Reviewing the Ensemble Prediction System at the Canadian Meteorological Centre

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The Canadian Meteorological Centre (CMC) started running an Ensemble Prediction System in January 1996 with an ensemble of eight members (*Houtekamer et al.* 1996; *Lefaivre et al.* 1997). This set using eight different versions of the spectral model (SEF) was extended to sixteen members in September 1999 by adding eight different versions of the Global Environmental Multi-scale model (GEM). The models differ in their physical parameterizations and their dynamical cores. The horizontal resolution was increased in June 2001: the SEF models went from T_L95 to T_L149 with an equivalent increase from 1.5 degrees to 1.2 degrees for the grid point GEM model (*Pellerin et al.* 2003).

In January 2005, the independent assimilation cycles driven by eight versions of the SEF model and the Optimum Interpolation technique were replaced by a ninety-six member ensemble with each member using the same version of the GEM model and the ensemble Kalman filter (EnKF). The EnKF introduced at the CMC (*Houtekamer and Mitchell* 2005) is a 4D data assimilation method that uses a Monte-Carlo ensemble of short-range forecasts to estimate the flow-dependent covariances of the guess fields. There is thus a reservoir of initial conditions which are all suitable to initiate a medium-range EPS. Sixteen of these analyses are chosen to initiate and run the SEF and GEM models up to 10 days.

To modernize the ensemble of prediction models, a new set of parameters and parameterizations was defined. CMC intends to extend the forecasts to a range of 16 days. We thus pay special attention to the behaviour of the models for week two. The use of algorithms, that are more recent and that are supported by the research community and therefore easier to maintain, led to a higher quality of our ensemble prediction system. The new system was developed in the context of an agreement to exchange ensemble data across North America: the North American Ensemble Forecast System (NAEFS). This agreement between the CMC, the National Centers of Environmental Prediction (NCEP) and the Mexican Meteorological Institute is meant to produce a grand (or multi-) ensemble forecast system. Verifications of the ensemble forecasts are presented with examples of the relevance of the modifications made to the system.

1 Introduction

The initialization of the ensemble prediction system (EPS) used at CMC is described in *Houtekamer et al.* (2005). The basis of the method is to produce perturbed analyses through sampling of uncertainty in the data assimilation procedure. In order to do this, 96 parallel analysis cycles are produced concurrently using the EnKF technique at the same resolution (1.2 degrees) as the GEM model that generates the trial fields. The quality control consists of a background check and a variational quality control procedure that are part of the deterministic 4D-Var analysis system. This is the only dependence on the deterministic operational analysis procedure which operates at 0.9 degrees resolution. The EnKF was implemented in January 2005. In December 2005, there were a few modifications done to the analysis cycle. These modifications are discussed in section 2 and are motivated by the desire to assimilate all data that are also assimilated in the deterministic 4D-Var system. Some additional observation types were added and some changes were made towards an algorithm which permits time interpolation (see *Houtekamer and Mitchell* 2005). Modifications were also made to the model characteristics of our EPS (the older system is summarized in Table 1). These modifications are discussed in section 3 and are motivated by the extension of the EPS forecasts to day 16. They involve the use of the same sub-grid scale parameterizations in both models, the removal of poorly performing schemes, the adoption of a scheme for surface interaction with the biosphere and atmosphere (ISBA, *Noilhan and Planton* 1989) which has been in use in the higher resolution version of the GEM model (regional configuration), and the application of a digital filter for all members. Currently at CMC, we tend to accumulate many changes for a parallel run in which two perhaps fairly different versions of an EPS are compared subjectively by the operational forecasters. In preparation for such a parallel run, we have to supply a convincing objective verification. We recently adopted a fresh approach for comparing two EPSs, a verification against observations which was proposed by *Candille et al.* (2006). Some results highlighting the benefits of our new system will be presented in section 4. Finally in section 5, we will discuss future plans for the Canadian EPS.

