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EPS skill improvements between 1994 and 2005

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EPS skill improvements between 1994 and 2005

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The predictability gains of the ECMWF Ensemble Prediction System (EPS) between 1994 and 2005 have been assessed. Results show that the accuracy of medium-range EPS probabilistic forecasts over Europe has improved by about twice the rate experienced by single forecasts given by the EPS control. The analysis of the skill of mid-tropospheric forecasts at days 5 and 7 over the Northern Hemisphere indicates that single forecasts have improved by between 1 and 1.7 days/decade and that probabilistic forecasts have increased by between 2 and 3.7 days/decade. For Europe, corresponding gains amount to ~0.8 days/decade for control forecasts and ~1.5 days/decade for probabilistic forecasts. The extra predictability gains of probabilistic predictions are linked to improvements in the representation of the probability distribution function of forecast states, achieved through the years by improvements in all aspects of the ensemble system (resolution, ensemble size, introduction of evolved singular vectors in the generation of initial perturbations and stochastic physics).

Ensemble Prediction at ECMWF

The skill of single forecasts (i.e. of forecasts given by one integration, for example by the EPS control forecast) is limited for two key reasons: the presence of uncertainties in the initial conditions and the approximate simulation of atmospheric processes achieved in the state-of-the-art numerical models. A further complication is that these two sources of uncertainties limit the skill of single forecasts in a rather unpredictable way. One way to alleviate this problem is to move from a ‘single’ to a ‘probabilistic’ approach to numerical weather prediction. In other words to estimate not only the most likely forecast scenario but also the time evolution of an appropriate probability density function in the atmosphere’s phase space. An ensemble of forecasts can be used to estimate the probability density function of forecast states.

Since 19 December 1992, ECMWF has been producing operationally global ensemble forecasts precisely to provide an estimate of the probability distribution function of forecast states. Initially, the ECMWF EPS included only a simulation of initial uncertainties, but since October 1998 the EPS included also a stochastic scheme designed to simulate the random model errors due to parameterized physical processes. Table 1 lists the key upgrades of the ECMWF from the implementation of a 33-member T63L19 system (spectral truncation T63 with 19 vertical levels) in December 1992.

Date	Description	Singular Vector Characteristics						Forecast Characteristics				
		HRES	VRES	OTI	Target Area	EVO SVs	Sample Method	HRES	VRES	Tend	Ensemble Size	Model Uncert
Dec 1992	Operational Implementation	T21	L19	36 h	Globe	No	Simm	T63	L19	10 d	33	No
Feb 1993	SV Local Projection Operator	"	"	"	NHx	"	"	"	"	"	"	"
Aug 1994	SV Optimization Interval	"	"	48 h	"	"	"	"	"	"	"	"
Mar 1995	SV Horizontal Resolution	T42	"	"	"	"	"	"	"	"	"	"
Mar 1996	Extratropical SVs	"	"	"	(NH+SH)x	"	"	"	"	"	"	"
Dec 1996	Resolution/Members	"	L31	"	"	"	"	T_L159	L31	"	51	"
Mar 1998	Evolved SV	"	"	"	"	Yes	"	"	L31	"	"	"
Oct 1998	Stochastic Physics	"	"	"	"	"	"	"	"	"	"	Yes
Oct 1999	Vertical Resolution	"	L40	"	"	"	"	"	L40	"	"	"
Nov 2000	Forecast Horizontal Resolution	"	"	"	"	"	"	T_L255	"	"	"	"
Jan 2002	Tropical SVs	"	"	"	(NH+SH)x+TC	"	"	"	"	"	"	"
Sep 2004	Sampling	T42	L40	48 h	(NH+SH)x+TC	Yes	Gauss	T_L255	L40	10 d	51	Yes

Table 1 List of key changes introduced in the ECMWF EPS configuration. Columns list the horizontal resolution (HRES, expressed in terms of spectral truncation), the vertical resolution (VRES, expressed in terms of number of vertical levels), the optimization time interval used (OTI, in hours) and the target area used to compute the singular vectors (Target Area), the use of evolved singular vectors (EVO SVs), the sampling method used to generate the initial perturbations (Sample), the forecast length (Tend, in days), the number of ensemble members (Ensemble Size) and whether model uncertainty is simulated or not (Model Uncert).

