Impact of truncation on variable resolution forecasts

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ECMWF Technical Memorandum 614 (version 28 January 2010).

Words: 7920 (text without figure captions).

Figures: 17.

Key words: numerical weather prediction, variable resolution, ensemble prediction.

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Abstract

The ECMWF variable resolution ensemble prediction system (VAREPS) uses a higher resolution up to the truncation time and a lower resolution afterwards. For variables with a large variance on the small scales such as total precipitation, ensembles run at higher resolution have larger spread than ensembles run with lower resolution (and with the same initial perturbations). Thus, it is not surprising that the VAREPS spread is higher up to the truncation time and lower afterwards, but besides this effect, results indicate that up to 24 hours due to the truncation the VAREPS spread decreases too excessively, to a level below the one expected for the lower resolution ensemble. Although this excessive reduction does not have any effect on upper-level variables, it is detectable in the time evolution of the ensemble spread for variables such as total precipitation. This work discusses results from a series of investigations performed to identify the main cause of this too large reduction in the VAREPS spread.

Results indicate that the main reason of the too excessive spread reduction is the interpolation of the high-resolution fields to define the initial condition of the low-resolution integration. After the interpolation, the VAREPS members have too little variability on the small scales, and as a consequence the VAREPS spread component that projects onto the small-scales is reduced. Experiments run with a realistic or a flat orography show a very small sensitivity to orographic forcing. Experiments performed in aqua-planet mode show that after the truncation the more active convection can more quickly re-generate spread on the small-scales. Considering the operational VAREPS, it is concluded that the current configuration with a 24-hour overlap period should not be modified.

1 The variable resolution approach to weather prediction

A variable resolution approach, with a higher resolution up to a forecast time up to which the forecast benefits from resolving also the small scales and a lower resolution afterwards, has been used since the early 1990s in the National Centers for Environmental Prediction (NCEP, Washington) Ensemble Prediction System (EPS), and since 2006 in the European Centre for Medium-Range Weather Forecasts (ECMWF) operational EPS. A variable resolution approach helps optimizing the use of computer resources, but it poses the challenge of how best to change resolution throughout the forecast. When resolution changes, a new orography and land-sea mask is used, and high-resolution forecast fields are interpolated to the low resolution to define the initial conditions of the low-resolution leg of the forecast.

Generally speaking, given the same initial perturbations, an ensemble system with a higher resolution has a larger spread than an ensemble system with a lower resolution. The difference in ensemble spread is small for upper level fields that represent large-scale, synoptic features, but it is more evident for variables that are more sensitive to small-scale processes, e.g. total precipitation, which in a hydrostatic model is strongly dependent on horizontal convergence. This has, for example, some implications when ensemble resolution is increased: to maintain the same level of ensemble spread, the initial amplitude has to be decreased. In fact, in 2007, the initial amplitude of the ECMWF ensemble prediction system (EPS) was reduced by approximately 10% following the resolution increase from $T_L255L40$ (spectral triangular truncation T255 in the horizontal with Linear grid, and 40 vertical levels) to $T_L399L62$ (*Palmer et al* 2007). Thus, it is not surprising that in a variable resolution ensemble system the spread is, on average, higher up to the truncation time, and lowers afterwards.

Unfortunately, besides this expected effect of the resolution change, results have indicated that after the truncation time and for the next 12 to 24 hours, the spread decreases to a level that is lower than the level expected for a lower resolution ensemble. This too large spread decrease does not have any impact on the spread and skill of upper-level forecasts, but has a small impact on the ensemble spread of variables such as total precipitation although it has a negligible impact on their skill (see e.g. *Buizza et al* 2007). This report discusses in details this larger than expected decrease in ensemble spread that can be detected in the ECMWF VAREPS, in particular on atmospheric fields with a substantial amount of power in the small scales (e.g. vertical velocity or total precipitation, as opposed to geopotential height or upper-level temperature). This investigation helps to understand the key reason why discontinuities might appear in some forecast statistics such as the ensemble spread measured by the standard deviation, and assess whether the current variable resolution configuration used in the ECMWF operational EPS is (still) adequate.

As mentioned earlier, the first operational variable resolution ensemble prediction system was implemented in the NCEP EPS in the '90s (*Tracton & Kalnay* 1993, *Toth & Kalnay* 1997). *Szunyogh & Toth* (2002) provided evidence of the value of a variable resolution approach in the NCEP ensemble prediction system, and concluded (see their discussion in section 2) that the variable resolution approach was '… *based on the experience that increased horizontal resolution for the first few days of model integration has significant positive impact on forecast quality for the entire forecast range*'.

At ECMWF, a 15-day variable resolution ensemble prediction system (VAREPS, *Buizza et al* 2007) has been running since March 2006. At the time of writing, VAREPS includes 51 members run with a $T_L399L62$ resolution from day 0 to day 10 and a lower $T_L255L62$ resolution from day 10 to day 15. The Thursday's ensemble starting at 00 UTC is extended to 32 days to cover the monthly forecast range (*Vitart et al* 2008). The reader is referred to *Palmer et al* (2007) for a review of the most recent and on-going developments of the ECMWF ensemble prediction system. The resolution of the system has been increase to $T_L639L62$ resolution from day 0 to day 10 and to $T_L319L62$ from day 10 to day 15 on the 26^{th} of January 2010.

VAREPS was designed to resolve the smallest possible scales for as long as their inclusion has a positive impact on the prediction of both the small and the synoptic scales, and not to resolve them afterwards, when including them has only a negligible impact on the synoptic scales. *Buizza et al* (2007) compared results based on a preliminary version of VAREPS, with a $T_L399L40$ resolution up to day 7 and $T_L255L40$ from day 7 to day 14, with forecasts generated using a constant resolution $T_L319L40$ EPS (these two systems required a similar amount of computing resources). In the early forecast range, thanks to the use of a higher resolution, *Buizza et al* (2007) detected a clear advantage of VAREPS, especially in the prediction of mean-sea-level pressure in extreme weather conditions such as the ones associated with tropical storms, but beyond the day 7 truncation time they found only limited evidence that VAREPS was providing better upper-level forecasts of synoptic-scale features (e.g. the ones represented by the geopotential height at 500 hPa or the temperature at 850 hPa). Although they could not find that VAREPS was statistically significantly better than the constant-resolution system beyond the truncation limit, they concluded that overall it was performing better than a constant resolution T_L319 system with comparable cost. VAREPS became part of the ECMWF operational suite in September 2006.

As mentioned earlier, the key challenge of a variable resolution system is that truncation changes the characteristics of the grid used in the numerical integration (e.g. the spacing of the grid point fields changes, the orography and the land-sea mask) and the interpolation from the higher to the lower resolution induces some form of smoothing in the atmospheric fields, and these changes can have a detectable impact on some forecast statistics. Earlier experimentation (*Buizza et al* 2007) indicated that the truncation from T399 to T255 (hereafter, the subscript 'L' in T_L399 and T_L255 will be dropped), despite being performed with the interpolation software that is used routinely at ECMWF to generated low resolution analyses from the high resolution operational one, induces changes that can be clearly detected in model fields such as divergence. Although these changes have a negligible impact on upper-air fields that describe the large-scales (e.g. the 500 hPa geopotential height or the 850 hPa temperature), they can affect variables strongly linked with convergence/divergence, thus influence the vertical motions and derived variables such as total precipitation. To reduce the impact of truncation on the operational ECMWF VAREPS, it was decided to introduce a 24-hour overlap period, whereby the T255 forecast starts from a t+9d instead of a t+10d T399 forecast: this gives the T255 system a 24-hour period to re-generate small-scale features that have a strong influence on, e.g., divergence and total precipitation. Tests had shown that without the overlap period the ensemble spread measured in terms of precipitation decreased systematically at the truncation time, while the introduction of the overlap period reduced this impact of the truncation on the ensemble spread without changing significantly the upper-air fields.

More recently, the value of a variable resolution approach to numerical weather prediction was further discussed by *Buizza* (2010), who compared the performance of forecasts generated with a T399 spectral truncation up to forecast day 3 and a T255 truncation from day 3 to day 8 (VAR3), with forecasts generated with a constant T319 truncation. When forecasts were verified in an idealized scenario where a higher resolution, T799 forecast was used as verification instead of the analysis, results clearly showed that VAR3 forecasts outperform constant, T319 forecasts (beyond the day-3 truncation time) for the entire 8-day forecast range, with the differences statistically significant at the 5% level. When forecasts were verified in a realistic scenario against T799 analyses the advantage of VAR3 could still be detected beyond day 3, but it was less evident and not statistically significant. Thus, there is no doubt that a variable resolution approach has merit.

This work does not discuss the value of a variable resolution approach, but focuses on the effect of the truncation of the horizontal resolution on the ensemble characteristics. Detailed diagnostics based on different verification measures is applied to forecasts run in three different configurations: with a realistic orography, with a flat orography or in an aqua-planet mode. The goal of this investigation is to identify the main cause of the reduction in ensemble spread detectable in certain variables and to assess whether the current configuration of the ECMWF variable resolution EPS should be revised.

After this Introduction, Section 2 describes the experimental set-up and the verification measures used to assess the forecast performance. Sections 3 and 4 summarize the results obtained with a realistic orography, a flat orography and in an aqua-planet mode. Finally, some conclusions are drawn in section 5.

2 Experimental set-up and methodology

Four ensemble experiments have been run with an 8-day forecast length, two with constant and two with variable resolution (VAR), with truncation applied at forecast day 3. The choice of an 8-

day forecast length and a day-3 truncation has been made to contain the cost of the experimentation to a reasonable level. The advantage of applying the truncation at day 3 is that, at this earlier forecast range, the forecast error for variables such as precipitation has not yet saturated, and thus the impact on forecast characteristics (spread and skill) is more evident. The two VAR experiments are VAR3, run without overlap, and VAR3-OV-24HD, run with a 24-hour overlap period and increased horizontal diffusion starting from 24 hours before the truncation time. As it is done routinely in the operational EPS (see *Buizza et al* 2007), horizontal diffusion has been increased to smooth the transition. Figure 1 is a schematic of the two VAREPS configurations.

The four ensemble experiments have been run in three different configurations:

- ***oro***: with a realistic orography and land-sea mask (LSM) and observed sea-surface-temperature (SST);
- ***flat***: with a flat orography, realistic LSM and observed SST;
- ***aqua***: in aqua-planet mode with sea everywhere and with a constant SST set to 303ºK.

Table 1 lists the key characteristics of the 5-member ensemble experiments run in the three configurations for one month (January 2008, with the ECMWF model cycle 33r2).

It is worth reminding the reader that ECMWF uses a spectral model with the tendencies due to the parameterized physical processes (e.g. moist processes, radiation, turbulence, ..) computed in the physical space on a reduced Gaussian grid. Every time-step, the dry part of the atmosphere state vector (surface pressure, temperature and the wind components; specific humidity is kept in grid-point space) is transformed from spectral to the grid-point space, the advection tendencies and the tendencies due to the parameterized physical processes are computed and added to the grid-point state field and then the state field is transformed back to spectral space. Total precipitation, one of the derived variables, is one of the grid-point fields that are available only on the reduced Gaussian grid.

To quantify the impact of truncation on the ensemble forecast characteristics, single forecasts have been verified in terms of average root-mean-square-error (RMSE), the ensemble spread has been measured in terms of the average standard deviation (STD), and probabilistic forecasts have been assessed using the average ranked probability skill score (RPSS), the Brier score and skill score (BS, BSS, see *Brier* 1950) and the area under the relative operating characteristics (ROCA, see e.g. *Wilks* 1995). Since the impact of truncation is almost negligible on upper-level fields that represents the large-scale flow, most of the discussion has been focused on 12-hour accumulated total precipitation (TP12) over the Northern Hemisphere (NH, which includes points with latitude north of 20ºN) and the tropics (the tropical band that includes all points with latitude between 20ºS and 20ºN). Forecasts have been verified on a regular latitude-longitude grid with a 2.5º spacing (the verification grid); forecast fields have been generated on the verification grid using bi-linear interpolation.