2 Changes to the analysis components

The algorithmic changes to the analysis procedure are discussed extensively in *Houtekamer and Mitchell* (2005). These changes include the introduction of a digital filter for the model that produces the 6h-forecast trial fields, the addition of model error after the production of the analysis, and the break-up of the ensemble into 4 groups of 24 members (instead of 2 groups of 48). The purpose of these fairly neutral changes is to enable the future implementation of an algorithm that does time interpolation in the data-assimilation window. The other changes made to the analysis cycle are the assimilation of the AMSU-A radiances from AQUA, and the MODIS derived winds from both AQUA and TERRA satellites. There are 96 analyses produced at every 6 hourly cycle, it is only a matter of randomly choosing 16 of these to feed the EPS to produce the 16-day forecasts. In actual fact, we choose the first 16 members, shifting them so that the mean of the 16 members is co-located with the mean of the 96 members. Subsequently, the distance from the centre is inflated by a factor of 1.8 and, finally, we correct any resulting negative humidity and over-saturation.

3 Changes To The forecast components

Currently, CMC is still using two sets of models for the EPS: a spectral model SEF (*Ritchie* 1991) and a grid point model GEM (*Côté et al.* 1998). The SEF models have a horizontal resolution of T_L149 with hyper-diffusion of form∇^8. These models are different in a selection of switches which prescribe different physical parameterizations. The different configurations are described in the top half of Table 1. In addition, some parameters are set with random values (horizontal diffusion, minimal roughness length and time filter). Perturbations are also introduced in the surface forcing through modifications (Gaussian perturbations) of the sea surface temperature, the albedo and the roughness length fields. The GEM models are grid point models with equivalent horizontal resolution of 1.2 degree. They have their own set of perturbations which are detailed in the bottom half of Table 1. These models differ mostly in the use of different convection schemes and soil moisture content. The new (ktrsnt) shallow convection scheme better handles moisture in the tropics and so does the moist boundary layer (turwet) which includes the saturation processes. These variations to the model configuration were producing sufficient variance at a lead time of 10 days to warrant their use, although at times, some integration would abort just before reaching the 10-day limit. The main reason was perhaps too wide a variation of the time filter parameter which is critical principally during the autumn season. The lower bound of this parameter was eventually raised to ensure model stability. The following table gives an overview of our system before its revision.

SEF (T149)	Convection/Radiation	GWD[0]	GWD[0] version	Orography	Number of levels	Time level
1	Kuo/ Garand	Strong	High altitude	0.3 σ	23	3
2	Manabe/ Sasamori	Strong	Low altitude	0.3 σ	41	3
3	Kuo/ Garand	Weak	Low altitude	Mean	23	3
4	Manabe/ Sasamori	Weak	High altitude	Mean	41	3
5	Manabe/ Sasamori	Strong	Low altitude	Mean	23	2
6	Kuo/ Garand	Strong	High altitude	Mean	41	2
7	Manabe/ Sasamori	Weak	High altitude	0.3 σ	23	2
8	Kuo/ Garand	Weak	Low altitude	0.3 σ	41	2
Control	Kuo/ Garand	Mean	Low altitude	0.15 σ	41	3
GEM (1.2°)	**Deep convection**	**Shallow convection**	**Soil moisture**	**Sponge**	**Number of levels**	**Coriolis**
9	Kuosym[1]	ktrsnt	Less 20%	Global	28	implicit
10	RAS[2]	conres	Less 20%	Equatorial	28	implicit
11	RAS[2]	conres	Less 20%	Global	28	implicit
12	Kuosym[1]	conres	More 20%	Global	28	implicit
13	Kuosym[1]	ktrsnt	More 20%	Global	28	explicit
14	Kuosym[1]	ktrsnt	Less 20%	Global	28	implicit
15	Kuosym[1]	conres	Less 20%	Global	28	implicit
16	Kuosun[3]	ktrsnt	More 20%	Global	28	explicit

Table 1 Combination of modules for different model versions used before the revision.

[0]Gravity Wave drag (see *McFarlane* 1987 and *McLandress and McFarlane* 1993)
[1]Deep Convection scheme (See *Wagneur* 1991)
[2]Relaxed Arakawa-Schubert (see *Moorthi and Suarez* 1992)
[3]See *Dastoor* 1994

In view of exchanging data in the context of the North American Ensemble Forecast System (NAEFS), it was agreed to extend the forecast period to 16 days to permit the development of second week products. This led to a revision (substitution) of certain parameterizations that were faulty at times or some others that would complicate the forecasting suite. A few alternatives were discussed for this revision, the first being a status quo which was unacceptable in view of occasional aborting of models. The most elaborate revision was one that would use only the GEM models, with a configuration close to the operational deterministic version and the inclusion of stochastic physics that would generate as much spread in the forecast as in the previous system. This latter approach, although attractive, requires a significant amount of testing and validation and could have threatened the target date for implementation fixed for spring of 2006. It was decided to keep the two model approach and to improve minimally by reducing the number of parameterizations, mainly keeping those that are supported by the research community.

