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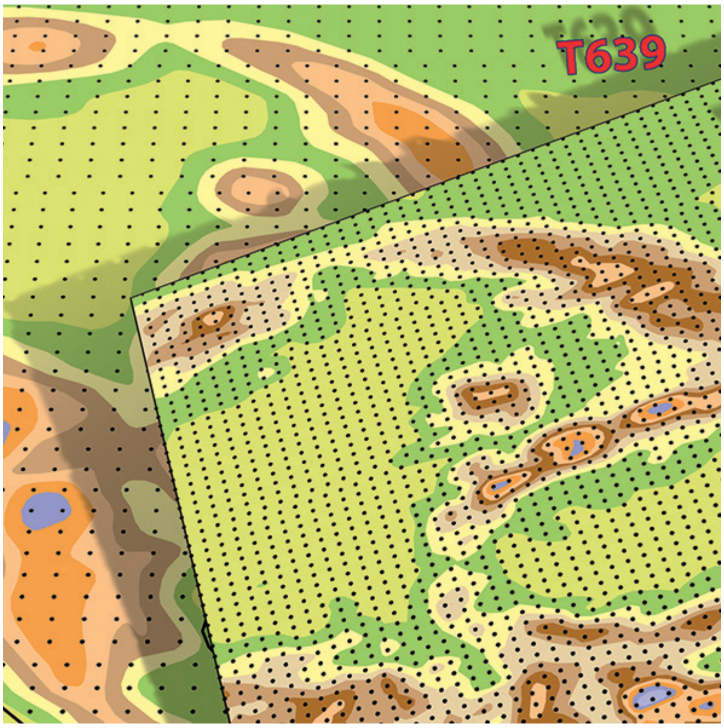
Increased resolution in the ECMWF deterministic and ensemble prediction systems



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Increased resolution in the ECMWF deterministic and ensemble prediction systems

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On 26 January 2010, ECMWF upgraded the horizontal resolution of the deterministic forecasting system and Ensemble Prediction System (EPS) which form components of the Integrated Forecasting System (IFS):

- For the deterministic forecast and analysis the horizontal resolution increased to T1279 (~16 km grid spacing) from T799 (~25 km).
- The resolution of the inner loops of the 4D-Var analysis changed to T159/T255/T255 (~125 km/78 km/78 km) from T95/T159/T255 (~210 km/125 km/78 km).
- The EPS resolution increased to T639 (~32 km) from T399 (~50 km) for leg1 (the first 10 days of the forecast) and to T319 (~65 km) from T255 (~80 km) for leg2 (day 9 to day 15 and day 32 for the monthly forecast).
- The coupled ocean wave model resolution was upgraded to 0.25° (~28 km) from 0.36° (~40 km) in the deterministic system, and to 0.5° (~56 km) from 1° (~111 km) in the EPS.

The vertical resolution remained unchanged at 91 levels for the deterministic system and at 62 levels for the EPS.

The various resolution increases have been implemented as IFS Cycle 36r1. In addition, a correction to the interaction of short-wave radiation with clouds is also included in this cycle.

Extensive experimentation accompanies a major operational change such as those described here.

This article describes the resolution upgrades in the different components of the Centre's forecasting system, 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 these resolution upgrades, their operational implementation and to the results presented here.

Previous resolution upgrades

IFS Cycle 36r1 is the sixth major horizontal resolution upgrade for the deterministic system in the 30 years or so of the Centre's operational activities and the fourth upgrade for the EPS.

The ECMWF model is a spectral model based on a spherical harmonics expansion. For the deterministic forecast, the previous resolution increase to T799, which also included an upgrade of the vertical resolution to 91 levels, was implemented four years ago on 1 February 2006. The notation T799 indicates that the largest wave number retained in the expansion is 799 and the letter 'T' specifies that a 'triangular truncation' is used to limit the number of terms in the expansion sum. Sometimes the notation is expanded to include the number of vertical levels – in this case the full resolution would be specified as T799L91.

The resolution of the EPS has previously been upgraded three times since it became part of the Centre's operational suite in December 1992: from T63L19 to T159L31 in December 1996, to T255L40 in November 2000, and then to T 399L62 on 1 February 2006. In October 2006 the Variable Resolution Ensemble Prediction System (VAREPS) comprising two forecast-legs (leg 1: 10-day forecast at T399L62 followed by leg 2: 6-day forecast from day 9 to day 15 at the lower resolution of T255L62) became operational, and in October 2008 the EPS was merged with the monthly prediction system which extends out to 32 days once per week.

Increases in horizontal and vertical resolutions of the Centre's assimilation-forecasting 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 ranges. 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, these refinements in resolution have brought systematic improvements

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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. Each change has contributed significantly to the long-term positive trend in forecast skill and the systems' ability to forecast severe weather.

Resolution increase in the deterministic system

In IFS Cycle 36r1 the horizontal resolution of the deterministic model has increased by about 60%, from T799 to T1279.