To understand the contribution of different spatial scales, TP12 fields have been verified either simply after an interpolation from the reduced Gaussian grid to the verification grid, and also after applying a T63 filter that eliminates all scales with a total wave number greater than 63 (Martin Leutbecher is acknowledged for suggesting applying this filter). This filter consists of (a) a grid-point-to-spectral transformation from the reduced Gaussian grid to the T399 spectral space,

(b) a spectral filter that sets to zero all spectral components with total wave number greater than T63, and (c) a spectral-to-grid-point transformation of the filtered field to the verification grid.

3 Impact of truncation on VAREPS forecasts run with real orography, flat orography and in aqua-planet

Before discussing in detail the impact of the VAREPS truncation on total precipitation forecasts, it is worth analysing its impact on the upper-level fields that represent the large-scale synoptic flow, such as the 500 hPa geopotential height (Z500) and the 850 hPa temperature (T850). Figure 2 shows the 30-case (1 to 30 January 2008) average RMSE of the ensemble-mean forecast and the ensemble spread (STD) of the four ensemble configurations run with real orography, for Z500 over NH and T850 over the tropics. For Z500 over NH (Fig. 2a), the spread of the four ensembles is very similar, and there is no indication of any impact of the day-3 truncation. For the RMSE of the ensemble-mean, the T255 configuration has the largest error and the T399 the smallest error, with the VAR3 ensemble-mean having the same average RMSE as the T399 ensemble. Similar conclusions can be drawn for T850 over NH. Results are different for T850 over the tropics (Fig. 2b), because the spread of the T255 ensemble is larger than the spread of the T399 ensemble, and as a consequence the spread of the VAR3 ensembles is equal to the spread of the T399 ensemble up to day 3 and then gradually asymptote towards the level of the T255 ensemble. Apart from this, there is no indication of any impact of the truncation on the ensemble spread. Considering the RMSE of the ensemble-mean, the T255 configuration has the largest and the T399 the smallest error, with the VAR3 ensemble-mean having the same average RMSE as the T399 ensemble-mean up to day 3 and then gradually increasing to the level of the T255 ensemble. In conclusion, these results show that truncation has a very small impact on VAREPS forecasts of upper level fields that represent synoptic scales, and that running with an overlap period and an increased horizontal diffusion on the small scales has a negligible impact.

In the next sub-sections attention will be focused on total precipitation, and the impact of truncation on VAREPS forecasts run with real orography, flat orography and in aqua-planet mode will be discussed.

3.1 Impact of truncation on forecasts run with real orography

Figure 3 shows the 10-case (1 to 10 January 2008) average error of TP12 ensemble perturbed forecasts and the average ensemble spread (measured by the standard deviation) of all four configurations, computed over NH and the tropics. The first conclusion that can be drawn from this figure is that both the error and the spread of the T255 EPS are lower than the ones of the T399 EPS. Secondly, note that the error and the spread of the VAR3-OV-24HD and VAR3 ensembles are very similar for all forecast steps apart from step t+84h, the first time-step after the truncation. Differences are more evident over the tropics than over the NH, and in terms of ensemble spread rather than average error. Consider for example the spread over the tropics: the VAR3 spread decreases to values below the T255 level at t+84h (Fig. 3d), while the transition from the T399 to the T255 levels of the VAR3-OV-24HD EPS is smoother. Note also that the ensemble spread increases faster during the first 12 hours over NH and the first 24 hours over the tropics that later on due to the combined effect of the growth of the EPS initial perturbations and of stochastic physics.

Figure 4 shows the average error of the perturbed members and the spread of the same four ensembles after they have been filtered to retain only scales with total wave number up to 63. Overall, the filter reduces both the spread and the average error of the perturbed members, since the grid point variability of each single field is reduced. As a consequence, there is no indication of the impact of truncation and of using the overlap period on the average error, but there is a small signal in the ensemble spread.

To understand the effect of the truncation and of the spectral filter, the average spectra of the squared 12-hour accumulated total precipitation ($TP12^2$) ensemble perturbed forecasts and of the squared TP12 ensemble spread (ensemble variance, STD^2) of the four ensemble configurations have been computed in terms of total wave number. Figure 5 shows that the higher resolution forecasts have a higher power spectra for wave numbers beyond about 65. A closer analysis shows that during the first 72 hours there is very little difference between the spectra of the VAR3-OV-24HD, VAR3 and T399 ensembles, while the T255 spectra has lower values, especially for total wave numbers larger than about 65. After t+72h, the T399 spectra maintains higher values for total wave numbers larger than about 65, while there is very little difference between the power spectra of the VAR3-OV-24HD and VAR3 ensembles and the T255 ensemble.

A similar impact of truncation can be seen in the ensemble variance (STD^2) of the TP12 forecast (not shown). During the first 72 hours, there is very little difference between the spectra of the VAR3-OV-24HD, VAR3 and the T399 ensembles, while the T255 spread has lower values especially for total wave numbers larger than ~65. After t+72h, the T399 spread remains higher while there is a very little difference between the spectra of the VAR3-OV-24HD, VAR3 and the T255 ensembles.

Consider now the differences between the ensemble variance of successive forecasts (Fig. 6). During the first 72 hours, there are very little differences between successive variance fields. The impact of the VAREPS truncation can be clearly seen in the difference between the variances at t+96h and at t+72h: for the VAR3-OV-24HD and the VAR3 ensembles, the t+96h variance is smaller than the variance at t+72h (i.e. negative difference) for total wave numbers larger than about 65. This is due to the reduction of the forecast variance after the truncation. The difference remains negative for large wave numbers also for the subsequent 24 hours, but becomes positive for all wave numbers afterwards. Note also that during the first 72 hours (i.e. before the truncation), there is no difference between the spectra of the VAR3-OV-24HD, VAR3 and T399 ensembles, while after t+120h there is very little difference between the spectra of the VAR3-OV-24HD, VAR3 and the T255 ensemble.

Thus, the VAREPS truncation has the effect of reducing the ensemble variance for all waves with total wave number larger than about 65, and explains why the impact of truncation is very small if fields are filtered at T63 (not shown). It would be interesting to investigate whether, if VAREPS were run with different resolutions (e.g. at higher, T639/T319, or lower, T255/T159, resolution instead of T399/T255), a different filter would deliver the same results: one would expect that, as resolution increases, the waves that are well resolved by both VAREPS resolutions should increase, and thus a higher T639/T319 VAREPS would require that fields are filtered at a higher resolution (Nils Wedi, personal communication, 2009). So far no experiments have been performed to investigate this point.

At the beginning of Section 3 we discussed the fact that the truncation has no impact on VAREPS forecasts of upper level variables that describe the large-scale, synoptic features. To understand the different response to truncation of these upper level fields and fields such as TP12, it is interesting to analyze the spectra of T850, a variable for which there is no evidence of the impact of truncation on the ensemble spread, and of the vertical velocity at 850 hPa (W850), a variable that depends on horizontal divergence and that strongly influences total precipitation.

Figures 7-9 show the spectra for T850, and Figs. 10-12 show the corresponding fields for the W850. The T850 ensemble forecasts (Fig. 7) have very low power in the small scales, while the W850 ensemble forecasts (Fig. 10) have a whiter spectrum, similar to the TP12 spectra (Fig. 5). Similarly, the spread measured in terms of T850 (Fig. 8) peaks at around total wave number 10, with a small component coming from the small scales. By contrast, the spread measured in terms of W850 (Fig. 11) peaks between total wave numbers 40 and 100, with a large contribution coming from the small scales, similar to the spread spectrum measured in terms of TP12. Correspondingly, there is no indication of any impact of truncation on the spread of the VAREPS ensembles measured in terms of T850 (Fig. 9), while there is a large impact on the spread of the VAREPS ensembles measured in terms of W850 (Fig. 12), similar to the impact detected on the spread measured in terms of TP12 (Fig. 6). The comparison of the T850, W850 and TP12 spectra indicate that the impact of the VAREPS truncation is larger, and can even affect the forecast error, for variables such as TP12 and W850 with large spectral amplitude in the small scales.

3.2 Impact of truncation on forecasts run with flat orography and those run in aqua-planet mode

One of the points raised in the introduction was that the impact of truncation on VAREPS forecasts might be influenced by the orography and by convection. This section discusses results obtained with a flat orography and in aqua-planet mode to assess whether the orography amplifies the effect of truncation or not and whether convection, which is more active in the aqua planet mode since the whole globe is covered by a sea with a 303ºK temperature, also amplifies the impact. Since the effect of truncation in the real orography experiments was more evident on the TP12 ensemble spread, attention here will focus on this diagnostic only.

Figure 13 shows the ensemble spread of the T399, T255, VAR3-OV-24HD and VAR3 ensembles computed for TP12 over the NH and the tropics (the top panels are the same as the right-hand panels of Fig. 3, which have been repeated here for ease of comparison) of the experiments run in the three configurations (oro, flat and aqua). Results show that running with a real or a flat orography has a very small impact on the spread. By contrast, the aqua-planet results are rather different. Firstly, the spread over NH of the aqua-planet ensembles changes dramatically. This is due to the fact that in the aqua-planet ensembles the NH is covered entirely by a warm sea. Secondly, the difference between the two VAREPS configurations is reduced, indicating that in the aqua-planet configuration the impact of using an overlap period is smaller. Over the tropics, for example (a region where the oro, flat and aqua configurations have a similar level of spread), during the 12 hours after the truncation the spread of the VAR3 and the VAR3-OV-24HD ensembles are very similar in the aqua ensembles. By contrast, the spread of the VAR3 ensembles is smaller than the spread of the VAR3-OV-24HD ensembles in the oro and flat configurations. These results are confirmed by the comparison of the difference between the spectra of the ensemble variance of TP12 at t+96h and t+72h. In all three configurations the truncation reduces the spread (STD) for total wave numbers larger than ~65 causing an overall reduction of the ensemble spread. The differences between the real/oro and the aqua-planet results can be attributed to the very different nature of the aqua integrations, which are characterized by more active and widespread convection that increases substantially the ensemble spread over NH. This indicates that convection, if anything, can reduce the VAREPS response to truncation.

These results leave the interpolation of the T399 fields to the T255 resolution as the possible main cause of the reduction in spread below the expected level of the T255 ensemble after the truncation. This issue will be discussed in the next section.

4 Impact of truncation on idealized grid-point fields

Firstly, let us summarize the key results discussed in the previous sections. Then, results from idealized ensembles, designed to help us understanding the role of interpolation, will be discussed.

4.1 Summary of the impact of truncation of TP12 spread (STD)

Figure 14 shows the impact of truncation on the TP12 ensemble spread (measured by the STD) for the ensembles run with real orography, with an estimate of the STD of the VAREPS ensembles at the truncation time for the VAR3 ensemble, and at truncation time and the next 24 hours for the VAR3-OV-24HD ensemble. These estimates have been computed assuming that the rate of change in the TP12 STD after the truncation was the same as in the T255 ensemble. Considering, for example, the VAR3 ensemble, its STD at t+72h (i.e. 0.30) has been estimated by decreasing the VAR3 t+84h STD (i.e. 0.311) by 4.5% (i.e. 0.013), which is the average relative change in the T255 STD between t+72h and t+96h. Similar estimates have been computed for VAR3-OV-24HD between t+48h (time when the T255 forecast started) and t+84h.