A surface blocking parameterization (*Zadra* 2003) had been included in the GEM models in May 2003, but when incorporated in the spectral model, it turned out that it considerably degraded the quality of the forecasts. Indeed this forced the removal of the different model topographies which had provided significant model variance. The surface blocking term may be applied or not, and this change resulted in a lack of model variance. The second change was the adaptation of a new vertical hybrid coordinate. This new coordinate reduces the numerical interactions with the model top and adds robustness to the SEF model. The third major modification was the introduction of a more evolved convection scheme to replace the Manabe algorithm which had been introduced at the very beginning of the EPS. The Relaxed-Arakawa-Schubert (RAS) convection scheme had been running since the introduction of our GEM members and was implemented in the SEF model. This scheme also permits future opportunity for stochastic perturbations in our models, the cloud function offering arbitrary choices at the onset of this convective scheme. The removal of the old convective scheme would also force the removal of the Sasamori radiation algorithm (Sasamori 1972) in favour of the radiation algorithm (Garand and Mailhot 1990) which is more recent in terms of model evolution. This parameterisation requires the model to transport the cloud fraction, and the cloud water/ice content for radiation interaction (greyness of clouds), but imposes restrictions on the choice of the corresponding condensation scheme. Here, the Sundqvist scheme is used to describe the generation and dissipation of liquid/solid cloud water/ice content. In order to reduce the number of parameterization schemes, it was felt that we should get closer to the global deterministic model. There is a good history of changes made to improve this model from which the EPS can benefit.

The unified GEM model used at CMC is intended to provide weather guidance at different scales (2.5 km, 15 km, 35 km and 100 km) and also provides a flexible tool for the research community. The 15 km version of this model (implemented for regional short-range forecasting) uses a comprehensive surface scheme which interacts with the biosphere and atmosphere (ISBA). This scheme takes into account many physical processes such as evolution of snow and ice, phase processes which may have a great impact on the incoming short-wave radiation, and hence on the resulting net heating of the soil. The better handling of the surface moisture and the resulting complexity associated with the biosphere provides a better simulation of the diurnal cycle of the surface temperature in the model. This comprehensive scheme was added to the new EPS. The latest version of the GEM model uses Cubic Lagrange interpolation when 3D advection is performed. It also includes a uniform mass re-injection done at every time step to compensate the total mass loss. Finally, a later version of the shallow convective scheme, which allows light precipitation under severe instability, was also introduced. This is important to forecast lake effects during northern cold spells, which are not unusual in the winter season in Canada. Our latest EPS is summarized in the following Table 2.

The resulting models are closer to each other in terms of the use of parameterizations, of the number of levels and in the variation of different coefficients. This will simplify the introduction of stochastic physics in the future. Our current first priority is to develop a set of EPS products for week two. Until now, the evaluation of changes to the EPS was mainly based on three different scores (*Pellerin et al.* 2003). We first measure, for the 500 hPa height field: the RMS error of the ensemble mean; the RMS error of individual members as well as the ensemble spread. For this variable, we also look at the rank histogram (*Talagrand et al.* 1999). We also look at the ROC curves (*Mason* 1982) used to validate the performance of the EPS for precipitation. This verification package presents some weaknesses. First, we have no real summary of the quality of the EPS, but a combination of scores that may or may not portray the actual skill of the new EPS. The RMSE intrinsically is a deterministic diagnostic; the rank histogram is a probabilistic score that only measures the statistical consistency, or reliability; the ROC curves measure the discrimination between the correct and incorrect predicted probabilities of occurrence of a binary event. Secondly, the verifications are mainly preformed against analyses and may depend on the choice of the analysis. Here both the parallel EPS and the operational EPS are verified against the analyses produced by the operational deterministic model. Thirdly, we do not quantify the significance of an improvement with the above-mentioned scores.

