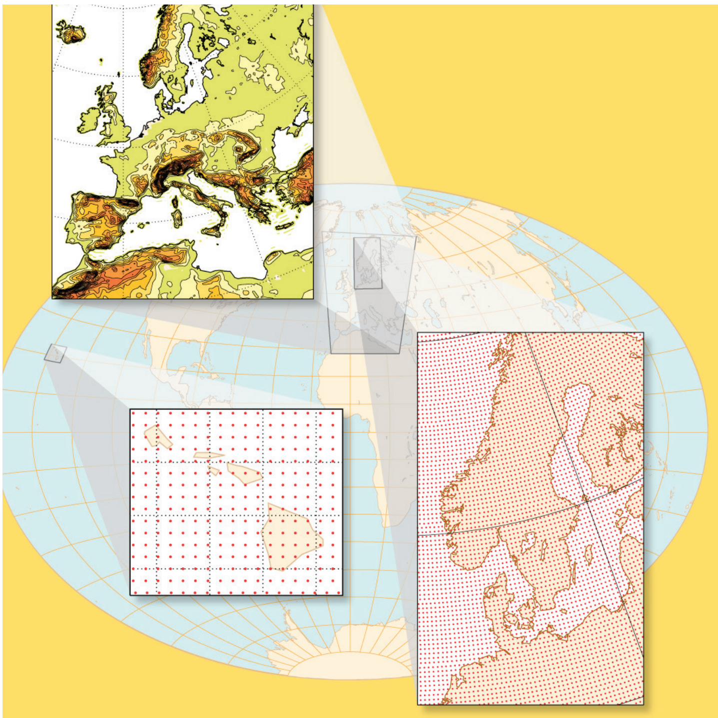
ECMWF Feature article

from Newsletter Number 108 – Summer 2006

METEOROLOGY

Towards a global meso-scale model: The high-resolution system T799L91 and T399L62 EPS



www.ecmwf.int/en/about/news-centre/media-resources

doi:10.21957/qr32av62gk

This article appeared in the Meteorology section of ECMWF Newsletter No. 108 – Summer 2006, pp. 6–13.

Towards a global meso-scale model: The high-resolution system T799L91 and T399L62 EPS

Agathe Untch, Martin Miller, Mariano Hortal, Roberto Buizza, Peter Janssen

On 1 February 2006, a major resolution upgrade of the operational ECMWF forecasting systems was successfully implemented as IFS Cycle 30r1. This article describes the main components of this change, their rationale, and expected impacts and benefits. It should be noted, however, that many people at ECMWF other than the authors of this article have contributed to the scientific development work for this high-resolution system and the results presented here.

Increases in horizontal and vertical resolution of the Centre's global model and assimilation system have been a cornerstone of the long-term development plans, and during its history have contributed major improvements to the forecast skill at all time ranges. The 25 years or so of the Centre's operational activities have seen four significant horizontal resolution changes with a similar number of changes in the vertical resolution also. Each change to higher resolution has been based on realistic expectations of improved accuracy in (a) the representation of basic components such as orography and land/sea definition, (b) synoptic and sub-synoptic systems, (c) weather features and parameters such as fronts, cloud and rain bands, jets, and (d) assimilating observations both space-based and surface-based. Also, the later refinements in resolution have brought systematic improvements to the ocean wave forecasts, not least in their quality near coastlines and in confined waters (typical of the European region) which particularly benefit from more accurate surface winds. In general, these changes have been well received by users and have also contributed significantly to the long-term positive trends in objective measures of forecast skill. They are also visible in a variety of other forecast verification exercises such as those carried out by WGNE (*Ebert et al.,* 2003) for precipitation and tropical cyclone tracking.

Before 1 February, the ECMWF operational resolution of T511 (grid spacing ~ 40 km) accurately resolved systems of only several hundred kilometres. It was clear that use of a higher resolution (e.g. 25 km) should improve both the description of important structures within active synoptic weather systems and provide opportunities to capture the true intensity of the highly energetic mesoscale systems associated with many severe weather events. The modelling of fine-scale filament-like potential vorticity features often associated with such events has been discussed by a number of authors (e.g. *Dritschel et al.,* 1999).

The representativeness of observations has always been an important issue in data assimilation and continues to be so. What is clear however is that the more accurate the assimilating model the more useful the observation can be. Hence a higher resolution assimilating model has several advantages in this regard: it can use low-level data better (due to more accurate orography etc.) and has a greater likelihood of representing the observed parameter since it can describe more accurately the local horizontal and vertical structures in that parameter. This is also the case for remotely sensed observations, many of which have much higher resolutions than are currently handled by assimilation systems that severely thin or sub-sample the data.

The resolution of the Ensemble Prediction System (EPS) has changed twice before: from T63L19 to T159L31 in December 1996, and then to T255L40 in November 2000. These upgrades were implemented following extensive experimentation that showed that the resolution improvement was beneficial, as confirmed by subsequent operational experience.