The following observations can be made from Fig. 14:

- *Constant resolution, T399 (red line) and T255 (blue line) ensembles* - The STD of the T255 ensemble is smaller than the STD of the T399 ensemble (about ~20% smaller at t+72h). For both ensembles, the STD grows more rapidly during the first 72 hours than later on. The STD increases very fast during the first 48 hours, due to a combination of the growth on the ensemble initial perturbations, the stochastic perturbations of the parameterized physical tendencies and adjustment processes that occur during the early forecast range. The STD grows very fast during the first 24 hours, between t+48h and t+72h the STD increases by ~ 10%, while afterwards it increases by ~5% or less.
- *VAR3 ensemble (black line)* - Up to t+72h the STD is the same as the T399 STD, while after t+96h it is very similar to the T255 STD. The t+72h truncation reduces the ensemble STD by ~18% (from 0.36 to 0.30, first black full circle). Between t+72h and t+84h, the STD grows more rapidly than in the T255 ensemble. This is mainly due to adjustment processes: the VAR3 T255-leg of the forecast is still in the early forecast range (0 to +12 hours), while the T255 ensemble is in a later forecast range (+72 to +84h), a range during which the TP12 STD grows faster (see the discussion in the first bullet).
- *VAR3-OV-24HD ensemble (green line)* - As for the VAR3 ensemble, up to t+72h the STD is the same as the T399 STD, while already at t+84h the STD is very similar to the STD of the T255 ensemble. This ensemble used a 24h overlap period, which means that the T255 part of each VAREPS integration started at t+48h. The t+48h truncation reduces

the STD by ~18% (from 0.33 to 0.275, first green full circle), which afterwards increases at a rate similar to the T255 ensemble. Between t+48h and t+84h, the VAR3-OV-24HD and the T255 STDs grow at a similar rate because the forecasts of both ensembles are in a forecast range (0 to +36 for VAR3-OV-24HD and +48 to +84h for T255) during which the TP12 STD grows faster.

4.2 An idealized experiment: impact of truncation on 2-dimensional fields

In this section, the question whether an interpolation from a high- to a low-resolution grid can cause the too excessive spread reduction, detected in the VAREPS ensembles, is discussed using idealized ensembles. More specifically, to understand the impact of truncation on 2-dimensional fields, first the interpolation impact on an idealized 2-dimensional field that represents precipitation is assessed, and then the interpolation impact on a 4-member ensemble defined by idealized fields is discussed.

Figure 15 shows three grids: the finest resolution grid (left panel) represents the high-resolution (T399) part of a VAR3 forecast, the intermediate grid (middle panel, blue) represents the low-resolution (T255) part of a VAR3 forecast, and the coarsest resolution grid (right panel, yellow) represents the regular latitude-longitude grid used to assess the characteristics of the ensemble forecasts. In the variable-resolution forecasting system, at truncation time a forecast available on the finest grid is interpolated on the intermediate grid.

The idealized TP12 fields have been defined on the high-resolution grid as follows. The grid point value x (on the high-resolution grid) of each individual field has been independently drawn from a gamma distribution $x \sim \Gamma(k,\theta)$ with shape parameter $k=1$; i.e., the probability density function of the (positive) random variable *x* has been defined by:

$$f(x;k=1,\theta)=\frac{e^{-x/\theta}}{\theta}$$

where θ is the scale parameter.

4.2.1 Impact of interpolation on one idealized 2-dimensional field

Figure 15 shows a single forecast defined on the finest resolution grid at the truncation time, and its linearly interpolated values on the two lower resolution grids: each value on the intermediate grid has been defined by averaging over the values defined at the middle grid point and its 8 closest neighbours, while each value on the lowest resolution grid is computed by averaging the values defined at the 4 closest intermediate grid points (please note that the values shown in Fig. 15 have been rounded to the nearest integer).

To measure the impact of interpolation from the original, high-resolution grid to the intermediate-resolution grid (a process that takes place at the VAREPS truncation time) the standard deviation of a 4-member ensemble of fields defined on the high-resolution grid has been compared to the standard deviation of the fields interpolated on the intermediate-grid for three different cases. The four high-resolution fields x_j have been defined on a high-resolution grid with 630 points by sampling the grid point values from the gamma distribution $x_j \sim \Gamma(k=1,\theta=5)$. Their corresponding interpolated equivalents have been defined on the corresponding 70 points of the intermediate-resolution grid. For all three cases, the STD of the interpolated fields has been between 40 to 60% smaller (not shown). The level of spread reduction depends on the spatial auto-correlation of the fields: with our choice of independently sampled values the impact is largest, larger than in the real case discussed above, due to the fact that precipitation fields have some level of spatial correlation. These idealized experiments, based on a linear interpolation method that is not exactly the same as the one used in the ECMWF model, provide a clear illustration of the fact that interpolation from a finer to a coarser resolution is smoothing even scales that are resolved by the coarse grid and is thus reducing the spread. Overall, they confirm our conjecture that interpolation reduces substantially the spread of the idealized ensemble.

4.2.2 Impact of interpolation on the ensemble spread of an idealized ensemble

Now consider the following 4-member idealized ensembles defined for 5 time steps using random samples from Gamma distributions (as discussed above) designed to represent the high-resolution (T399) ensemble, the low-resolution (T255) ensemble, and the variable-resolution (VAR3) ensemble:

- *HR-IEPS, the high-resolution (HR) idealized ensemble prediction system (IEPS):* for t=1, 2, .., 5 each member is defined on the 630 grid points of the high-resolution grid by $h_j(t+1) = h_j(t) + y_j$ with $y_j \sim \Gamma(1,1)$;
- *LR-IEPS, the low-resolution idealized EPS:* for t=1, 2, .., 5 each member is defined on the 70 grid points of the intermediate-resolution grid by $l_j(t+1) = l_j(t) + y_j$ with $y_j \sim \Gamma(1,1)$;
- *VAR-IEPS, the variable-resolution idealized EPS*:
  - for t=1,2 each member is defined on the 630 grid points of the high-resolution grid by $v_j(t+1) = v_j(t) + y_j$ with $y_j \sim \Gamma(1,1)$;

- t=3: since at t=2 each member is interpolated on the 70 intermediate-resolution grid, the t=3 values are defined by t=3 by $v_j(3) = \langle v_j(2) \rangle + y_j$, where $\langle v_j(2) \rangle = \frac{1}{9} \sum_{k=1,9} v_k(2)$ and $y_j \sim \Gamma(1,1)$;
- for t=4,5 each member is defined on the 70 grid points of the intermediate-resolution grid by $v_j(t+1) = v_j(t) + y_j$ with $y_j \sim \Gamma(1,1)$;

Note that it has been assumed that at each time step the new contribution $y_j \sim \Gamma(1,1)$ is sampled from the same distribution (i.e. the new contribution is independent of the resolution). This is equivalent to assuming that the amount of precipitation generated during consecutive steps is not sensitive to model resolution and the model climate is not sensitive to the time step (i.e. there is no spin-up or spin-down during the first time steps).

Figure 16 shows the spread of the three idealized ensembles for two (randomly chosen) steps. The spread has been measured by the STD of the 4-member ensembles on the low-resolution grid that represents the regular, 2.5 º latitude-longitude grid used in the verification of the real ensembles.

The spread of the HR- and the LR-IEPS are not identical but have a similar growth rate with time because, by construction, the new contribution $y_j(t)$ at each time step has been sampled from the same distribution. Consider now the VAR-IEPS: at t=1 and t=2 the STD of the VAR-IEPS system is equal to the STD of the HR-IEPS. At t=2, the VAR-IEPS fields are interpolated on the intermediate-resolution grid: this induces a reduction of the ensemble STD, as can be seen by comparing the STD of the HR-IEPS with the red circles, which show the STD of the interpolated fields $\langle v_j(2) \rangle = \frac{1}{9}\sum_{k=1,9} v_k(2)$. At t=3, the VAR-IEPS STD is lower than at t=2, still suffering from the spread reduction due to the interpolation.

These idealized results confirm that it is the interpolation of the high-resolution fields that causes the reduction in ensemble spread below the expected level of the T255 ensemble for fields such as total precipitation. After the interpolation, the VAREPS members have a smaller variability on the small scales, and as a result the VAREPS STD component that projects onto the small-scales (say with total wave number larger than 65) is very small. This is illustrated in Fig. 17, which is a schematic of the impact on the ensemble STD of removing the small-scale variability at the truncation time.

5 Conclusions

Since March 2006, ECMWF has been running a variable-resolution ensemble prediction system (VAREPS was actually run in experimental mode from March to September 2006, and in operation since then). At the time of writing, VAREPS includes 51 members run with a T399L62 resolution from day 0 to day 10 and a lower T255L62 resolution from day 10 to day 15, with the ensemble starting at 00 UTC on each Thursday extended to 32 days to cover the monthly forecast range (*Vitart et al* 2008). At the end of January 2010, when the resolution on the ECMWF analysis and single high-resolution increase from T_L799L91 to T_L1279L91, the EPS resolution will be increased from T_L399/T_L255L62 to T_L639/T_L319L62.

VAREPS is designed to resolve the smallest possible scales for as long as their inclusion has a positive impact on the prediction of both the small and the synoptic scales, and not to resolve them afterwards, when including them has only a negligible impact on the synoptic scales. Results published in the literature have concluded that VAREPS performs better than a constant resolution system with comparable cost, but it poses the challenge of changing resolution during the forecast.

When resolution changes, a new orography and land-sea mask is used, and at the truncation time a high-resolution forecast from the first leg is interpolated on the low-resolution grid to define the initial conditions of the second, low-resolution leg. Results have shown that the interpolation has a negligible impact on upper-air fields that represent the large-scale flow (e.g. the 500 hPa geopotential height, of the 850hPa temperature), but it induces changes that can be detected in forecast variables strongly linked to divergence and vertical motion, such as total precipitation. For these fields, the ensemble spread after the truncation and for the next 12 to 24 hours showed unexpectedly large reductions, below the level for a T255 ensemble. To reduce the impact of truncation on these fields, the operational VAREPS has been running with a 24-hour overlap period. Without the overlap period, the ensemble spread measured in terms of precipitation decreased systematically at the truncation time. The introduction of the overlap period reduced the impact of truncation on the ensemble spread without changing substantially the upper-air fields.

This work discussed in details the effect of the truncation on VAREPS forecasts performed in three different configurations, with a realistic orography, with a flat orography and in an aqua-planet mode. The aim of this work was to identify the main cause of the excessive reduction in ensemble spread detectable in variables such as total precipitation and therefore to assess whether the current configuration of the ECMWF variable resolution EPS should be revised.

The comparison of ensembles run with real or flat orogarphy has shown that the change in the orography is not one of the main causes of the unexpectedly reduction in ensemble spread. The comparison of the ensembles run with realistic land-sea distribution and in aqua-planet mode has shown that convection can actually help to re-generate ensemble spread on the small scales more quickly. This is clearly evident over the NH, where the ensembles run in aqua-planet mode had twice as large spread as the ensembles run with realistic land-sea distribution. The differences between the real/flat and the aqua-planet experiments can be attributed to the very different nature of the aqua-planet integrations, which are characterized by more active and diffused convection.

Generally speaking, the impact of truncation in the three configurations (real and flat orography, and aqua-planet) is qualitatively very similar, with truncation reducing the ensemble spread below the T255 level especially over the tropics. In all three configurations, the truncation reduces the spread (STD) for total wave numbers larger than ~65, and this causes an overall reduction of the ensemble spread.