SEF (T149)	GWD Taufac	Deep Convection	Shallow convection	Surface scheme	Number of Levels	Time level
1	1.2e-5	KUO[3]	conres	ISBA	27	3
2	1.2e-5	RAS	turwet	Fcrest	27	3
3	4.0e-6	KUO[3]	conres	Fcrest	27	3
4	4.0e-6	RAS	turwet	ISBA	27	3
5	1.2e-5	RAS	turwet	Fcrest	27	2
6	1.2e-5	KUO[3]	conres	ISBA	27	2
7	4.0e-6	RAS	turwet	ISBA	27	2
8	4.0e-6	KUO[3]	conres	fcrest	27	2
Control	8.0e-6	KUO[3]	conres	fcrest	27	3
GEM (1.2°)		**Deep Convection**	**Shallow convection**	**Surface Scheme**	**Number of levels**	**Time level**
9	8.0e-6	Kuosym[1]	ktrsnt	Fcrest	28	2
10	8.0e-6	RAS[2]	conres	ISBA	28	2
11	8.0e-6	RAS[2]	conres	Fcrest	28	2
12	8.0e-6	Kuosym[1]	ktrsnt	ISBA	28	2
13	8.0e-6	Kuostd[4]	ktrsnt	Fcrest	28	2
14	8.0e-6	Kuostd[4]	conres	ISBA	28	2
15	8.0e-6	Kuosym[1]	conres	ISBA	28	2
16	8.0e-6	KUO[3]	conres	Fcrest	28	2

Table 2 Combination of modules for different model versions used after the revision.

[0]Taufac is a scale factor representative of sub-grid scale orography (See *McFarlane* 1987)
[1]Deep Convection scheme (See *Wagneur* 1991)
[2]Relaxed-Arakawa-Schubert (See *Moorthi and Suarez* 1992)
[3]See *Dastoor* 1994
[4]Same as KUO with a later version of the Sundqvist scheme.

The weaknesses of the current verification package led to the consideration of new verification tools in order to provide an objective comparison between two EPSs. To this end, a verification against observations which was proposed by *Candille et al.* (2006) is used to remove the inbreeding due to the dependence on the model in both the forecasts and the verifying analyses. We use the Continuous Ranked Probability Score (CRPS, *Stanski et al.* 1989) which measures the global skill of an EPS. This score can be decomposed into reliability-resolution partition (*Hersbach* 2000) in order to evaluate the two main attributes required of a probabilistic prediction system (*Toth et al.* 2003). We apply the bootstrap technique in order to define confidence intervals for the comparisons.

Before we examine the performance in terms of the CRPS, we show that, in general, forecast biases are less severe in the new package. Figures 1a and 1b show the evolution over 10 days of the 500 hPa height field biases over North America for the old and the new configurations. Two aspects are clear from this comparison. Firstly, the new configuration produces weaker biases as shown by the values of the vertical scale which were reduced significantly. Secondly, in the upper panel, we can see the positive biases for members 2, 4, 5 and 7 which were generated by the Manabe/Sasamori schemes. The mean (dark black curve) is about the same in both systems. We may also realize that there is still a warm bias (Fig. 1b) coming from members with the SEF models in the proposed configuration. Statistical techniques may remove model biases in the post-processing step, but nevertheless it is preferable to reduce these as much as possible beforehand. Another interesting aspect of the evolution of these scores is the behaviour of the different model configurations with time. We can assess the behaviour of some parameterizations and possibly correct them when possible. It is clear that the Manabe/Sasamori schemes were generating a large bias which was corrected by its RAS/Garand replacement. The results indicate that the revision has reduced the bias in the members with the GEM models. Note that the version of the GEM model that is used in the EnKF would behave much like the operational global deterministic model (the dotted black curve labelled globop). Both of these models use a convection parameterization of the Kuo type along with a simulated shallow convection scheme (conres).

