GLAMEPS – the HIRLAM/ALADIN Grand Limited Area Model Ensemble Prediction System

Trond Iversen[1]*, Inger-Lise Frogner[1], Kai Sattler[2], Stjepan Ivatek-Sahdan[3], Jan Barkmeijer[4], Henrik Feddersen[2], Edit Hágel[5], Richard Mladek[6]

[1] *Norwegian Meteorological Institute, Oslo, Norway*
[2] *Danish Meteorological Institute, Copenhagen, Denmark*
[3] *Meteorological and Hydrological Service of Croatia, Zagreb, Croatia*
[4] *Royal Netherlands Meteorological Institute, DeBilt, The Netherlands*
[5] *Hungarian Meteorological Service, Budapest, Hungary*
[6] *Czech Hydrometeorological Institute, Praha, Czech Republic*

** Corresponding author. E-mail: trond.iversen@met.no*

Abstract

A snapshot of the ongoing development of short range probabilistic NWP in the European HIRLAM, ALADIN, and Lace consortia is given. The initial system will be based on global ensembles constructed by combining the ECMWF operational northern hemispheric singular vectors (SVs) with SVs targeted at final time to three sub-domains in Europe. This "TEPS for Europe" provides initial and lateral boundary data to limited area models (HIRLAM and ALADIN) integrated in a common domain. LAM EPS forecasts are made up to 60 hours with ~20km horizontal resolution and 40 layers in the vertical. New developments will gradually refine this system. Experimental developments include LAM-specific initial perturbations (SVs, ETKF, SLAF), stochastic physics, and variation of physical parameters. In practice, the idea is to utilize computer power distributed amongst national weather services, and synthesize the entire ensemble at ECMWF. Statistical methods will be used for bias corrections and calibration, and an ECMWF-based presentation and verification package will be applied. The paper shows a few preliminary examples of results.

1. Introduction

Predicting severe weather is of the highest priority for weather services. Often extreme weather events occur highly localized with duration of minutes to a few hours in connection with hydraulic shocks, sharp fronts, deep convection, etc., even though also larger scale features occasionally are considered extreme. Many extreme weather events are connected with fine-scale structures embedded into larger scale phenomena.

Upscale cascading of atmospheric un-predictability, from the range of hours for convective systems to a week or two for the synoptic scales, renders the prediction of pure dynamically produced structures a considerable challenge. Lorenz (1969) demonstrated this "butterfly" effect using stochastic differential equations for low-dimensional chaotic eddy-like motion with different shapes of the equilibrium (climate) energy spectra. Small amplitude and fine scale perturbations gradually amplify until reaching a saturation level, whilst simultaneously cascading energy upscale until the amplitudes at all scales are saturated. This behaviour is similar to two-dimensional turbulence on a sphere (Fjørtoft, 1953), which corresponds to the unstable and non-linear dynamics of large-scale atmospheric flows. Verification results from ECMWF confirm this behaviour as well (e.g. fig. 3 in Simmons (1996)).

This leads to gloomy prospects for numerical weather prediction (NWP), as huge errors on the finest scales are unavoidable. Also, since the predictability diminishes with decreasing scales, forecasting extreme events beyond a few hours may appear almost impossible. The numerical experiments by Anthes *et al.* (1985) provided reasons for new optimism, and Boer (1994) obtained similar results using results from an earlier version of the ECMWF-model with finer resolution. He confirmed the paradigm from Lorenz (1969) for intermediate-scale synoptic eddies, but found considerably slower error growth for quasi-stationary long waves and for the meso-scale. This is partly connected with the strong influence of ground-surface properties, in particular topography, on both these scales. These findings offer some optimism for the prospects for short-range NWP of meso-scale features applying limited area models (LAMs), even though it is realized that some meso-scale features are weakly influences by ground surface forcing.

In weather prediction a general aim is to protect life and property, implying that predicting high impact events with skill is important. Assuming that nature and society is adapted to the local climate in some sense, high impact events should be rare, and thus extreme, relative to the local climate statistics. The damaging potential of the same type of weather event can therefore be large in one region but negligible in another. Furthermore, if or when climate may change, this implies that high impact events may become more frequent and thus statistically less extreme. In this perspective, the challenges for short-range NWP become increasingly important in order to fulfill the mandate of regional weather services.