The new grid used for grid-point computation (linear Gaussian grid) has 1280 latitude rows, an increase by 480 rows with respect to the T799 grid (800 latitude rows). Along each latitude row near the equator there are 2560 grid points in the new resolution. In the 'reduced' Gaussian grid, used by the Centre's model, the number of grid points along a latitude is decreased gradually towards the poles, thereby reducing the total number of grid points by roughly ⅓ compared to the unreduced Gaussian grid. In total, the new horizontal grid has 2,140,704 grid points, 1,297,214 more than the T799 reduced Gaussian grid (843,490 grid points). This corresponds to a 2.5 fold increase in the number of grid points.

Figure 1 gives an impression of the difference between the new and the old resolutions by contrasting the orography of Iceland at T1279 and T799. Also shown are the locations of the grid points of the corresponding reduced Gaussian grids. The coastline of the higher resolution orography follows much more closely the real coastline of Iceland. Most striking is the improvement in the shape of the large bifurcated peninsula in the northwest of Iceland. The increase in orographic detail and realism with T1279 for the mountainous interior of the island is also noteworthy. Such improvement in the representation of the orography leads directly to improved forecasts of weather events which are strongly influenced by orographic features.

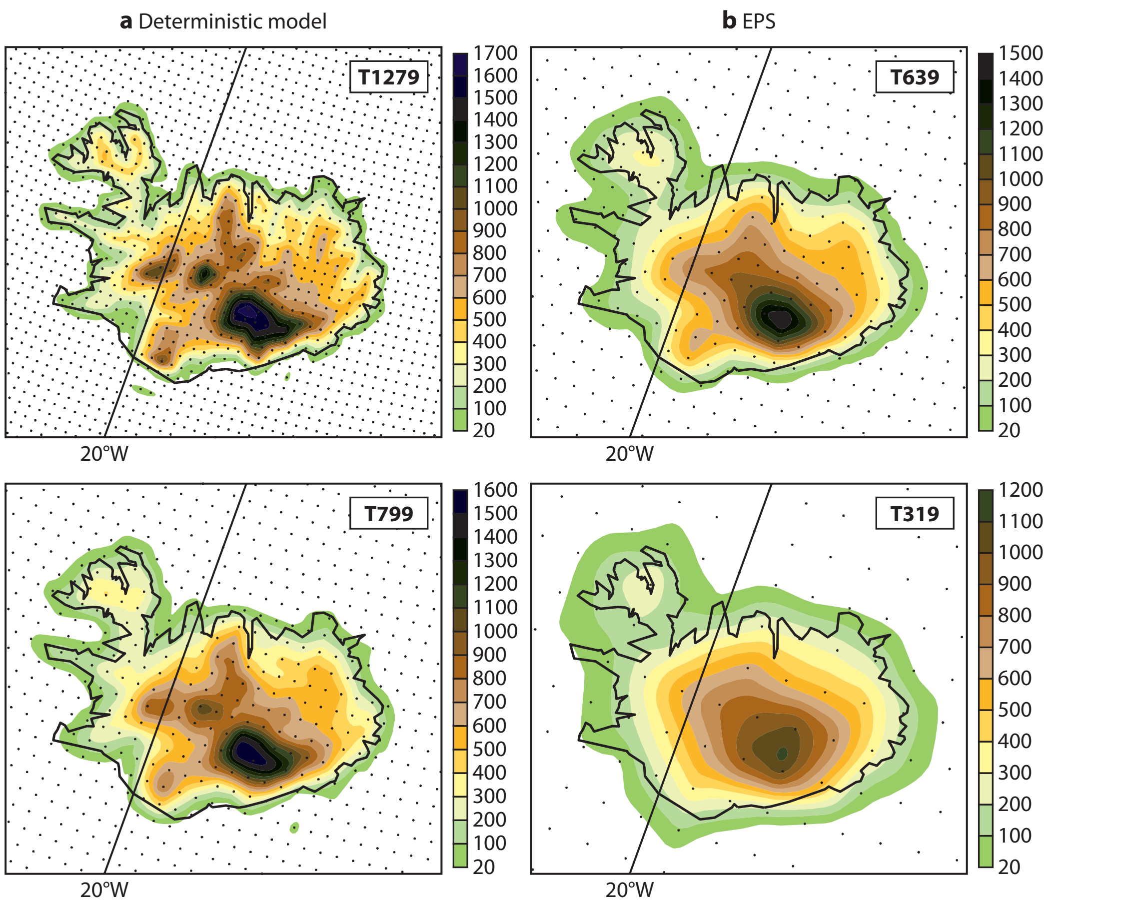

Figure 1 Orography and location of grid-points for (a) the deterministic model: new resolution T1279 (grid spacing ~16 km) (top) and previous operational resolution T799 (grid spacing ~25 km) (bottom), and (b) for the new resolutions of the two legs of the EPS: T639 (grid spacing ~32 km) (top) and T319 (grid spacing ~65 km) (right).

The horizontal resolutions of the different components in the 4D-Var assimilation system have also been upgraded: the outer loop changed to T1279 like the deterministic model, while the resolutions of the first and second inner loops have been upgraded to T159 (from T95) and T255 (from T159), respectively. The resolution of the third inner loop remained unchanged at T255. Experimentation with a third inner loop resolution of T399 did not give the anticipated improvement in analysis and forecast quality due to problems with the new background error statistics computed at T399. Work is in progress to gain a better understanding of the problems and how to solve them, with the aim of upgrading the resolution of the third inner loop to T399 in the future.