Resolution and severe weather prediction

The majority of severe weather events are notable for either their local nature or for more local features embedded in somewhat larger-scale phenomena. It is therefore obvious that resolution is a crucial issue in capturing the nature and intensity of such events. Our ability to forecast severe weather is partly limited by the inherent unpredictability of the phenomena in question, and partly by the forecast skill of the large-scale patterns with which they are associated. The recent marked improvements in forecast skill both in the early medium-range and beyond are an important step forward in this regard (e.g. *Grazzini,* 2005). Furthermore, whether it is through improved detail in surface forcing, improved use of observations or through improved dynamics and physics of the mesoscales, higher resolutions are a key driving factor in improving the accuracy in the prediction of severe weather (both at ECMWF and other NWP Centres). Examples of this can be found in *Miller* (1999).

 doi:10.21957/qr32av62gk

The new high-resolution deterministic system T799L91

Horizontal resolution increase

The horizontal resolution of the deterministic system has been increased from T511 to T799. The ECMWF model is a spectral model, and horizontal resolution is denoted by the highest wavenumber represented in the model. The notation T799 means that the highest wavenumber represented with the new resolution is 799. This corresponds to a wavelength of 50 km. The smallest wavelength represented in the previous operational resolution T511 is 78 km. In the above notation 'T' stands for 'triangular spectral truncation'.

In gridpoint space, the linear Gaussian grid corresponding to the new T799 resolution has 800 latitude rows, an increase by 288 rows from the T511 grid (512 latitude rows). Along each latitude row near the equator there are 1,600 grid-points in the new resolution. This number decreases gradually for latitudes approaching the poles since a 'reduced' Gaussian grid is used in the ECMWF model. In total, the new horizontal grid has 843,490 grid-points, 494,962 more than the T511 grid (348,528 grid-points in total). This corresponds to a 2.42 fold increase in the number of grid-points per vertical level.

Figure 1 shows the orography for the British Isles at T511 and at T799. The coast lines in the higher resolution model follow much more closely the shape of the real coast lines. For the hilly areas of the U.K. and Ireland, the increase in orographic detail and realism with T799 is noteworthy. As is well-recognized, this improvement in the representation of the orography leads directly to improved forecasts of weather events which are strongly influenced by orographic features.

In the 4D-Var assimilation, the outer loops also change to T799 while the horizontal resolution of the second inner loop has been upgraded from T159 to T255. The first inner loop resolution remains unchanged at T95.

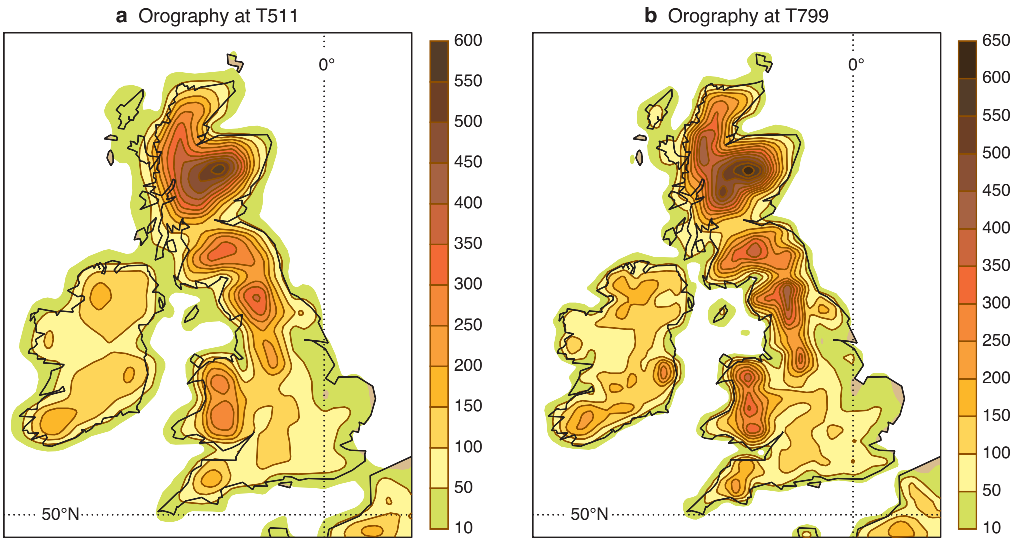


Figure 1 Orography at (a) horizontal resolutions T511 (grid spacing ~ 40 km) and (b) T799 (grid spacing ~ 25 km).

Vertical resolution increase

Concurrent with the horizontal resolution increase the vertical resolution of the deterministic model has been upgraded. The deterministic 10-day forecast and the analysis use now 91 vertical levels (previously 60 levels).

In the new 91-level resolution (L91), and depending on latitude and season, approximately 45–50 of the 91 levels are located in the troposphere. The remaining 40–45 levels resolve the stratosphere and mesosphere up to an altitude of about 80 km (0.01 hPa). Figure 2 shows the distribution of levels in L91 compared to the previous operational 60-level distribution (L60). The vertical resolution has increased everywhere in the atmosphere compared to L60. However, the largest increase is around the tropopause, where the resolution has nearly doubled. The model top has been raised from 0.1 hPa (~64 km) to 0.01 hPa (~80 km) partly to create a deeper sponge layer for wave absorption, but also to provide the basis for a possible future replacement of Rayleigh friction by parametrized non-orographic gravity wave drag. Currently a simple Rayleigh friction is applied to the zonal wind in layers above 5 hPa to slow down the otherwise excessively strong polar night jets at the stratopause level.

