Improving the assimilation of water in a NWP model

Final ALATNET Report

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1. Introduction

It is known that the forecasts from NWP models are very sensitive to small errors in the initial state (known as analysis). The aim of the meteorological data assimilation is to determine this initial state, trying to make it as close as possible to the true state of the atmosphere.
The size of the model state vector is given by the number of gridpoints in the horizontal times the number of level times the number of prognostic variables. One of the first difficulties in data assimilation is that the problem of determining the initial model state is grossly underdetermined, because the observation vector is much smaller than the model state vector. In order to solve this problem a prior information is needed. In data assimilation this information comes from a short range (6 hours) forecast, known as first guess or background. So, the analysis field results from a combination of background and observations. The weights given in the analysis to observations and to background are determined by the magnitudes of errors at each location (variances) and the correlations between errors at different locations (covariances). In this sense data assimilation can be seen as a least squares or a regression problem.
It is very important to notice that the accuracy of the analysis depends on the accuracy of the two sources of information and on the weights given to them. Moreover, the analysis is only optimal (that is, the uncertainties about the true state are decreased as much as possible) if the observation and background errors statistics are correctly specified in the analysis system. So, it is very important to have a good estimate of these statistics.
The aim of the present work is to diagnose and investigate the background error features in order to improve the analysis and consequently the forecasts of a NWP model.
Until 2003, in the operational ARPEGE assimilation system, the covariances of the background error were estimated using the NMC method (Parrish and Derber, 1992). In this method the background errors are given by the differences between 12h and 36h forecasts valid at the same time. In 2001, another method, known as the Analysis Ensemble Method, hereafter referred as the Ensemble method, which was tried before in Canada (Houtekamer et al., 1996) and at ECMWF (Fisher, 1999) was implemented and tested in the ARPEGE 3D-Var (Belo Pereira, 2002). Presently, the Ensemble method is operational in the ARPEGE 4D-Var.

2. Ensemble Method

In this method an ensemble of independent analysis experiments is performed. For each experiment (member) and for each analysis cycle, all observations are perturbed adding an independent random number, which has a gaussian distribution with mean zero and variance equal to the prescribed variance of observation error. These perturbations will create a perturbed analysis for each member. The differences between the perturbed analyses of different members are a measure of the uncertainties in the analysis. Afterwards, a 6h integration of the numerical model is performed, using the perturbed analysis. So, in this way the uncertainties in the analysis fields are propagated to the 6h forecast and consequently to the next analysis cycle, in the form of uncertainties in the background. After a few days of assimilation, the statistics of the differences between background fields for pairs of members of the ensemble equilibrate. Then, it is assumed that the differences between the 6h forecasts of independent members of the ensemble represent the background error.

3. Estimation of the length scale of autocovariance

Using the Helmholtz's theorem, we obtain the rotational part of the meridional wind, $v^{\psi}=\frac{\partial\psi}{\partial x}$. So, the covariance of v^{ψ} between two points is given by

$$\left\langle v_1^{\psi} v_2^{\psi}\right\rangle=\left\langle\frac{\partial\psi_1}{\partial x_1}\frac{\partial\psi_2}{\partial x_2}\right\rangle=\frac{\partial^2}{\partial x_1\partial x_2}\left(\left\langle\psi_1\psi_2\right\rangle\right)$$

and the covariance of the stream function (Ψ) can be expressed as a function of its autocorrelation function ρ and of its variances $\sigma(\psi_1)$ and $\sigma(\psi_2)$, respectively at point 1 and 2:

$$\left\langle\psi_1\psi_2\right\rangle=\sigma(\psi_1)\sigma(\psi_2)\rho$$

When derivating the above equation and defining $\tilde{x}=x_2-x_1$, we can assume that the first derivative of ρ vanishes at $\tilde{x}=0$ (this assumption is reasonable since ρ is maximum at $\tilde{x}=0$ and decreases as the distance from the origin increases).

And using the definition of length scale (Daley, 1991) for the unidimensional case

$$\left(L_x^{\psi}\right)^2=-\left(\rho\Big/\frac{d^2\rho}{d\tilde{x}^2}\right)_{\tilde{x}=0}$$

we obtain the length scale for the streamfunction autocovariance:

$$\left(L_x^{\psi}\right)^2=\frac{\sigma^2(\psi)}{\sigma^2\left(\frac{\partial\psi}{\partial x}\right)-\left(\frac{\partial\sigma(\psi)}{\partial x}\right)^2}$$

The length scale defined according to Daley (1991) gives an idea about how the autocorrelation function decays with distance from its initial value. For a sharp autocorrelation function, the curvature is large and the length scale is small. On the contrary, if ρ is broad, $\boldsymbol{L}$ is large.

4. Ensemble method applied to ARPEGE with stretched und unstretched geometry

4.1 Experiment description

The background error statistics were estimated for three data sets of differences between 6h forecasts. In the first set (called *metropole*), the background errors come from the differences between two 4D-Var cycles of ARPEGE model with T298 and stretching factor equal to 3.5 (c=3.5). The second set (denominated *tropic*) uses two 4D-Var cycles of ARPEGE with T299 and constant resolution (c=1). The observations used for this set include the tropical cyclone pseudo-observations (*bogus* observations). In both *metropole* and *tropic* sets, the uncertainties are caused only by the perturbations in the observations. So, it is assumed that the model is perfect and the background errors are only due to the

propagation of observations uncertainties. The third set (called *arpf_arpt*) uses one experiment with constant resolution and another one with c=3.5. So, in the last set the model is not considered as perfect anymore and it is considered that the background error is also related with the horizontal resolution.
The background differences come from 6h forecasts valid at 18UTC, during the period between 4 of February and 14 of March.