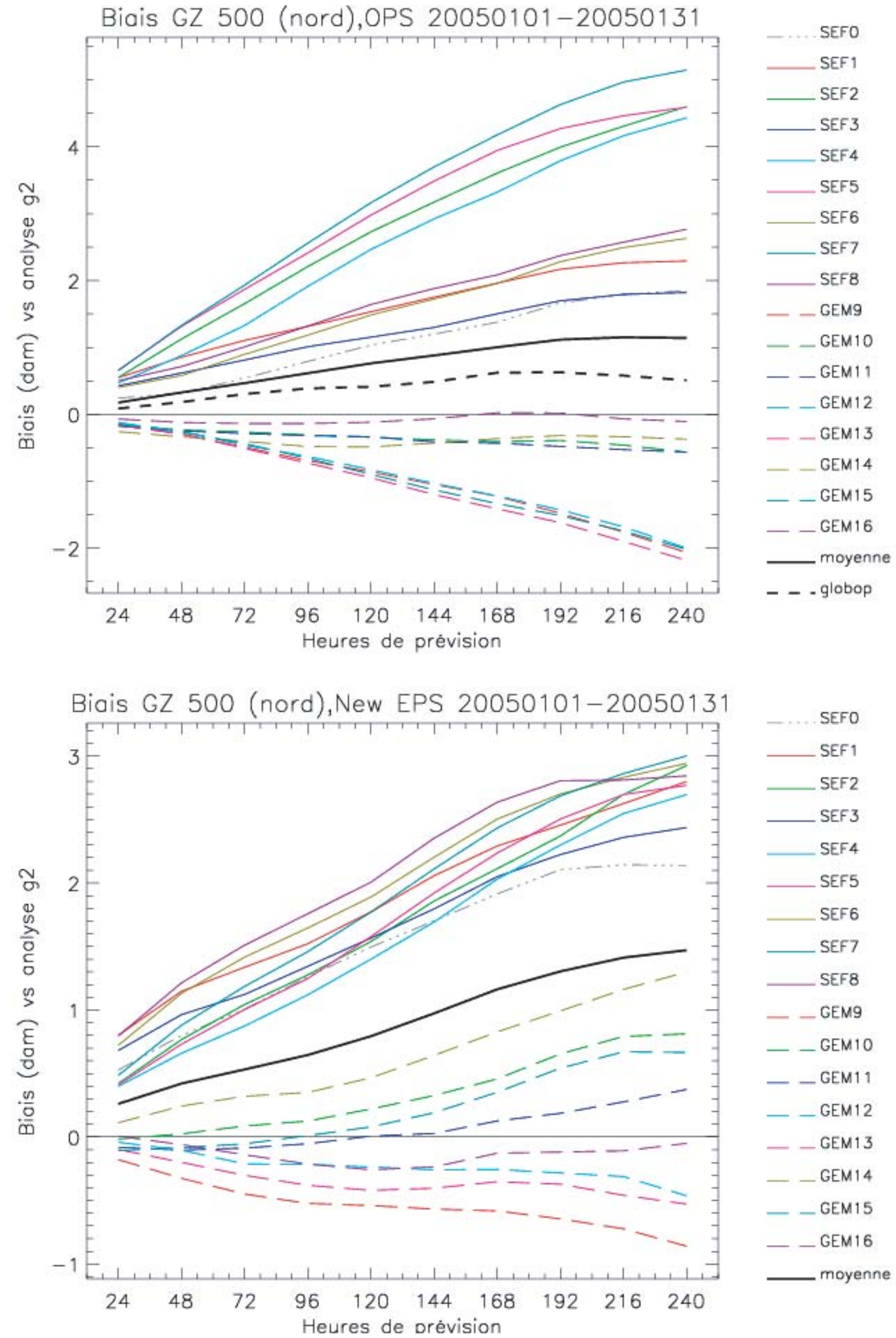

Fig. 1 The evolution of the bias of the 500 hPa height field for 10 days for the month of January 2005, respectively for the old (top) and the new (bottom) model configurations. Note the difference in scale for the vertical axis in the two figure panels.

Figure 2 shows the evolution of the error in the global temperature field at 850 hPa for January 2005. Note the reduction in the vertical scale in Figure 2b, which became possible due to the reduced biases in the new EPS; nevertheless, the mean biases are similar in both EPSs. Again, the combination Manabe/Sasamori is seen to generate a warm bias which does not appear in the new set of configurations. The new proposed configuration (Fig. 2b) also displays different model behaviours which may be explained by the selection of schemes available in the physics package. For instance, some of the GEM-model members (9, 12, 13 and 15) that use a convective scheme different from the Kuo scheme show a decreasing bias in time after the initial shock of adapting to the EnKF analyses. In particular, members 9 and 13 display an increasing negative bias which may be attributable to the use of the moist planetary boundary scheme (turwet) along with a shallow convection mechanism (ktrsnt) to remove the moisture trapped under the inversion. Such meteorological situations occur with strong cold air advection. This combination may benefit from some readjustment in the future. Most of the SEF models display a slight warm bias, particularly those members using the combination RAS/Garand. Other scores such as RSME for the 24-hour cumulative precipitation show a net reduction in bias (not shown here). Overall, the verification against analyses suggests that the proposed new EPS is a better package.