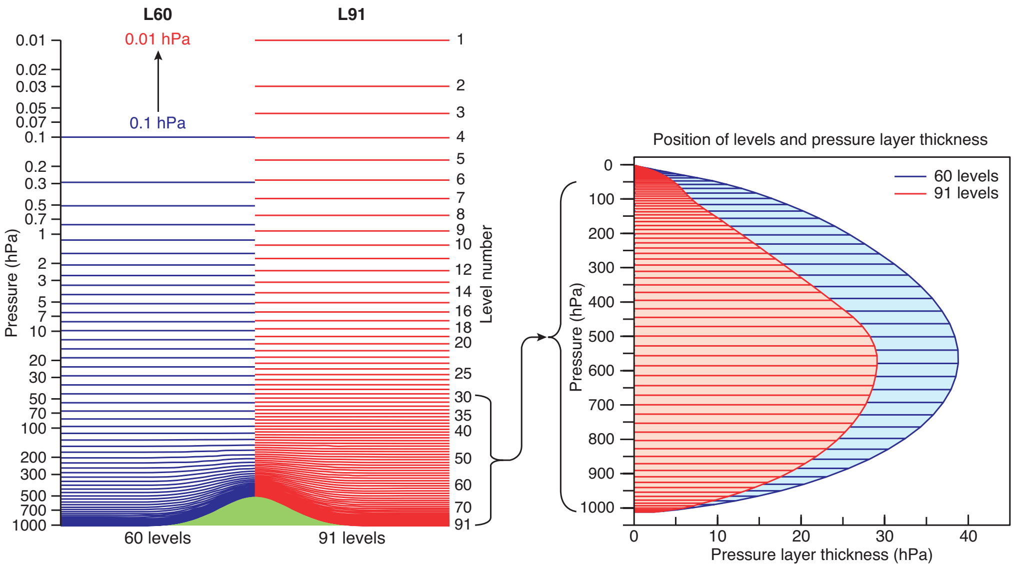


Figure 2 The left-hand panel shows the distribution of vertical levels in the L60-model (purple) and L91-model (red). The right-hand side panel shows the position of the levels in the troposphere with the length of each horizontal bar indicating the thickness of the layer centred about the corresponding level.

Time step decrease

Whenever the model resolution is increased numerical stability constraints usually force a reduction in the length of the time step which can be safely used. However, with a semi-implicit semi-Lagrangian time stepping scheme, as used in the ECMWF model, the stability constraints are not very strict. Nevertheless, mainly for accuracy reasons, the time step for the T799L91 model was decreased from 15 minutes as used with the T511L60 resolution to 12 minutes. The time step in the second inner loop of 4D-Var was kept at 30 minutes although the resolution was increased from T159L60 to T255L91.

Resolution increase in the coupled ocean wave model

In tandem with the increase in horizontal and vertical resolution of the IFS, resolution in the ocean wave prediction model was increased as well. For the deterministic forecast the spatial resolution was increased from 0.5° to 0.36°. A further increase from 0.36° to the nominal atmospheric resolution of 0.25° is not needed, because the smallest scale features in the atmospheric model are heavily damped. Also experiments with matching atmospheric and ocean wave resolution have shown that there is no additional gain in information on ocean waves or atmospheric parameters. To facilitate a coupling between the wind and waves every atmospheric model time step, the advection and wave physics time step was reduced from 15 to 12 min. However, the ocean wave model is only responsible for about 5% of the total forecast CPU time. No modifications to the source term formulation were required.

The T399L62 high-resolution EPS

The resolution of the ECMWF Ensemble Prediction System was also increased. The main differences between the new and the old system are the following.

- ***Forecast model resolution:*** T399L62 (30 min time step) used instead of T255L40.
- ***Initial perturbations resolution:*** Perturbations are generated using T42L62 instead of T42L40 singular vectors.
- ***Initial perturbation amplitude:*** The contribution to the amplitudes of the initial perturbations generated using the 48-hour evolved singular vectors has been decreased by approximately 30% (this change was needed to compensate for the faster growth of the T42L62 initial perturbations when non-linearly integrated in the T399L62 model).

Like the previous 40-level model, the new 62-level model for the EPS is primarily a 'troposphere only model' with the top at ~5 hPa and with only a few levels in the stratosphere. In the troposphere (up to about 200 hPa), the distribution of levels in L62 is identical to the L91 distribution. Both the ensemble size (50 perturbed and one unperturbed member) and the forecast length (10 days) have been kept the same. This resolution change is part of the upgrading process that will lead to the implementation of the Variable Resolution Ensemble Prediction System (VAREPS), designed to extend the forecast range covered by the ensemble system initially to 15 days and eventually to 32 days, through the merging of the medium-range and monthly ensemble prediction systems. See the article by *Buizza et al.* in this Newsletter for more details.

doi:10.21957/qr32av62gk

For the ensemble prediction of ocean waves, spectral resolution was increased from 25 frequencies and 12 directions to 30 frequencies and 24 directions, and is now identical to the representation of the wave spectrum in the deterministic forecast. The EPS is an important tool for assessing the probability of the occurrence of extreme ocean wave conditions. Experience has shown that the increase in directional resolution was particularly beneficial for representing rapidly varying extreme conditions. No increase of spatial resolution (at the moment the ocean waves EPS has a resolution of 1°) was introduced for cost reasons, and because this was not really needed due to the lack of atmospheric variability at the small scales.