Numerical stability constraints usually require a reduction in the length of the time step whenever the model resolution is increased. 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 was reduced to 10 minutes from the 12 minutes used with the T799 resolution. All three inner loops of 4D-Var are run with a 30-minute time step.

Resolution increase in the coupled ocean wave model

The spatial resolution of the WAve Model (WAM), which is part of the IFS and coupled to the atmospheric model, has also been upgraded: from 0.36° (~40 km) to 0.25° (~28 km) in the T1279 deterministic model and from 1° (~111 km) to 0.5° (~56 km) in the ensemble prediction system. At the same time the representation of the wave spectrum was improved, with the spectrum now consisting of 36 frequencies and 36 directions (previously 30 frequencies and 24 directions). In addition, the correlation length scale which controls the spread of observed information in the wave data assimilation was reduced from 300 km to 150 km.

Resolution increase in the ensemble prediction system

Since 2006 ECMWF has been running operationally a Variable Resolution Ensemble Prediction System (VAREPS) where each ensemble member is generated by a two-leg forecast with different horizontal resolutions in the two legs. The vertical resolution is the same for both legs (62 levels). For a detailed description of this system and the rationale behind it see the article by *Buizza et al*. in ECMWF *Newsletter No. 108*.

Concurrent with the resolution upgrade of the deterministic system for IFS Cycle 36r1, the horizontal resolution of the EPS has also been increased: leg 1 is now run at T639 with a time step of 20 minutes and leg 2 at T319 with a 45-minute time step. These two resolutions are illustrated in Figure 1 along with the old and new resolutions of the deterministic model.

The resolution of the ocean wave model coupled to the EPS forecasts has also been increased from 1° to 0.5° for both legs of the EPS forecasts (i.e. for the whole 15 days). The representation of the wave spectrum was upgraded for leg 1 to 36 frequencies and 36 directions (from 30 frequencies and 24 directions), and for leg 2 to 30 frequencies and 24 directions (from 25 frequencies and 12 directions).

The number of vertical levels in the EPS has been kept to 62. No changes have been introduced in the initial perturbations, and both the ensemble size (50 perturbed and one unperturbed member) and the forecast lengths of the two legs have been kept the same. The increased resolution EPS will be denoted throughout this article as 639v319 EPS and the previous operational system as 399v255 EPS.

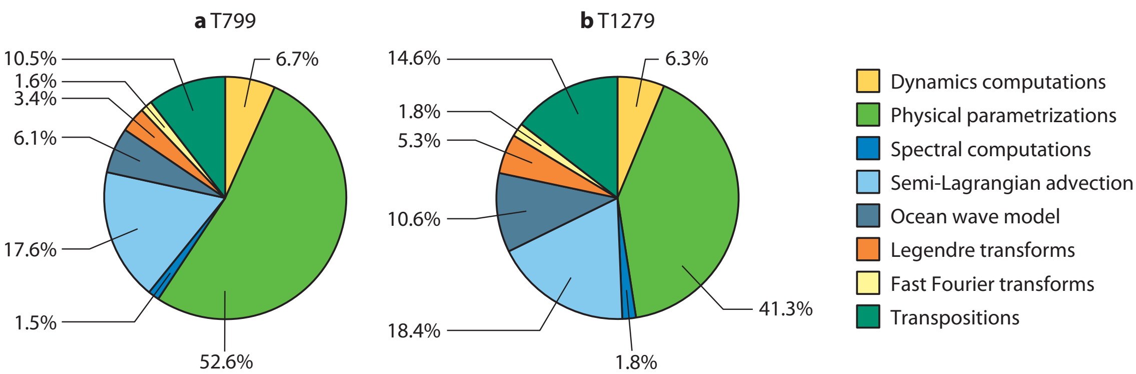

Figure 2 Pie charts showing the relative cost of various parts of the model at horizontal resolutions (a) T799 and (b) T1279.

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Computational cost of the resolution upgrade

The 2.5 fold increase in the number of grid-points and the reduction in the time step to 10 minutes, together with the upgrades to the coupled wave model have led to a 3.7 fold increase in the total number of floating point operations necessary to complete a 10-day forecast (at the operational vertical resolution of 91 levels). Hence there are 6.3×10^{15} floating point operations at T1279 as compared to 1.7×10^{15} at T799.

Figure 2 shows the relative contributions to the cost from the different parts of the model for the two resolutions. Not surprisingly, the relative cost of the wave model has increased (from 6.1% to 10.6% of the total cost) due to the resolution increase and the enhancement of the spectrum. Also, the relative costs of the Legendre transforms and of the transpositions, required for the spectral computations, have grown faster with increased resolution than much of the rest of the model, as was expected. However, the spectral model is still very affordable, and work is in progress on adapting a fast Legendre transform algorithm for the IFS to keep the spectral model affordable at future, much finer, resolutions.