4.2 Results

On average, the largest vorticity background errors are found in the high troposphere, for wavenumbers between 30 and 70, for all the 4D-var experiments, but the error magnitude is significantly larger for the *arpf_arpt* set. On the other hand, the smallest errors occur for the *metropole* set and its maximum is shifted towards larger scales relatively to the *tropic* set.

Moreover, the results show that for the *metropole* set the vorticity errors are concentrated in the high resolution areas, decreasing as the resolution decreases (see figure 3.1 from ALATNET 3rd year report). At first sight, this result is quite surprising because one would expect that the largest background errors occur in the lower resolution areas. The fact that the largest contributions for vorticity errors come from small scales can contribute to this unexpected result. Moreover, assuming that the background error is caused only by the time evolution of observation uncertainties (that is, that the model is perfect) can lead to an underestimation of the background errors.

The surface pressure background errors are significantly larger when computed using *arpf_arpt* set than with other sets. The largest differences occur for synoptic scales, for wavenumbers between 5 and 20 (figure 4.1). The same result is found for temperature and specific humidity errors.

The variance spectrum of stream function background error is very similar for both *tropic* and *metropole* data sets. This result can be explained by the fact that the largest contributions for the stream function background errors comes from the planetary scales (figure not shown). The results show also that with the *arpf_arpt* set the error variance is larger than with the other data sets.

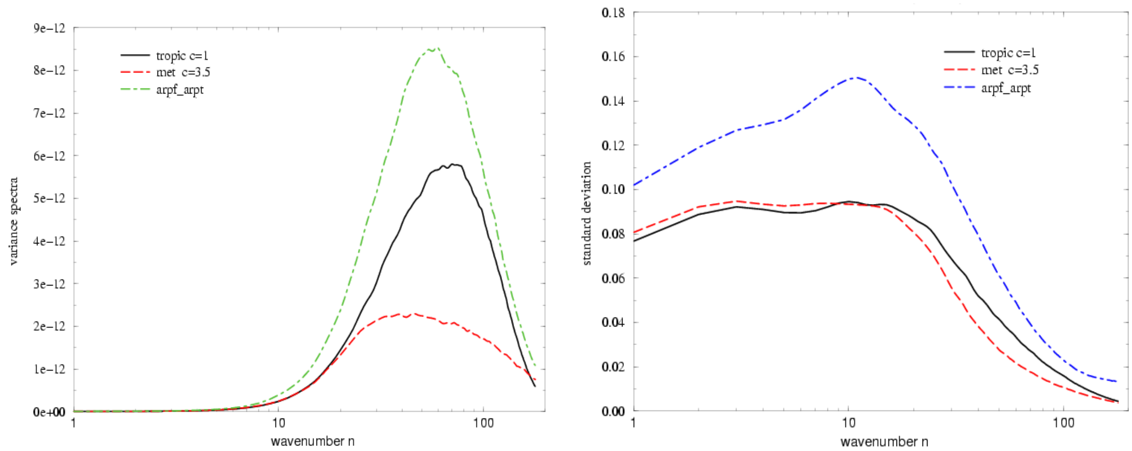


Figure 4.1 Variance spectrum for vorticity errors for model level 21 (near 500hPa) (left side). Standard deviation (hPa) spectrum of surface pressure background error (right side).

The results also show that for the *tropic* set the correlation functions tend to be broader in the tropics (larger length scales) than in middle and high latitudes, while on the 4D-Var with stretching the horizontal correlation length scale tends to increase towards the coarser resolution areas.

5. Analysis versus background error estimated by the Ensemble Method in 4D-Var of unstretched ARPEGE

5.1 Experiments decription

The results presented in this section are derived from an ensemble which contains five 4D-Var cycles of the non-stretched version of ARPEGE model with T299 and 41 levels, for the period from 1 of February to 24 of March of 2002. The members of this ensemble were arbitrarily numbered from 33 to 37. The differences between the 6-hours forecasts for consecutively numbered members were computed for each 12UTC cycle between 4/2/2002 and 24/3/2002. This provides 4 x 49 = 196 differences between background fields, from which the global standard deviation, the vertical and horizontal correlations of the background error are diagnosed.

5.2 Results

The results show that the largest surface pressure background errors are found near North Pole, to the north of Russia. Moreover, large errors occur in the extra-tropics over the oceans (figure 5.1). So, the largest errors occur in the areas of larger surface pressure variability and in data sparse areas, which seems to be a reasonable result. Moreover, comparing the variances of the background and analysis both valid at 18 UTC, it can be seen that on average the analysis variance is smaller than the background variance. This means that the observations used by the analysis system contribute to decrease the dispersion of surface pressure in the background. This is consistent with the expected decrease of the background uncertainties by the observations in the analysis cycle. Moreover, there is a good correlation between the areas where the analysis variance is smaller than the background variance and areas where the coverage of SYNOP and TEMP observations is good. This result is more notorious over Europe (figure 5.2).