Cycle 30r1

In addition to the various resolution increases discussed above, there were several other important changes implemented.

- ***Grid-point humidity and ozone in 4D-Var:*** The analysis was changed such that humidity and ozone are no longer required in spectral space in the inner loops of 4D-Var, thus eliminating errors in these fields resulting from the spectral transformations.
- ***Ozone chemistry:*** Revised coefficients (version 2.3) from Météo-France were used for the linearised ozone chemistry scheme of Cariolle and Déqué.
- ***Wave information:*** Additional wave height observations from the Jason Altimeter were introduced in the wave analysis while the SAR image spectra from ERS-2 (available every 200 km along track) were replaced by ASAR images from the ENVISAT satellite, available every 100 km.

Such a major upgrade in horizontal and vertical resolutions together with the changes listed above inevitably raised problems and issues during the extensive testing the new system underwent prior to operational implementation. Among the problems encountered were unphysical increments in the upper stratospheric and mesospheric humidity and a few cases of numerical instability in the inner loops of 4D-Var. Ways to alleviate these problems were found and included in Cy30r1, and ongoing research into these issues will deliver more elegant solutions in the near future.

Computational cost of the resolution increase

The 2.42 fold increase in the number of grid-points per vertical level, together with the increase in the number of vertical levels by 31 and the reduction in the time step to 12 minutes (from 15 minutes), led to a four fold increase in the total number of floating point operations necessary to complete a 10-day forecast: 1.7×10^{15} floating point operations at T799L91 as compared with 0.4×10^{15} at T511L60.

Figure 3 shows the relative cost contributions of the different parts of the model for the two resolutions. As was expected, the cost of the spectral transforms has grown faster with increased resolution than the rest of the model, but the spectral method is still very affordable. Tests with even higher horizontal resolutions (e.g. T2047) have shown that the spectral method will continue to remain affordable for the foreseeable future.

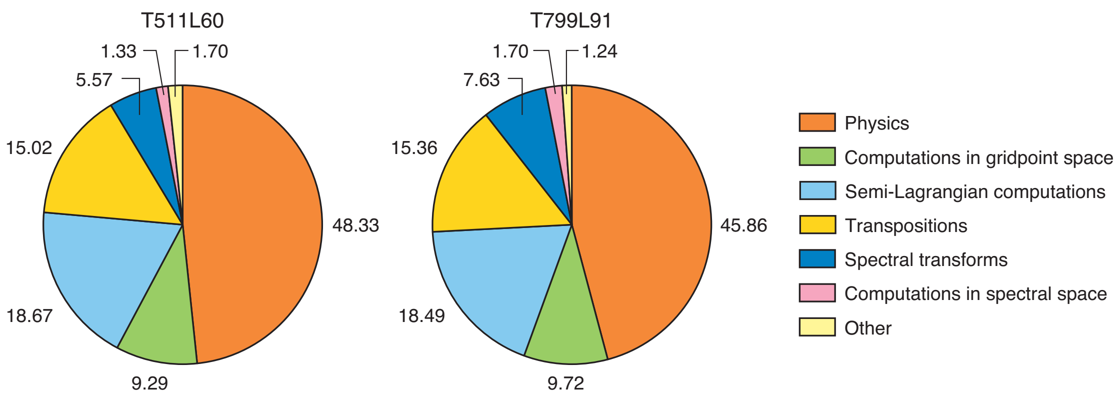


Figure 3 Pie charts showing the relative cost of various components of the model at T511L60 and T799L91 resolutions.

Performance of the high-resolution deterministic system

A total of ten months of assimilation-forecast experimentation were run with Cy30r1: four months (1 October 2005 to 31 January 2006) in experimental mode (e-suite 29) by the Operations Department and six months by the Research Department. The mean scores are in general better than the control scores with T511L60 and Cy29r2, with the largest gain and highest statistical significance in the southern hemisphere. Table 1 summarizes the statistical significance obtained with the t-test for Z500 scores for the northern hemisphere, southern hemisphere and for Europe.

Better representation of the orography and increased vertical resolution led to more observations being accepted in the analysis. As an example Figure 4 shows statistics on how many radiosonde temperature measurements are being accepted in the northern hemisphere and how well the background and analysis fit these observations in data assimilation with T799L91 and with T511L60 for the month of August 2005 (62 analysis cycles). The significant increase in the number of observations accepted near the surface is due to the more realistic orography and coastlines, while the increase near the tropopause stems from the improvement in vertical resolution.

One severe weather example that occurred during the pre-operational testing of the high-resolution system is shown in Figure 5. Very strong onshore winds along the Norwegian coast on 12 December 2005, due to an intense polar low, caused surges along the coast and fjords. Comparison with the verifying analyses (left-hand side panels in Figure 5) shows that location and strength of the gale are much better captured with the new high-resolution system at the two forecast ranges of 3 and 5 days shown (middle and right-hand side panels in Figure 5, respectively).