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EPS configuration operational since November 2000

Each ensemble member is defined by the time integration of a version of the ECMWF model that includes stochastic perturbations to simulate the effect of random model errors, starting from perturbed initial conditions. The use of stochastic perturbations and of singular vectors to generate the initial perturbations are two key features of the ECMWF EPS that distinguishes it from the two leading global ensemble systems implemented at the Meteorological Service of Canada and the National Centers for Environmental Prediction of the United States.

Singular vectors identify perturbations of maximum growth during a finite time interval, named the optimization time interval: small errors in the initial conditions along these directions would amplify most rapidly, and affect the forecast accuracy. Singular vectors are usually located in regions of strong barotropic and baroclinic activity. At initial-time, they have most of their energy confined in the small scale and are confined vertically in the lower troposphere. During the optimization time interval, they change shape and grow in scale, and vertically propagate upward. As an example, Figure 1 shows the amplification rate (i.e. the singular value) of the leading 25 Northern-Hemisphere singular vectors used in the EPS started at 12 UTC on 1 December 2003. The corresponding average vertical distribution of total energy and the total energy spectra for these singular vectors are given in Figure 2. These two figures summarize two of the key characteristics of the singular vectors.

- The decreasing spectra of singular values, with all the first 25 singular vectors showing an amplification rate in terms of total energy greater than 10, and the leading singular vectors showing a 15-20 amplification rate.
- The upward energy propagation during the optimization time interval coupled with the conversion of initial-time potential energy into final-time kinetic energy, and the upscale energy propagation from the small- to the large- (synoptic) scales.

The EPS configuration operational in 2005 (Table 1) includes 50 perturbed members and one unperturbed member (the control forecast) run at TL255L40 resolution. The control starts from the unperturbed analysis, while the 50 perturbed members start from perturbed initial conditions. These are generated by adding to the unperturbed analysis a linear combination of the leading singular vectors growing to have maximum energy, at optimization time, inside three sets of area covering the whole globe. During this linear combination, the leading singular vectors are re-scaled to have amplitude comparable to analysis error estimates.

Figure 3 shows the EPS ensemble-mean forecast and the ensemble standard deviation, which is a measure of the ensemble spread, at initial and at three forecast times, for the EPS started on 1 December 2004. The ensemble standard deviation at initial time shows the areas where the EPS initial perturbations were located, and their average amplitude (see Figure 3(a)). Note that the initial perturbations were located in regions of strong gradient (e.g. the exit of the North Atlantic jet stream) and intense baroclinic activity (e.g. the area of cyclonic depression over Spain). During the subsequent forecast the perturbations grow following the atmospheric flow (see Figures 3(b), 3(c) and 3(d)). These results illustrate how the ensemble standard deviation varies geographically with the forecast time. More specifically, its variation can be used to estimate predictability: regions with small standard deviation (i.e. with small ensemble spread) should be more predictable than regions with large values, since in these regions the verifying analysis should be closer to the forecast states. Considering Europe, for example, the ensemble standard deviation is small compared to the other regions during the early forecast range (Figure 3(b)), but starts being relatively large on day 4 of the forecast (Figure 3(c)).