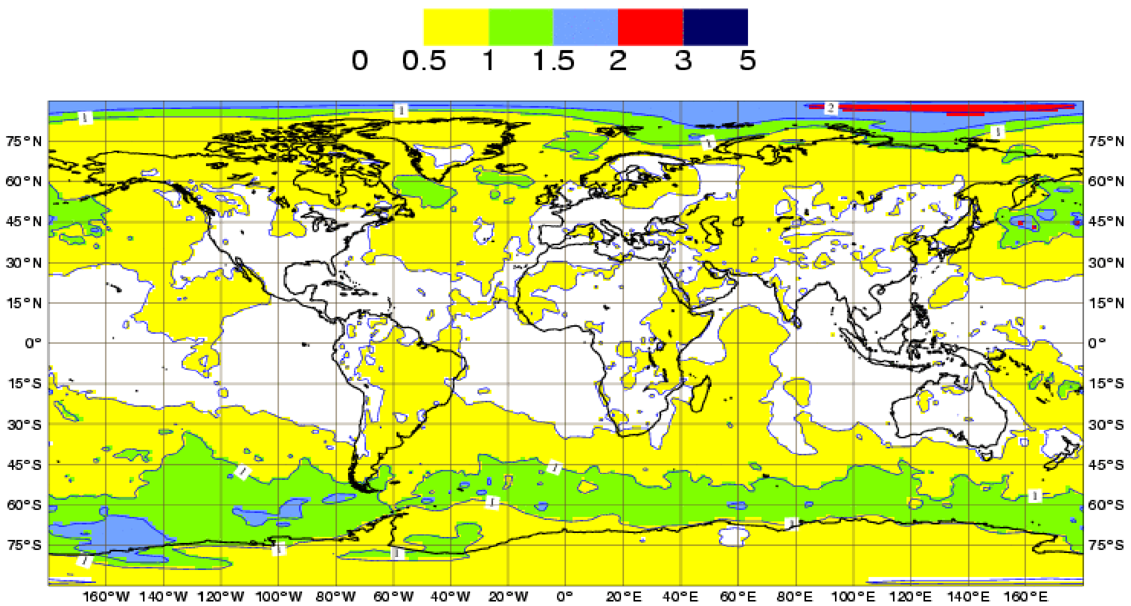


Figure 5.1 Standard deviation (hPa) of surface pressure background error.

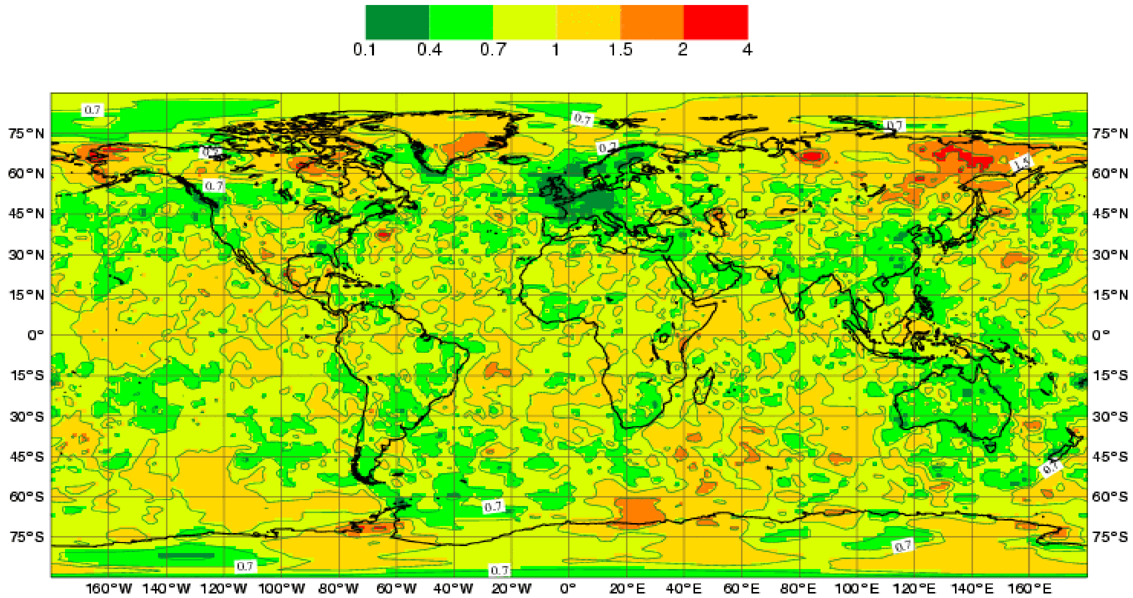


Figure 5.2 Ratio between analysis and background error variances of surface pressure. The green areas identify the areas where the impact of the analyis is positive.

Furthermore, it was found out that on average the analysis variances of the vorticity and divergence are smaller than the background ones, except in the top levels (above level 4) (figures not shown).

The results show also that the analysis of humidity is able to decrease only slightly the dispersion in the background in the middle and upper troposphere. Moreover, the vertical profile of these dispersion ratios suggests that the impact of the analysis is neutral in the Planetary Boundary Layer and lightly negative in the stratosphere, both at 12 and 18UTC (figure 5.3).