Given that hazardous weather is unusual, a probabilistic approach is particularly appropriate for its prediction. The existing global ensemble prediction systems (e.g. the ECMWF Ensemble Prediction System – EPS) presently have considerable probabilistic skill on synoptic and large meso-scales. However, many meso-scale processes and the lower boundary forcing are not sufficiently well captured for the short-range. A well designed high-resolution, limited-area ensemble prediction system (LAMEPS) using a skilful synoptic-scale EPS at the open boundaries may improve this situation. Running a LAMEPS provides an ensemble with higher horizontal resolution. Limiting our forecast interest to a smaller target domain may also enable to cover the prediction uncertainty with a smaller ensemble size than the global EPS.

This short note mainly presents ideas for a short-range “grand” LAMEPS (“GLAMEPS”) using different versions of the HIRLAM (http://hirlam.org/) and ALADIN (http://www.cnrm.meteo.fr/gmapdoc/) LAMs and with different initial and lateral boundary perturbations. Only a few results are available for presentation at this stage, and the paper therefore only give snapshots into a process under development. There are presently a few operational or quasi-operational attempts at short range ensembles using LAM in Europes, for example in Italy and the the COSMO consortium (Molteni et al, 2001; Marsigli et al, 2001 and 2005), in Norway (Frogner and Iversen, 2002 and Frogner et al., 2005), in Spain (Garcia-Moya, pers. comm.), in UK (Legg and Mylne, 2004), and in Austria and ALADIN/Lace (Wang et al., 2006; Hagel and Horanyi, 2007; Mladek and Ivatek-Sahdan, pers. comm.). Important activities also take place outside Europe (e.g. Stensrud et al. 1999; Du et al., 2006). GLAMEPS aims in the first instance to build a system for probabilistic forecasting based on existing operational experience and scientific competence, and in particular from HIRLAM, ALADIN and LACE. In parallel new approaches to the generation of ensemble members are developed in research mode for further gradual extension and refinement.

2. The idea

There is a need for probabilistic forecast systems with resolution and coverage between those presently used in global EPSs for the medium range (Molteni et al. 1996; Palmer et al. 1997; Palmer et al 2007), and those required in systems for “nowcasting” deep convective storms, hydraulic shocks, etc. GLAMEPS sets forth to establish a system for operational numerical ensemble prediction for probabilistic forecasting up to 60 hours ahead on the intermediate “grey-zone” scales. The idea is to utilize the distributed computer resources in countries participating in the HIRLAM and ALADIN consortia. A number of partners will then produce a minor subset of the ensemble members and submit the result to a common data centre. Probabilistic forecast products can then be synthesized from the entire ensemble of results, and be downloaded by the partners.

The intention is that the system should transform all quantifiable sources of uncertainties in the LAM formulation and in the input data into forecasts of probability density functions for weather elements. The integration domain for each ensemble member is as common as the numerics in the LAM versions permit (Fig. 1). The shape of the pdfs will vary in space and time in intentional coherence with actual weather predictability. Several practical obstacles as well as scientific issues need to be solved before an operational GLAMEPS becomes a reality.

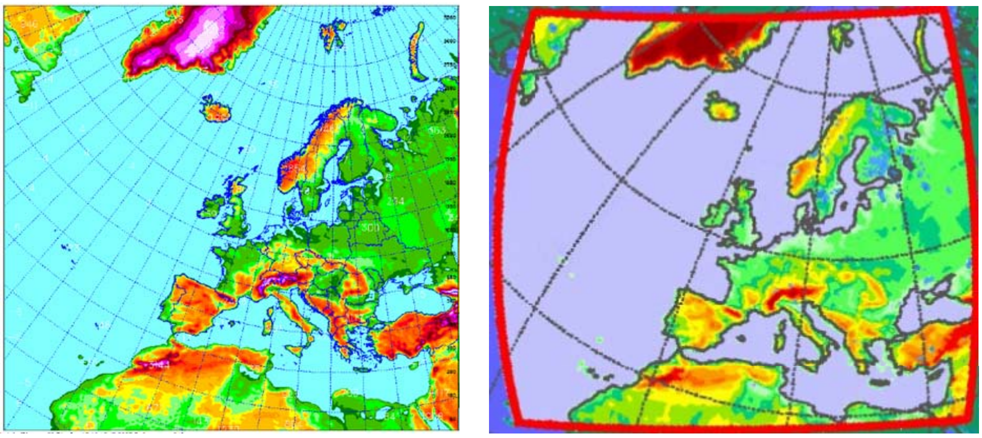

Figure 1: Scheduled horizontal integration domains for HLAMEPS. Left: The Aladin domain. Right: The HIRLAM domain.