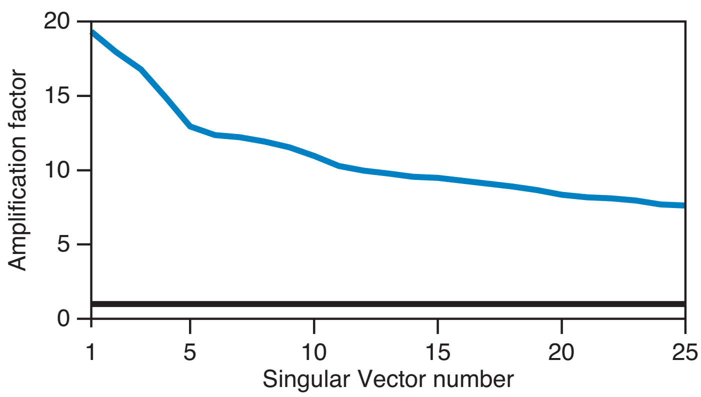

Figure 1 Amplification rates (i.e. singular values) of the leading 25 singular vectors used in the operational EPS started at 12 UTC on 1 December 2003, ranked from the fastest growing singular vector (number 1) to the 25th one (number 25). These singular vectors were computed at T42L40 resolution, with simplified dry physics, a 48-hour optimisation time interval, and final time total energy norm maximized over the Northern Hemisphere extra-tropics (latitude 30°N).

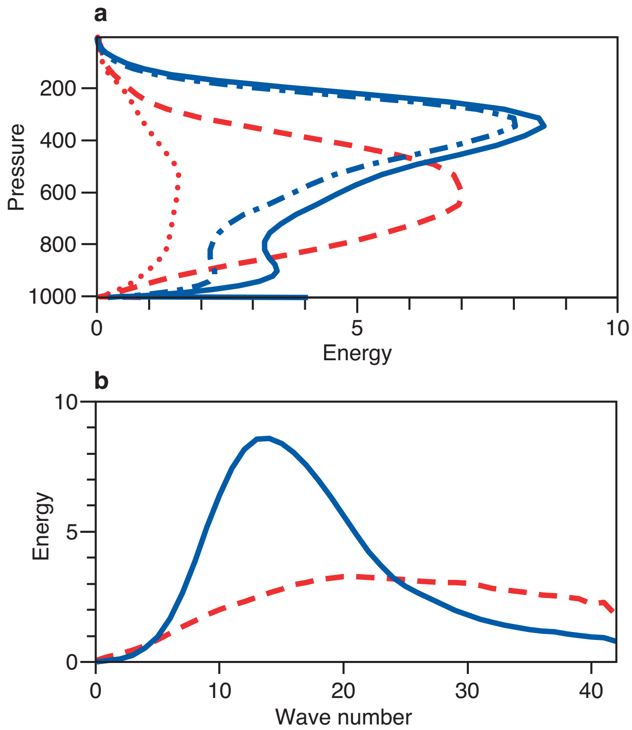

Figure 2 (a) Average initial-time total (red dashed line) and kinetic (red dotted line) energy, final-time total (blue solid line) and kinetic (blue chain-dashed line) energy vertical cross section. (b) Average initial-time (red dashed line) and final-time (blue solid line) total energy spectra. The averages have been computed considering the leading 25 singular vectors used in the operational EPS started at 12 UTC on 1 December 2003.

