors for temperature at 200 hPa in the tropics averaged over 12 cases.

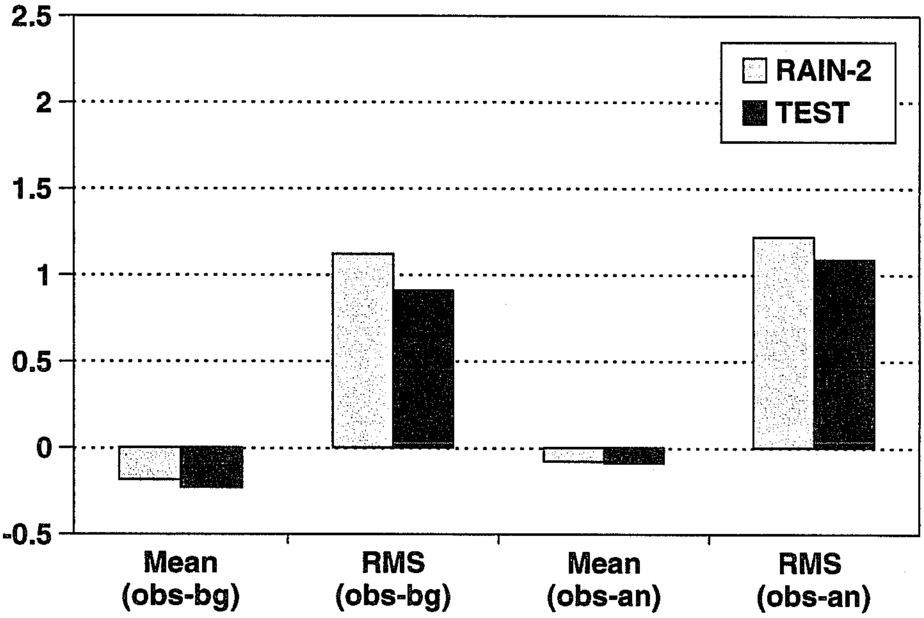

Figure 14: As Fig. 2 for the 3-day period (from 18 August 1998 at 1200 UTC to 21 August 1998 at 1200 UTC) of the "Test" experiment. The number of observations used to compute the statistics is 23253 for the "Rain-2" experiment and 23839 for the "Test" experiment.

Experiment	Mean analysed TCWV	RMS of TCWV increments
Control	35.98	1.81
Rain-1	36.01	1.76
Rain-2	35.92	1.66

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

Experiment	Correlation with TMI observations	RMS (model - observations)
Control	0.269	0.691
Rain-1	0.291	0.672
Rain-2	0.295	0.639

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

Experiment	Shortwave radiation	Longwave radiation
Control	41.1	14.3
Rain-1	41.1	14.3
Rain-2	40.8	14.0

Table 3: Global comparison for the 15-day period of the model radiative fluxes at the top of the atmosphere with CERES measurements. Values given are the RMS of the difference between the model values and the observations in W m^{-2}. Model values are averaged over a 6 hour period starting on the analysis time and compared with CERES measurements averaged over the same time period.

Experiment	Mean analysed TCWV	RMS of TCWV increments
Control	36.09	1.75
Rain-2	35.96	1.58
Test	35.95	1.57

Table 4: As for Table 1 for a 3-day period (18 August 1998 at 1200 UTC to 21 August 1998 at 1200 UTC).

Experiment	Correlation with TMI observations	RMS (model - observations)
Control	0.211	0.687
Rain-2	0.229	0.616
Test	0.218	0.621

Table 5: As for Table 1 for a 3-day period (18 August 1998 at 1200 UTC to 21 August 1998 at 1200 UTC).