3. TEPS for Europe

The first version of a pre-operational GLAMEPS is presently being developed and tested in hindcast mode at ECMWF (Iversen, 2007). This version is built on the Norwegian NORLAMEPS which has been run daily in operational routine for almost three years (March 2008). Basic in this system is a dedicated version of the global ECMWF EPS to provide initial and lateral boundary perturbations for the LAM models. The system employs singular vectors targeted at final time to an area in Northern Europe (Frogner and Iversen, 2001; see also Hersbach et al., 2000.). It is run with Norwegian computer time as a time-critical facility at ECMWF, at 12 UTC each day and for 72h forecasts.

For GLAMEPS, a further elaborated version of this system is developed at ECMWF and named a *TEPS for Europe*. In the development phase the system is run in hindcast mode using national quota from HIRLAM countries with a surplus from the special project SPNOGEPS. It uses the ECMWF IFS to calculate unit length singular vectors at initial time which produce maximum total energy after 24h inside selected target areas. The three target areas used are depicted in Fig. 2. They are chosen for the purpose of accounting for forecast spread in all the parts of Europe. Following the method of Leutbecher (2007) the targeted SVs are constructed to be orthogonal to the regular 48h northern hemispheric SVs produced for the EPS (Buizza, 1994) and also mutually orthogonal.

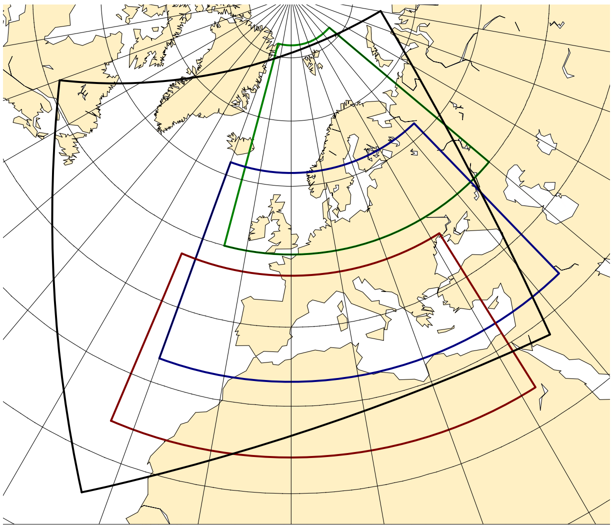

Figure 2: Target areas for singular vectors at final time used in "TEPS for Europe". Green: Northern domain; Blue: Middle domain; Red: Southern domain. Black area is the HIRLAM

In the present development phase, 10 targeted SVs are calculated for each of the three target areas in Fig. 2, and their resolution are T159 (~75km) as opposed to T42 (~280km) for regular northern hemispheric SVs. By requiring orthogonality, the 30 TSVs are constrained to complement the regular SVs as well as each other. The entire set of initial SVs and TSVs, together with their evolved counterparts valid at the same time, are finally combined by Gaussian sampling (Leutbecher and Palmer, 2008) in order to construct initial state perturbations for targeted ensemble (TEPS) forecasts. Each ensemble consists of 1 control run and 20 alternative members started off by adding and subtracting 10 perturbations to the best possible estimated initial state. In addition, the "stochastic physics" is used with the ECMWF IFS (Buizza et al. 1999). There are numerous possibilities for choosing initial amplitudes of the different SVs when constructing the TEPS forecasts, and work is ongoing to obtain a good relationship between ensemble spread and skill of the ensemble mean. Fig. 3 shows one example of the geographical distribution of added mean sea-level pressure ensemble spread in the TEPS relative to the operational EPS. For this period TEPS do produce added spread over most parts of Europe.