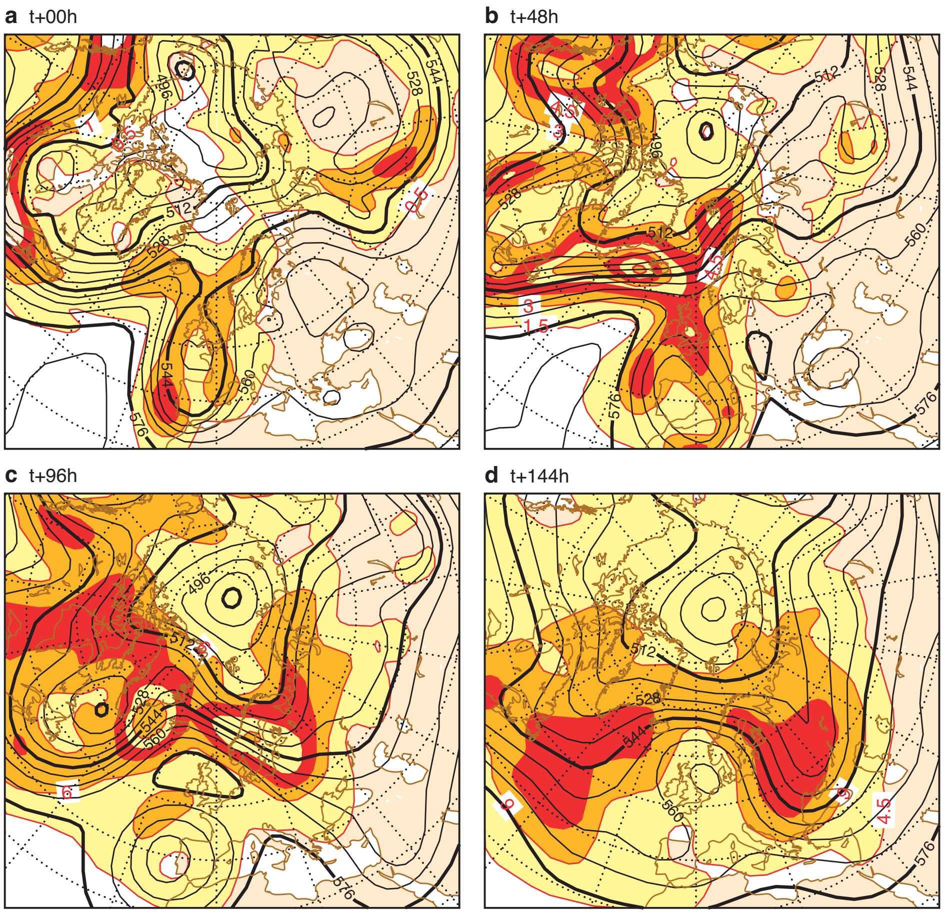

Figure 3 (a) Initial time ensemble mean (which coincide with the unperturbed analysis) and standard deviation. (b) Ensemble mean and standard deviation at forecast day 2. (c) Ensemble mean and standard deviation at forecast day 4. (d) Ensemble mean and standard deviation at forecast day 6. Fields shown refer to the 500 hPa geopotential height field of the EPS started at 12 UTC on 1 December 2003. Contour interval for ensemble mean is 80 m; contour shading for the ensemble standard deviation are: 5 m at initial time, 15 m at day 2, 30 m at day 4 and 45 m at day 6.

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EPS performance from May 1994 to April 2005

EPS forecasts are used to generate 'single' products (e.g. the forecasts given by the EPS control or the ensemble-mean) and probabilistic products, such as the probability of occurrence of some selected events (e.g. the probability of occurrence of positive anomalies, or of positive/negative anomalies great-than/smaller-than one standard deviation of monthly variability). The accuracy of single and probabilistic forecasts of the 500 hPa geopotential height fields has been assessed over the Northern Hemisphere and Europe, from 1 May 1994 to 30 April 2005. Probabilistic forecasts have been assessed using 3 skill measures: the area under the relative operating characteristic curve (ROCA), the Brier skill score (BSS) and the ranked probability skill score (RPSS).

For each skill measure, first a linear regression line has been determined, and then the slope of the linear regression curve has been translated into predictability gains measured in terms of days-per-decade (d/de). In other words, the predictability gain of the time t forecast gives a measure of the trend in skill between 2005 and 1994. For example, a gain of 1 day/decade for a 5-day forecast means that the improvement in skill between 1 May 1994 and 1 May 2004 of the 5-day forecast is equal to the average difference between the skill of 4.5-day and a 5.5-day forecast during that period.

Considering for example 7-day forecasts over the Northern Hemisphere, Figure 4 shows the time evolution of the skill of the control and the ensemble-mean forecasts in terms of anomaly correlation coefficient. Results indicate a continuous improvement, equivalent to a predictability gain of 1.06 d/de (days per decade) and 1.68 d/de, respectively, for the control and ensemble-mean. The corresponding results for the skill of probabilistic forecasts measured in terms of ROCA, BSS and RPSS, are given in Figure 5. In this case the predictability gains range between 1.98 and 2.90 d/de.