As mentioned previously, verifying an EPS against analyses is problematic. Following Candille et al. (2006), we now show verifications against observations using the CRPS (Hersbach 2000). To this end, the bootstrap method is used to get the confidence interval from 5% to 95% for verifications with respect to observational data. We look at the evolution of the CRPS scores for the surface temperature for both EPSs. Figure 3 shows the evolution of the CRPS to ten days for the month of August 2004 at 12UT validation time and the corresponding confidence intervals for the difference between the two EPSs. It is clear that the proposed EPS is significantly better than the old one. We must go back to some of the changes to explain this gain. The new configuration makes use of two surface interaction schemes: the Force-Restore scheme also used in the old EPS and the more comprehensive ISBA scheme. It is known (from the regional version of the GEM model with 15 km resolution) that this scheme produces better air-soil interactions than its older counterpart. It more realistically takes into account interactions with the vegetation and snow processes such as melting and freezing. It is the most important change in going to the new package. It does, however, add some complexity since we have to provide different surface analyses which are not yet provided by the global deterministic model; (the current global model does not use the ISBA scheme). To this end, a special procedure was put in place to provide these fields from the current deterministic global model. Essentially, this model is run every 6 hours (with the switch for ISBA activated) to provide the screen-level temperature and the soil moisture trial fields. A pseudo-analysis is then performed to nudge these fields with new observations. These surface analyses are then fed to the EPS as initial fields before the 16-day forecasts (now done twice daily) are submitted.