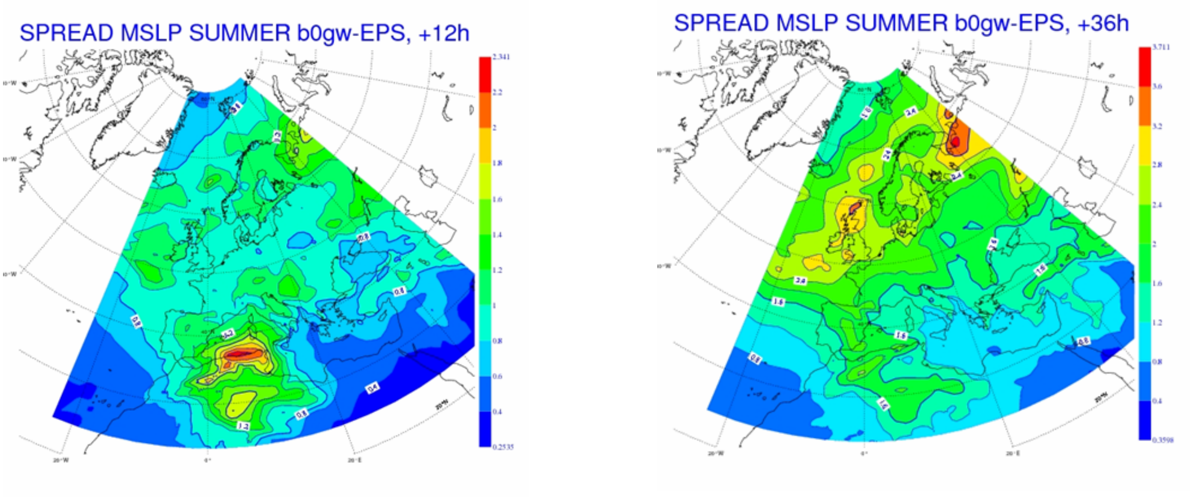

Figure 3. Added contribution to root mean square ensemble spread around ensemble mean of mean sea-level pressure in 21-member TEPS relative to the operational EPS. Statistics are for daily calculations over a three-week period in August 2007. Left: 12h forecast; Right 36h forecast.

These calculations are based on quasi-adiabatic tangent-linear and adjoint models also used to produce operational SVs, and the optimization is made with respect to the total energy inner product. As the scale of the systems decreases, diabatic mechanisms will generally become increasingly important in determining the amplification of perturbations (Mahfouf, 1999). The next step is therefore to investigate the added value of employing diabatic (moist) TSVs. Furthermore, for shorter optimization times it should benefit the TEPS to explicitly account for actual initial state errors. Initially, actual errors may generally be dominated by components which grow more slowly than the amplitudes of leading total energy SVs, even though the fast-growing modes eventually will dominate the forecast errors. Using so-called Hessian SVs, which take into account the analysis error covariance, should produce more realistic ensemble spread in the initial part of the forecast range (Barkmeijer et al., 1999; Reynolds et al., 2005; Bowler, 2006). Unfortunately, this option is at present operationally unavailable. Hence, GLAMEPS will also investigate alternative methods as indicated below.

4. The LAM EPS and model uncertainty

The next stage in the production chain of GLAMEPS is to apply limited area models (LAMs) to interpret the ensemble members produced in TEPS for Europe over the integration domains shown in Fig. 1. Latest versions of the HIRLAM and ALADIN models are used, and sub-selections of ensemble members should be produced in different countries before submitted back to the data-centre (presently scheduled to be at ECMWF) for synthesized probabilistic products. Two versions of HIRLAM are set up so that some ensemble members can be run with "STRACO" cloud parameterization scheme (Unden et al., 2002) and others with the combined RKKF-scheme (Rasch and Kristjansson, 1998; Kain and Fritsch, 1993). HIRLAM is set up with 3D-Var data-assimilation (will later become 4D-Var) for the control run, whilst ALADIN will downscale the control produced with TEPS for Europe. ALADIN is also set up for downscaling the EPS produced at MeteoFrance with the Arpege model, and this may become exploited later as a part of GLAMEPS.

Scripts are presently developed for full operational production at ECMWF's computers, and partly for linux platforms. Present tests are performed at ECWMF with 0,2 degree rotated lat-lon grid and 40 levels for HIRLAM, and 22km and 37 levels with ALADIN. Examples of results based on TEPS are at present stage not available. An example from applying the operational EPS as input is given below.

