Use of an ensemble Kalman filter in the Canadian ensemble prediction system

Introduction

An ensemble Kalman filter (EnKF) has been developed to provide the 16 initial conditions that are needed by the Canadian global medium-range ensemble. It assimilates most data that are used in the higher-resolution deterministic 3d-variational system. Both systems also use similar versions of our centre's global grid-point model.

Currently, prior to January 2005, the operational ensemble prediction system (EPS) obtains its initial conditions from eight independent data-assimilation cycles, that use an optimal interpolation (OI) algorithm and the SEF spectral forecast model. The OI algorithm still uses satellite derived thickness (SATEM) observations as opposed to directly assimilating radiance observations. Eight additional initial conditions are obtained by means of a correction towards the higher-quality variational analysis.

Extensive testing, including the running of over one hundred data-assimilation cycles, was necessary to arrive at an EnKF configuration of potentially acceptable quality. The eventual configuration was tested off-line for one winter month and for one summer month and proposed to the committee that controls operational and parallel runs (CPOP). An EPS, with initial conditions coming from the EnKF, was subsequently tested in parallel for the period 26 August 2004 - 12 December 2004.

Use of the EnKF was seen to lead to the following, related, advantages in 10-day EPS forecasts: a higher-quality ensemble mean for in particular the southern hemisphere, a smaller, more realistic, initial spread of the ensemble, a faster growth-rate of the perturbations, an improved agreement between the ensemble spread and the ensemble mean error, and better verification scores for the individual members.

Considering this evidence, on December 12 2004, CPOP unanimously decided in favor of operational implementation of the EnKF. The actual replacement of the operational EPS with an EnKF-based EPS followed on January 13, 2005. With this, the Canadian Meteorological Centre is the first center to use an EnKF for operational atmospheric data-assimilation. In this document, however, when we refer to the “operational system” we mean the system that was operational prior to January 13, 2005.

This text briefly describes the old and the new EPS system, which both have already been extensively documented in the scientific literature. The bigger part of the document will describe the comparative verification of the two EPS systems.

Design of the operational ensemble prediction system

A description of the methodology can be found in the following three papers:

- A system Simulation Approach to Ensemble Prediction, 1996, P.L. Houtekamer, Louis Lefaivre, Jacques Derome, Harold Ritchie and Herschel L. Mitchell, Monthly Weather Review, Volume 124, pages 1225-1242.

- Using Ensemble Forecasts for Model Validation, 1997, P.L. Houtekamer and Louis Lefaivre, Monthly Weather Review, Volume 125, 2416-2426.

- Increasing the horizontal resolution of ensemble forecasts at CMC, 2003, G. Pellerin, L. Lefaivre, P. Houtekamer and C. Girard, Nonlinear Processes in Geophysics, Volume 10, 463-468.

The reader may note that a fair amount of scientific documentation can be found here.

We did, of course, not start working on a successor for the current EPS because we were completely happy with it. After the transition for the global deterministic analysis from an OI to a 3D-VAR algorithm, the ensemble prediction group was the only remaining user of the OI algorithm. It would not have been easy, at least requiring major changes to the data structures, to use satellite radiance observations in the context of the OI algorithm. On the other hand, it would have been computationally expensive to run an ensemble of 3D-VAR analyses.

In order to correct the ensemble mean analysis to the higher quality deterministic analysis we developed a special procedure (figure 1). This produces 8 additional initial conditions by adding a set of correction fields to each member. Thus, using only 8 continuous data-assimilation cycles, we obtain 16 initial conditions that can be used to start a medium-range forecast. This doubling was implemented on August 24 1999, when the medium-range ensemble prediction system was expanded to also include 8 members with the GEM model. The procedure also permits starting the medium-range ensemble prediction with an ensemble mean that is close to the high-quality deterministic 3D-VAR analysis. Unfortunately, as the 3D-VAR analysis continued to improve, the special procedure became more and more important, leading to concerns about the possibility of imbalance in the initial conditions. Gradually the special procedure has become known as "the kick". The reasons for this terminology will become clear later.

Thus as time went by, the EPS continued to depend on a stable data-assimilation system with a fixed fairly conventional observational network and an equally stable set of 8 slightly different versions of the SEF model. Because the development of the SEF model and of the OI system were virtually frozen, it was difficult to make small incremental improvements. It was decided to work on a major move towards dramatically different algorithms.

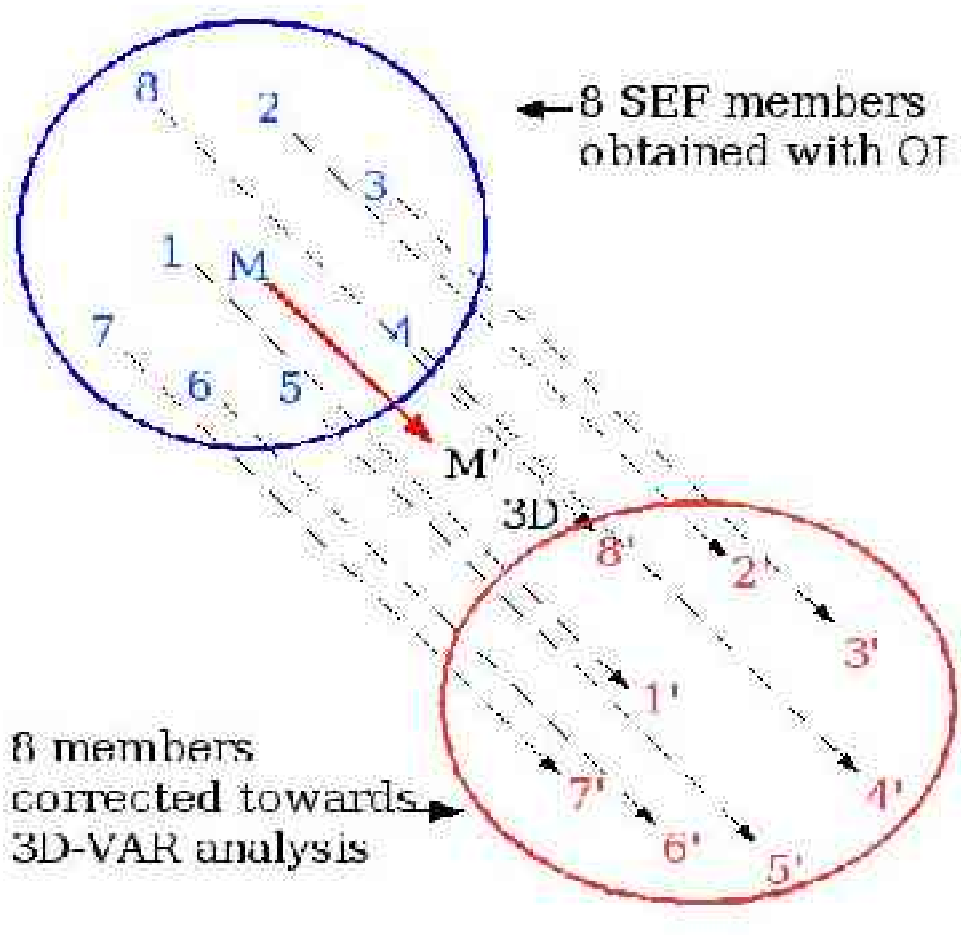

Figure 1 . The special procedure to double the number of initial conditions. The initial conditions coming from the OI data-assimilation cycles are in blue. The deterministic analysis is at location 3D. The 8 additional (primed) initial conditions are in red.

Design of the ensemble Kalman filter

The Meteorological Service of Canada is the first service to use an ensemble Kalman filter for atmospheric data assimilation. A long sequence of papers in the Monthly Weather Review by Houtekamer, Mitchell and co-authors documents this effort. Again, these papers can be found here.

Note in particular the paper by Houtekamer and Mitchell on Practical ensemble data assimilation for the 8-12 September 2003 ECMWF seminar on recent developments in data assimilation for the atmosphere and ocean.

The ensemble Kalman filter (EnKF) is a 4D data assimilation method that uses a Monte-Carlo ensemble of short-range forecasts to estimate flow-dependent covariances of the guess fields. The EnKF analysis consists, in fact, of an ensemble of states with differences that, to the best of our knowledge, respect the flow-dependent and network-dependent statistics of the analysis error. We thus have a reservoir of initial conditions which are all suitable to initiate a medium-range EPS.

Considering that the initial conditions of the EnKF are to be used in the EPS, we decided to have matching characteristics for the two systems. We, in particular, use an identical 300 by 150 global grid and 28 eta levels with a model top at 10 hPa. We also used the recent version 3.1.1 of the GEM-DM forecast model. The selected options for the model dynamics and for the physical parameterizations are almost identical to those of the higher resolution version of the GEM-DM model that is used for deterministic forecasts and uses a 400 by 200 horizontal grid. We note, however, the following differences:

- For the EnKF, we decided to locate the poles of the model at the geographical poles, to minimize interpolations between the model and the analysis.

- We also decided to use cubic-lagrangian vertical interpolations in the model, to reduce narrow vertical oscillations near the model top. The same procedure had been adopted for the tangent linear model in the 4D-VAR procedure.

- We use a modified procedure to compute heat fluxes over sea-ice. It is noted that work is in progress at our center to arrive at improved heat fluxes over all snow-covered areas. In the future, we hope to benefit from this work.

- We noted a problem with the redistribution of the intense heat fluxes, from the ocean to the air, in the case of very cold air flowing over a water surface. This problem is related to having long time steps, narrow vertical levels and an explicit treatment of the process. We adopted a procedure that corrects the temperature and humidity profiles.

While it is difficult to maintain identical version of the model in the context of different development projects with different critical delivery dates, we do attempt to benefit as much as possible from the research on the GEM-DM model and we will regularly revisit the need for having different versions.

We have a similarly close link to the software that is used for the variational assimilation of observations. The EnKF is a modern data-assimilation code that can assimilate, in principle, any type of observation for which an interpolation operator is available. We are, for instance, able to use the RTTOV-7 package that is also used in the 3D/4D-VAR to assimilate AMSU A and AMSU B radiances. As input to the EnKF, we use the postalt file with quality controlled observations from the currently - i.e. prior to the implementation of the 4D-VAR - operational 3D-VAR algorithm. We do not, however, assimilate the following types of observations:

- Surface humidity observations are not yet assimilated. Their use, however, is being evaluated for the EnKF and scheduled for the next upgrade to the EnKF.

- AMSU-A observations from the AQUA satellite are similarly currently being evaluated for use in the EnKF.

- The use of MODIS wind observations is likewise expected for the next upgrade of the EnKF.

- We will likely not be ready to use either GOES IR radiance observations or wind profiler observations in our next upgrade.

One notices, as a consequence of the timing of our test procedures, that we were not able to perform tests with those data that went into the deterministic system on September 21 2004. Because we depend on the variational algorithm for the quality control of the observations, we will always have some delay with respect to the set of observations that we use. In the future, as the observation operators will be coded in a modular fashion for use in both the variational and the direct analysis, this delay will likely be shorter.