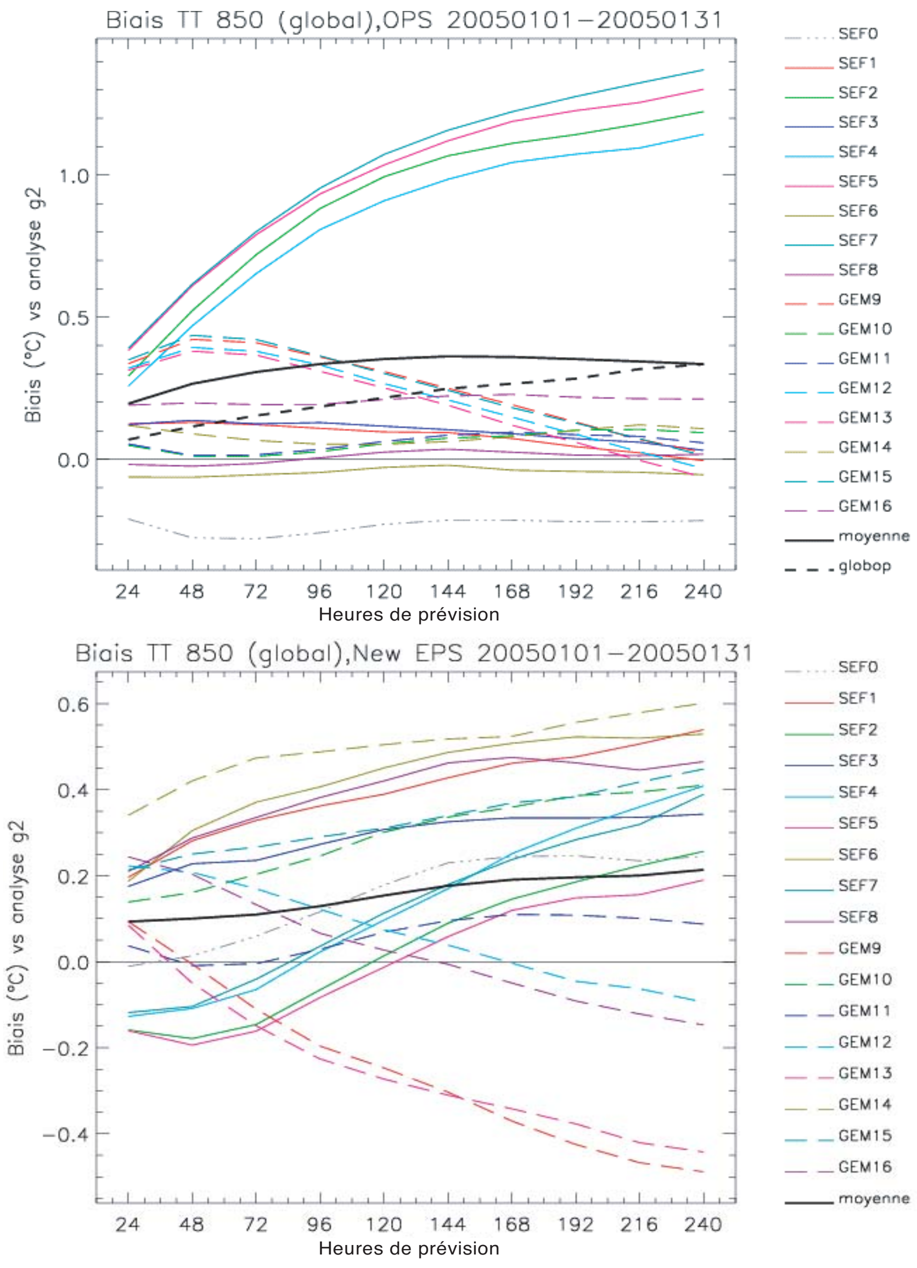

Fig. 2 The evolution of the bias of the 850 hPa global temperature field for 10 days for the month of January 2005, respectively for the old (top) and the new (bottom) model configurations. Note the difference in scale for the vertical axis in the two figure panels.

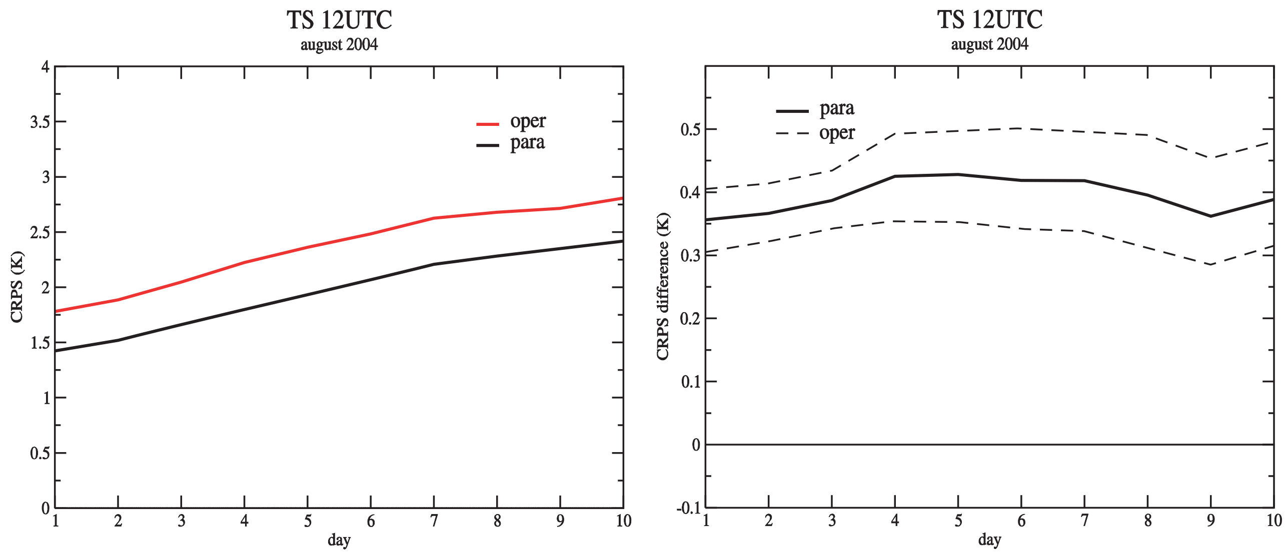

Fig. 3 The left panel shows the CRPS for the surface temperature forecasts to 10 days for the month of August 2004 at 12 UT validation time. The top (red) curve is for the operational model configurations, the lower (black) curve is for the new model configurations. The right panel shows the CRPS difference and 5-95% confidence intervals.

Figure 4 shows the evolution of the CRPS for the month of August 2004 at 00 UT lead time and the corresponding confidence intervals for the comparison between the two EPSs. The gain is less spectacular than at 12 UT, but the new EPS with both ISBA and Force-Restore is nevertheless significantly improved with respect to the old system which employs only the Force-Restore scheme. The ISBA scheme is still evolving and improvements are regularly made to its regional counterpart. In the future, the EPS will be able to benefit from these changes.