Performance of the T1279 deterministic system

The high-resolution system has undergone extensive testing by the Research Department for the forecast period December 2008 to July 2009 and then by the Operations Department in e-suite mode (used for pre-operational testing) for the forecast period mid-July 2009 to 25 January 2010.

Objective verifications scores show statistically significant improvements in geopotential height at 1000 and 500 hPa for both hemispheres and for Europe out to at least day 5. Figure 3 shows the normalised difference in anomaly correlation of 500 hPa geopotential height between T1279 and T799 together with the 95% confidence interval computed from over 600 assimilation/forecast cases. The resolution increase results in a clear forecast improvement at all ranges up to eight days in the northern hemisphere and five and a half days in the southern hemisphere and in Europe. There is also a systematic improvement of 850 hPa temperature and winds at all levels.

The improved representation of the orography at T1279 leads to a significant increase in the number of near-surface observations accepted by the first-guess quality control in the 4D-Var assimilation. For example, 1.5% more temperature observations from upper-air soundings were assimilated at 1000 hPa in the northern hemisphere and 2% more in the tropics in the T1279 e-suite than in the T799 control. Similar increases are also seen for wind soundings.

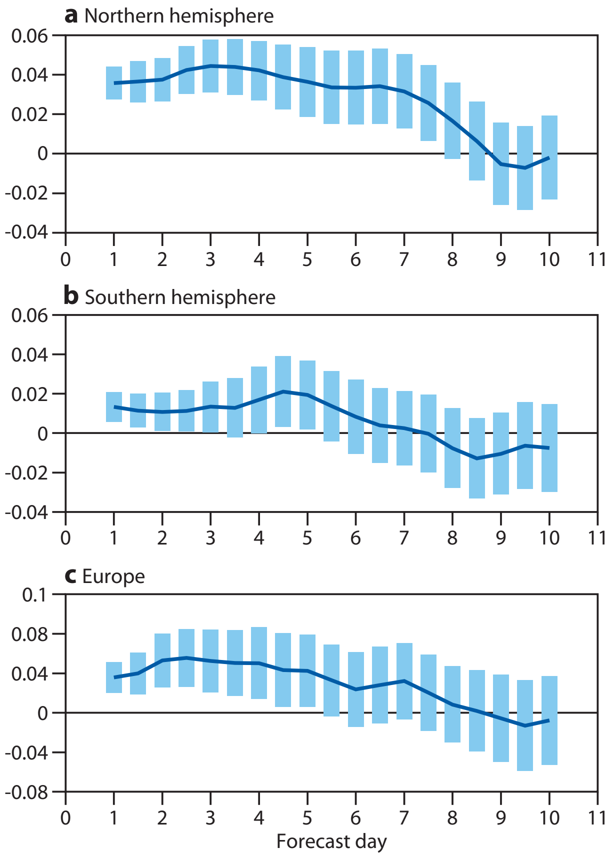

Figure 3 Impact of the horizontal resolution upgrade on the deterministic forecast skill. The figure shows the normalised difference in anomaly correlation of 500 hPa geopotential height between T1279 and T799 (blue line) together with the 95% confidence interval (blue bars) for (a) northern hemisphere, (b) southern hemisphere and (c) Europe. The sample comprises 615 forecasts from December 2008, and the verification of the two models is against their own analysis.

In general, the intensity and location of synoptic features are improved in the high-resolution system and the frequency of occurrence of intense rainfall events has increased, resulting in a better agreement with precipitation observations as shown in Figure 4. The overall impact on weather parameters is however modest.

As was anticipated, the enhanced resolution has a positive effect on the analysis and forecast quality of tropical cyclones, and both position and intensity errors are reduced on average in the higher-resolution system.

The T1279 model has also been tested in two continuous 47-year integrations as part of Project Athena. This is an international project led by the Center for Ocean-Land-Atmosphere Studies (COLA), USA on the importance of high spatial resolution in climate modelling. One of the long integrations is a 'historic' run for the period 1961–2007 with observed sea surface temperatures and the other is a 'future scenario' run (A1B-scenario) for 2071–2117. Forty eight 13-month hindcasts for the years from 1960 to 2007 were also run at T1279. The computer resources for these runs were made available by the U.S. National Science Foundation on the CRAY-XT4 supercomputer 'Athena' at the National Institute for Computational Sciences at Oak Ridge National Laboratory, USA, and are gratefully acknowledged. (For more information about Project Athena see the news item on the Athena Workshop in this issue of the *ECMWF Newsletter*.) While most of the diagnostics on the vast amount of data generated by these simulations have still to be produced, these runs show that the T1279 model in its operational configuration (no changes were made specifically for these simulations) can be run stably and efficiently over long time periods and for different boundary forcings.