Since GLAMEPS will use a small multitude of models and model-versions, the uncertainty inherent in the forecast methods are taken care of to some extent. Further accounting of model uncertainty is investigated. In HIRLAM, the scripts have been developed to include "stochastic physics" (see example in Fig. 4). Additional experiments will include adjusting the scheme to space and time scales more relevant for the resolution of the LAMs, and also to combine with TEPS produced without stochastic physics in the IFS.

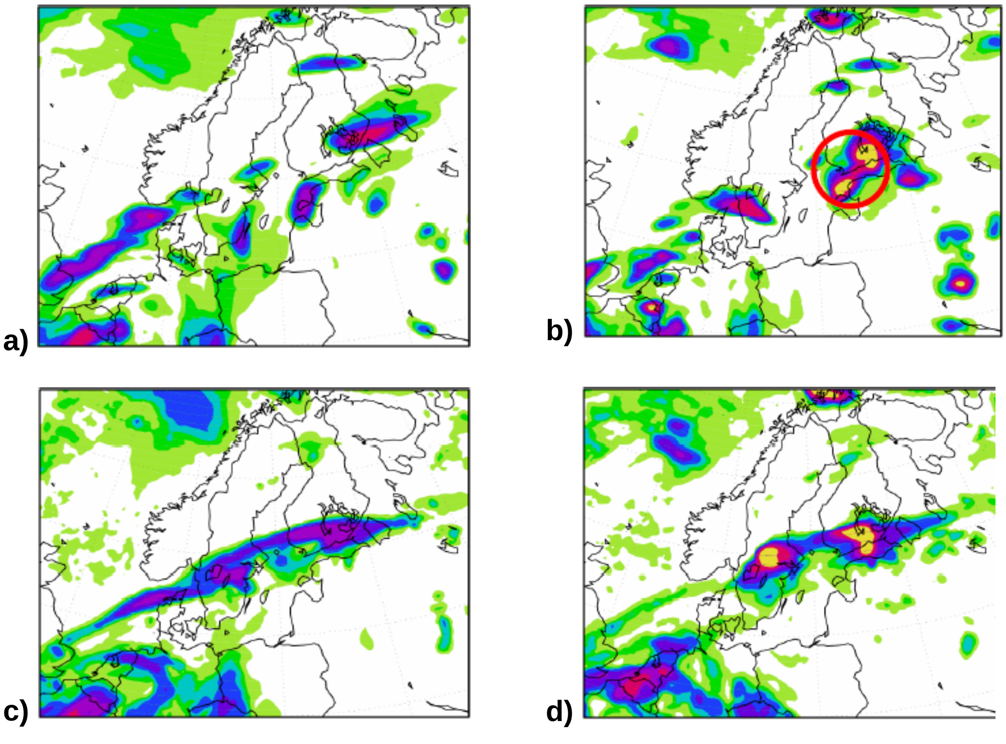

Figure 4: Example of impact of stochastic physics with HIRLAM EPS. The 4 maps show forecasted precipitation accumulated over range +42 to +48 valid on 22.06.2007 06-12 UTC. Upper panels (A and B) show ensemble member no. 2 for model version with STRACO, and lower panels show ensemble member no. 2 for model version with RKKF. Results in the left panels use regular physics, whilst those on the right include stochastic physics. (H. Feddersen)

Perhaps a more appealing approach is to perturb selected uncertain parameters in the physics parameterizations, which is partly motivated by *ClimatePrediction.net* (Stainforth et al, 2005). This is under development, but preliminary tests have been made by varying three parameters in the Straco cloud parameterization (not shown), and a number of uncertain parameters are identified in the RKKF cloud scheme.

Finally, calculating and applying forcing SVs and forcing sensitivities (Barkmeijer et al, 2003) is another possibility which is planned to be further explored.