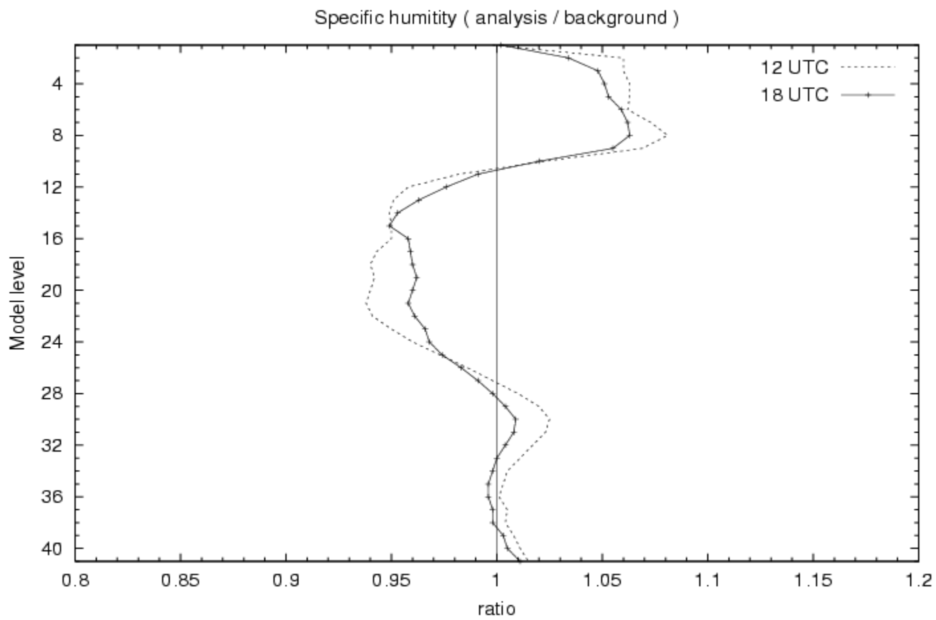


Figure 5.3 Vertical profile of the ratio between analysis and background error variances of specific humidity.

It is interesting to mention that the impact of the analysis at 12UTC on the temperature is globally positive, except in the lowest levels of PBL. However, at 18UTC, the analysis error variance is slightly larger than the background one, except in middle troposphere (figure 5.4). This slightly negative impact of the analysis can probably be explained by the small number of TEMP observations at 18UTC when compared with 12UTC.

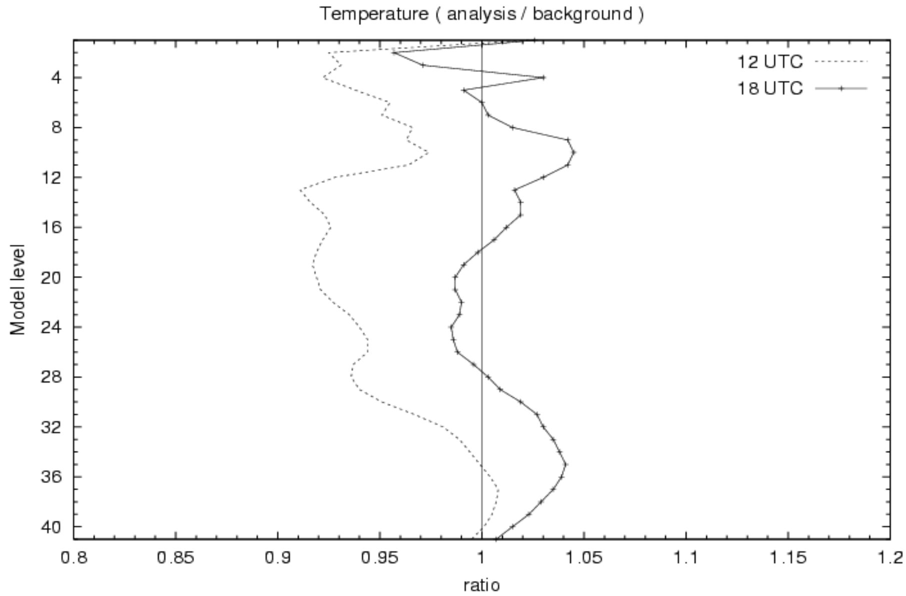


Figure 5.4 Vertical profile of the ratio between analysis and background variances of temperature.

6. Horizontal length scale of autocorrelation function in gridpoint space

The computation of the B matrix in spectral space can be very simplified if it assumed that the autocorrelation function is homogeneous and isotropic. The method described in section 3 to calculate the length scale of autocorrelation allows the relaxation of such assumptions and the computation of zonal and meridional length scales (L_x and L_y) in a relatively cheap way. This gives one the opportunity of studying the validity of such hypotheses.
The results show that the zonal length scale is larger in the tropics, mainly over the oceans, and that the autocorrelation function is sharper (smaller length scale) over data rich areas (for instance over Europe, see figure 6.1 for zonal wind). The meridional length scale is also larger over tropical regions. However, it is more homogeneous (less dependent on the geographical localization) than the zonal length scale (figure 6.2). This result is valid for all variables.

The horizontal autocorrelation function is said to be isotropic if its length scale is independent of direction, that is, if L_x is approximately equal to L_y. Figure 6.3 shows the vertical profile of the ratio between L_x and L_y of the zonal wind background error. It is clear from the figure that the zonal wind is more isotropic over sea in PBL, but more anisotropic over sea in the middle and upper troposphere. Moreover, the zonal length scale is larger than the meridional length scale in all troposphere, except near the surface, where the opposite is verified. This is consistent with the larger contribution of the rotational wind in the free atmosphere (Daley, 1985). It is also interesting to notice that the zonal wind is more anisotropic near the surface (over land) and near the tropopause (over sea).