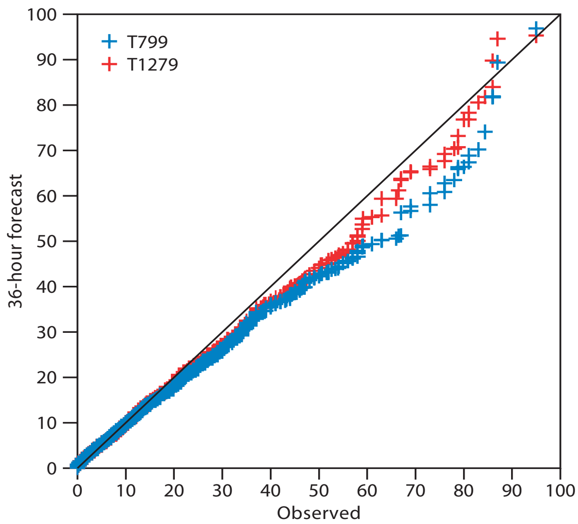

Figure 4 Quantile-Quantile plot comparing the 36-hour forecast and observed distributions of precipitation for T1279 (red) and T799 (blue) for the month of December 2008.

Performance of the wave model

The e-suite has shown considerable improvements in the wave-related forecast scores in all areas. Figure 5 shows the improvement in wave height anomaly correlation in the northern and southern hemispheres.

For a large part these improvements are thought to be caused by the reduction of the correlation length scale and the improved representation of the wave field. However, the accuracy of the forcing wind field has increased as well. This can be shown with the help of the European shelf model, which is a standalone version of WAM at 11 km resolution forced by 3-hourly winds produced by the deterministic forecast. With the introduction of the T1279 model the specifications of the European shelf model remained unchanged, only the forcing wind fields changed. By verifying the forecasts performance against independent wave height observations from buoys it is therefore possible to attribute the improvements seen with T1279 forcing winds over T799 winds directly to the improved quality of the T1279 winds. The average reduction in root-mean-square error scores of forecast wave height and wind speed verified against buoy data obtained with forcing winds from the T1279 e-suite is shown in Figure 6.

The resolution increase and enhancements made to the wave model have led to an improved specification of the sea state, in particular in coastal areas. Based on the evidence presented here it is thought that even freak wave prediction should have improved, as this depends sensitively on how accurate the mean sea state is modelled. On 3 March 2010 in the north-western Mediterranean near Marseilles the cruise ship Louis Majesty was hit by freak waves causing two fatalities and 14 injuries. Figure 7 shows the 15-hour forecast of maximum wave height for this date. In the area of the accident, the maximum wave height exceeds 10 m, in good agreement with the reported height of the waves that damaged the Louis Majesty.

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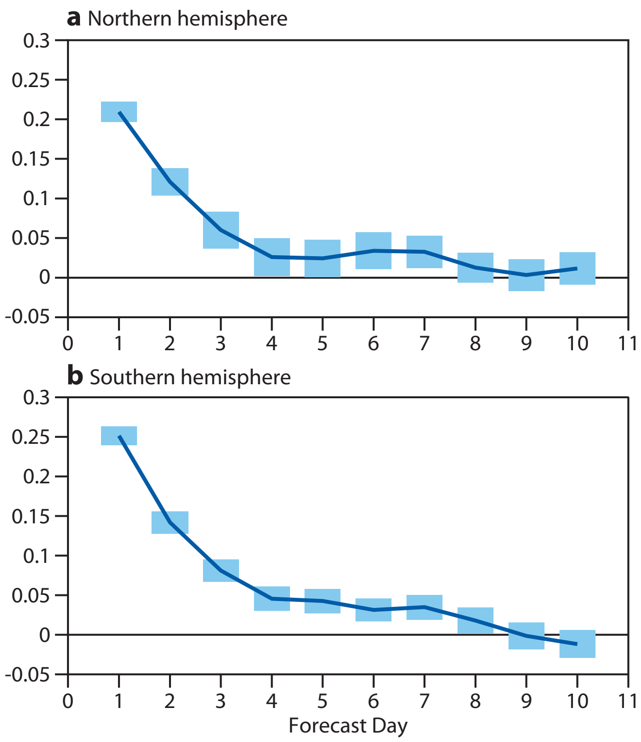

Figure 5 Improvement in wave height correlation of the wave height forecasts against own analysis for (a) northern hemisphere and (b) southern hemisphere. Shown are the normalised differences between the new system and the old. Large improvements are seen up to day 5 in the forecast. Results are shown for 16 July 2009 to 24 January 2010.