Having ruled out changes in the orography and convection, the interpolation of the T399 fields to the T255 resolution remained as the possible cause of the reduction in spread. To investigate the impact of interpolation on 2-dimensional fields characterized by a large power on the small scales, 4-member idealized ensembles have been generated to represent constant high- and low-resolution ensembles, and a variable resolution ensemble. The total precipitation fields of these idealized ensembles have been generated by sampling gamma distributions. Results from these idealized ensembles have indicated that, indeed, it is the VAREPS interpolation of the high-resolution fields on the intermediate-resolution grid that causes the too large reduction in the ensemble spread of variables such as total precipitation. After the interpolation, the VAREPS members have much less variability on the small scales, and as a result the VAREPS STD component that projects onto the small-scales (say with total wave number larger than 65) is very small. Figure 17 is a schematic of the impact on the ensemble STD of removing the small-scale variability at the truncation time.

Having identified the main cause of the too large spread reduction after truncation, it is interesting to discuss three possible options to further reduce the impact of truncation in variable resolution ensembles. The first two requires changes in the way the VAREPS integrations are performed, while the third way requires changes in the post-processing of VAREPS forecasts.

a) Use the same grid to compute the tendencies due to physical processes in the two VAREPS legs

The same physical grid is used in the high- and low-resolution spectral integrations to compute the effect of physical processes on the state vector, does not seem feasible. Suppose that both the T399 and the T255 integrations could use the *low-resolution physical grid* (the reduced Gaussian grid that corresponds to the T255 spectral truncation): this would make the T399 integrations less accurate since the model will not benefit from having a higher resolution orography, and having the tendencies due to the physical processes computed on the higher-resolution Gaussian grid that corresponds to the T399 spectral truncation. Vice versa, suppose that both the T399 and the T255 integrations could use the *high-resolution physical grid* (the reduced Gaussian grid that corresponds to the T399 spectral truncation). It is not clear whether this will remove the problem, but it will definitely make the T255 more expensive (the physical processes are responsible for about 65% of the CPU cost), thus reducing the benefit of using a variable resolution approach.

b) Change the horizontal diffusion used in the high- and low-resolution legs of VAREPS

The reduction of the small-scale variance after the interpolation could be compensated by changes in the formulation of horizontal diffusion (Nils Wedi, personal communication, 2009), designed to achieve more similar treatment of all scales up to a chosen wave number (e.g. 255) in both legs. For example, it could be interesting to test whether using the spectral viscosity approach proposed by *Gelb & Gleeson* (2001) would resolve the problem of the excessive spread reduction after the truncation.

c) Filter the forecast fields

The effect of interpolation on the VAREPS ensemble spread could be reduced if a more accurate interpolation process that includes some filtering is applied to the forecast fields. Results discussed in this work have indicated that if fields such as total precipitation are filtered to T63 before computing the ensemble spread, the impact of truncation is negligible. This is due to the fact that filtering removes the small-scale variability of the individual members, and this has the overall effect of reducing the impact of truncation. If this approach is used routinely, the VAREPS ensemble could be run without an overlap period, since results have shown that using a 24-hour overlap period has a negligible impact on the ensemble scores. The negative implication of this approach is that all the small-scale information contained in the waves with total wave number above 63 would be removed, including skilful small-scale features. This would raise the question of the value of running the forecasts at a T399 and T255 resolution.

Option (a) is not possible yet, but would be interesting to test. Option (b) could be tested with small modifications of the VAREPS system. Option (c) does not appear to make sense. Overall, this work indicates that the current approach with a 24-hour overlap period that relies on the numerical model to re-generate the small-scale variability removed by the truncation provides probably the best approach and should be maintained.

Acknowledgements

Nils Wedi is thanked for his help in setting up the possibility to run ensemble experiments with a flat orography and in aqua-planet mode. Martin Leutbecher, Mariano Hortal and Agathe Untch are thanked for the time they devoted to discussing some of the issues investigated in this work. Peter Bechtold, Elias Holm, Erland Källen, Martin Leutbecher, Nils Wedi and Agathe Untch are thanked for their valuable comments to an earlier version of this work.

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	Truncation	**Overlap**	**Increased horizontal diffusion**	**Configuration (orography, land-sea mask and SST)**
T399	No	No	No	real/flat/aqua
T255	No	No	No	real/flat/aqua
VAR3-OV-24HD	Yes (day-3)	Yes (24 hour)	Yes (24 hour)	real/flat/aqua
VAR3	Yes (day 3)	No	No	real/flat/aqua

Table 1. Experiments' list.

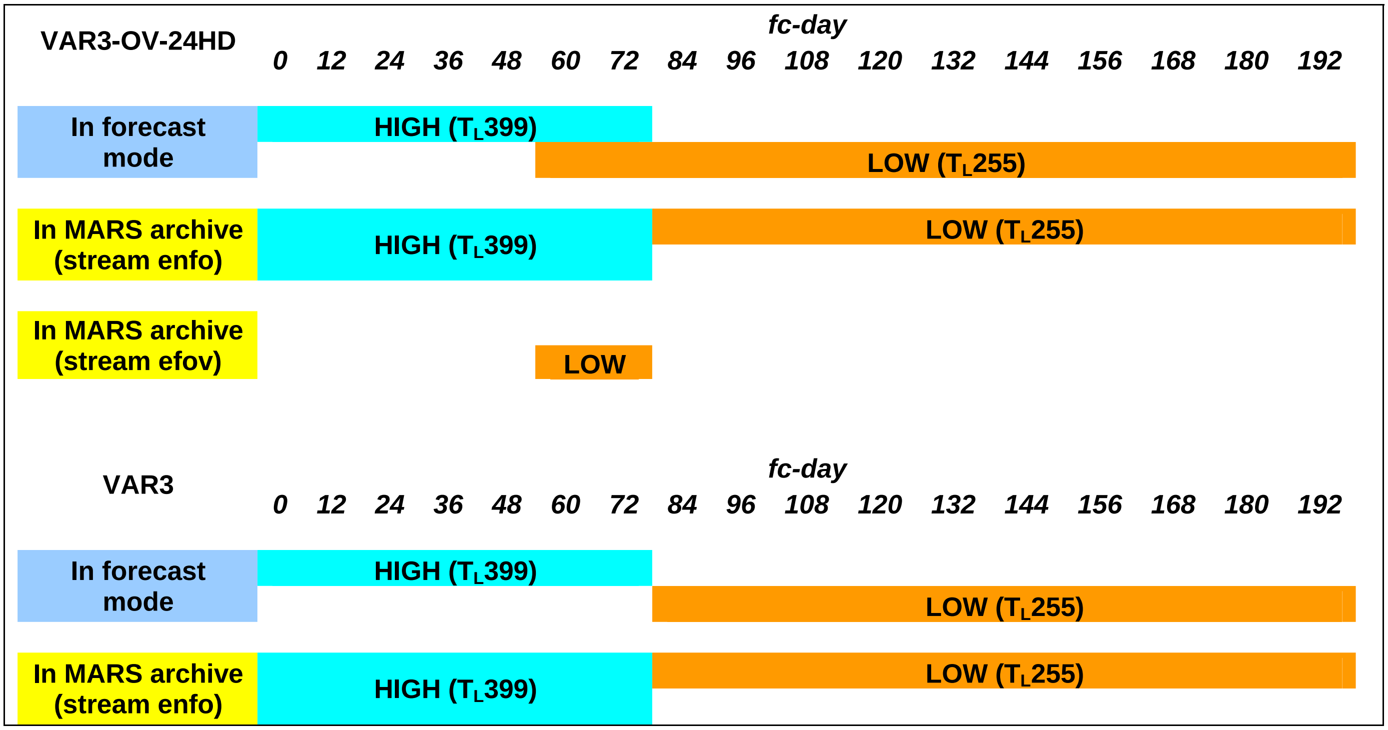


Figure 1. Schematic of the VAR3-OV-24HD and the VAR3 configurations. The VAR3-OV-24HD EPS uses a 24h overlap period: the low-resolution (T_L255) forecast starts at t+48h and have a 24h overlap with the high-resolution (T_L399) forecast. The ensemble archive (stream enfo) contains the high-resolution fields between 0 and t+72h, and the low-resolution fields from t+72h. The low-resolution fields produced between t+48h and t+72h can be accessed from the archive stream efov. The VAR3 EPS does not have any overlap period: the low-resolution (T_L255) forecast starts at t+72h.

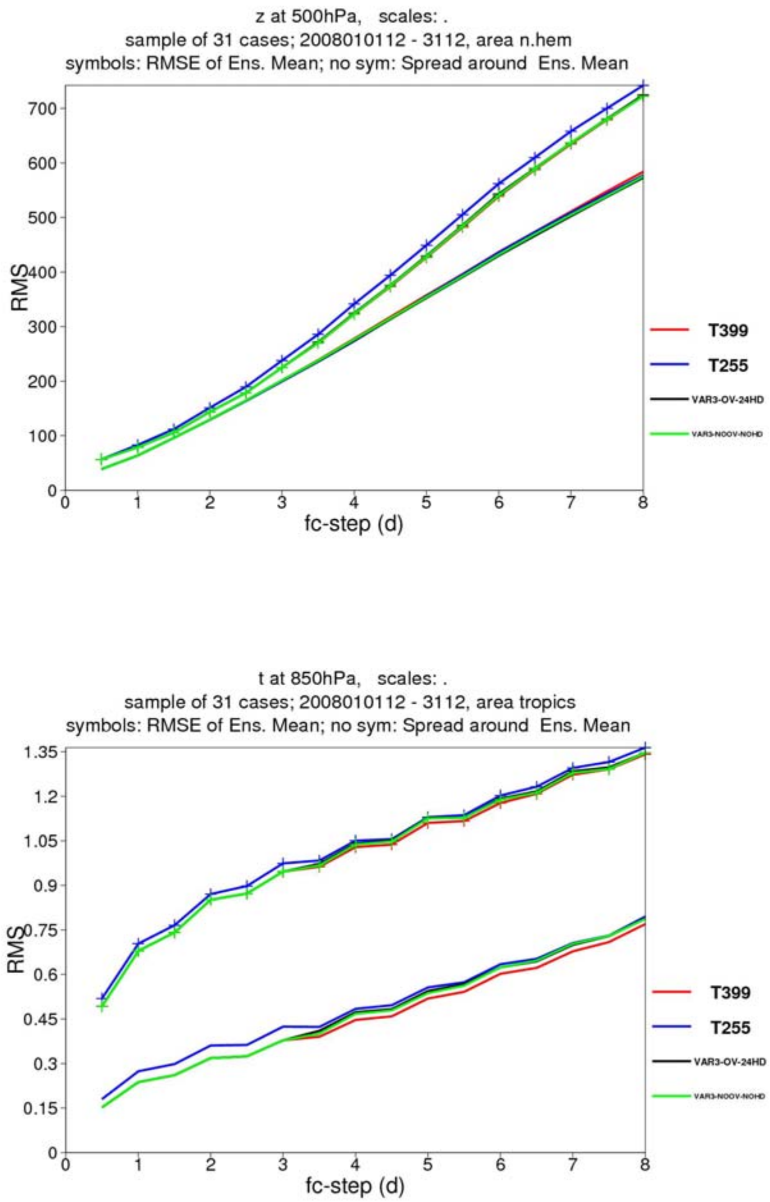


Figure 2. Root-mean-square-error (RMSE) of the ensemble-mean forecast (solid lines with symbols) and ensemble standard deviation (solid lines) of the T399 (red), T255 (blue), VAR3-OV-24HD (black) and VAR3 (green) ensembles, computed for Z500 over NH (top panel) and for T850 over the tropics (bottom panel). Values are expressed in m for Z500 and in degrees for T850.