A critical advantage of the new system that consists of the EnKF and the GEM model, over the currently (December 2004) used OI procedure that is coupled with the SEF forecast model, is that we can now provide a short list of differences with the deterministic system and, more importantly, that we can remove, after a short development project, any of the items of the list. From a development point of few, we have a strong coupling to the deterministic system, that allows us to benefit from work for that system.

In order to obtain a sufficient amount of spread in the medium-range ensemble, we still need a special procedure (figure 2) to inflate the spread of the ensemble. This procedure is not part of the continuous EnKF data-assimilation cycle. It is applied prior to starting an ensemble of medium-range forecast. As we will see, this new procedure does not cause significant imbalance in the initial conditions. Also note from figure 2, that we use only the first 16 initial conditions - out of 96 provided by the EnKF - to initiate medium-range forecasts. It will clearly be possible to increase the ensemble size of the medium-range EPS in the future. The current implementation, however, only deals with the data-assimilation component of the EPS. The forecast component has not been modified.

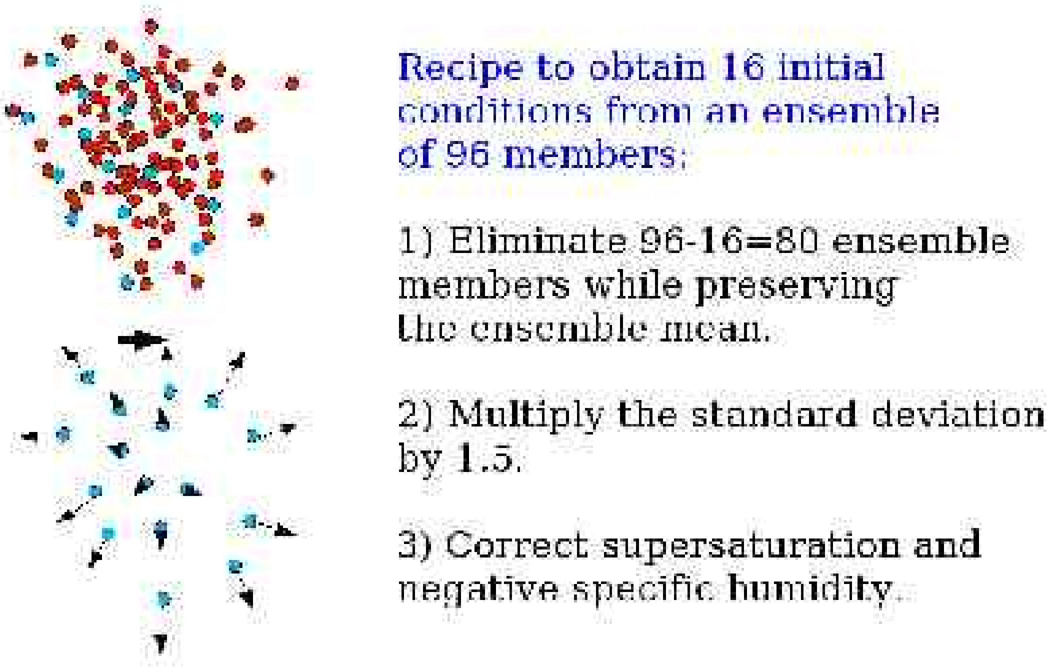

Figure 2 . The new procedure to obtain 16 initial conditions. We begin by taking the first 16 members (in blue) of the 96 member ensemble. Next, we shift them so that the mean of the 16 members is co-

located with the mean of the 96 members. Subsquently the distance from the center is inflated with a factor 1.5. Finally, we correct negative humidities and over-saturation.

Evaluation procedure

Results have been obtained for a pre-parallel summer cycle, a pre-parallel winter cycle and for the parallel run.

The winter cycle starts on 2004 January 7, 0 UT. The results of the first 4 days, during which the ensemble statistics stabilize, have been discarded. The verifications have been averaged over the period from 2004 January 11, 0 UT until February 10, 12 UT. Note that the first days of January have not been considered because of a problem with the coordinates of the ATOVS observations in that period.

The summer cycle starts on 2003 July 27, 0 UT. The verifications are for the entire month of August 2003.

The parallel run started on 2004 August 26, 0 UT. The first period for verification of the parallel run is 2004 August 26, 0 UT - 2004 September 23, 12 UT. The second period is 2004 September 24, 0 UT - 2004 October 23, 12 UT. The last period is 2004 October 24, 0 UT - 2004 November 23, 12 UT.

The results are very similar for the five different months of verification. In the current document, we will only show some typical results.

Innovation statistics

To measure the quality of the EnKF, O-P innovation statistics have been computed using the ensemble mean field. Here the averaging is over the 96 guess fields used in the EnKF. The operational ensemble prediction system uses 8 independent data-assimilation cycles, that use an Optimal Interpolation method for the data-assimilation and 8 different versions of the SEF spectral forecast model to obtain the guess fields. For the operational system, that we intend to replace with the EnKF, innovation statistics have been computed with respect to the mean over the 8 available guess fields. To have an additional point of reference we also computed innovation statistics using guess fields from the deterministic high-resolution system which uses a uniform 400 times 200 horizontal grid.

A typical example is the verification for the first month of the parallel run for the Northern Hemisphere (figure 3). For each of the verified variables (UU, VV, GZ, TT and ES), the standard deviations obtained with the EnKF are at least of the same quality as those from the OI system. Note that, in all figures of this document, the curves for the EnKF-based system are in red and the curves for the reference system are in blue. For most panels the improvement is fairly significant. A problem for the EnKF, however, is the large bias in the geopotential height field above 200 hPa. For Southern Hemispheric winds (figure 4) the mid-tropospheric improvement is of the order of 30 percent!

Comparing the ensemble mean with the deterministic 3D-Var (figure 5), we observe a similar problem with the bias in the geopotential height. Apparently, the handing of observations, the interaction between the model and the analysis and the versions of the GEM model are sufficiently similar for us to have similar bias problems. This argues for a joint study towards the removal of the bias problem. The archives of operational implementations did not permit the identification of a single culprit among: the replacement of SATEM observations by TOVS observations, the removal of the radiation correction on radiosondes, the use of temperature and surface pressure as analysis variables and the introduction of the GEM forecast model.

In conclusion we may note that the EnKF behaves much like a state-of-the-art analysis system, whereas the OI-based system depends on more old-fashioned data handling. This does not necessarily imply that an EnKF-based medium-range forecast ensemble will beat the currently operational EPS, which benefits from a correction towards the 3D-Var analysis. To arrive at that conclusion, we will now compare the verifications of 10-day forecasts from the two systems.

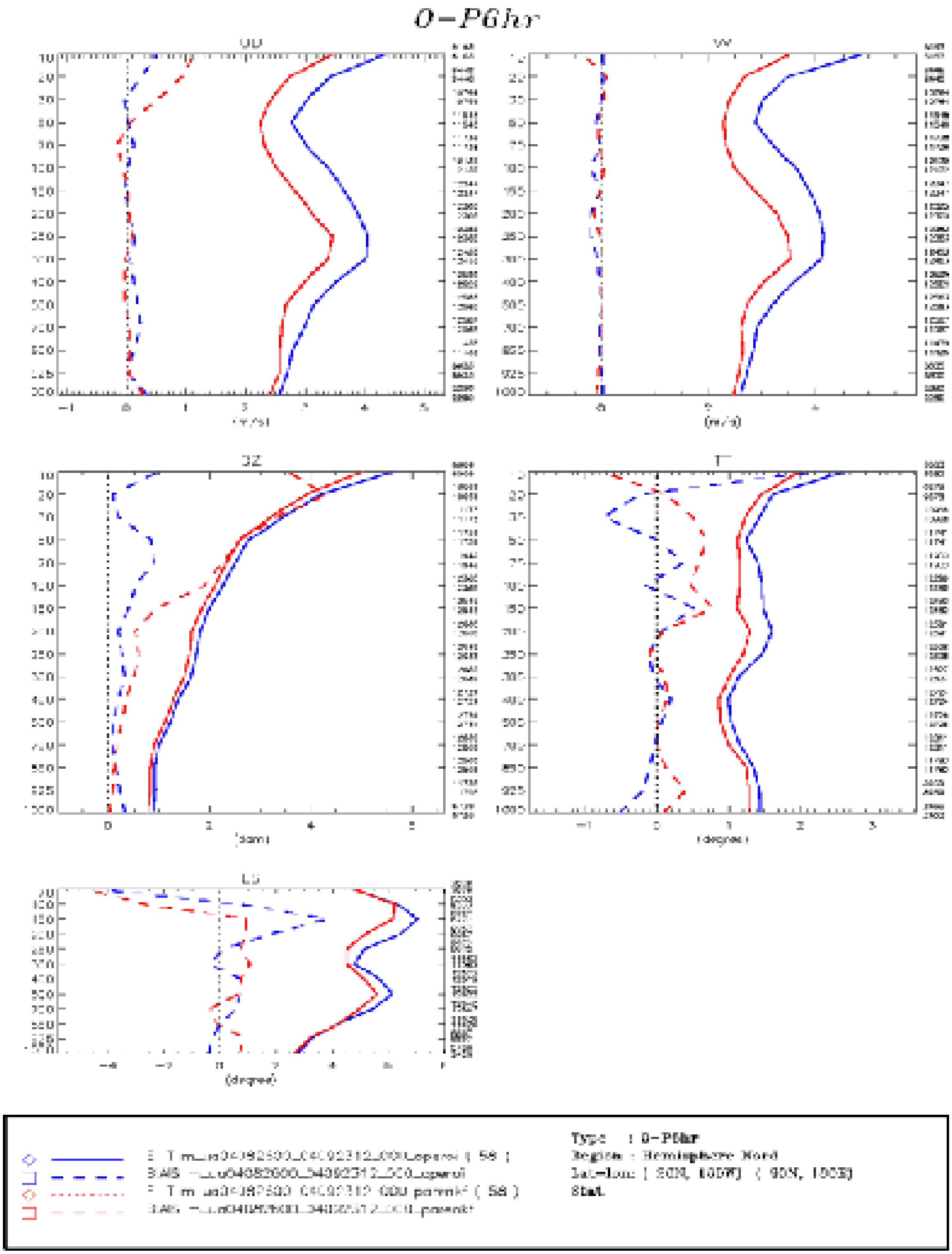

Figure 3. Comparison of the innovation statistics for the EnKF system (in red) and for the OI (in blue) for the Nothern Hemisphee for the period from August 26 2004 until September 23 2004. The rms errors are indicated with solid lines and the biases with dashed lines.