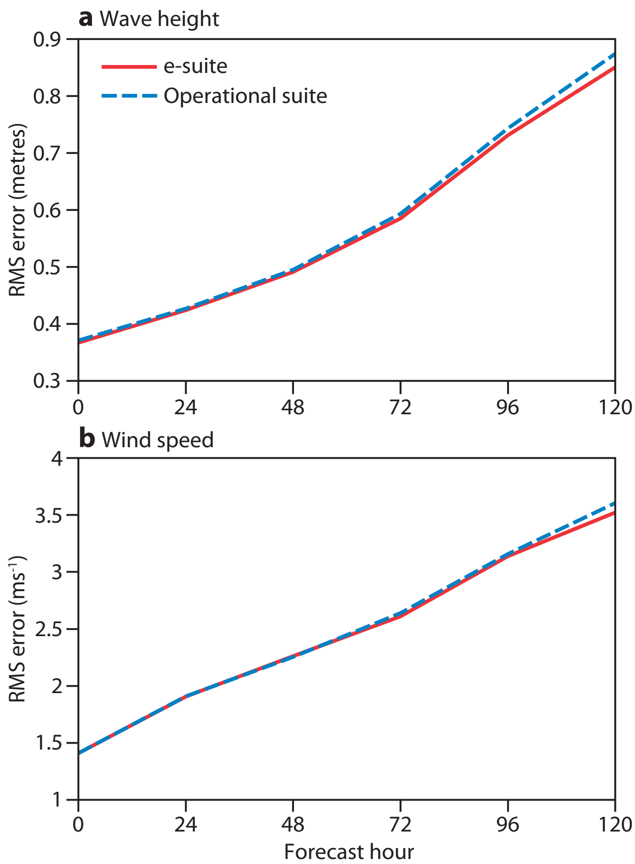

Figure 6 Root-mean-square (RMS) error scores of forecast (a) wave height and (b) wind speed from the e-suite (red) and the operational suite (blue) verified against buoy observations for the European shelf model for the period 1 November 2009 to 31 January 2010. A reduction in RMS error of wave height due to improved T1279 winds is clearly seen.

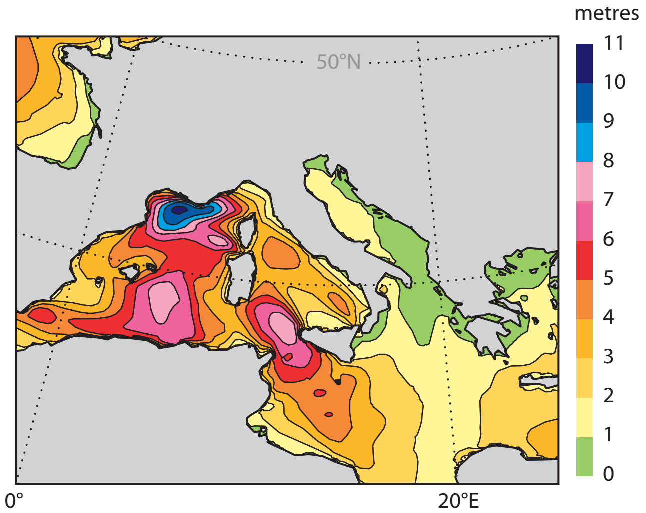

Figure 7 15-hour forecast of maximum wave height at the time that the Louis Majesty was hit by a freak wave causing two casualties and 14 injuries. The reported individual wave height was estimated at around 10 metres. The forecast was run from 00 UTC on 3 March 2010.

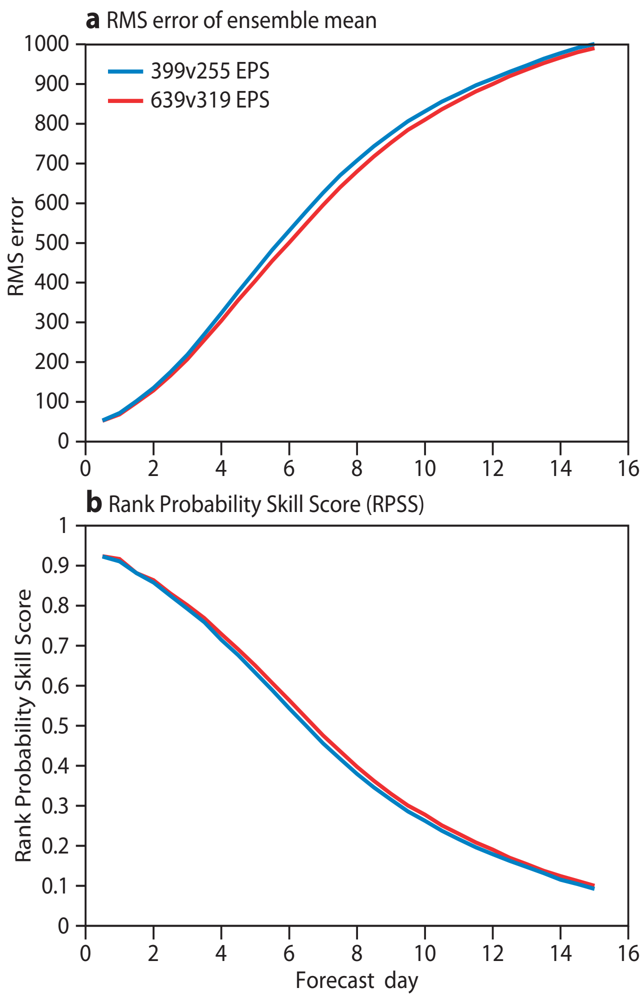

Figure 8 88-case average (5 October to 31 December 2009) of (a) root-mean-square error of the ensemble-mean (EM) and (b) rank probability skill score (RPSS) for forecasts of the 500 hPa geopotential height for the northern hemisphere from the old 399v255 EPS (blue lines) and the new 639v319 EPS (red lines).

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Performance of the new 639v319 EPS

Forecasts from the new 639v319 EPS starting from T1279L91 unperturbed initial conditions have been compared to forecasts from the old 399v255 EPS starting from T799L91 initial conditions for 88 cases (5 October to 31 December 2009). This comparison gives the users an estimate of the improvements that they should be able to detect, on average, following the resolution increase. Each system has been verified against its own unperturbed analysis.