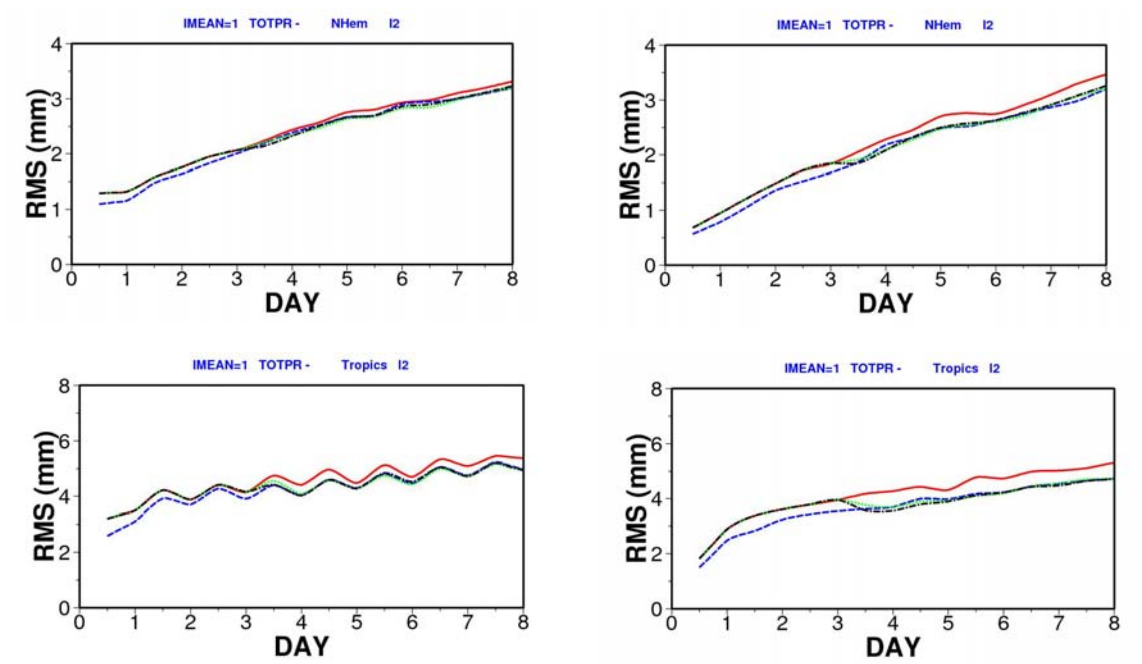


Figure 3. Top panels: average RMSE of the EPS perturbed-forecasts (left) and average spread (STD, right) of 12-hour accumulated total precipitation (TP12) over NH for the T399 (red solid lines), T255 (blue dashed lines), VAR3-OV-24HD (green dotted lines) and VAR3 (black chain-dashed lines) ensembles. Bottom panels: as top panels but for TP12 over the tropics. Values are expressed in mm.

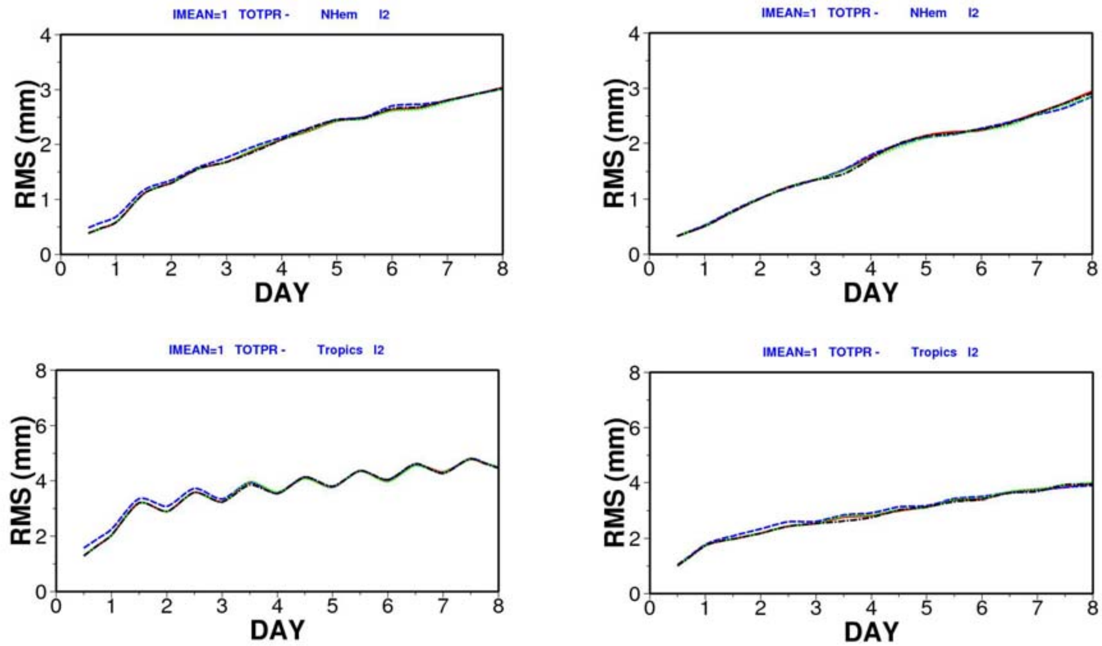


Figure 4. As Fig. 3 but for after T63 filtering. Top panels: average RMSE of the EPS perturbed-forecasts (left) and average spread (STD, right) of the T63-filtered 12-hour accumulated total precipitation (TP12) over NH for the T399 (red solid lines), T255 (blue dashed lines), VAR3-OV-24HD (green dotted lines) and VAR3 (black chain-dashed lines) ensembles. Bottom panels: as top panels but for filtered TP12 over the tropics. Values are expressed in mm.

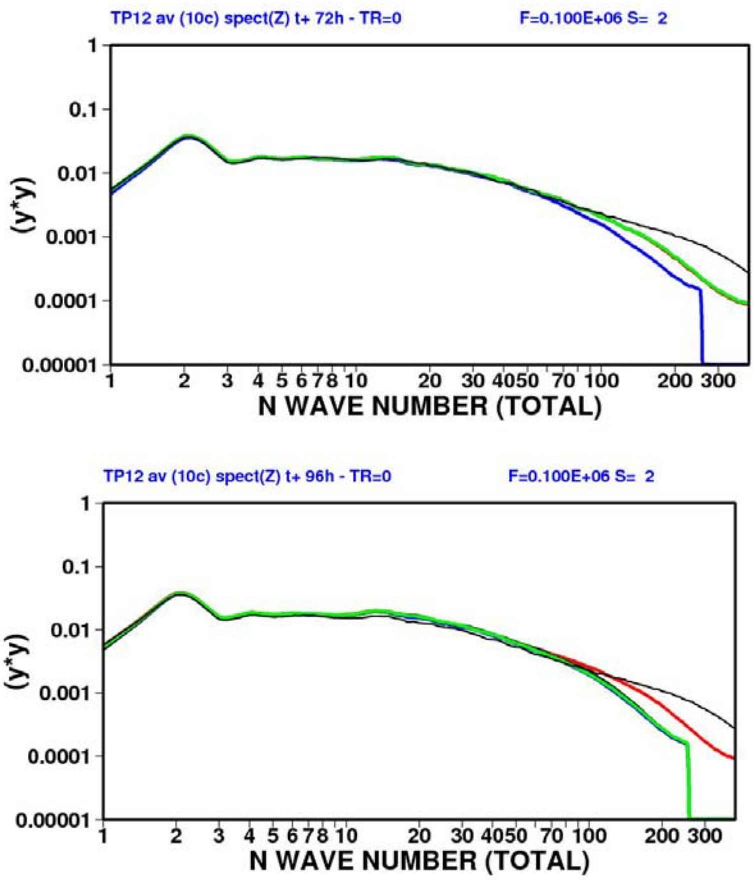


Figure 5. Spectra of the squared ensemble forecasts of 12-hour accumulated total precipitation ($TP12^2$) for the T399 (red solid lines), T255 (blue solid lines), VAR3-OV-24HD (black solid lines) and VAR3 (green solid lines) ensembles at t+72h (top panel) and at t+96h (bottom panel). The thin black solid line visible in both panels shows the spectra of a proxy of verification given by the t+12h and the t+24h TP12 forecast by the operational, T799 ECMWF forecast. At t+72h, the T399 and VAR3-OV-24HD curves coincide with the VAR3 line and thus are not visible, while at t+96h the VAR3-OV-24HD and VAR3 curves are very similar to the T255 curve. $TP12^2$ values (in m^2) have been multiplied by 10^{-5}.

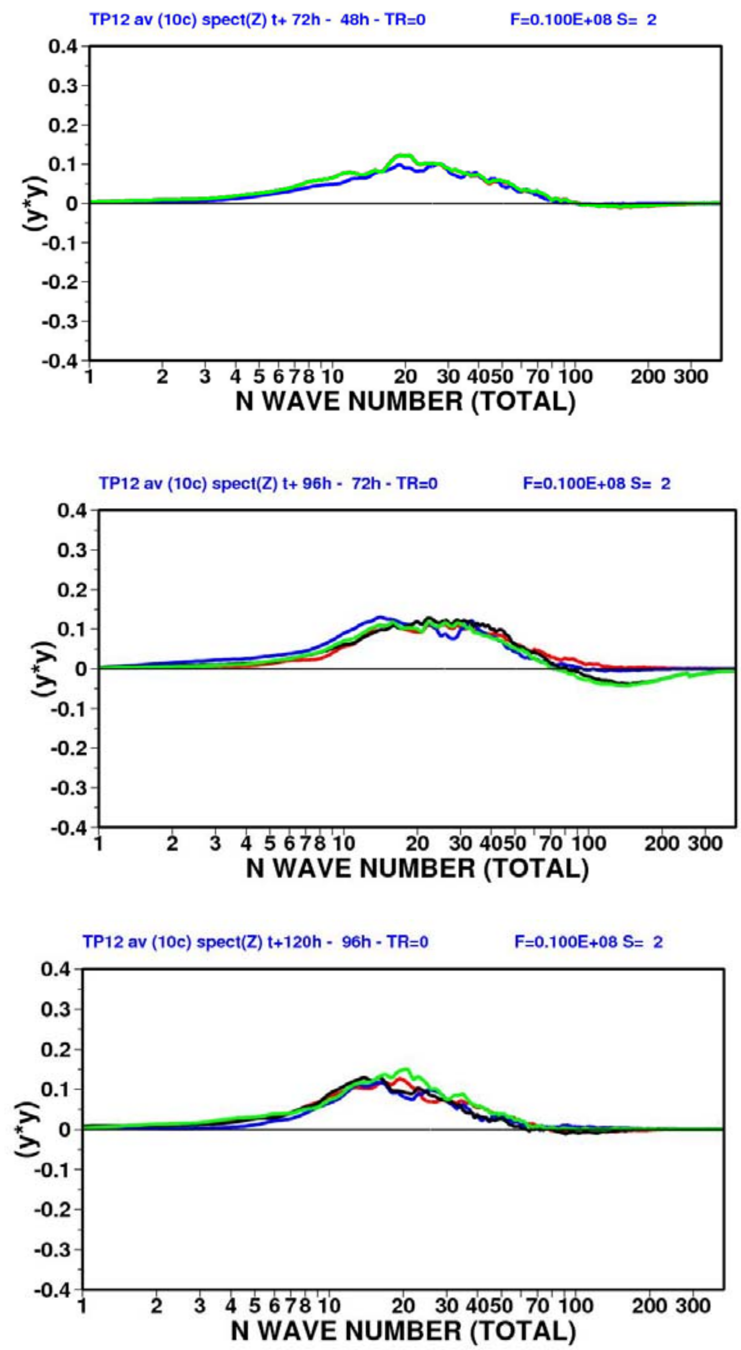


Figure 6. Difference between the variance (STD^2) spectra of 12-hour accumulated total precipitation (TP12) for the T399 (red solid lines), T255 (blue solid lines), VAR3-OV-24HD (black solid lines) and VAR3 (green solid lines) ensembles: [STD^2(72h)-STD^2(48h)] (top panel), [STD^2(96h)-STD^2(72h)] (middle panel) and [STD^2(120h)-STD^2(96h)] (bottom panel). In the first panel, the T399 and VAR3-OV-24HD curves coincide with the VAR3 line and thus are not visible. STD^2 differences (in m^2) have been multiplied by 10^{-7}.