The behaviour of the other meteorological variables is very different. For instance for the meridional wind, L_x is smaller than L_y and this difference is larger in middle troposphere and over land (figure 6.4). Moreover, in the area of Europe and North Atlantic (EURATL) the L_x is 30% smaller than L_y, so in such area, the assumption of isotropy is not reasonable.

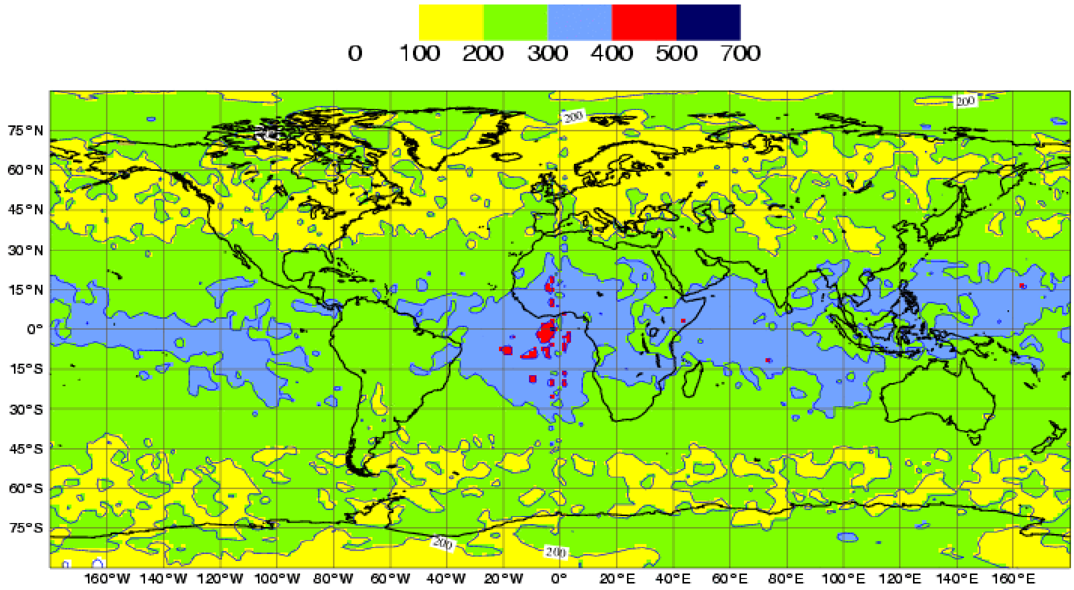


Figure 6.1 Zonal length scale of autocorrelation of zonal wind background error at level 21 (near 500hPa).

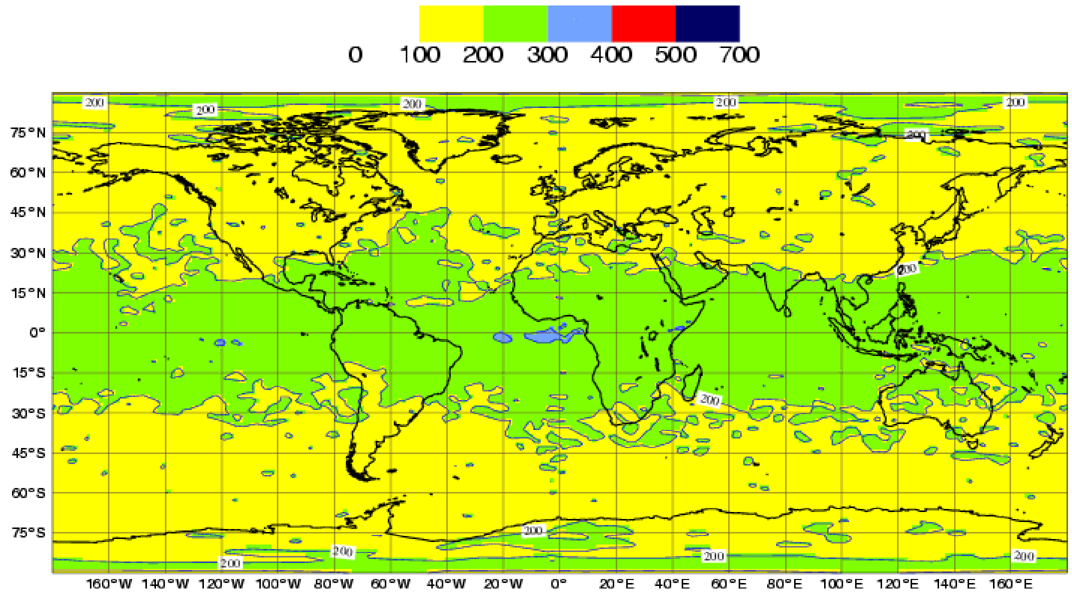


Figure 6.2 Meriodional length scale of autocorrelation of zonal wind background error at level 21.

The results also show that for the other variables L_x is smaller than L_y and the autocorrelation is more anisotropic over land than over sea, like for the meridinal wind. However, for the other variables it is found that the assumption of isotropy is less valid near the surface. The isotropy assumption is valid in the stratosphere, for all variables.