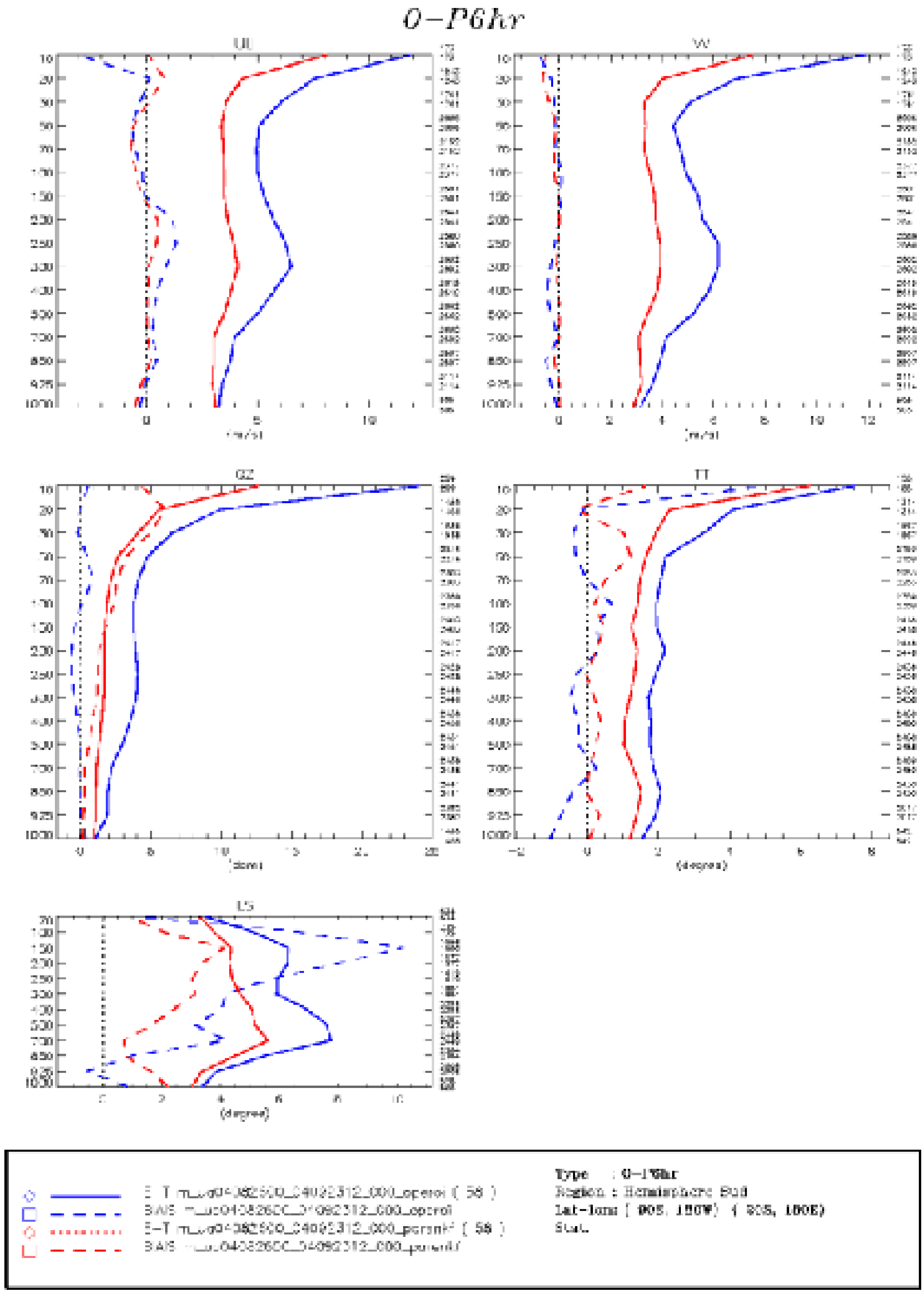

Figure 4. As in figure 3 but for the Southern Hemisphere.

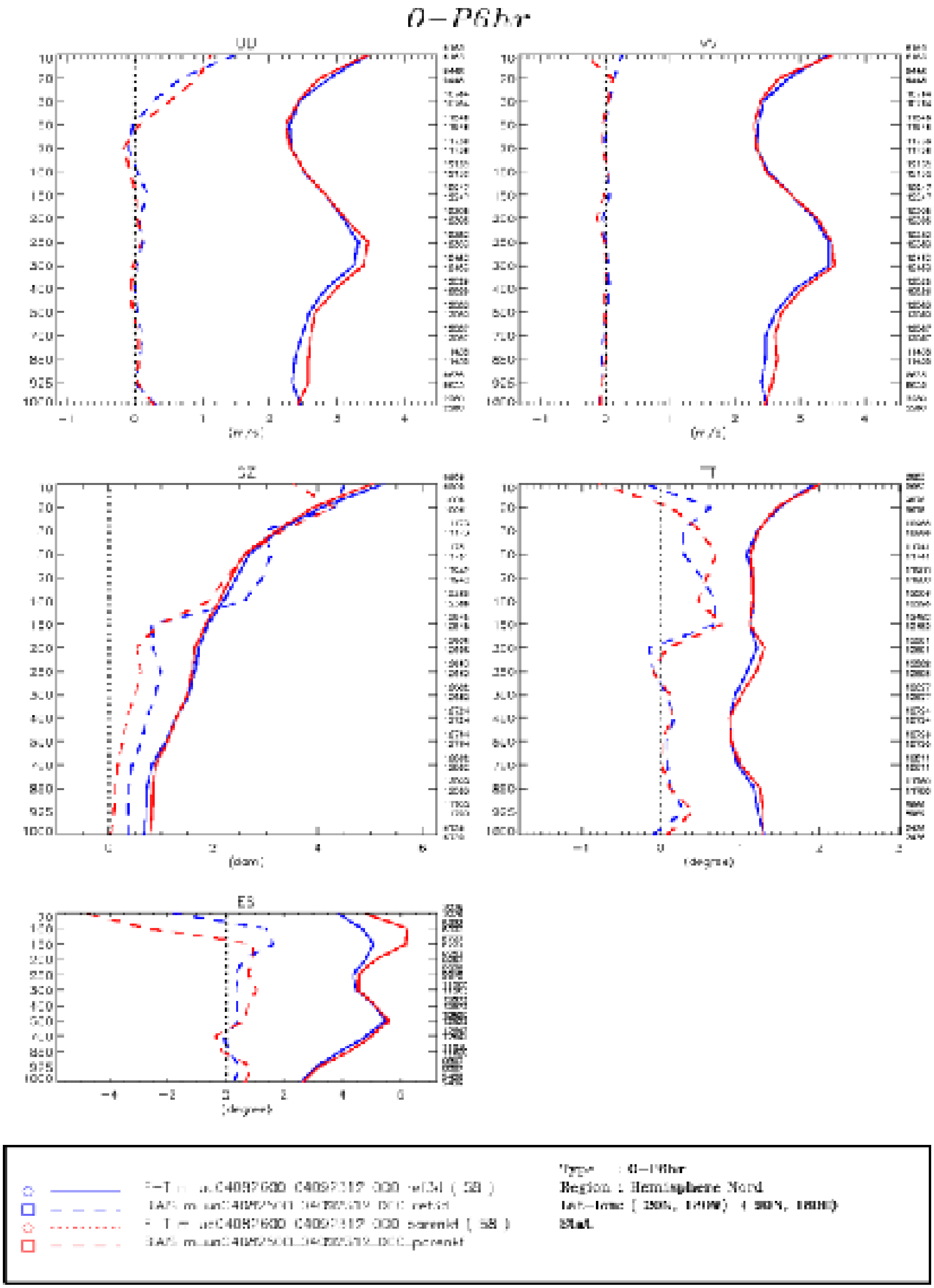

Figure 5. As in figure 3 but comparing the deterministic analysis (in blue) with the EnKF (in red).

Verification of the 500 hPa geopotential height forecast

Traditionally the EPS system is mostly verified with respect to the 10-day forecast of the 500 hPa geopotential height variable.

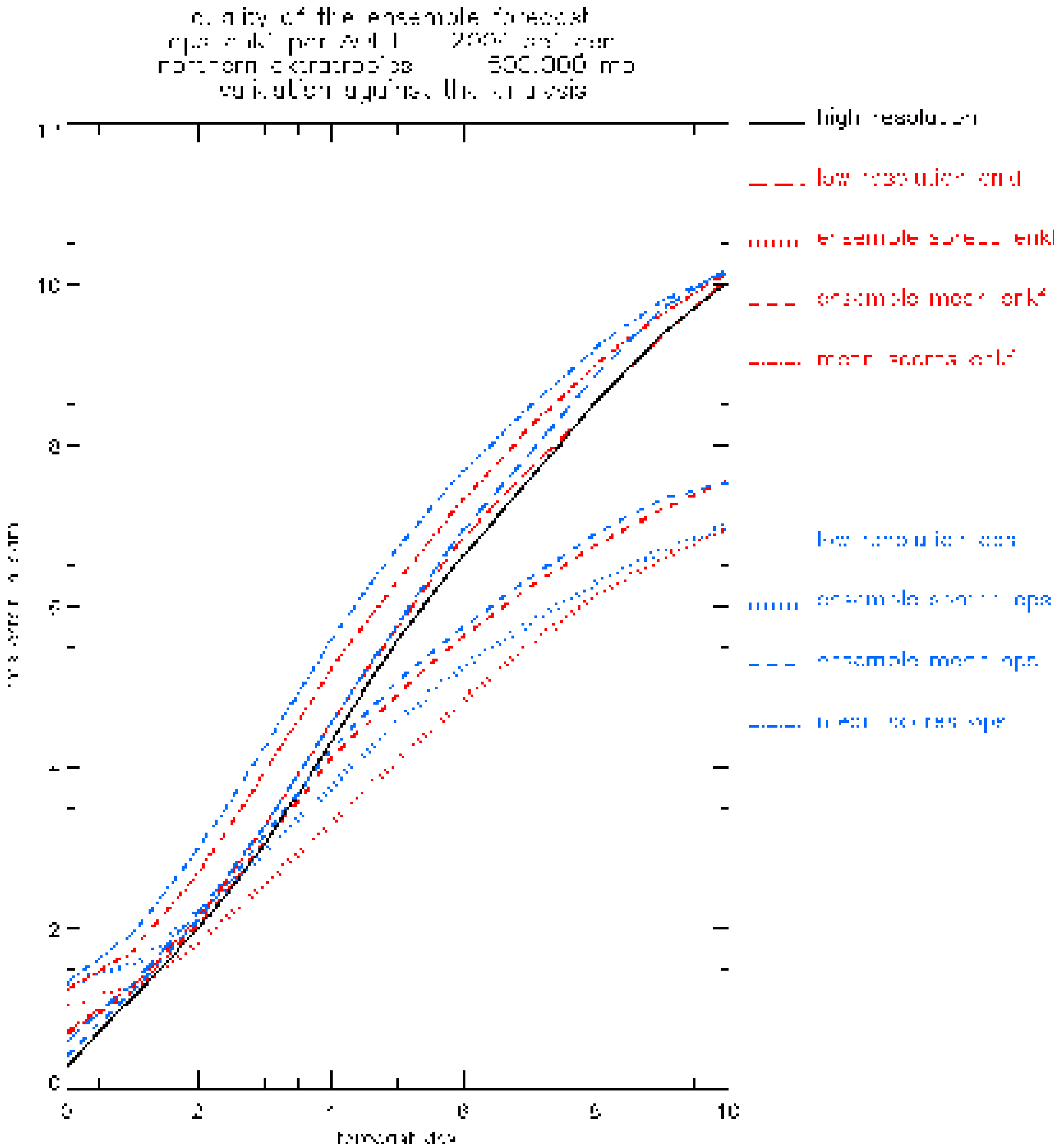

Figure 6. Comparison of the operational 10-day forecasts (in blue) and the parallel forecasts (in red) for the northern extra tropics for August 2004. The deterministic forecast is in black.