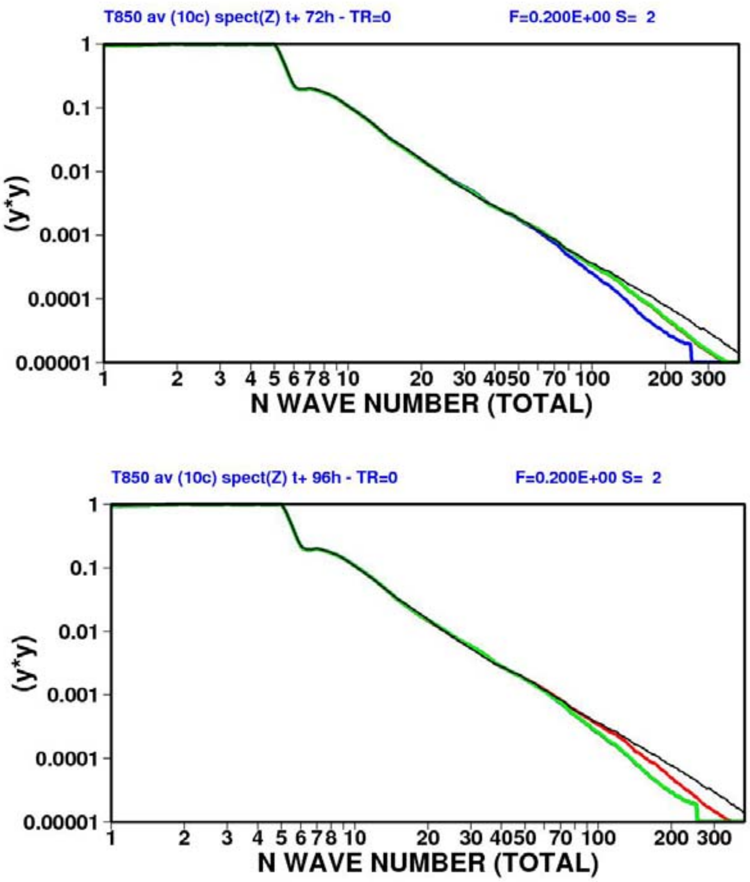


Figure 7. As Fig. 5 but for the spectra of the squared ensemble forecasts of the 850hPa temperature ($T850^2$) for the T399 (red solid lines), T255 (blue solid lines), VAR3-OV-24HD (black solid lines) and VAR3 (green solid lines) ensembles at t+72h (top panel) and at t+96h (bottom panel). The thin black solid line visible in both panels shows the spectra of the T799 ECMWF verifying analysis. At t+72h, the T399 and VAR3-OV-24HD curves coincide with the VAR3 line and thus are not visible, while at t+96h the VAR3-OV-24HD and VAR3 curves are very similar to the T255 curve. $T850^2$ values (in degrees) have been multiplied by 5.

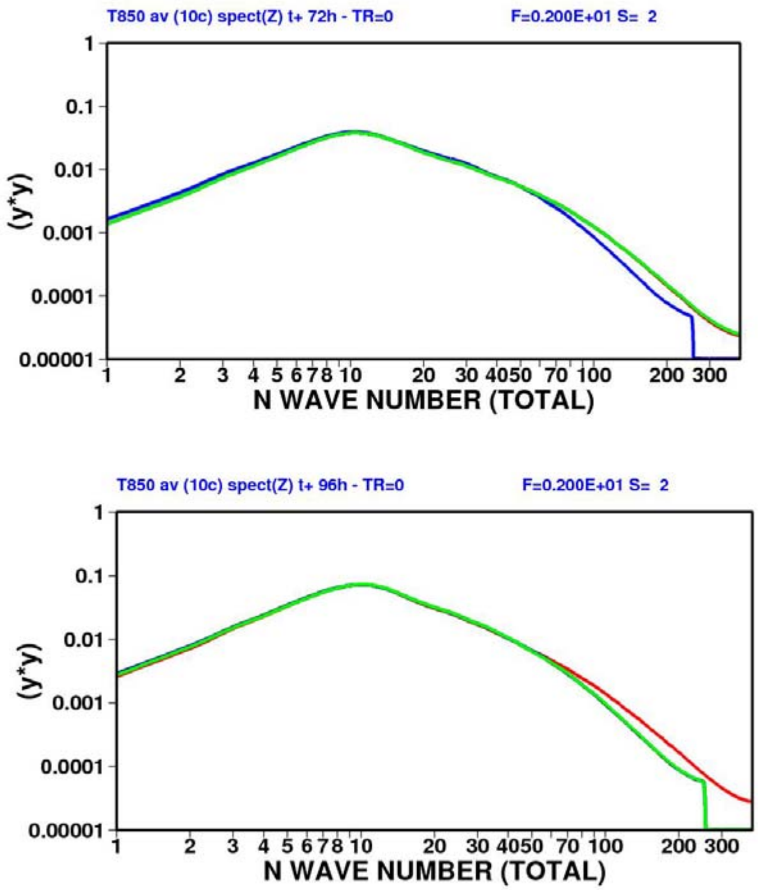


Figure 8. As Fig. 7 but for the spectra of the ensemble variance of the 850 temperature (T850) for the T399 (red solid lines), T255 (blue solid lines), VAR3-OV-24HD (black solid lines) and VAR3 (green solid lines) ensembles at t+72h (top panel) and at t+96h (bottom panel). At t+72h, the T399 and VAR3-OV-24HD curves coincide with the VAR3 line and thus are not visible, while at t+96h the VAR3-OV-24HD and VAR3 curves are very similar to the T255 curve. STD^2 values (in degrees) have been multiplied by 0.5.

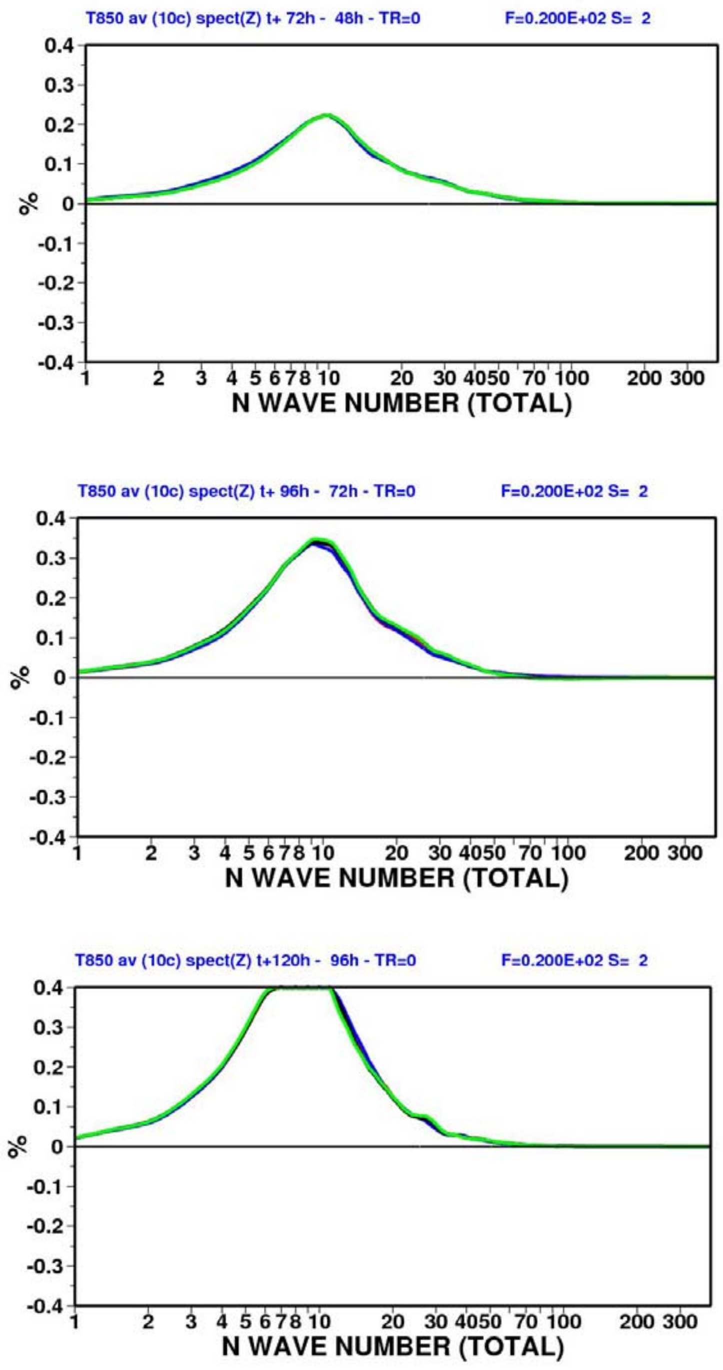


Figure 9. As Fig. 6 but for the difference between the spectra of the ensemble variance (STD^2) of T850 for the T399 (red solid lines), T255 (blue solid lines), VAR3-OV-24HD (black solid lines) and VAR3 (green solid lines) ensembles: [STD^2(72h)-STD^2(48h)] (top panel), [STD^2(96h)-STD^2(72h)] (middle panel) and [STD^2(120h)-STD^2(96h)] (bottom panel). In the first panel, the T399 and VAR3-OV-24HD curves coincide with the VAR3 line and thus are not visible. STD^2 differences (in degrees) have been multiplied by 0.05.