As was anticipated, the enhanced resolution also has a positive effect on the quality of the forecasts of tropical cyclones, and both position and intensity errors are reduced in the high-resolution system at all forecast ranges. Hurricane Katrina, which devastated New Orleans in August 2005, was one of the strongest storms ever recorded in the Gulf of Mexico (category 5), with maximum sustained winds of 280 km/h and a minimum central pressure of 902 hPa at its peak. By the time it made landfall on the Louisiana coast on 29 August it had decreased to a category 3 storm with a minimum central pressure of 920 hPa. Figure 6 compares the performance of the high-resolution and the T511L60 systems in forecasting this storm at landfall 36 h and 72 h in advance. Clearly, the high-resolution system captures position and intensity of the storm better at both forecast ranges. Note that the positive impact of increased resolution on the VAREPS forecast of Hurricane Katrina is considered in the companion article by *Buizza et al.* in this edition of the Newsletter.

Validation of the experimental suite for ocean waves against buoy data (located mainly in the northern hemisphere) shows small improvements in the scatter index of forecast wave height up to day 6 (see Figure 7).

Area	Score	Day 2	Day 3	Day 5	Day 7
Northern Hemisphere	ACC	0.1%	2%	–	–
	RMSE	0.1%	0.1%	10%	–
Southern Hemisphere	ACC	0.1%	0.1%	0.1%	0.1%
	RMSE	0.1%	0.1%	0.1%	0.1%
Europe	ACC	–	–	2%	–
	RMSE	0.5%	2%	10%	5%

Table 1 The statistical significance obtained with the t-test for Z500 scores for Anomaly Correlation Coefficient (ACC) and Root Mean Square Error (RMSE) for the northern hemisphere, southern hemisphere and for Europe. Numbers in green cells mean the high-resolution system T799L91 (Cycle 30r1) is better than T511L60 (Cycle 29r2) with a statistical significance given by the value. Smaller values mean higher statistical significance. The sample size is 311 forecasts.

 doi:10.21957/qr32av62gk

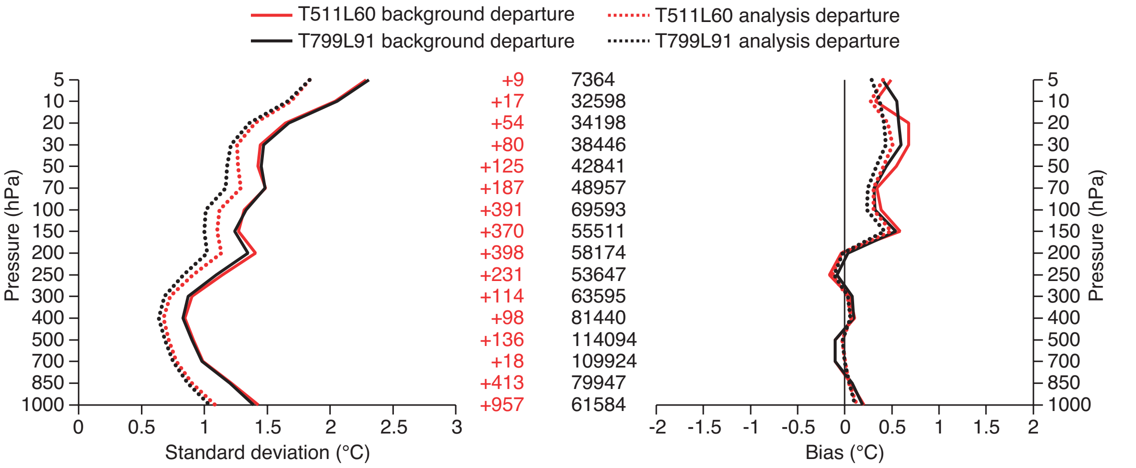


Figure 4 Fit of background and analysis to TEMP temperature observations in the northern hemisphere (averaged over 62 analysis cycles) in terms of standard deviation and bias: black lines T799L91, red lines T511L60. The numbers in black in the middle of the figure give the total number of TEMP temperature observations accepted by the T799L91 analysis per vertical band and the numbers in red give the difference in the number of observations used by the two analyses (a plus sign means more observations are accepted by the T799L91 analysis).