Again looking at the first month of the parallel run, at the northern extra tropics, which are north of 20 degrees north, we observe (figure 6) some typical advantages for the 16 member ensemble based on initial conditions for the EnKF (in red) over the operational system (in blue):

- a higher-quality ensemble mean (short dashed lines),
- a smaller, more realistic, initial spread of the ensemble (dotted lines),
- a faster growth-rate of the perturbations (dotted lines),
- an improved agreement between the size of the ensemble spread and the ensemble mean error (comparison of the short dashed and corresponding dotted lines),
- better verification scores for the individual members (dash dotted lines).

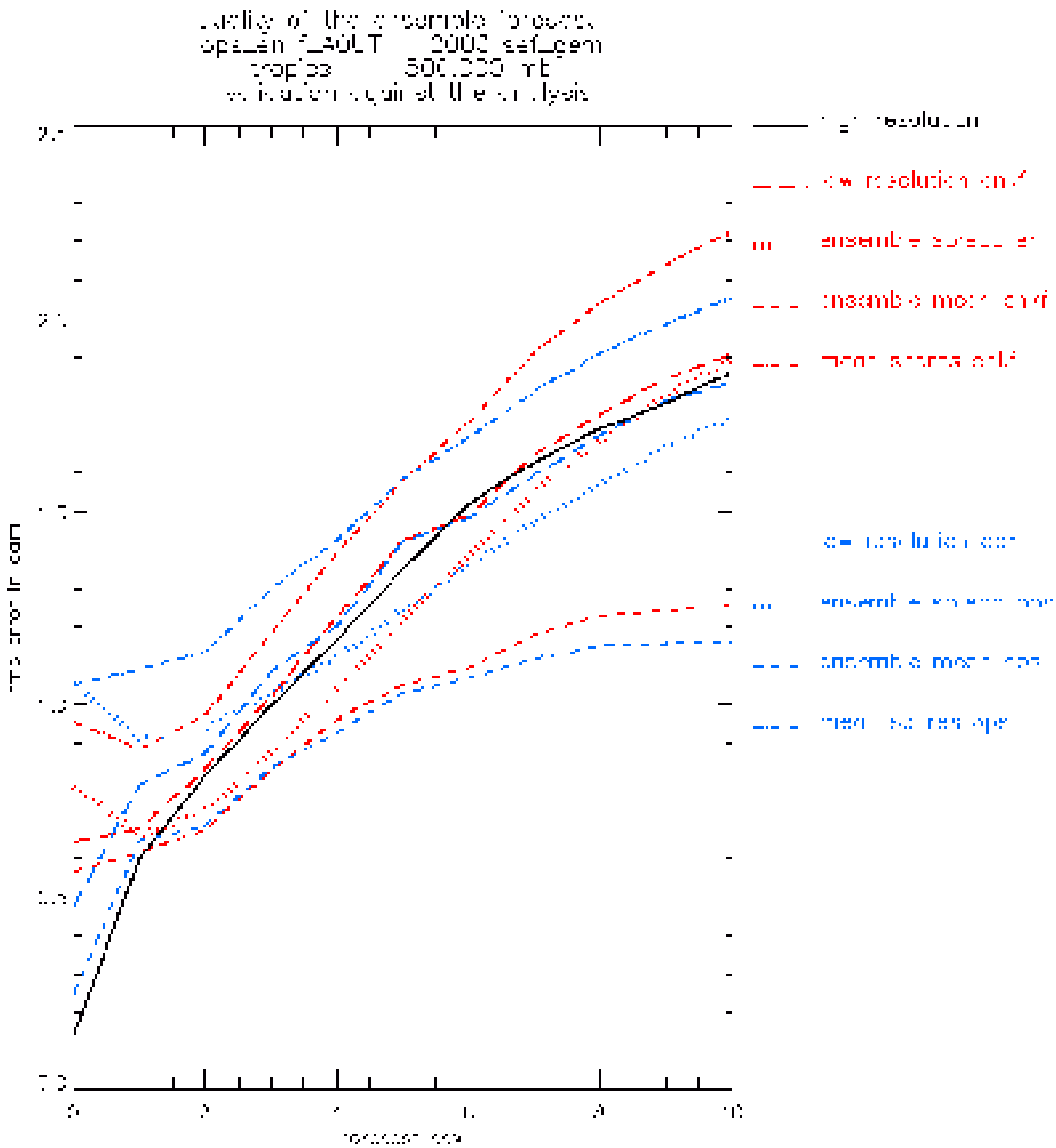

Figure 7. As in figure 6 but for the tropical region for August 2003.

The only exception is the August 2003 verification for the tropics (figure 7), where the operational system is better after forecast day 4. For the southern extra tropics (figure 8) the difference in favor the EnKF-based system is huge. This is likely related to the use of radiances in the EnKF system.

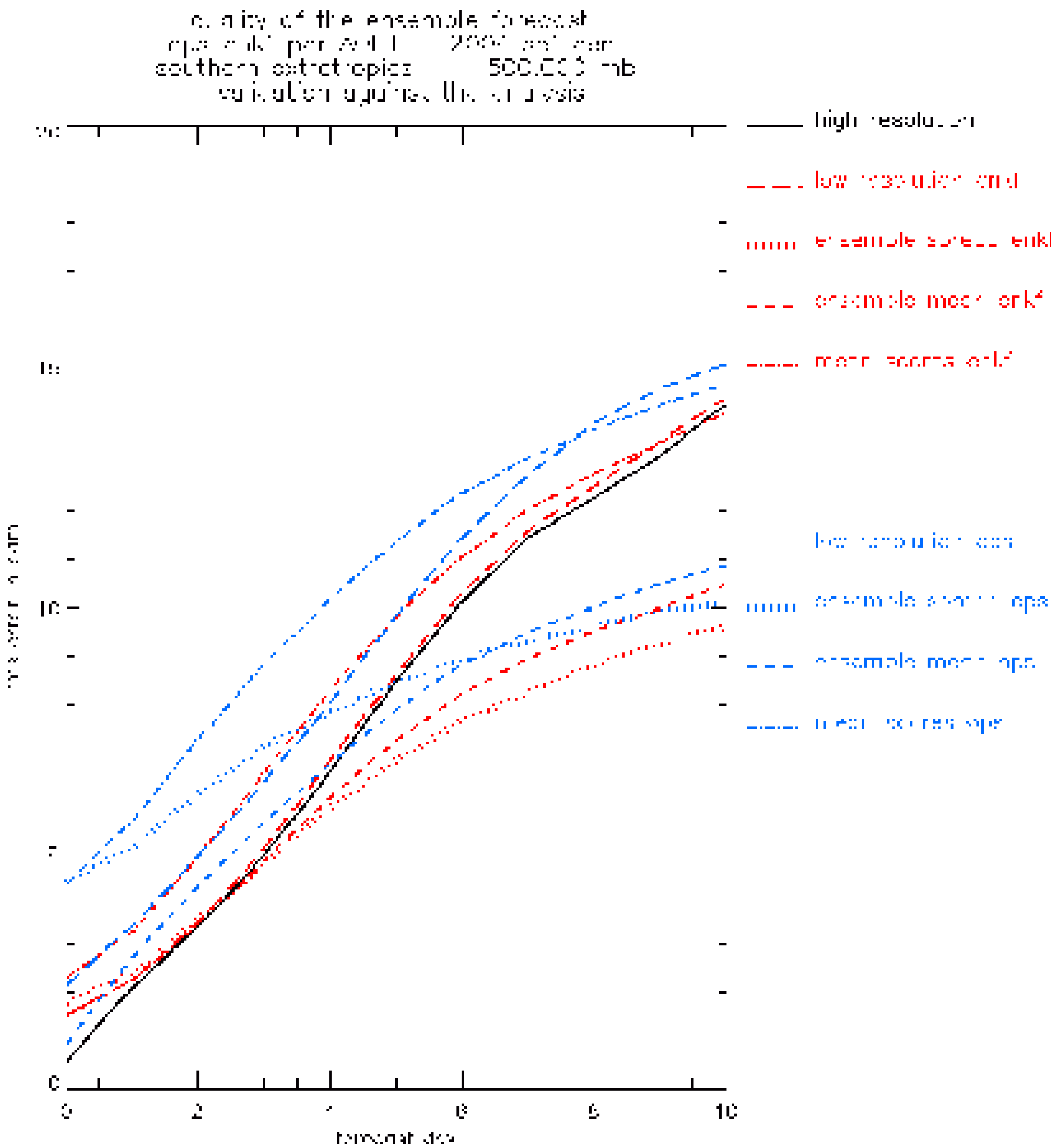

Figure 8. As in figure 6 but for the Southern Hemisphere.

During the parallel run, we did not see a disadvantage for the EnKF in the tropics. During the last month of the parallel run, the northern extra tropical verification scores for the ensemble mean (figure 9), seem to be slightly in favor in the operational system.