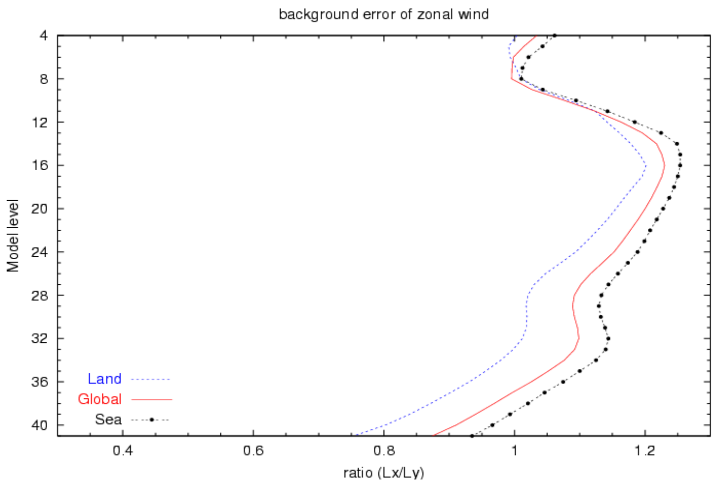


Figure 6.3 Vertical profile of the ratio between L_x and L_y of zonal wind background error over Land (dashed blue), over sea (black) and for the global average (solid red).

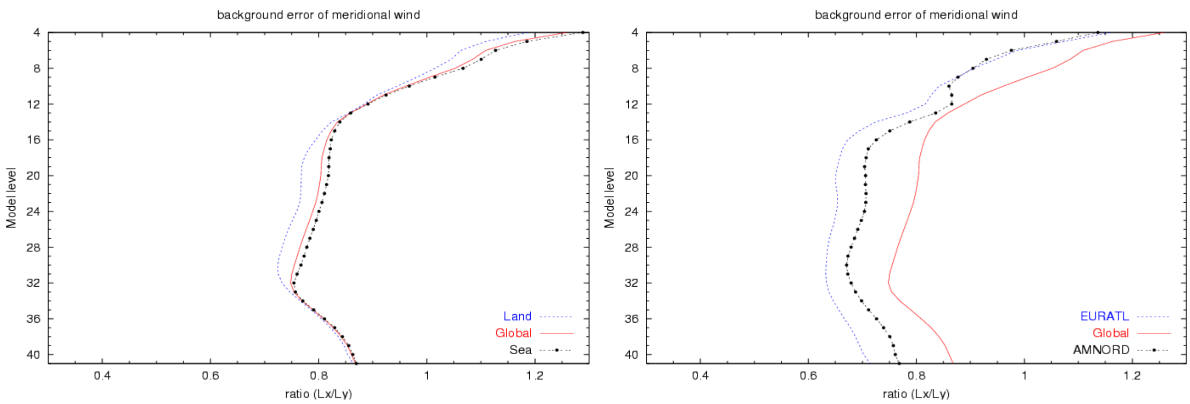


Figure 6.4 Vertical profile of the ratio between L_x and L_y of meridional wind background error over different regions.

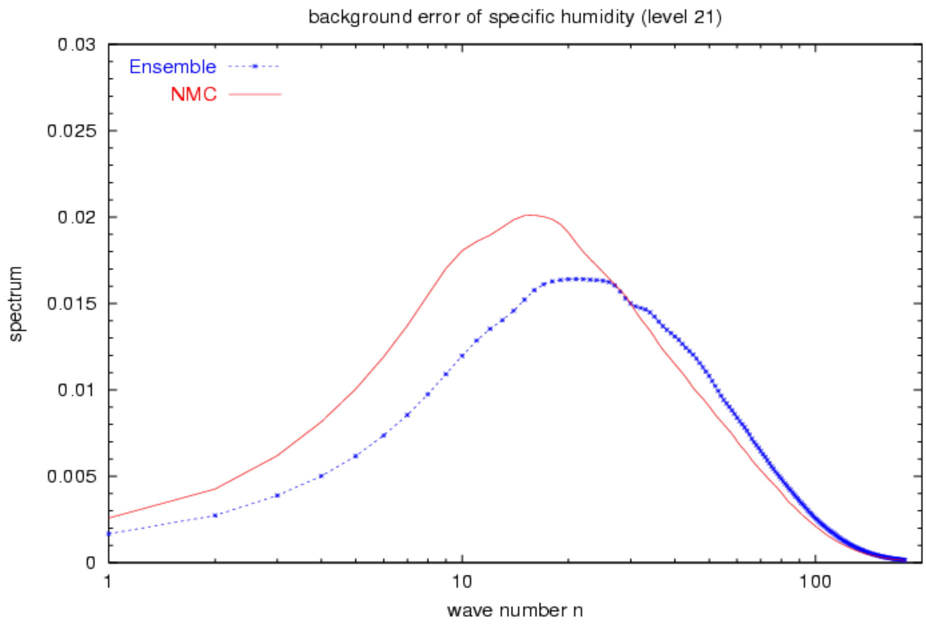
7. Ensemble versus NMC method in 4D-Var of unstretched ARPEGE

7.1 Horizontal and vertical Autocorrelation

Figure 7.1 shows the auto-correlation spectra of vorticity and specific humidity at level 21 (near 500hPa) estimated by the two methods. The results show that according to the NMC method the largest contribution for the background errors of specific humidity (q) in the middle troposphere comes from wavenumbers between 10 and 20. In the Ensemble method, the variance maximum is shifted towards the smaller scales. This means that the variance of q background error has a larger contribution from the mesoscale phenomena and smaller contribution from the large scales, when estimated by the Ensemble method than by the NMC method. This occurs also for temperature.

Both methods agree that the maximum variance of vorticity background errors is due to the mesoscale phenomena. However, the peak is shifted towards the smaller scales in Ensemble method. The autocorrelation spectrum of divergence is less sensitive to the method used.