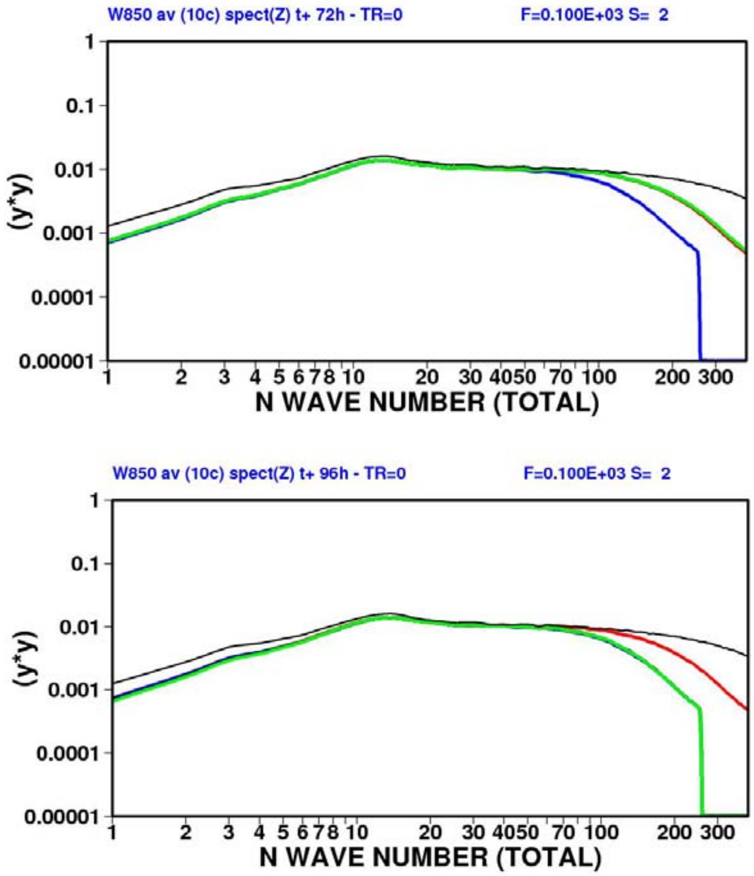


Figure 10. As Fig. 5 but for the spectra of the squared ensemble forecasts of the squared vertical velocity at 850 hPa ($W850^2$) for the T399 (red solid lines), T255 (blue solid lines), VAR3-OV-24HD (black solid lines) and VAR3 (green solid lines) ensembles at t+72h (top panel) and at t+96h (bottom panel). The thin black solid line visible in both panels shows the spectra of the T799 ECMWF verifying analysis. At t+72h, the T399 and VAR3-OV-24HD curves coincide with the VAR3 line and thus are not visible, while at t+96h the VAR3-OV-24HD and VAR3 curves are very similar to the T255 curve. $W850^2$ values (in ms^{-1}) have been multiplied by 10^{-2}.

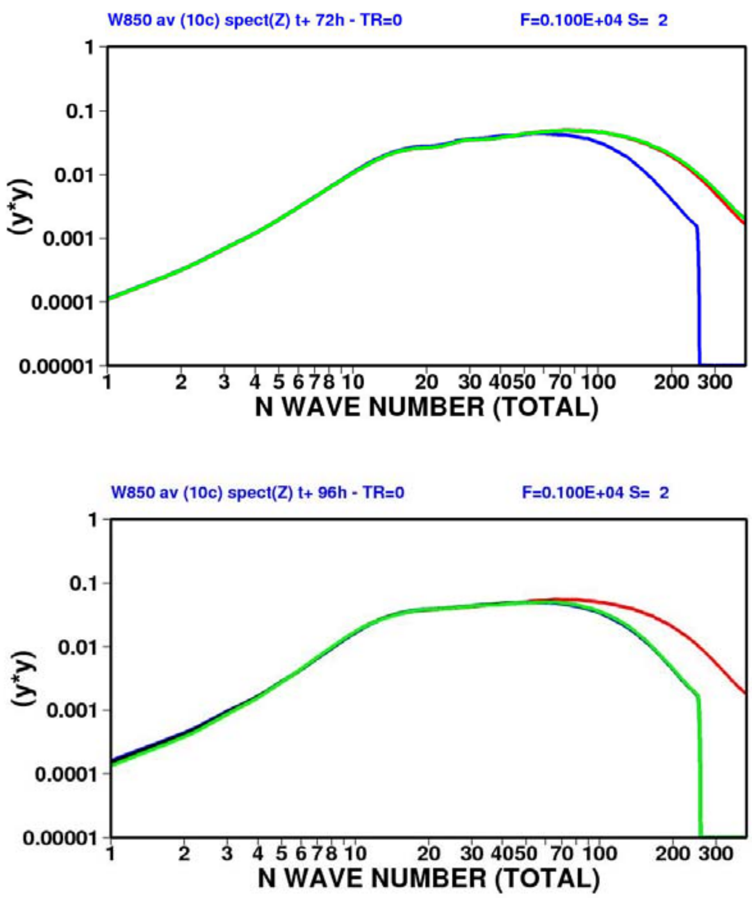


Figure 11. As Fig. 10 but for the spectra of the ensemble variance of the 850hPa vertical velocity (W850) for the T399 (red solid lines), T255 (blue solid lines), VAR3-OV-24HD (black solid lines) and VAR3 (green solid lines) ensembles at t+72h (top panel) and at t+96h (bottom panel). At t+72h, the T399 and VAR3-OV-24HD curves coincide with the VAR3 line and thus are not visible, while at t+96h the VAR3-OV-24HD and VAR3 curves are very similar to the T255 curve. STD^2 values (in ms^{-1}) have been multiplied by 10^{-3}.

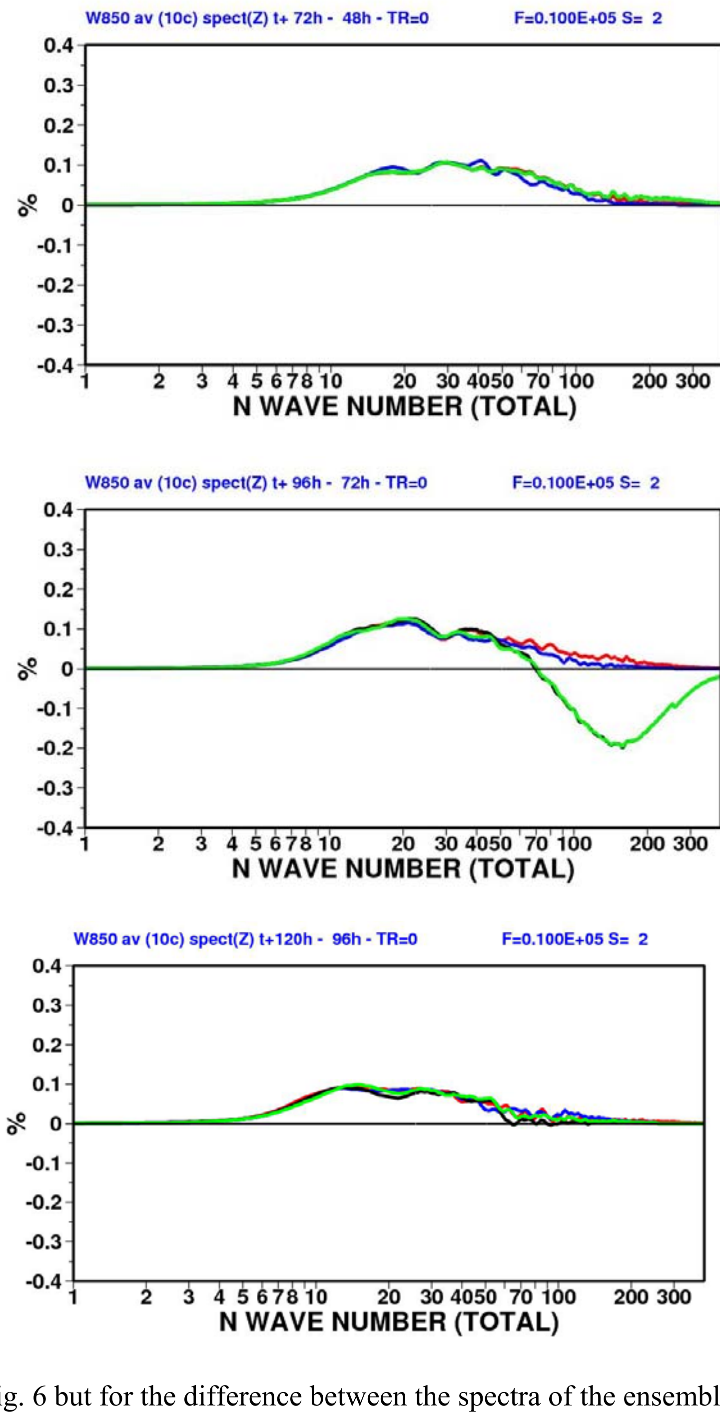


Figure 12. As Fig. 6 but for the difference between the spectra of the ensemble variance (STD^2) of the 850hPa vertical velocity (W850) for the T399 (red solid lines), T255 (blue solid lines), VAR3-OV-24HD (black solid lines) and VAR3 (green solid lines) ensembles: [STD^2(72h)-STD^2(48h)] (top panel), [STD^2(96h)-STD^2(72h)] (middle panel) and [STD^2(120h)-STD^2(96h)] (bottom panel). In the first panel, the T399 and VAR3-OV-24HD curves coincide with the VAR3 line and thus are not visible. STD^2 differences (in ms^{-1}) have been multiplied by 10^{-4}.

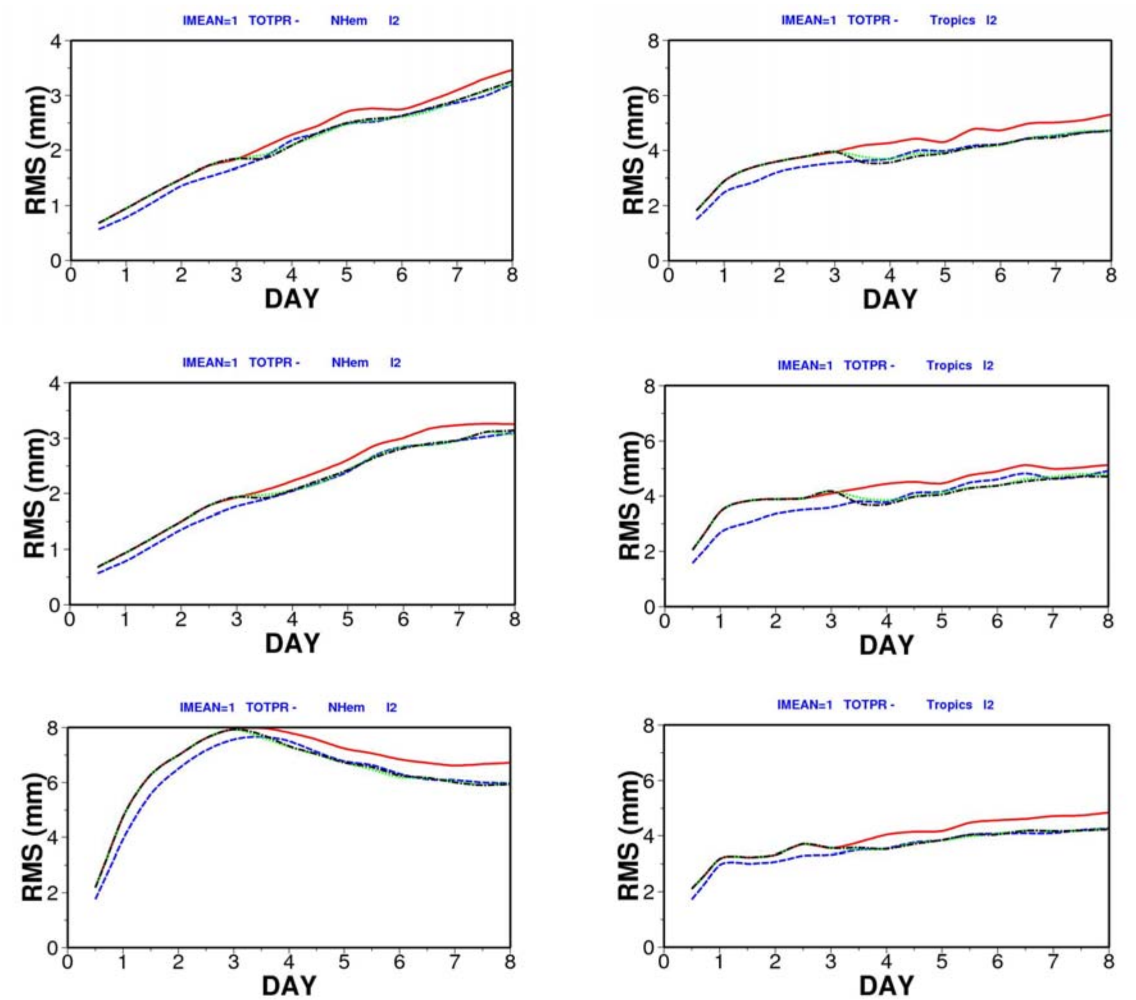


Figure 13. Top panels: average spread (STD) of 12-hour accumulated total precipitation (TP12) over NH (left) and the tropics (right) for the T399 (red solid lines), T255 (blue dashed lines), VAR3-OV-24HD (green dotted lines) and VAR3 (black chain-dashed lines) ensembles run with real orography. Middle panels: as top panels but for ensembles run with flat orography. Bottom panels: as top panels but for ensembles run in aqua-planet mode. Values are expressed in mm.