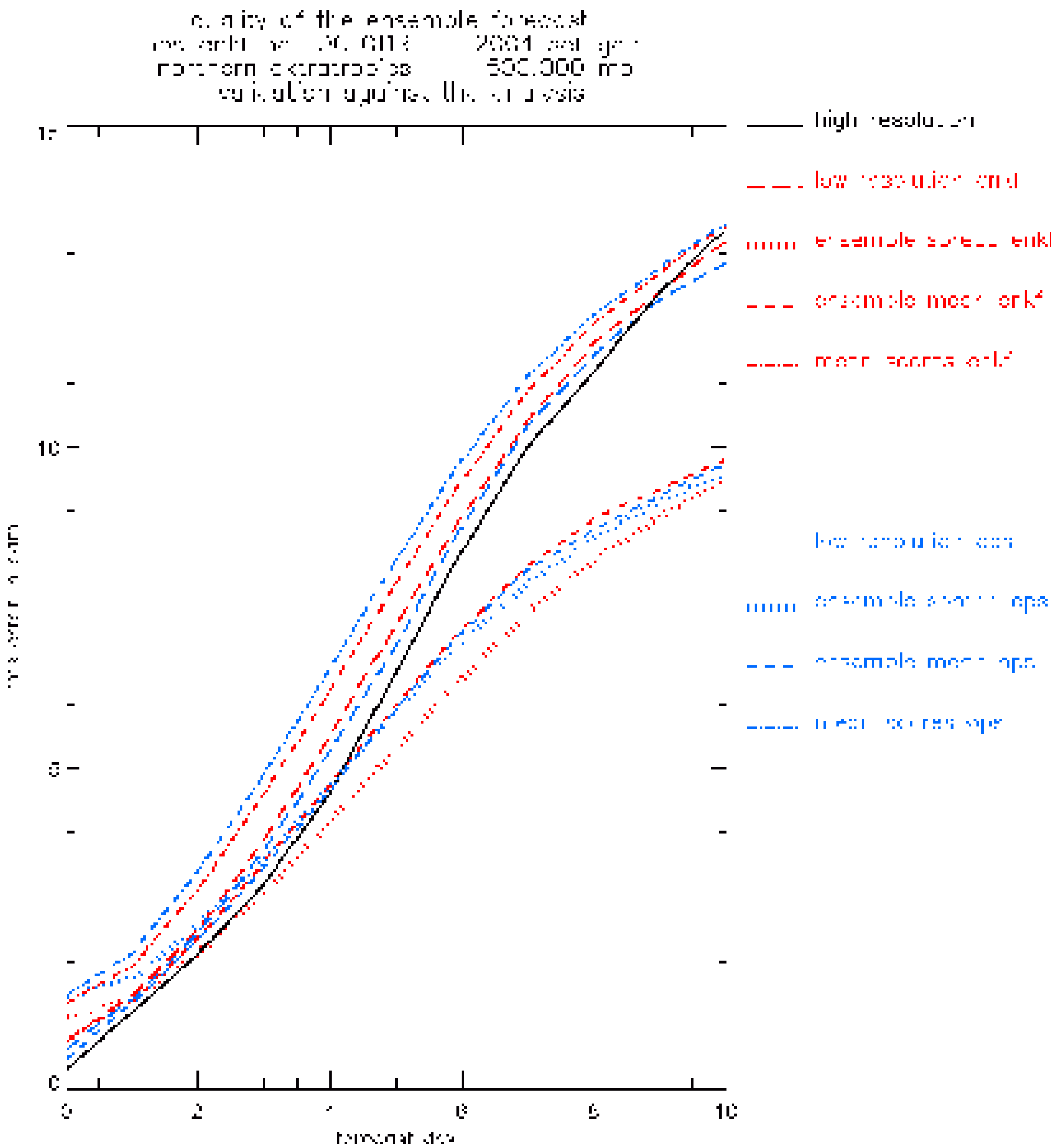

Figure 9. As in figure 6 but for October 2004.

Talagrand diagrams for forecasts of the geopotential height

With a Talagrand diagram we check where the verifying analysis usually falls with respect to the ensemble forecast data (arranged in increasing order at each grid point). Note that the first (last) bin is selected if the analyzed value is lower (higher) than any of the values in the ensemble. Since all perturbations are intended to represent equally likely scenarios, this distribution should be flat.

Several common "problems" can be diagnosed from the diagrams. A "U-shape" diagram is obtained if the spread in the ensemble is typically too small. If the spread in the ensemble is too big one obtains an "n-shape" (highest in the middle). If the diagram is asymmetric the model has a bias to one side. An "L-shape" would correspond to a warm bias for the model.

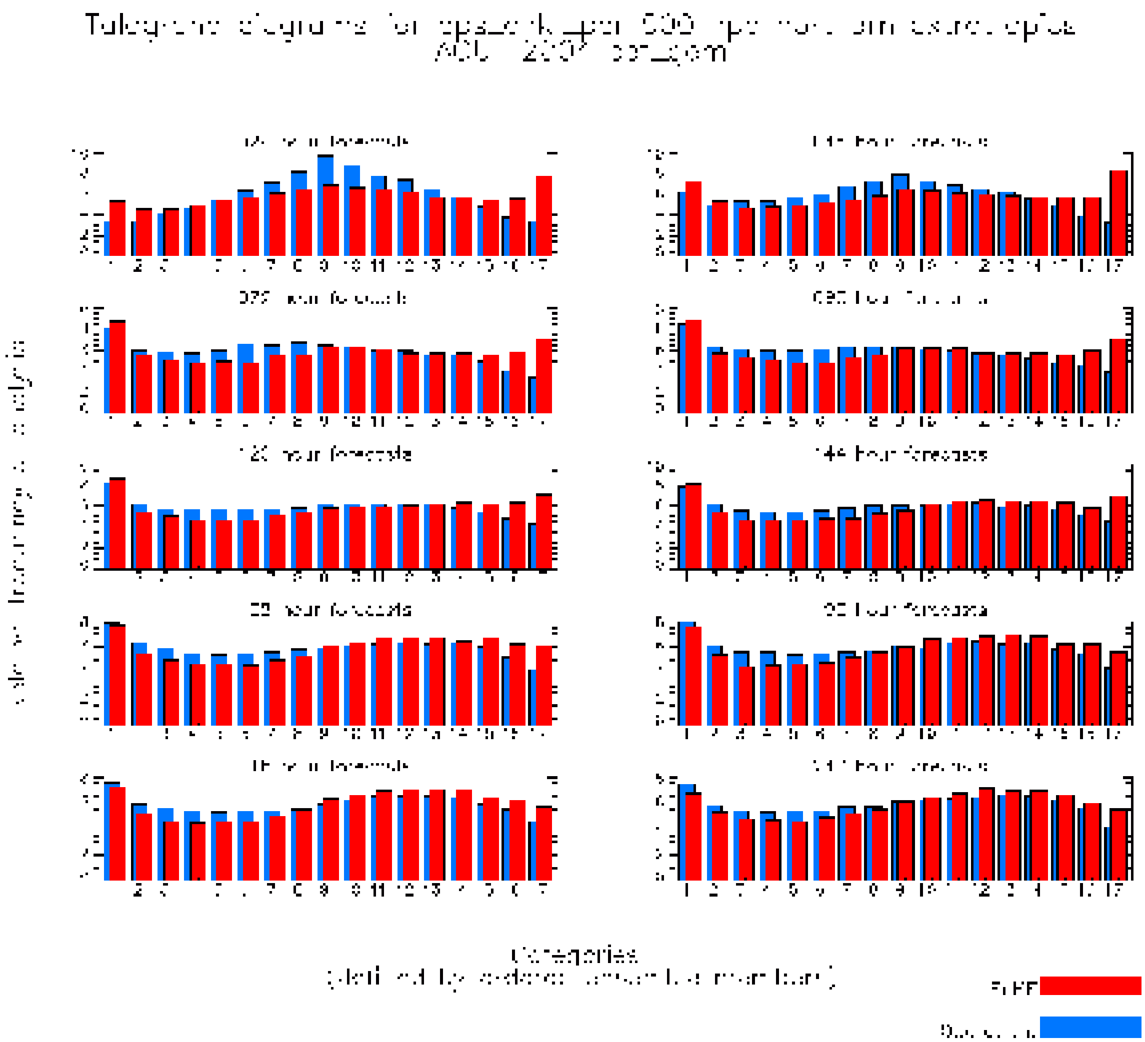

Figure 10. Talagrand diagrams for the geopotential height forecasts at 500 hPa for the northern extra tropics and for the first month of the parallel run. Results are in red for the parallel system and in blue for the operational system.

We will now look at the Talagrand diagram for the 500-hPa geopotential height forecast for the northern extra tropics for the first month of the parallel run (figure 10). We observe a central bulge in the Talagrand diagrams at 24 and 48 hours for the operational system (in blue). This reflects the excessive initial spread of the operational ensemble. The EnKF system does not have the central bulge. This system, however, has a slight U-shape between 48 and 120 hours. Beyond 120 hours, we note that the two systems have somewhat different bias properties. This is surprising because only the initial conditions differ between the two systems.

For the southern extra tropics (figure 11), we note a more pronounced central bulge for the operational system between 24 and 72 hours. Beyond 72 hours, both systems appear to be almost perfectly reliable.

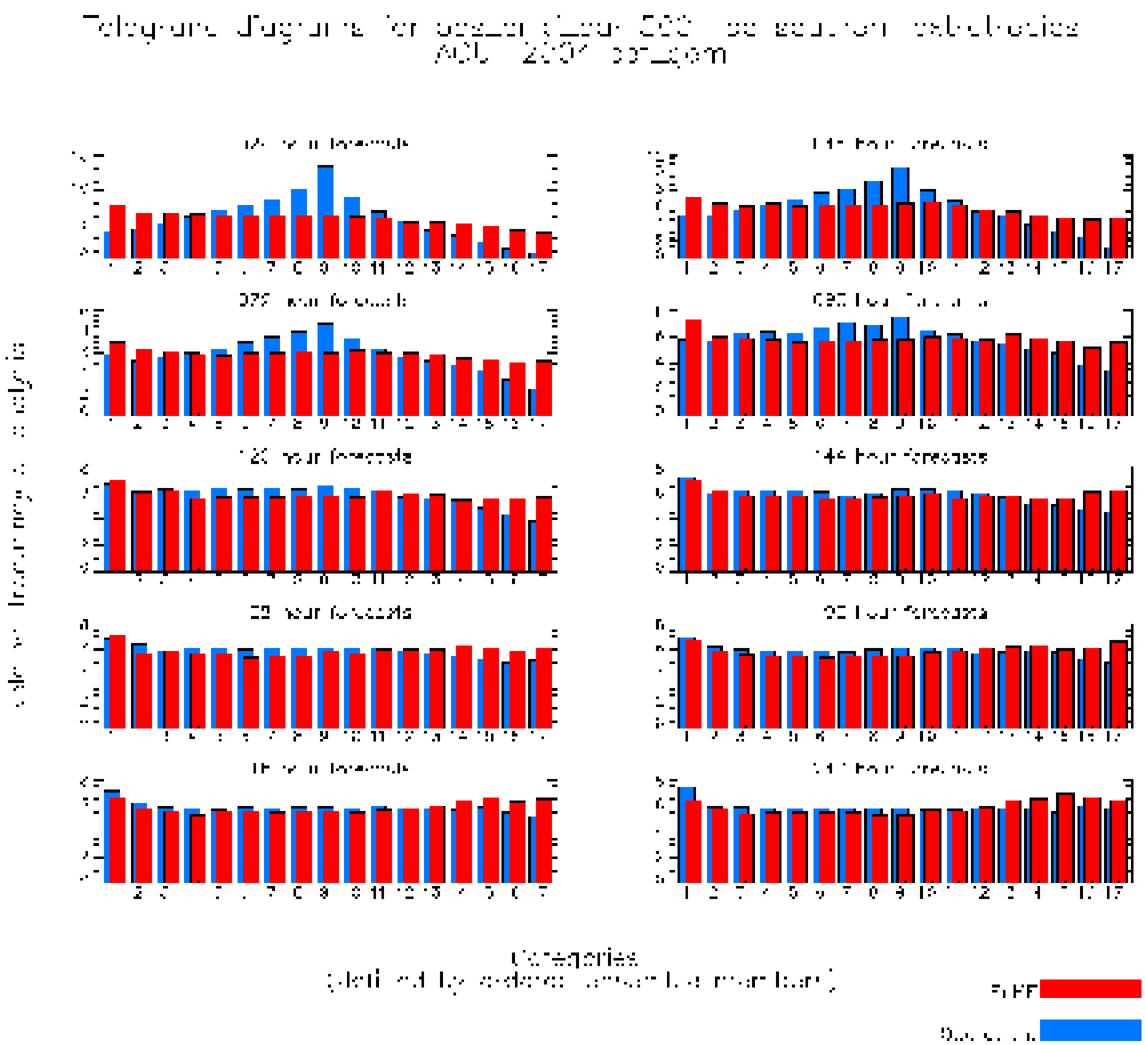

Figure 11. As figure 10 but for the Southern Hemisphere.