It is also interesting to mention that according to the NMC method the larger contribution for the background error of surface pressure comes from the synoptic scales, while in the Ensemble method the contribution from the planetary scales seems to be as important as the one from the synoptic scales (figure not shown).



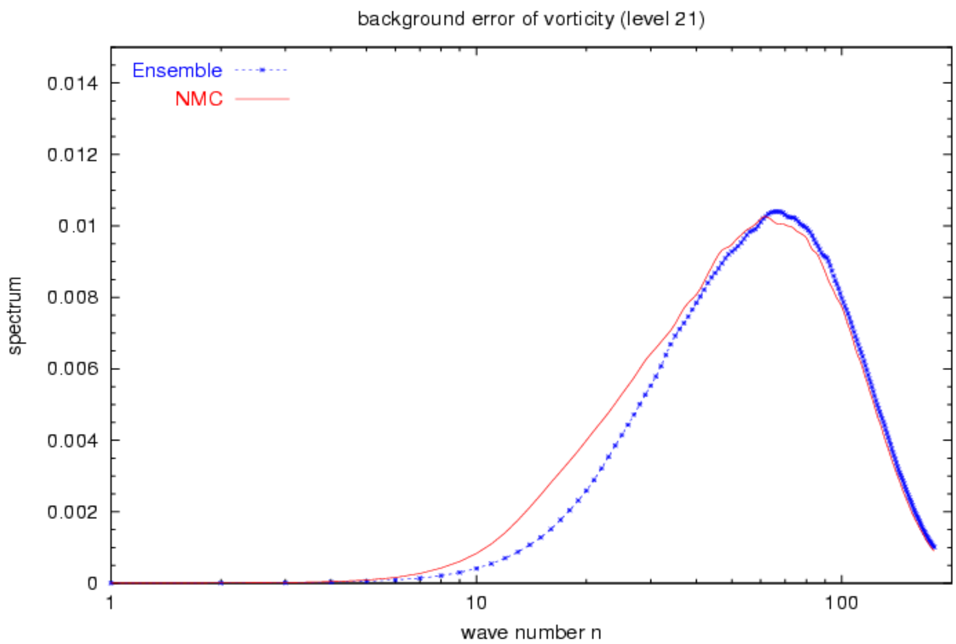


Figure 7.1 Auto-correlation spectra of vorticity (top) and specific humidity (bottom) at level 21 (near 500hPa) for NMC and Ensemble methods.

Figure 7.2 shows the horizontal length scale of auto-correlation function of temperature and vorticity estimated by the two methods. The results show that for both methods the length scale of vorticity is smaller than the one of temperature, as it would be expected. Moreover, it can be seen that according to the Ensemble method the horizontal length scale is smaller than when estimated by the NMC method. This difference is more notorious for temperature. On the contrary, the horizontal length scale of divergence is very similar in the two methods.

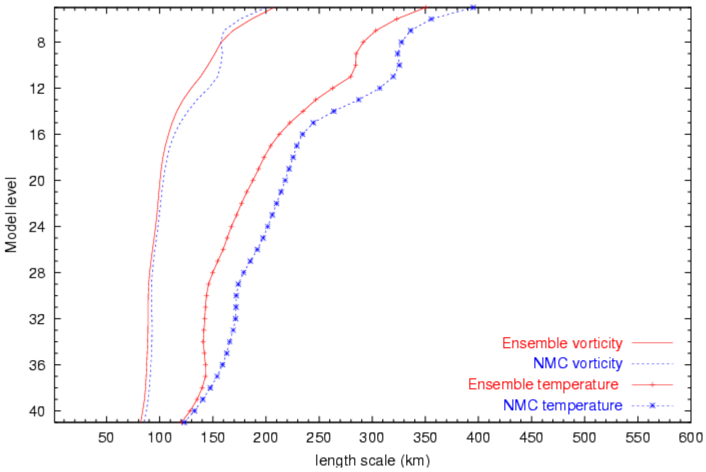


Figure 7.2 Horizontal length scale of auto-correlation function of temperature and vorticity estimated by NMC and Ensemble methods.

The mean vertical correlations and the north-south variation of the vertical correlations were both analyzed. The results show that the Ensemble method produces much sharper vertical correlations than the NMC method, mainly for the middle and high latitudes (see figure 7.3).