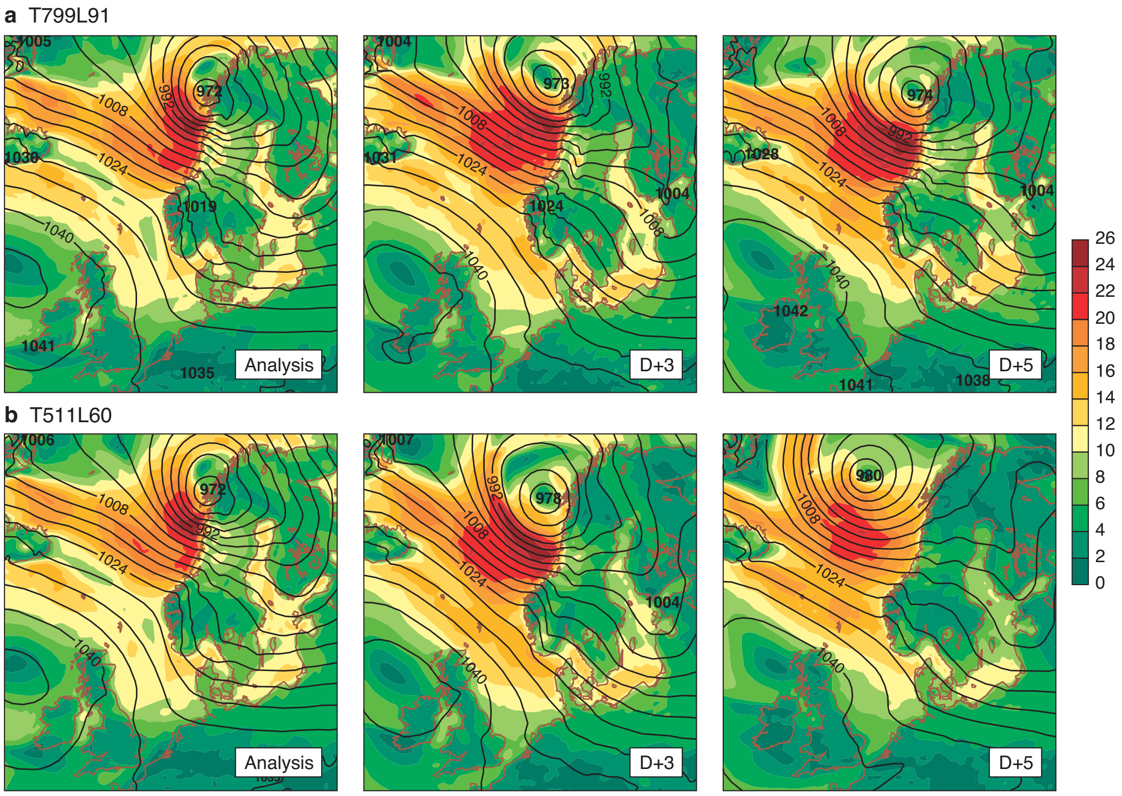


Figure 5 Mean sea level pressure and 10 m wind speed at 00 UTC on 12 December 2005 as analysed and predicted by (a) T799L91 and (b) T511L60: analysis (left), 3 day forecast (middle) and 5 day forecast (right).