Average results based on these 88 cases indicate that the error of the 639v319 ensemble-mean is lower and the 639v319 probabilistic forecasts have higher skill. The spread of the 639v319 EPS starting from T1279 analysis is slightly larger (~5%) than the spread of the 399v255 EPS starting from T799 analysis. This is due to the T1279 analysis error estimate being locally larger than that of the T799 analysis, which is used to scale the ensemble initial perturbations. With this and the reduction of the error of the ensemble-mean, the new 639v319 EPS has a larger spread overestimation in terms of 500 hPa geopotential over the northern hemisphere, but it has a better tuned spread in terms of 850 hPa temperature, for which the old 399v255 EPS used to be under-dispersive.

Figure 8a shows the impact of the resolution increase on the root-mean-square error of ensemble-mean forecasts of 500 hPa geopotential and 850 hPa temperature over the northern hemisphere extra-tropics. The positive impact (i.e. smaller root-mean-square error) of the resolution increase is statistically significant at the 5%-level at all forecast ranges, with the largest positive impact shown at around forecast day 6.

Figure 8b shows the impact on the rank probability skill score (RPSS) of 500 hPa geopotential forecasts over the northern hemisphere. Positive differences (i.e. larger RPSS) are statistically significant at the 5%-level between forecast day 2 and day 10 for the geopotential. Similar positive impacts are also seen on other variables over different areas (not shown). Overall, these differences correspond to gains of up to 8 hours in forecast accuracy.

The impact of increased EPS resolution has also been evaluated using a series of 15-member ensemble integrations with a 32-day forecast length starting from the 15th day of November, December and January 1989 to 2008 (a total of 90 winter cases). The probabilistic skill scores of weekly forecasts obtained for the two sets of hindcasts are very close, except for temperature at 850 hPa for the time range day 5–11 where the new 639v319 EPS has slightly improved probabilistic scores. Model biases of the two systems are very similar.

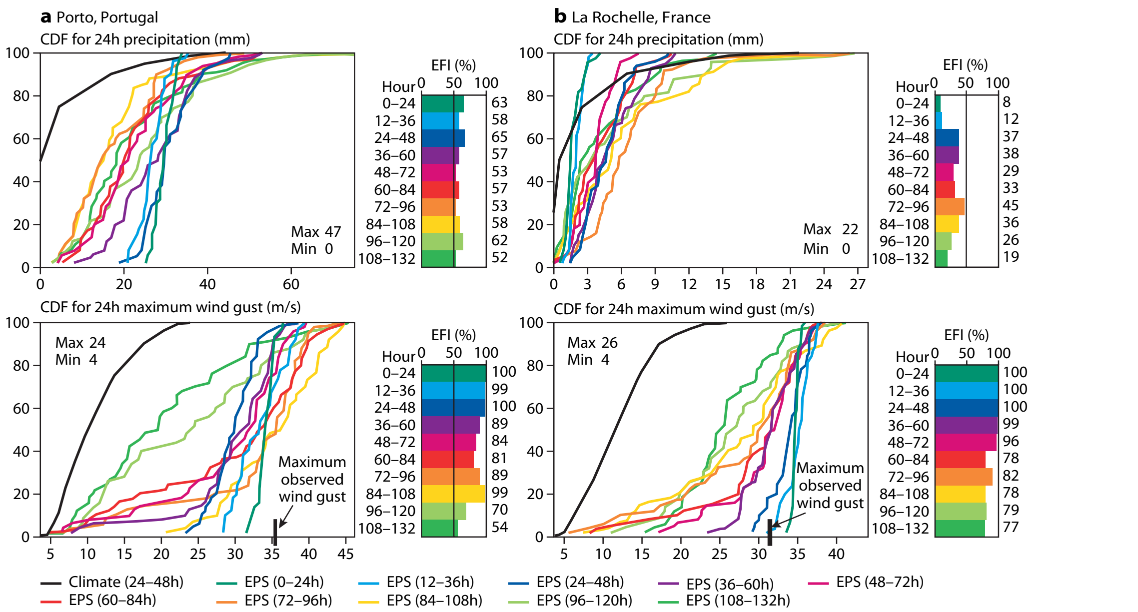

Figure 9 Storm Xynthia at (a) Porto, Portugal and (b) La Rochelle, France: Cumulative Distribution Function (CDF, left panels) and Extreme Forecast Index (EFI, right panels) forecasts of 24-hour precipitation and wind gust issued by subsequent 639v319 EPS forecasts from 12 UTC on 22 (t+132 h) to 27 (t+24 h) February 2010 for 00 UTC on the 28 February. The EFI indicates the difference between the model climatic distribution the EPS forecast, measured by the area between the climate (black line) and the forecast CDF computed between the minimum and maximum climate values; it scales from –1 to 1 (for more information see 'Recent developments in extreme weather forecasting', *ECMWF Newsletter No. 107*, 8–17).