5. Developments of alternative initial perturbations

TEPS for Europe provides perturbations of initial and lateral boundary data for the LAM EPS. As these perturbations are developed with the ECMWF IFS and with a considerably coarser resolution than used by the LAMs, we investigate the potentials of enhancing the initial state perturbations by LAM-specific SVs. So far only some very preliminary results applied to a few cases are available with the ALADIN (Mladek et al., 2007) and the HIRLAM (Stappers and Barkmeijer, 2006) models. The total energy inner product and relatively small target areas in parts of Europe are so far used for experimentation. Only quasi-adiabatic SVs have been calculated using optimization times of 12h and 24h, and ~20km or the double resolution.

Fig. 5 shows singular values for ALADIN, HIRLAM, and ECMWF IFS for specific cases. Only HIRLAM and the IFS are run for the same dates. Since the inner products are calculated over different areas and the target areas are different, only the shapes of the curves should be compared across the models. For the case of IFS for example, the NH singular values are larger than the targeted. Both LAMs show higher values for increased resolution and longer optimization time.

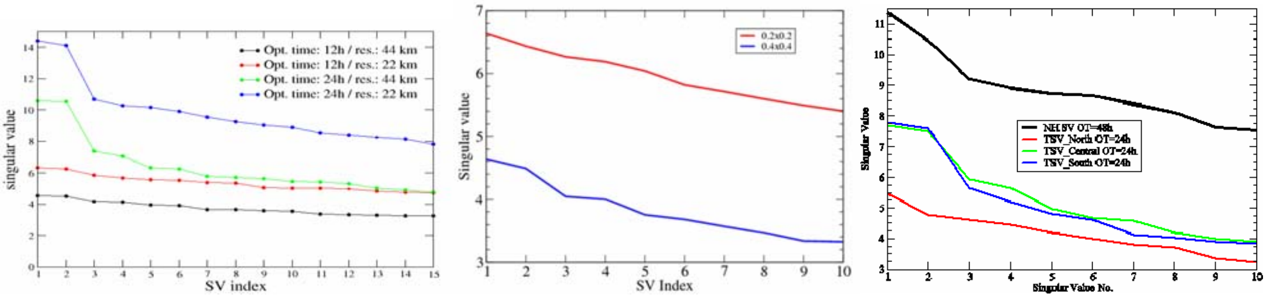

Figure 5. Calculated singular values for the ALADIN model (27.08.2007 12UTC, left), the HIRLAM model (28.06.2006 12UTC, middle) and the ECMWF IFS (28.06.2006 12UTC, right). Curves are for different optimization time interval (ALADIN and IFS), different horizontal resolution (all models), and different target areas (IFS).

Lower tropospheric patterns of initial and tangent-linearly evolved leading singular vectors are shown in Fig. 6 for a common evolved time for ALADIN, HIRLAM and IFS targeted singular vectors. They are all targeted areas in central Europe, although not common. All models point to unstable structures in the same area, even though there are certain differences. In particular the IFS TSV is displaced to the west and south of the patterns found by the LAMs, which presumably is partly caused by the double optimization time, although this is not investigated.

All models give upscale developments of the singular vectors over the optimization time (not shown) even though this development is tangent-linear. This is due to the non-normality of the linear operators brought about by linearized advection terms. Also, whilst initial SVs are are dominated energetically by the temperature fields, the evolved SVs are dominated by wind perturbations. These features are produced in all models.

The use of LAM SVs to add initial state perturbations to those produced by the TEPS depend on the results from the ongoing development, and some careful evaluation studies. Given the high resolution and the very short optimization (12h), diabatic SVs and a metric which measures actual analysis error may be required in order to exploit the benefits from the singular vector technique.