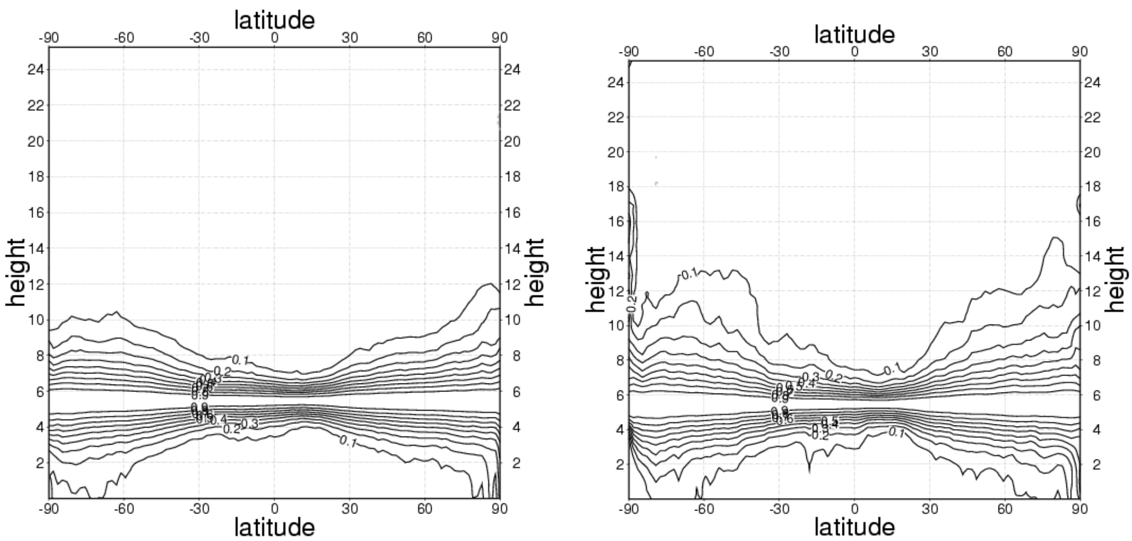


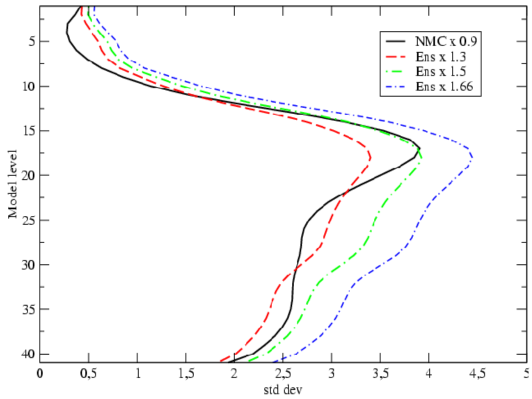
Figure 7.3 – North-South variation of vertical correlation (at level 21) of vorticity background error estimated by the Ensemble method (left side) and by the NMC method (right side).

7.2 Impact on forecasts

On operational 4D-Var assimilation system, the vertical profiles of total standard deviation of the background errors are rescaled by a factor of 0.9 in order to account for the mismatch between the magnitudes of the 12/36-hours forecast differences and the 6-hour forecast errors. In order to study the impact of the statistics from the Ensemble Method against the ones from NMC method, some tests were performed to find out the optimal factor to rescale the vertical profile of the standard deviation of the background errors. Figure 7.4 shows the vertical profile of the standard deviation of vorticity and temperature for the NMC method and for the Ensemble method, multiplied by different factors.

For both methods the largest errors of vorticity are located at the jet level. However, if the factor of 1.3 is used, the Ensemble method gives larger errors in the middle troposphere, but smaller error in the low troposphere than the NMC method. On the other hand, if the factor of 1.5 is used, the background errors of vorticity given by the Ensemble method are larger in all troposphere than the ones given by the NMC method.

Both methods agree that the largest errors of temperature are located in the top level. Nevertheless, the Ensemble method produces larger errors at this level than the NMC method. Moreover, according to the NMC method the second maximum of the temperature background error is located at all tropopause, while according to the Ensemble method the second maximum error occurs in middle troposphere.



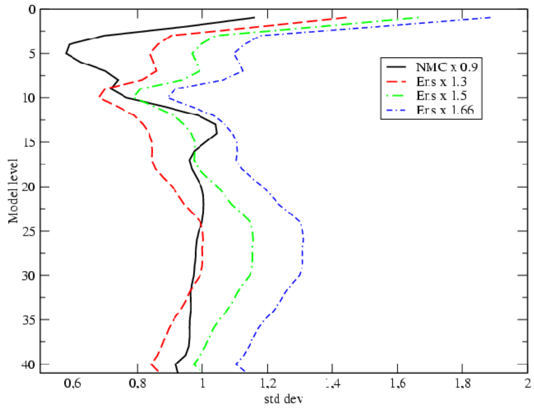


Figure 7.4 - Vertical profile of rescaled standard deviation of vorticity (left side) and temperature (right side) background error estimated by NMC and Ensemble methods.

The impact of the statistics derived from the Ensemble method against the ones from NMC method were tested for two different periods; from 5 of February to 4 of March of 2002 (here referred as first period, which includes the period from which the statistics were computed) and from 24 of October to 20 of November of 2002 (referred as second period). The results of the impact experiences reveled that the factor of 1.5 is the optimal value, since the scores were clearly better than when using factor of 1.3 and the differences between using factor of 1.5 or 1.66 were neutral.

The wind scores against ECMWF analysis are clearly positive over the regions of North America, Europe and North Atlantic, for forecast ranges larger than 24-hours. This positive impact is larger in the middle and upper troposphere and increases with the forecast range. In the tropics, the scores for wind are positive on stratosphere and on middle and upper troposphere, for all forecast ranges. On the other regions, the scores for wind are slightly positive or neutral. The positive impact is less impressive for the second period.

For both periods, the scores for geopotential are clearly positive on the stratosphere over the first day of forecast and on the troposphere for forecast ranges larger than 36-hours. For the first period, the scores of geopotential are strongly positive in the stratosphere in the North Hemisphere, for all forecast ranges. In the South Hemisphere and in the tropics the scores are positive on the high troposphere. However, for the second period, the scores for geopotential are negative in the South Hemisphere for all forecast ranges.

The temperature scores are slightly positive (for instance near the 10hPa) or neutral.

8. References

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In preparation:
The use of an Ensemble approach to study the Background Error Covariances in Global NWP model, Belo Pereira, M. and L. Berre