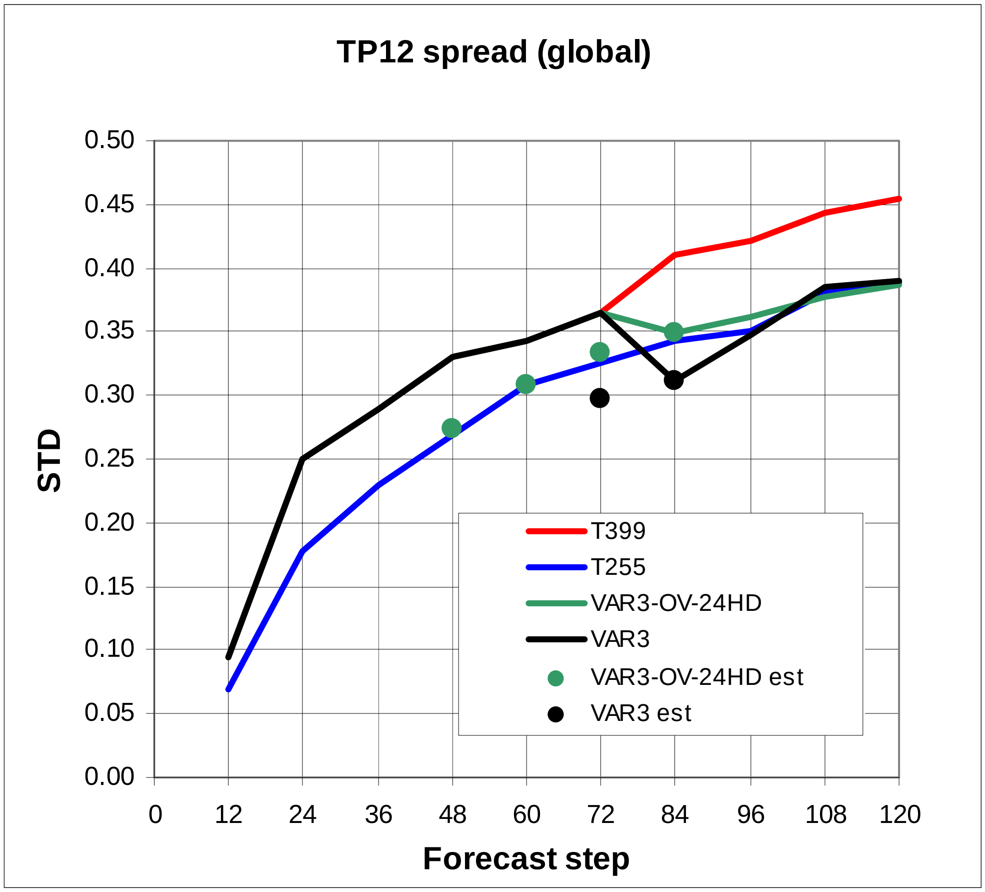


Figure 14. Global average ensemble spread (STD) of 12-hour accumulated total precipitation (TP12) for the T399 (red solid lines), T255 (blue solid lines), VAR3-OV-24HD (green solid lines) and VAR3 (black solid lines) ensembles run with real orography. The green dots show estimated VAR3-OV-24HD values during the overlap period (i.e. between t+48h and t+72h), and the black dots show the VAR3 estimated value at t+72h. STD values are expressed in mm.

High resolution (HR)

1	14	1	4	4	11	8	2	1
3	11	0	4	1	14	4	1	0
2	0	2	5	2	13	2	0	5
4	1	7	3	6	2	3	5	10
6	1	0	1	1	5	12	2	18
9	1	1	0	5	6	2	0	4
2	6	4	8	2	3	3	14	2
0	6	1	4	12	5	3	7	2
4	4	1	2	14	1	4	1	12

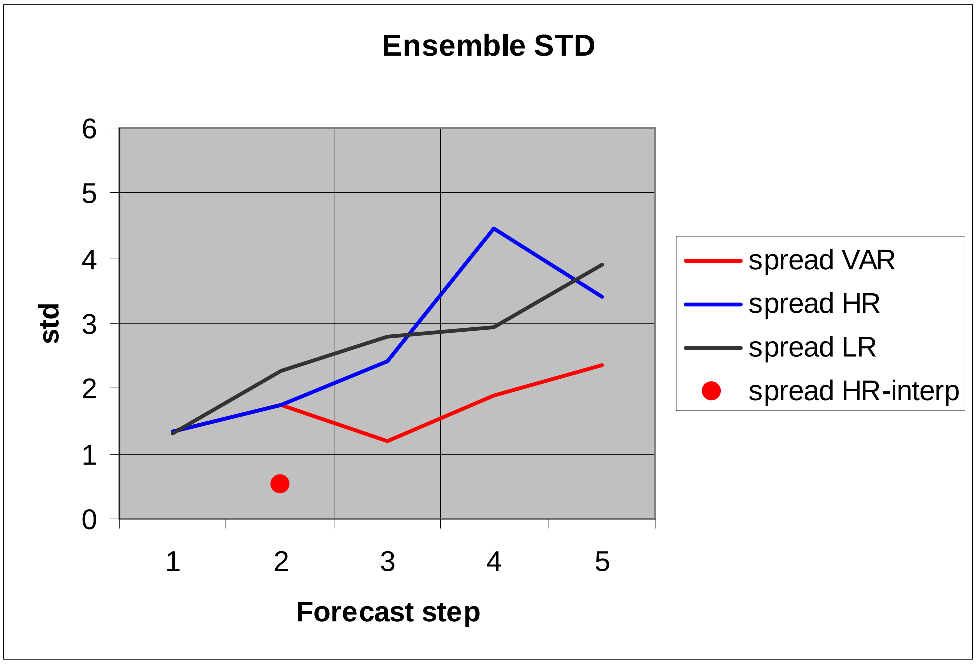
HR interpolated on LR grid

	4		3		7		3	
	3		3		5		6	
	3		3		4		6	
	3		5		5		5	

HR on output grid

		3				5		
		4				5		

Figure 15. Example of one idealized high resolution field (left) and its interpolated field on the coarser production grid (middle) and on the coarsest output grid (right panel).



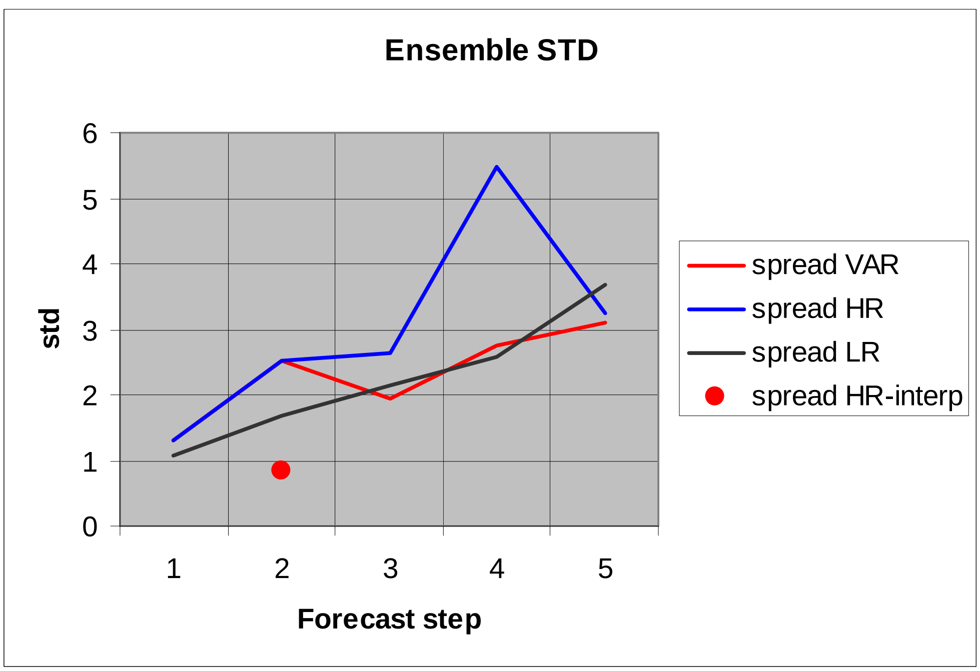


Figure 16. Spread (STD) of the high-resolution (HR, blue lines), low-resolution (LR, black-lines) and variable-resolution (VAR, red lines) idealized ensembles for two cases (see section 4 for more details). The red solid circle denotes the STD of the HR-fields after having been interpolated on the low-resolution grid.

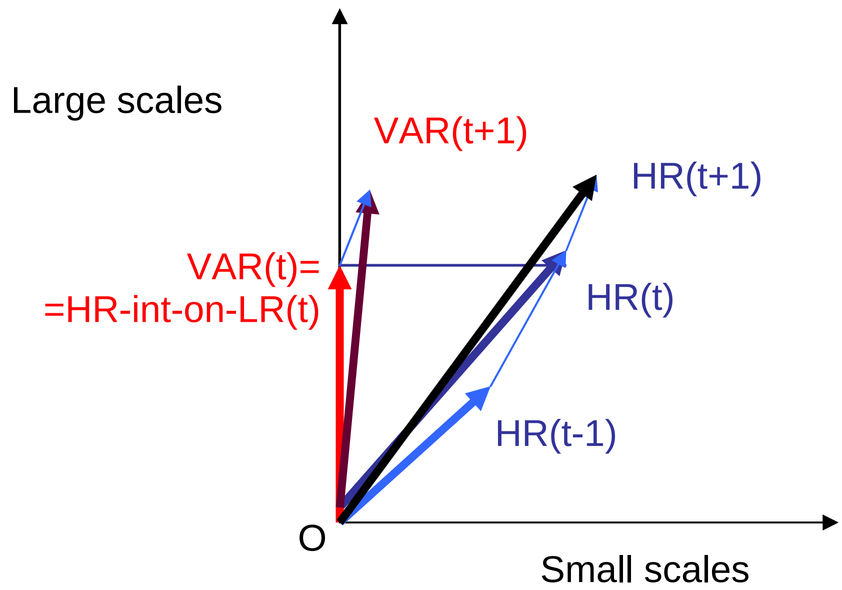


Figure 17. Schematic of the impact of the VAREPS truncation on the total precipitation spread (STD) large- and small-scale components. Vectors starting at the origin represent the ensemble spread at a specific forecast time. ||HR(t-1)|| and ||HR(t)|| are the HR-IEPS STD 1-day before and at the truncation time t, and ||HR(t)-HR(t-1)|| is the increase in STD between (t-1) and t. At time t, the VAR(t) STD is equal to the HR(t) STD. But the interpolation of the HR(t) fields onto the LR-grid sets to zero the small-scale component of the VAR fields. As a result, ||VAR(t+1)||, which is the STD of the VAR ensemble, can be smaller than ||VAR(t)||=||HR(t)||, which is the STD of the VAR ensemble the day before. This results in a decrease in the STD of the VAR ensemble during the first day after the truncation time.