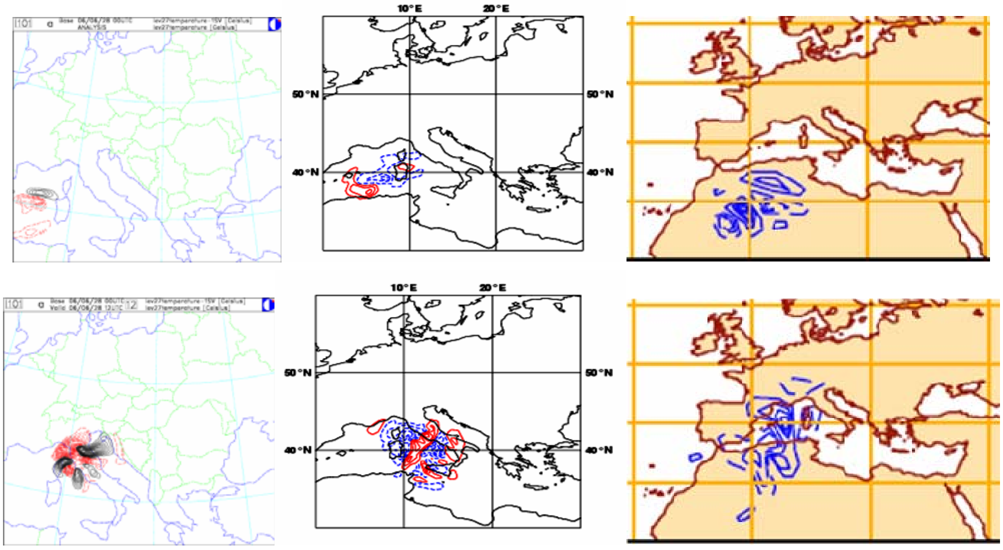

Figure 6: Example of leading singular vectors depicted by temperature perturbations in the lower portion of the troposphere. The total energy inner product is used with different targets at final time in central Europe. Upper row: initial leading SV; lower row: evolved leading SV. Left: ALADIN 22km, 12h optimization time (Mladek et al. 2007); middle: HIRLAM 0.2 degrees, 12h optimization time (Stappers and Barkmeijer, 2007); right: IFS TSV T159, 24h optimization time (I.-L. Frogner)

Another approach, which is possibly easier and more flexible to apply technically, is the Ensemble Transform Kalman Filter technique (ETKF) (Bishop and Toth, 1999; Bishop et al., 2001). Recent comparative studies indicate that ETKF combined with other methods (random perturbations) fits the needs for a short range EPS (Wang and Bishop, 2003; Bowler, 2006), even though the full ensemble kalman filter method (EnKF, Evensen, 1994; Houtekamer and Mitchell, 1998) would be required to catch the crucial background error information.

To perturb observations directly and use ensemble members generated by multiple analyses is probably even better (Hamill et al. 2000). However, both this method and EnKF are computationally too costly to apply fully at present stage. GLAMEPS will nevertheless use a small multitude of analyses by employing different models and model versions, and the implementation of the simplified method of ETKF has also started.

Also the technique of scaled lagged average forecasting (SLAF; Hoffman and Kalnay, 1983; Dalcher et al., 1988) is implemented as an option due to its simplicity and cheapness, even though this method has some practical limitations. Time-lagging of full ensembles will also be investigated as a possible way of extending the number of ensemble members in a cheap way.

6. Combination, calibration, products, and validation

In the GLAMEPS data centre, which presently is ECMWF, all the ensemble members will be combined to form the basis for probabilistic forecasts. All output is first interpolated as necessary to a common grid system for generation of products. This will be the rotated lat-lon grid used by the HIRLAM model (Fig. 1 to the right). Before combining all ensemble members to probabilistic products, methods for bias corrections will be employed. Also bayesian techniques will be investigated (e.g. BMA; Raftery et al., 2005).

A separate package for standard probabilistic products, including ensemble averaging, forecast spread, and probability maps for events, is readily available. This is the Metview-based so-called Hppv-package developed at the Spanish weather service (thanks to Carlos Santos), and implemented at ECMWF (ecgate).

The Hppv-package does also include a number of standard validation products based on comparison with standard observations.

One example: The Finnish storm on August 22. 2007.

At the time of writing this paper, there are activities underway for producing results from a first laboratory version of GLAMEPS at ECMWF. It is only possible to show single examples so far, and we have chosen a case of meso-scale extreme rainfall over Southern Finland in the morning of 22. August 2007. These results are entirely based on using ensemble members from the operational EPS as input to produced LAM EPS produced with HIRLAM.