In summary, we may say that the EnKF corrects the initial overspreading of the operational system with - thanks to the faster growth rates of the perturbations - no corresponding negative impact at the later forecast ranges.

Relative Operating Characteristics

ROC stands for relative operating characteristic. A ROC curve shows the hit rate as a function of the false alarm rate. Here the hit rate is defined as the probability, given the occurrence of an event, that the event was forecast. The false alarm rate is the probability that a non-occurrence of the event was preceded by a forecast of occurrence. Points on the major diagonal represent chance performance and can be achieved by forecasting at random with hit rate equal to false alarm rate. Always forecasting occurrence gives the upper right point (hit rate=false alarm rate=1) and always forecasting non-occurrence gives the lower left point (hit rate = false alarm rate =0).

A measure of forecast skill is the surface under the ROC curve. The greater the area, the greater the skill that has been achieved. In other words, the greater the area, the greater the likelihood for high hit rates to be associated with low false alarm rates, which is a widely accepted feature of good forecast skill.

Reference: Gary M. Williams, An evaluation of precipitation probability forecasts using signal detection theory. 9th conference on probability and statistics in atmospheric sciences. AMS. Oct 9-11 1985. Virginia Beach VA.

For the three months of the parallel run, ROC curves have been computed for precipitation thresholds of 2, 5 and 10 mm/day at a set of Canadian stations. Because it is hard to visually compare the different figures, the ROC areas have been gathered in a table for forecasts valid at day 1, 4, 7 and 10 days.

Area under the relative operating characteristic						
forecast	**2 mm/day**		**5 mm/day**		**10 mm/day**	
day	**operational**	**parallel**	**operational**	**parallel**	**operational**	**parallel**
1	0.905	0.898	0.919	0.912	0.935	0.929
4	0.816	0.819	0.834	0.839	0.844	0.855
7	0.686	0.696	0.714	0.716	0.748	0.734
10	0.642	0.649	0.674	0.690	0.713	0.688

For the 3-month parallel run, we observe that 58 percent of the verifications are in favor of the EnKF system. In all likelihood, this improvement is not significant. This lack of significance may be partly due to an intermediate interpolation to a low-resolution polar stereographic grid and to the limitation to Canadian stations. It is clearly desirable to improve and extend the package to verify the ensemble-based precipitation forecasts.

In a one-month verification period, the operational forecasters did note differences between the QPF's of the two systems on many occasions. They generally concluded in favor of the parallel system.

WMO verification of individual forecast against analyses

For a number of levels and variables, we computed the rms error with respect to analyses. This was done for each member and also for the ensemble mean. The main purpose of this exercise is to obtain information on the relative quality of individual members. A priori, one would not expect much interesting information from this verification for the current parallel run in which only the initial conditions were changed. Indeed, for the first month of the parallel run for temperature at 500 hPa for the northern extra tropics, we obtain fairly similar images for the operational system (figure 12) and for the parallel system (figure 13).

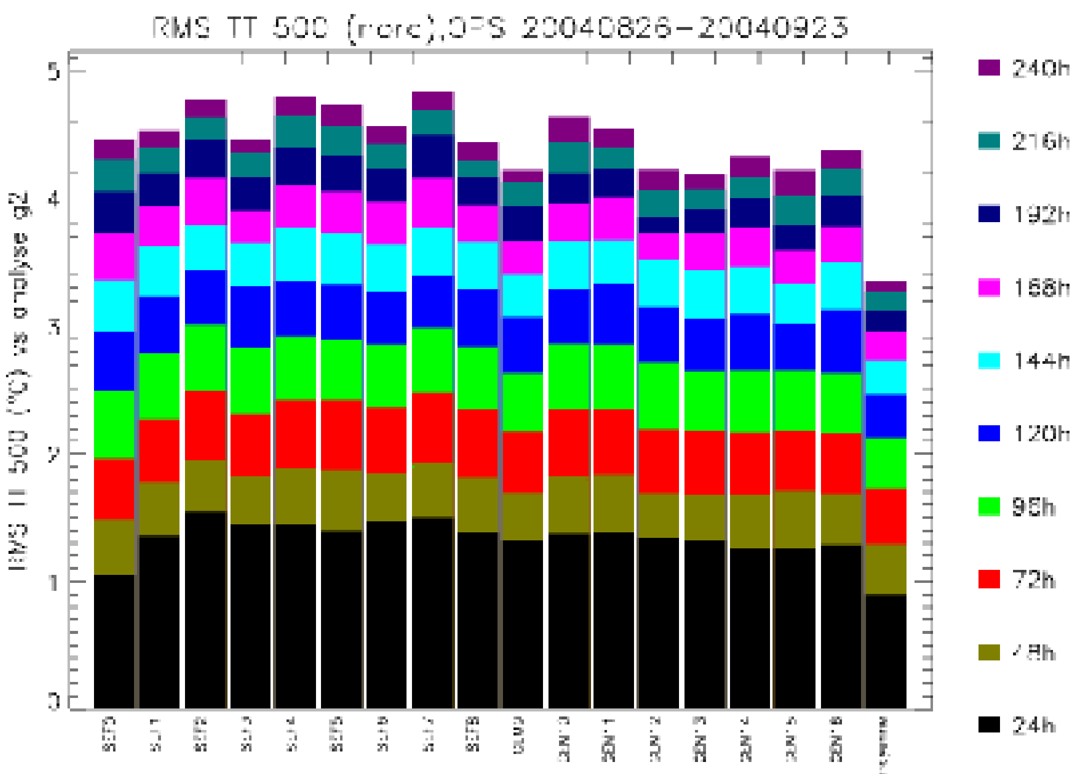

Figure 12. The rms errors for each member of the operational system for the first month of the parallel run for 500 hPa temperatures for the northern extra tropics. The control member is indicated as SEF0 and the mean is over 16 members.

In general, we remark that the EnKF-based ensemble prediction system has slightly smaller medium-range errors than the operational system, as would be expected from a system with a somewhat smaller ensemble spread.

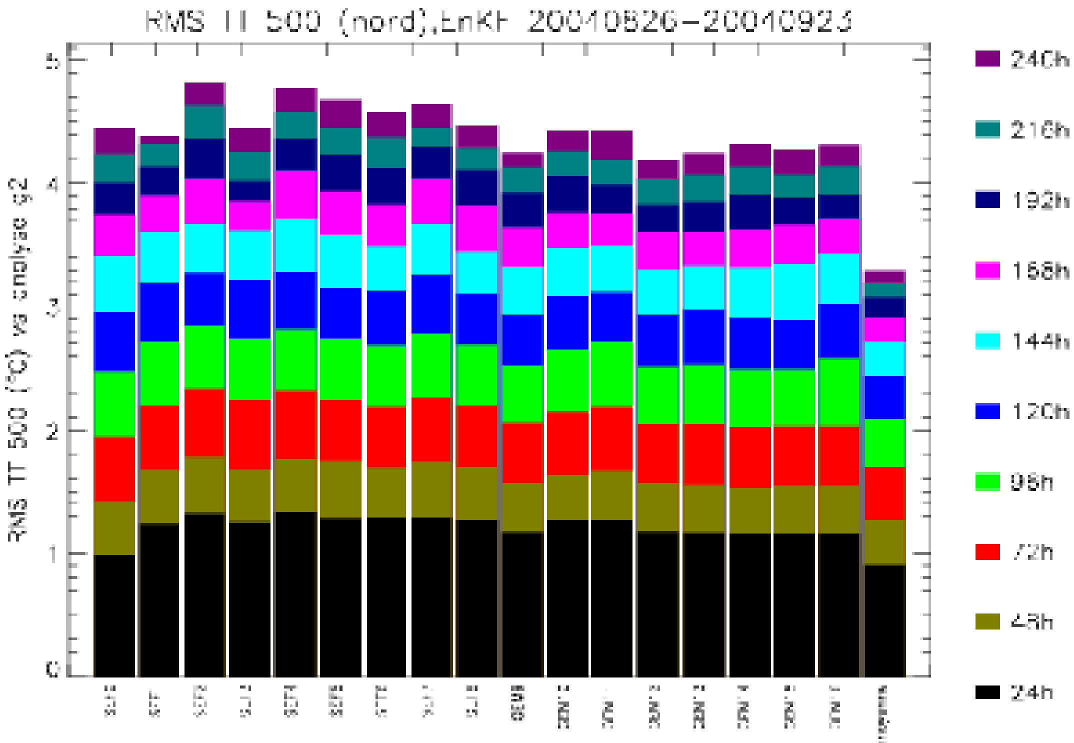

Figure 13. As figure 12 but for the parallel system.

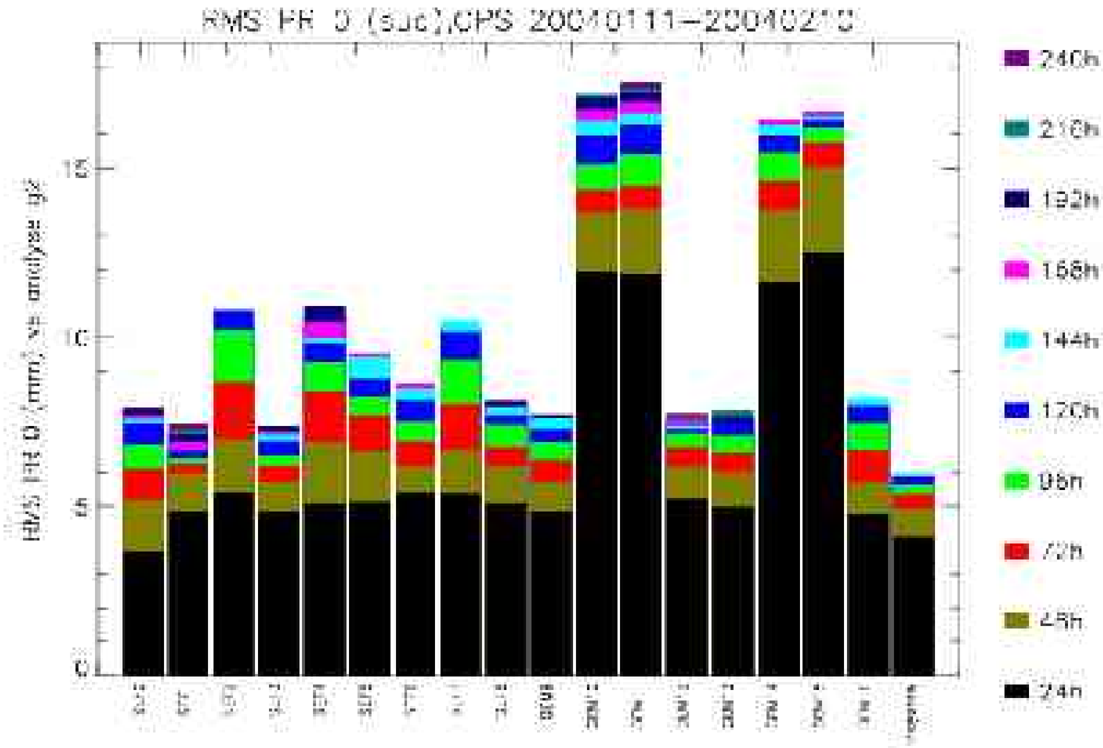

Figure 14. Verification of the precipitation from the operational system for January 2004 for the Antarctic region.