doi:10.21957/qr32av62gk

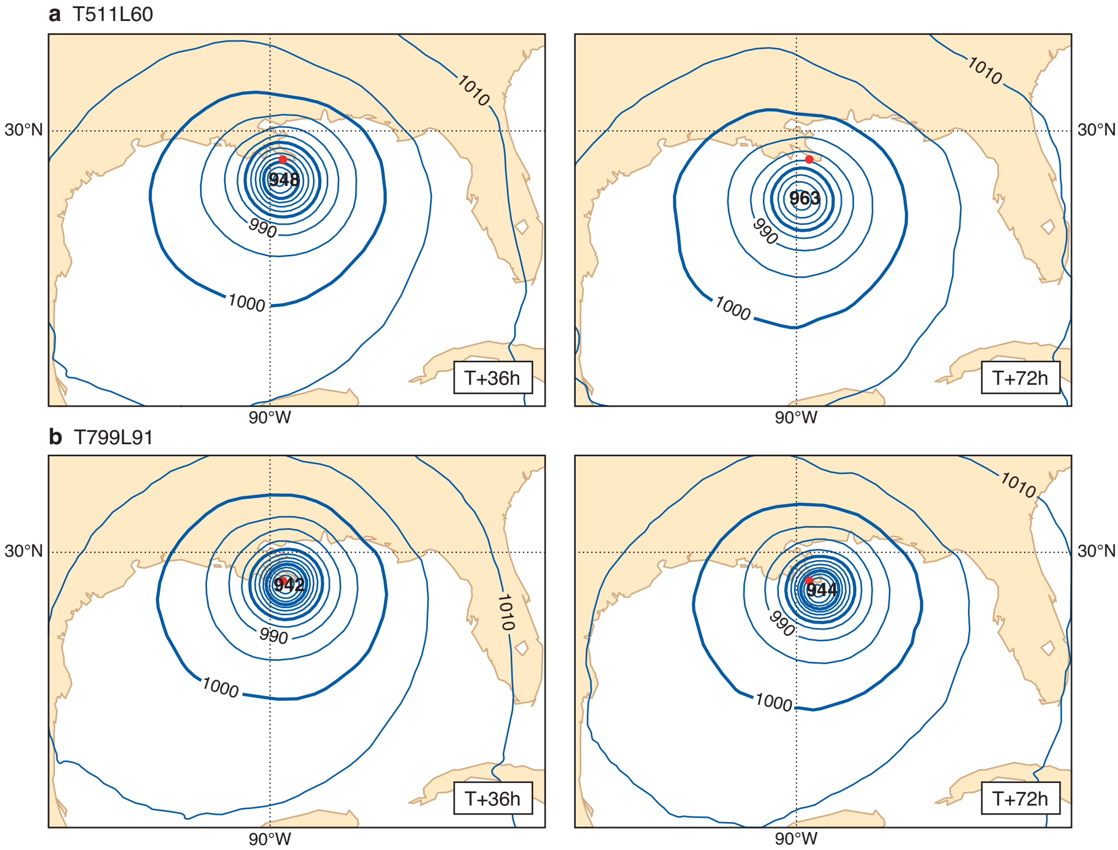


Figure 6 Forecasts of mean sea level pressure at 36 h and 72 h of hurricane Katrina for 12 UTC on 29 August 2005 using (a) T511L60 and (b) T799L91. The observed minimum pressure was 920 hPa at landfall, and the red dot marks the observed position of the cyclone.

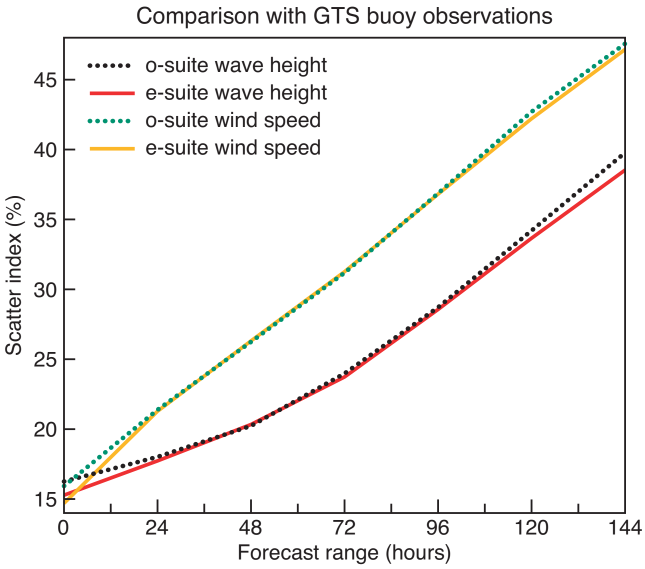


Figure 7 Comparison of scatter index (normalized standard deviation of error) in forecast wave height against buoy data between experimental suite (e-suite) and operational suite (o-suite). Period is from 1 October 2005 until 31 January 2006 and consists of 246 cases. The corresponding results for wind speed are shown as well.

doi:10.21957/qr32av62gk

Performance of the T399L62 EPS

The EPS performance for February, March and April (FMA) 2006 in predicting the 500 hPa geopotential height (Z500) over the northern hemisphere and Europe has been compared to its performance in the same period but for the previous three years, using a range of scores.

Results indicate that the new system has achieved the best performance of the past four FMA periods up to forecast day 7 with a better tuned ensemble spread, more skilful control and perturbed members, a more skilful ensemble-mean, and higher probabilistic scores.

On average in FMA 2006, the difference between the ensemble spread measured using the ensemble standard deviation, and the error of the ensemble-mean is the smallest up to forecast day 6 for the northern hemisphere (Figure 8(a)). During the same period, the ensemble-mean has an Anomaly Correlation Coefficient (ACC, computed with respect to the T799L91 analysis) above 0.6 out to day 10, and has a higher ACC than the ensemble control forecast and the high-resolution (T799L91) after day 3 (Figure 8(b)). It is noteworthy that the skill difference between the EPS control and the high-resolution system has decreased.

Probabilistic scores for the northern hemisphere for the same period using the area under the relative operating characteristic curve (which is a measure of the system to discriminate between hit and false alarm rates) show, for anomalies up to one climatological standard deviation, values greater than 0.75 up to forecast day 10 (Figure 9(a)). The Brier Skill Score (with the skill computed with respect to a climatological probabilistic prediction) for these thresholds is positive for the whole forecast range. Compared to the previous three years, the area under the relative operating characteristic curve and the Brier Skill Score have the highest values (Figure 9(b)).

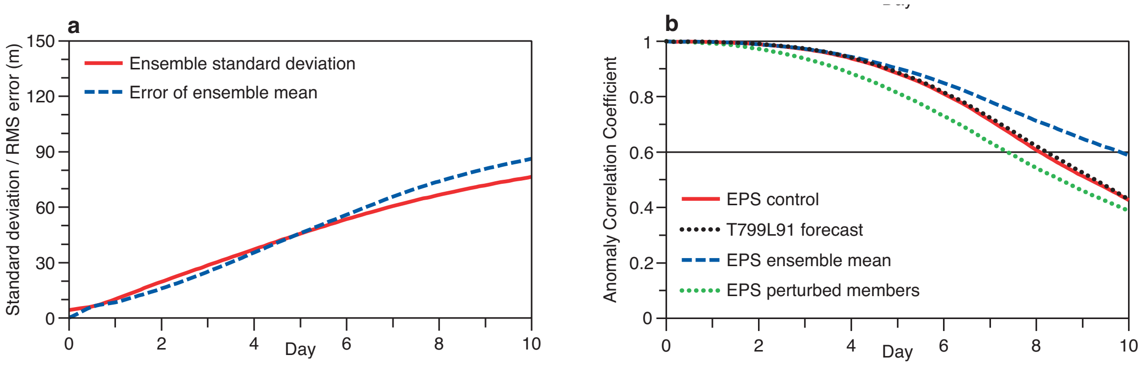


Figure 8 Average scores for Z500 over the northern hemisphere for February, March and April 2006. (a) Ensemble standard deviation and error of the ensemble-mean. (b) Anomaly Correlation Coefficient of the EPS control, T799L91 high-resolution forecast, EPS ensemble mean and the EPS perturbed members.