Forecast of the European winter storm Xynthia

Between 27 and 28 February 2010 a violent storm, named Xynthia, caused much damage and loss of lives along the western European coast and in northern Europe. In France it was described by the civil defence as the most violent since storms Lothar and Martin struck the country in December 1999, with more than 50 people killed. Most of the deaths in France occurred when a powerful storm surge, topped by battering waves of up to 7.5 metres high and a high tide, smashed through the sea wall of the coastal towns of L'Aiguillon-sur-Mer and La Faute-sur-Mer. The severe storm surge (up to 1.5 metres) was also the principal cause of the damage. The surge was the result of the combination of a high astronomical tide, very low pressure (965 hPa) and very strong winds.

The maximum wind gusts observed at several airports in Portugal (e.g. at Porto) and western France (e.g. at La Rochelle) have been well predicted by the new 639v319 EPS, as shown by the Cumulative Distribution Functions of wind gusts at these two locations (Figure 9).

The following analysis concentrates on mean sea-level pressure (MSLP) forecasts valid at 12 UTC on 28 February 2010, a time when the operational T1279 analysis recorded a minimum MSLP of 973 hPa at (51.5°N, 3.5°E). For this verification time the intensity and position error of MSLP forecasts from the operational T1279 deterministic system, the new 639v319 EPS, and from the old 399v255 EPS have been compared. There is little sensitivity to resolution for forecasts up to 48 hours. At 60 hours all three forecasts have a MSLP minimum that is too deep, with intensity errors of 8.0 hPa for both EPS control runs and of 6.5 hPa for the deterministic run. In terms of position error, the old 399v255 EPS control has the largest error (~200 km). For longer forecast times, the three forecasts start to diverge both in terms of intensity and position error. Up to 84 hours, the T1279 deterministic system provides the best forecasts, confirming the benefit from higher resolution to severe weather prediction.

Figure 10 shows the number of 639v319 EPS and 399v255 EPS perturbed members with intensity and position errors smaller than, respectively, 2.5 hPa and 100 km. On average, the 639v319 EPS has a larger number of skilful members than the 399v255 EPS showing that there is a clear advantage for the 639v319 EPS up to 84 hours, while the signal is more mixed afterwards.

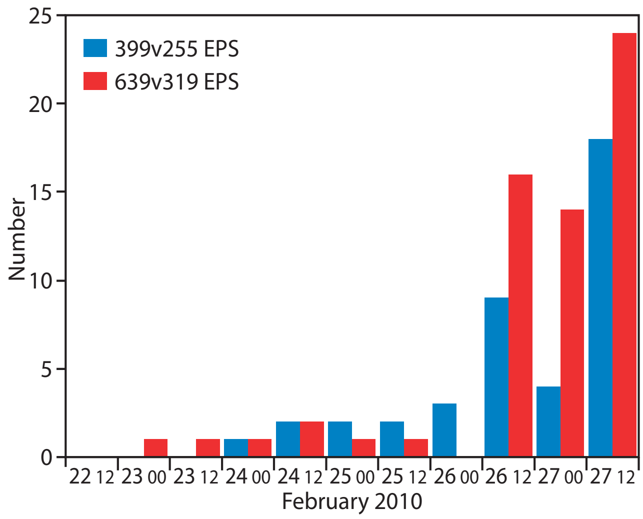

Figure 10 Storm Xynthia: number of EPS members with intensity error less than 2.5 hPa and position error less than 100 km for mean sea-level pressure (MSLP) perturbed forecasts from the 399v255 EPS (blue) and the 639v319 EPS (red). The forecasts are issued every 12 hours from 12 UTC on 22 to 12 UTC on 27 February 2010 and valid at 12 UTC on 28 February. At the verification time the ECMWF operational T1279 analysis had a minimum MSLP of 973 hPa at (51.5°N, 3.5°E).

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Plans for future resolution upgrades

Following this major upgrade in horizontal resolution across the ECMWF forecasting system, an upgrade in vertical resolution by about 50% from the current 91 levels is planned for mid-2011.

The next horizontal resolution upgrade is planned to bring the grid spacing down to 10 km (T2047) in the middle of this decade. Some experimentation with this resolution has already been carried out. In particular, twenty 13-months and nine 4-months hindcasts have been run as part of Project Athena.

Preliminary results from these tests indicate that this resolution will probably require only small changes to the current dynamics, numerics and physical parametrizations, but no data assimilation has yet been run.

Beyond this resolution however, more fundamental changes to the Centre's IFS will be required. As the horizontal grid spacing decreases to well below 10 km, the hydrostatic approximation to the pressure field (used in the operational version of the IFS) becomes progressively less accurate, making a non-hydrostatic dynamical core for the IFS essential. Also, the numerics of the IFS will have to be adapted to cope with the very steep gradients such fine resolution can resolve. Furthermore, convection will become partly resolved by the dynamics and the convection parametrization will have to account for this new regime.

The Centre is already taking steps to prepare for the new challenges by working on a non-hydrostatic dynamical core in collaboration with Météo-France, ALADIN and HIRLAM, the implementation of a fast Legendre transform algorithm, and the development of a more scalable data-assimilation system.

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.

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