In addition, however, we remark that the operational system shows pathological behavior for the members 10, 11, 14 and 15. These members sometimes show intense precipitation during the first 24 hours of the forecast. This occurs in response to the imbalance caused by the correction towards the operational analysis. This is evident from, for instance, the Antarctic RMS precipitation (variable PR) scores for Winter 2004 as verified using the g2 analysis (figure 14 and 15).

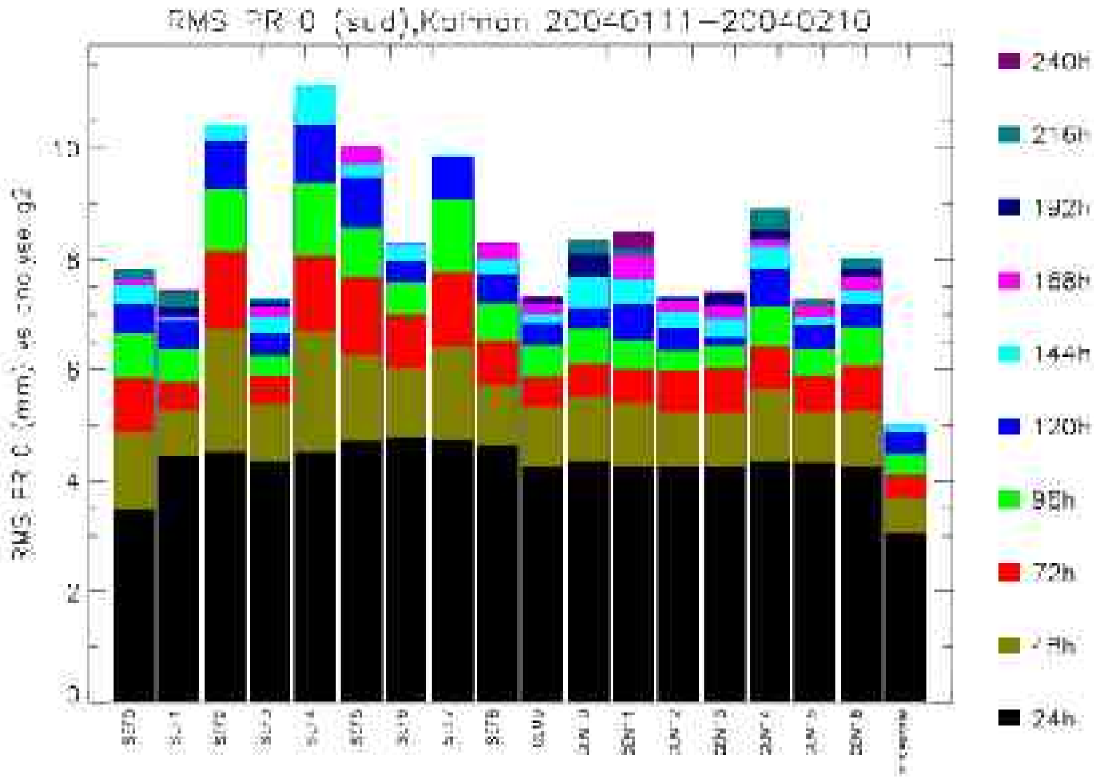

Figure 15. As figure 14 but for the parallel system. Note the different scales.

The problem is not limited to the Antarctic precipitation fields; the bias diagrams for temperature at 250 hPa show a developing temperature bias for these 4 members for all areas in the operational system. The problem is less severe, but still present, in the summer verifications. A case example shows that member 14 of the operational system features excessive precipitation accumulation during the first 24 hours of the forecast for the southern areas. Member 14 of the parallel system, as well as member 16 in both systems, looks much better.

A case with intense precipitation over the first 24 hours			
Member 14 operational (figure 16)	Member 14 parallel (figure 17)	Member 16 operational (figure 18)	Member 16 parallel (figure 19)

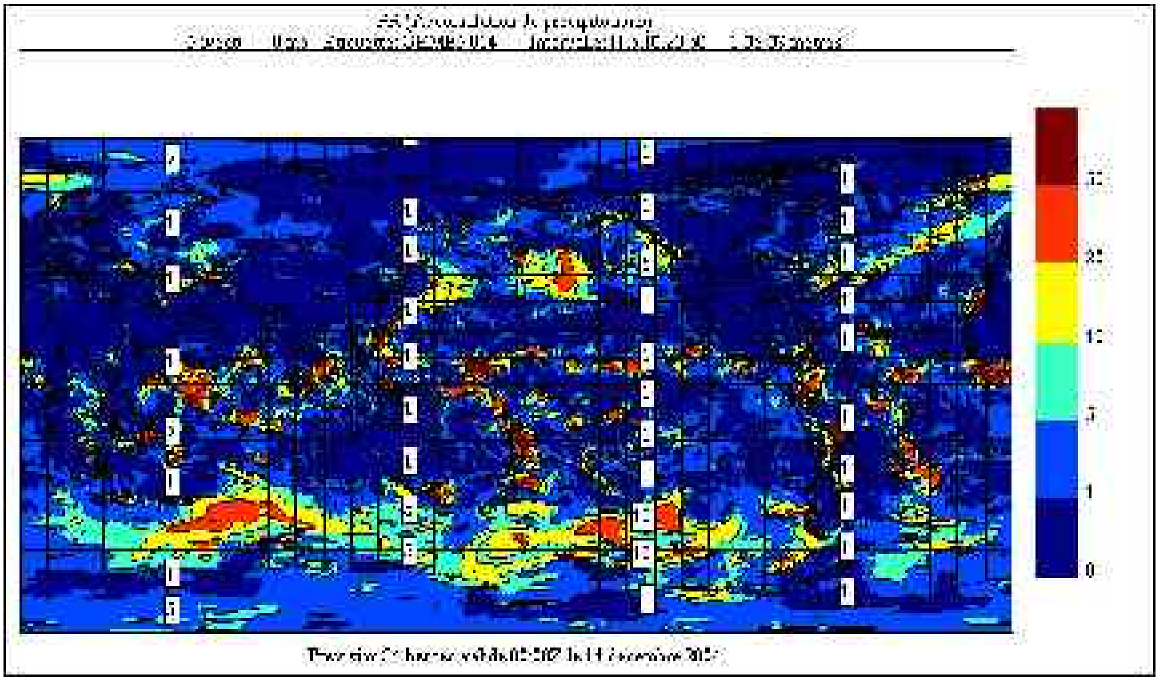

Figure 16. Accumulation of precipitation during the first 24 hours for member 14 of the operational system.

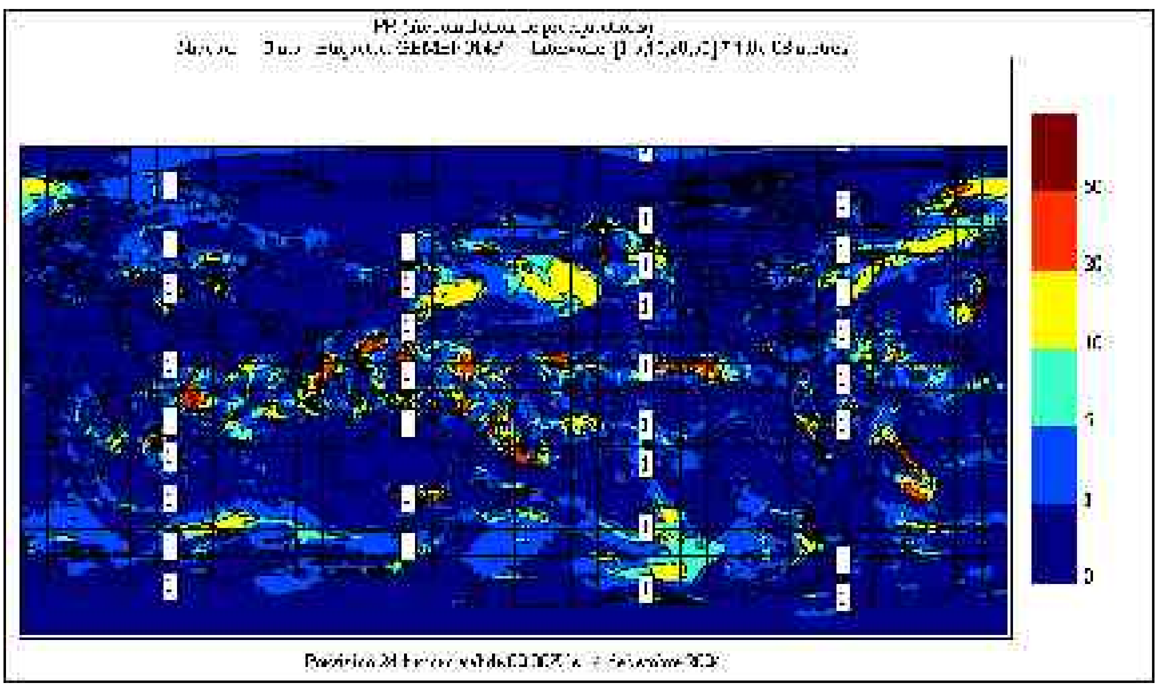

Figure 17. As figure 16 but for member 14 of the parallel system.

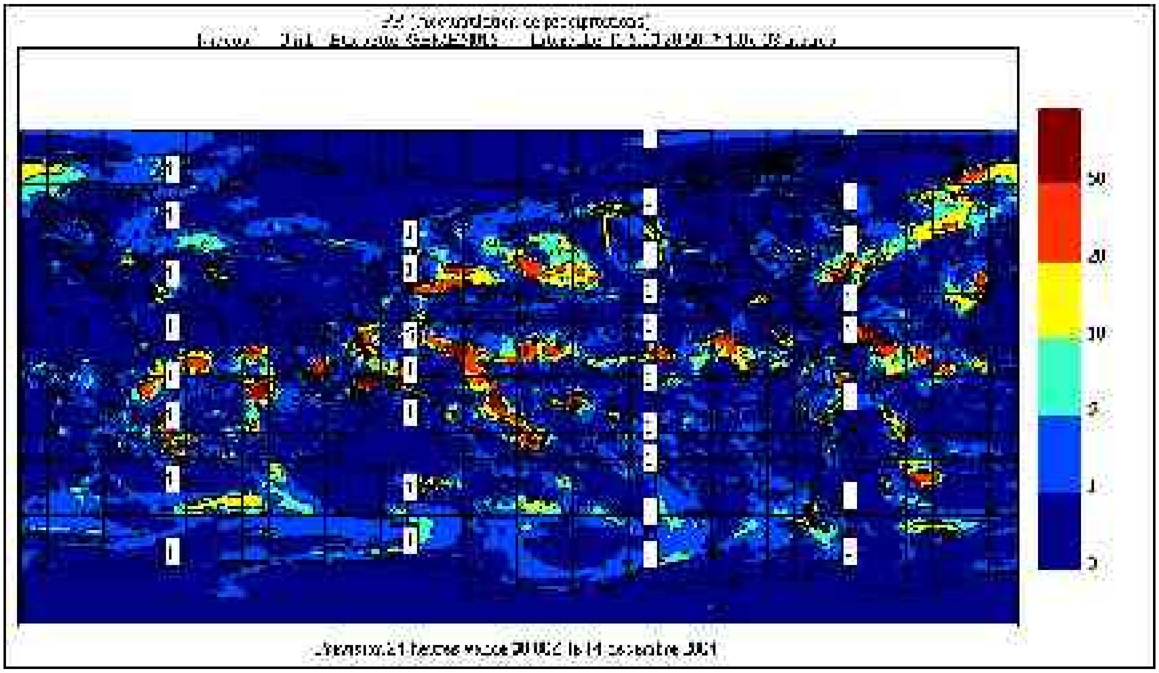

Figure 18. As figure 16 but for member 16.