Figure 6 summarizes the predictability gains of the single and probabilistic forecasts achieved between 1994 and 2005 at forecast day 5 and 7 and for the Northern Hemisphere and Europe. *Results indicate that for both the Northern Hemisphere and Europe the predictability gains of medium-range EPS probabilistic forecasts has improved by about twice the value shown by EPS single control forecast.*

The improvement of ensemble forecasts first of all indicates that the EPS benefits from ameliorations of the ECMWF data assimilation and forecast model. But it also indicates that changes introduced in the EPS (Table 1) played an important role in improving the prediction of the probability distribution function of forecasts states. Although it is difficult to clearly identify which of the changes of the EPS configurations had the largest impact on the EPS scores, published works suggest that the improvements shown in Figure 6 are mainly due to three causes.

- Increases of the EPS resolution in 1996 and 2000.
- Increase in the ensemble size in 1996.
- Introduction of evolved singular vectors and of stochastic physics in 1998.

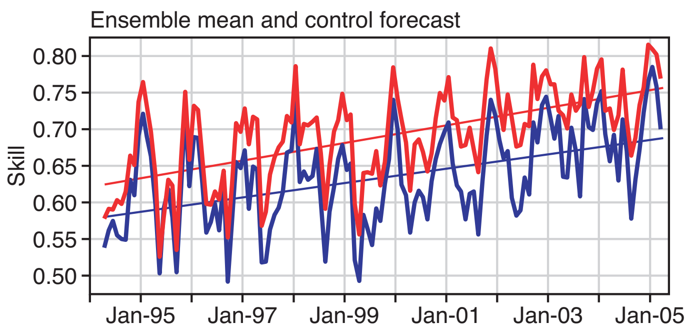

Figure 4 Monthly average anomaly correlation coefficient of the control (blue line) and the ensemble-mean (red line) 7-day forecasts of 500 hPa geopotential height fields over the Northern Hemisphere. Straight lines show linear regression curves.

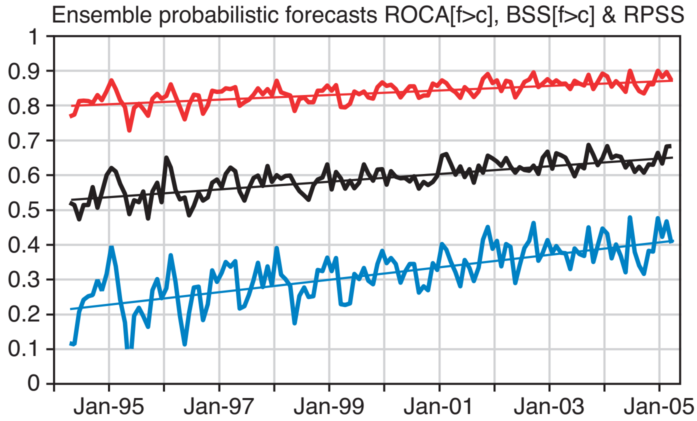

Figure 5 Monthly average area under the relative operating characteristic curve (red line) and Brier skill score (blue line) of the 7-day probabilistic forecasts of positive anomalies, and ranked probability skill score (black line) of the 7-day probabilistic forecasts of 500 hPa geopotential height fields over the Northern Hemisphere. Straight lines show linear regression curves.