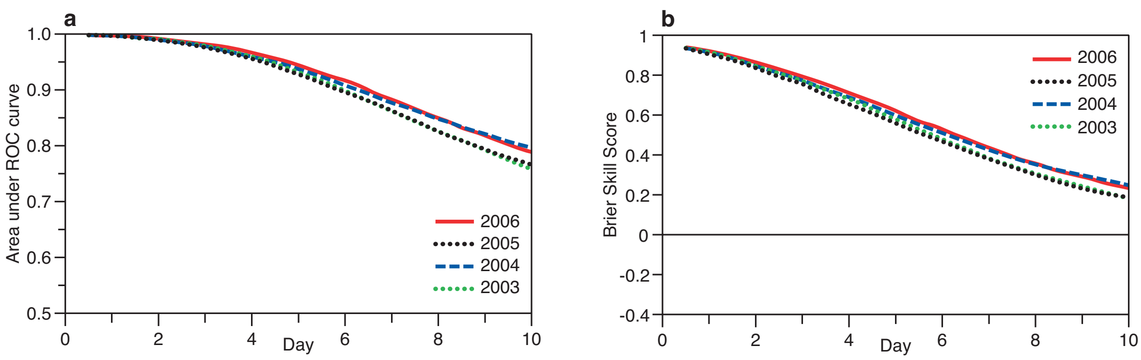


Figure 9 Spring average of Z500 over the northern hemisphere for (a) area under the relative operating characteristic curve for the prediction of positive Z500 anomalies and (b) Brier Skill Score (computed with respect to climatology) for 2006, 2005, 2004 and 2003.

doi:10.21957/qr32av62gk

What does the future hold?

There has been a particularly large improvement in operational forecasts over the past seven or so years, and evidence discussed here and elsewhere indicates that improvements have stemmed from improved data assimilation (improved assimilating models as well as improved analysis techniques), the availability of new or improved types of observation, refinements in physical processes, and from resolution increases across the entire forecast system.

In addition to the results presented here, forecasts of weather elements such as near-surface temperature, winds, cloud and precipitation have all improved. These benefit directly from model improvements as well as from the improved definition of the synoptic environment.

The spectral breakdown of error shows that there has been a distinct recent improvement in the handling of smaller scales of motion in the ECMWF system. In the new system's incremental 4D-Var data assimilation, the higher spectral truncation of the highest-resolution minimization is now at wavenumber 255. It has been shown previously that forecast error is still some way from saturation after twelve or even twenty-four hours for a range of wavenumbers higher than 159, making the case for further increasing the resolution of the minimisation to produce more accurate initial conditions for the forecasts.

The refinements in resolution of the analysis and deterministic forecasts transfer their benefits to the Ensemble Prediction System both through the improved quality of the initial conditions and the fact that the EPS uses resolutions that have been previously well tested and efficiently configured.

Any discussion on future developments splits into what is planned under current constraints (e.g. computer budget) and what would be possible without. Realistically, the new forecast systems will provide a framework on which to progressively develop our analysis and forecasting capabilities during the next 4-5 years. This will undoubtedly lead to better forecast guidance at all ranges, as the assimilation algorithms, physical parametrizations and ensemble methods take advantage of the more accurate global model framework provided at these higher resolutions.

Much higher resolution tests of the IFS, at T1279 (15 km) and T2079 (10 km) suggest that with sufficient computer power such resolutions could be implemented with versions of our current numerics and physics. It is planned to implement these resolutions operationally in 2010 and 2015 respectively, but the precise schedule will depend critically on the available budget for the high performance computing facility.

Further reading

Buizza, R., J.-R. Bidlot, N. Wedi, M. Fuentes, M. Hamrud, G. Holt, T. Palmer & **F. Vitart,** 2006: The ECMWF Variable Resolution Ensemble Prediction System (VAREPS). *ECMWF Newsletter No. 108,* 14–20.

Dritschel, D.G., L.M. Polvani & **A.R. Mohebalhojeh,** 1999: The contour-advective semi-Lagrangian algorithm for the shallow water equations. *Mon. Wea. Rev.,* **127,** 1551–1565.

Ebert, E.E., U. Damrath, W. Wergen & **M.E. Baldwin,** 2003: The WGNE assessment of short-term quantitative precipitation forecasts. *Bull. Am. Meteorol. Soc.,* **84,** 481–492.

Grazzini, F. 2005: The skill of the ECMWF forecasting system in the prediction of heavy rain events in the Alpine regions. *Submitted to Weather and Forecasting.*

Miller, M.J., 1999: Resolution studies. *ECMWF Tech. Memo No. 299.*

 doi:10.21957/qr32av62gk