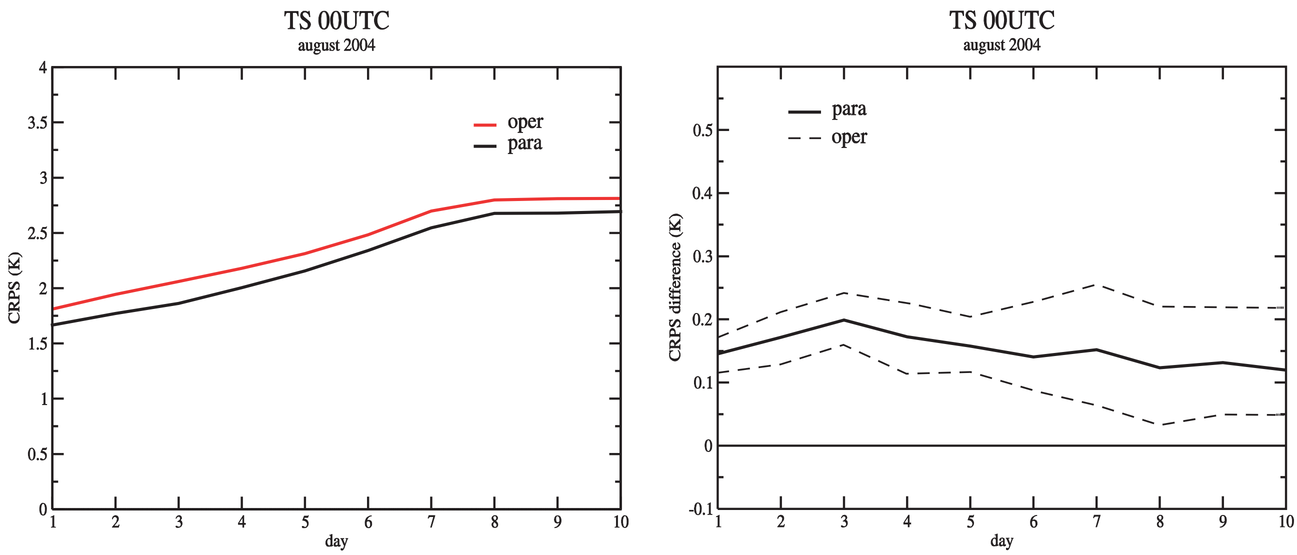

Fig. 4 As in Fig. 3, but at 00 UT.

This verification procedure was also used for other dynamical variables to demonstrate that the new EPS is better than the previous system. For the upper-level variables, however, the improvements were less significant. Therefore, after a parallel test which began on 2 September 2005, the new system became operational in the Canadian ensemble forecasting system on 13 December 2005.

4 Summary And future plans

Following the introduction of the Ensemble Kalman Filter technique (EnKF) for the generation of initial conditions for the Canadian EPS in January 2005, a few further changes have been made to the EPS. They include changes to the assimilation (both more data and algorithmic improvements) and changes to the model configurations (use of parameterizations that are more recent and that are supported by the research community). These changes resulted in a better Canadian EPS and a system which is easier to maintain. The new system was developed in the context of an agreement to exchange ensemble forecasts with the United States and Mexico to produce a grand North American Ensemble Forecast System (NAEFS).

Verifications of the ensemble forecasts have been presented with examples illustrating the improved performance of the new system. Weaknesses of the current verification package motivated the development of a new package for the objective comparison of two EPSs. Verification against observations removed the inbreeding due to the dependence on the model in both the forecasts and the verifying analyses. We use the Continuous Ranked Probability Score (CRPS) which measures the global skill of an EPS. This verification score was computed for different upper-air variables and for surface temperature and precipitation and indicated that the new model configurations were significantly better than those used in the previous system. The new EPS became operational on 13 December 2005.

The analysis, forecast and post-processing components of the Canadian EPS are still evolving. Significant improvement in the EnKF results can be expected from the addition of time interpolation. As for the forecast component, we intend to continue to simplify our procedures, using only the GEM model and parameterization perturbations generated with stochastic physics. It is planned to increase the number of members to 20 and to increase the horizontal resolution to 0.9 degree. These changes may be implemented as early as the third quarter of 2006. Also, we will continue to support the NAEFS agreement with a special attention to the behaviour of the models for week two.

5 References

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