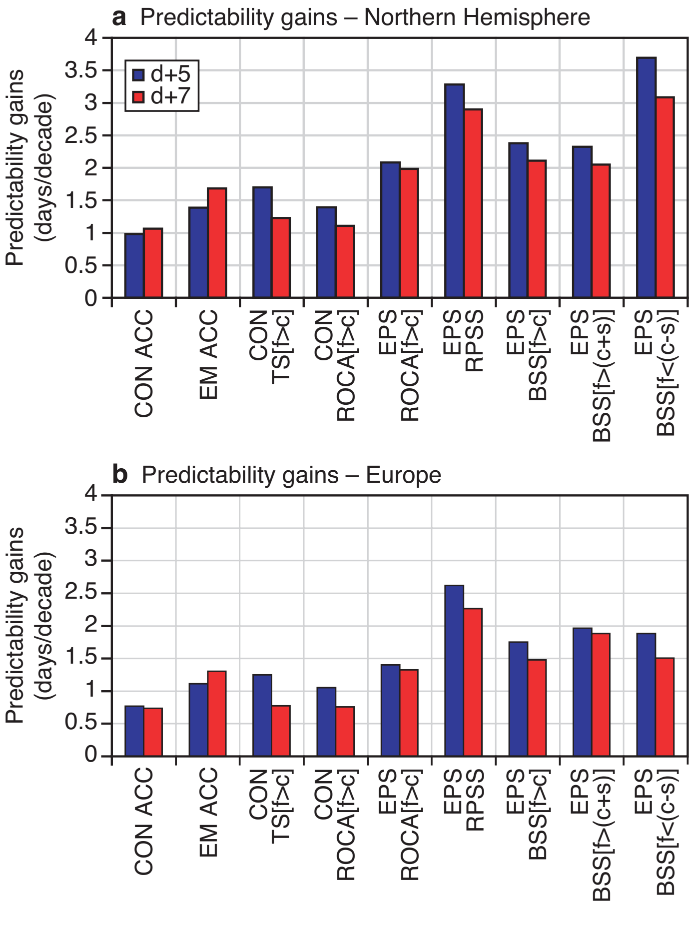

Figure 6 (a) Gains in predictability of five-day (blue bars) and seven-day (red bars) forecasts of 500 hPa geopotential height fields over the Northern Hemisphere, computed from different forecasts. (b) As top panel but for Europe. **CON ACC:** control anomaly correlation coefficient. **EM ACC:** ensemble-mean anomaly correlation coefficient. **CON TS[f>c]:** control threat score of positive anomalies. **CON ROCA[f>c]:** area under the relative operating characteristics of the probabilistic forecast of positive anomalies given by the control. **EPS ROCA[f>c]:** area under the relative operating characteristics of the probabilistic forecast of positive anomalies given by the EPS. **EPS RPSS:** ranked probability skill score of the EPS. **EPS BSS[f>c]:** Brier skill score of the probabilistic prediction of positive anomalies. **EPS BSS[f>(c+s)]**: Brier skill score of the probabilistic prediction of positive anomalies greater than one standard deviation. **EPS BSS[f>(c-s)]:** Brier skill score of the probabilistic prediction of positive anomalies less than one standard deviation.

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EPS future upgrades

Work is in progress to improve the current system in three key areas.

- ***Simulation of initial uncertainties*** — Work in this area includes developments in the definition of the norm used to compute the singular vectors, in the use of moist, higher-resolution singular vectors, and in the combination of ensemble data assimilation and singular vectors.
- ***Simulation of model imperfection*** — Work in this area focuses in the revision of the scheme designed to simulate the effect of near-grid scale and sub-grid scale processes.
- ***System design*** — Work in this area involves changes in the ensemble resolution and forecast length, including the possibility to run the each single forecast with variable resolution (with a T_L399 resolution up to forecast day 7, and with a T_L255 resolution from the truncation time to forecast day 14).

The ECMWF EPS is based on the Integrated Forecasting System/Arpege software, developed in collaboration by ECMWF and Météo-France, and is the result of the work of many ECMWF staff members and consultants. Without their contributions the ECMWF EPS would not have reached the mature development stage and accuracy that it has reached now: their work is fully acknowledged.

Further reading

On singular vectors: **Buizza, R.** & **T.N. Palmer,** 1995: The singular-vector structure of the atmospheric general circulation. *J. Atmos. Sci.,* **52,** 1434–1456.

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