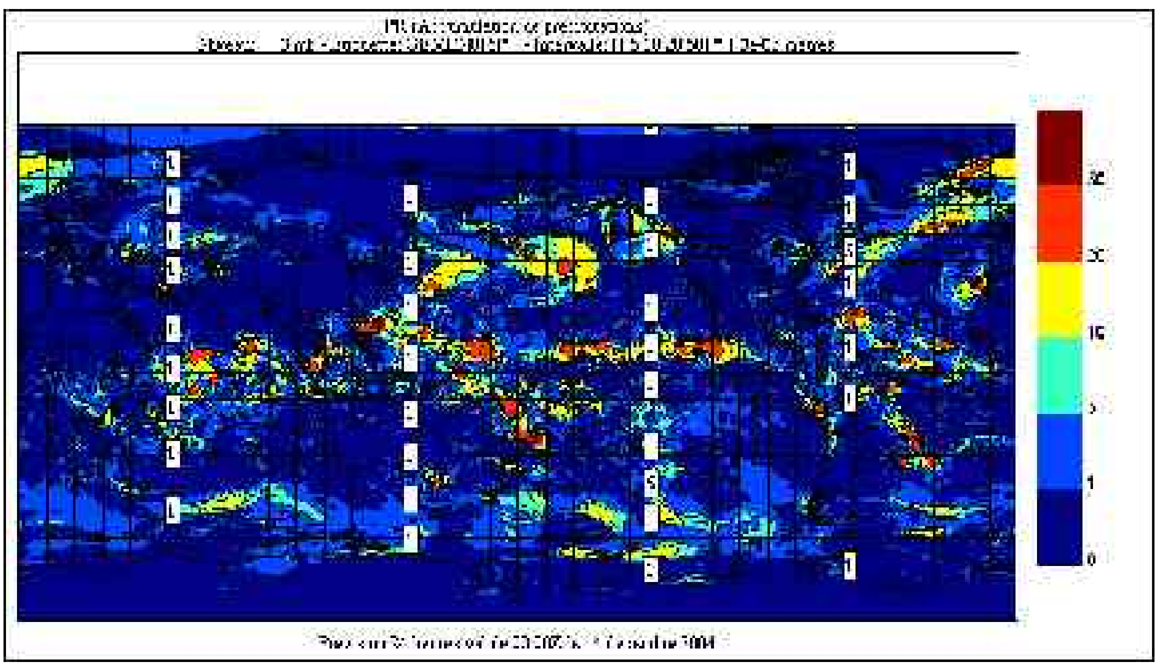

Figure 19. As figure 17 but for member 16.

We remark that the members 10, 11, 14 and 15 of the operational system "benefit" from a correction towards the deterministic 3D-Var analysis. To understand the problem with this correction, we need to look at the interpolations that are performed to arrive at the initial conditions for the GEM model.

- The OI/SEF analysis system provides initial conditions on pressure levels using sub-orographic extrapolations with the fixed lapse rate used by the SEF model.

- These fields are compared with, and corrected to, the deterministic analysis that uses the GEM model. The deterministic GEM model uses a different extrapolation procedure as well as a different mountain field. The resulting temperature corrections may be very large. In general, because of a horizontal interpolation, the sub-orographic temperature fields of the GEM analysis are warmer, sometimes by as much as 20 degrees, than the corresponding fields of the SEF model.

- The relatively warm near-surface temperatures, in the initial conditions of the members 10, 11, 14 and 15, lead to intense convective structures over Antarctica. The effects of this heat transport do not dissipate during the 10-day forecasts.

In the EnKF-based data-assimilation cycles, the GEM model is used to produce the guess fields and there is no correction towards the deterministic analysis. Therefore, the observed pathological behavior is unique for the operational system.

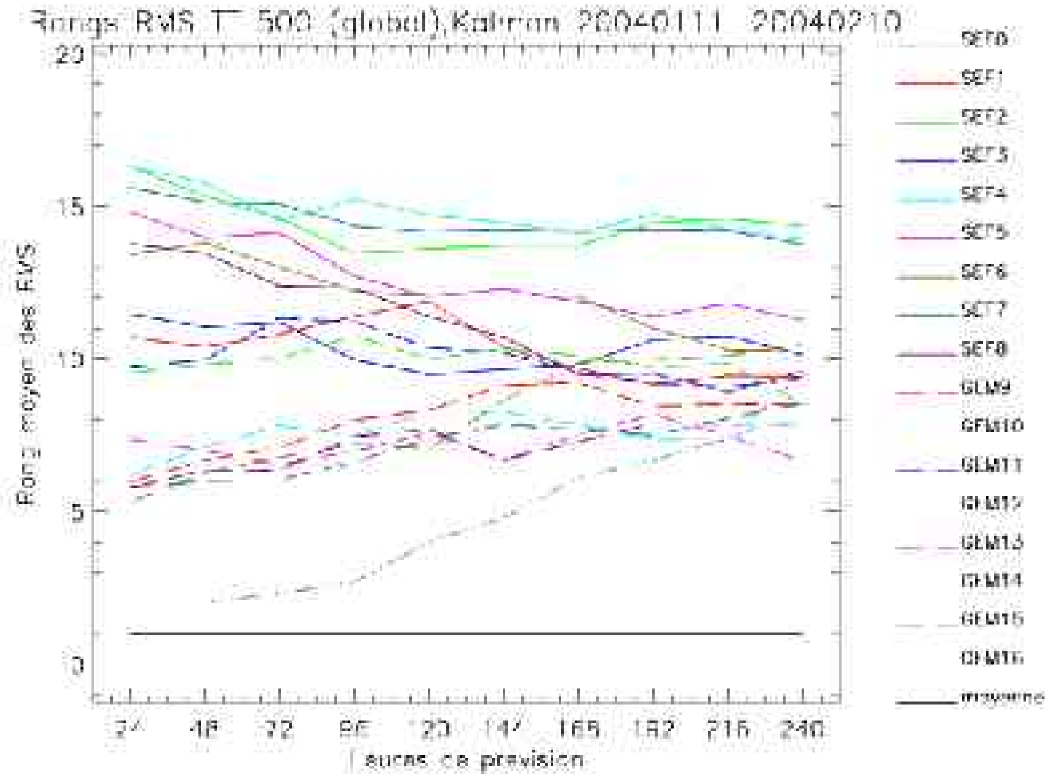

Figure 20. The mean rank of the members for January 2004 for temperature at 500 hPa. The mean is always best (with rank 1) and the control member is often second.

Finally, from the information on the ranks (figure 20) for TT at 500 hPa for Jan 2004, one has the impression that the members using the GEM model benefit more from the change to the EnKF than the members using the SEF model. In the new system, the GEM members outperform the SEF members. This may be due to move from the SEF to the GEM model in the data-assimilation cycle. Summary of the objective verifications

Summary of the objective verifications

Objective verifications have been performed for one summer and one winter month as well as for three one-month periods during the parallel run.

Innovation statistics for the data-assimilation cycles

For all periods, and for each of the verified variables, the standard deviations obtained with the EnKF are at least of the same quality as those from the OI system. For most variables the improvement is fairly significant. For southern hemispheric winds, the mid-tropospheric improvement is of the order of 30 percent! A problem for the EnKF, however, is the large bias in the geopotential height field above 200 hPa. We share this problem with the deterministic analysis group.

In the operational ensemble prediction system, the initial conditions are corrected towards the deterministic 3D-VAR analysis. The better innovation statistics for the EnKF do, therefore, not imply that the medium-range ensemble will be better as well.

Verification of medium-range forecasts

The verifications of the medium-range forecasts are generally positive, neutral or inconclusive. Comparing the EnKF-based parallel system with the operational system we note that:

- The perturbations have faster, more realistic, growth rates.

- The ensemble mean errors as well as the errors of individual members are smaller. The improvement for the southern hemisphere is large. This is likely related to the assimilation of radiance observations in the ensemble Kalman filter and to problems with the correction to the deterministic analysis in the operational system.

- The initial over spreading of the ensemble has been corrected and, consequently, the Talagrand diagrams are much flatter at 24 hours.

- The impact on ROC precipitation scores is very small, perhaps positive.

The pathological behavior of the members 10, 11, 14 and 15, which have strongly unstable initial conditions, is not present in the EnKF-based system - this is shown by the WMO verifications. The WMO verifications, as well as the Talagrand diagrams, also show that the evolution of the bias for the individual forecasts is different in the two systems. This is surprising because only the initial conditions are different between the operational and parallel ensemble prediction systems.

Many, of order 10, medium-range forecasts of the operational system aborted during the parallel run. The model aborts are likely related to unrealistic humidity values that result from the way in which we correct the initial conditions for some members toward the deterministic 3d-var analysis. It is not clear how to permanently fix this problem in the operational system. It would likely involve using a unique method for the extrapolations below the topography for the SEF model, for the low-resolution GEM models, that are used in the ensemble prediction system, and for the deterministic GEM model.

Alternatively the model aborts could be caused by the humidity bias in the upper levels in the operational analysis, which in fact does not truly analyse humidity above 300 hPa. None of the integrations from the parallel system aborted. We note that the sub-orographic extrapolations are not an issue, because we do not need to double the ensemble size by correcting towards the 3D-VAR analysis. We also analyse humidity above 300 hPa like is done in the deterministic analysis (we do not yet use all the same data, but we do assimilate AMSU-B radiances).

Conclusion

In view of:

- the generally positive evaluation of the EnKF-based EPS by our forecasters,
- the positive or neutral objective verifications, and
- the sometimes pathological behavior of members in the operational system,

it has been decided to use the EnKF to provide the initial conditions for the operational ensemble prediction system.

This modification has additional strategic benefits:

- it will no longer be necessary to handle SATEM observations,
- the use of the 3D-VAR quality control assures the continuing high quality of the input data,
- it will now be easier to benefit from developments for the deterministic data-assimilation system,
- it will be possible to have more than 16 members in the medium-range ensemble prediction system.

Operations did implement the new EPS on 0 UT January 13, 2005.