The case was brought to attention by the following message from the Finnish Meteorological Institute to some HIRLAM and ALADIN research communities: "*At the moment we are experiencing a very intense thunderstorm in southern Finland. The system has moved in from the southwest in the course of the morning and is by no means a local phenomenon. Although the scenery is spectacular, our joy is reduced by the fact that the RCR has failed to forecast this storm in any of the cycles verifying this morning.*"

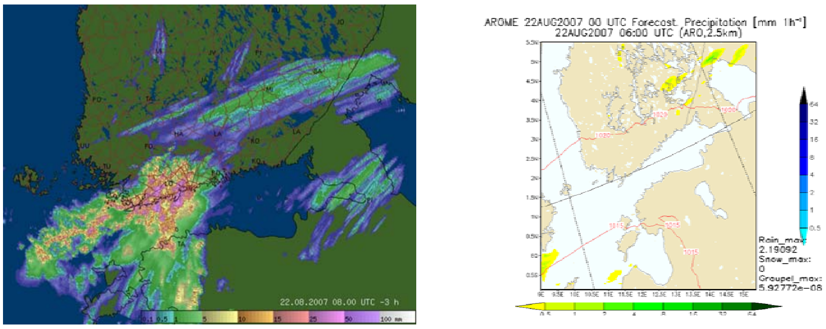

Figure 7. Radar echo composite for 22.08.2007 05-08 UTC (left), and "Arome" 6h forecast of 1h precipitation valid at 06 UTC (right). (From C. Fortelius, FMI.)

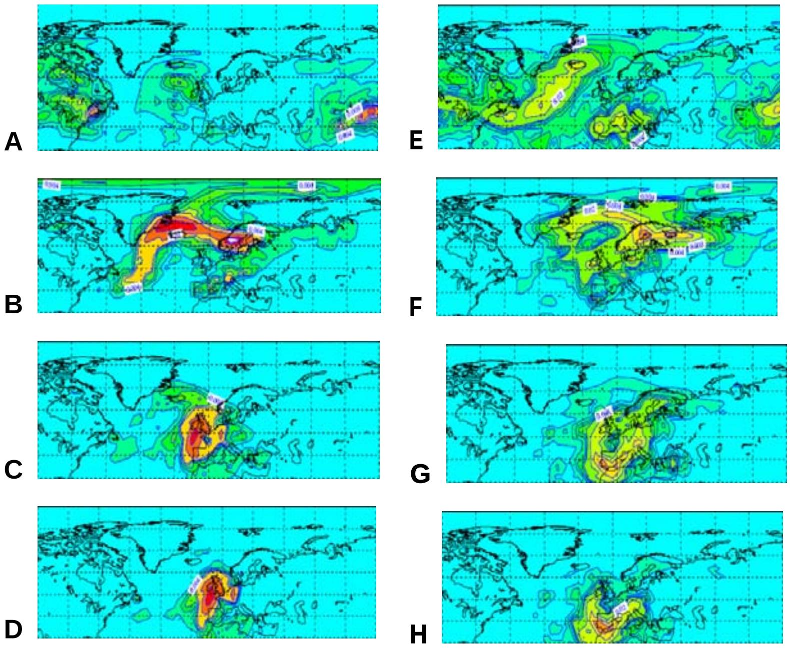

Figure 8: RMS of mid-troposphere temperature patterns for 10 leading initial (A-D, left) and evolved (E-H, right) ECMWF IFS singular vectors. A and E are operational 48h NHSVs. The others are 24h TSVs targeted to the northern (B, F), central (C, G), and southern (D, H) sub-domains in Fig. 1. The time for evolved SVs is common on 22.08.2007 12 UTC. All TSVs are orthogonal to NHSVs, but those shown are not internally orthogonalized. (I.-L. Frogner).

Fig. 7 shows a composite map of precipitation radar echo pictures for the case, together with a very short range (6h) high resolution (2.5 km) numerical forecast (“Arome”) of 1h-accumulated precipitation valid for the period when high precipitation intensity was observed. The same missing precipitation was also seen in the operational, 6h (or longer) numerical forecasts from e.g. HIRLAM. Fig. 8 illustrates the diagnosed instability properties during the 1-2 days leading up to 12 UTC on the date. The operational and targeted IFS singular vectors are used by taking root mean square over the 10 leading SVs in each case. The storm does not appear to be captured by the regular NH SVs, whilst the SVs targeted to the northern domain in Fig. 1 shows considerably energy at the evolved time (and even at initial time). This indicates that the TSVs, and thus the TEPS, provide potentially important information in addition to that available from a sub-selection of ensemble members from the operational EPS. An evaluation of this aspect will be made for a selection of extreme cases, as well as for periods of more moderate and normal weather.

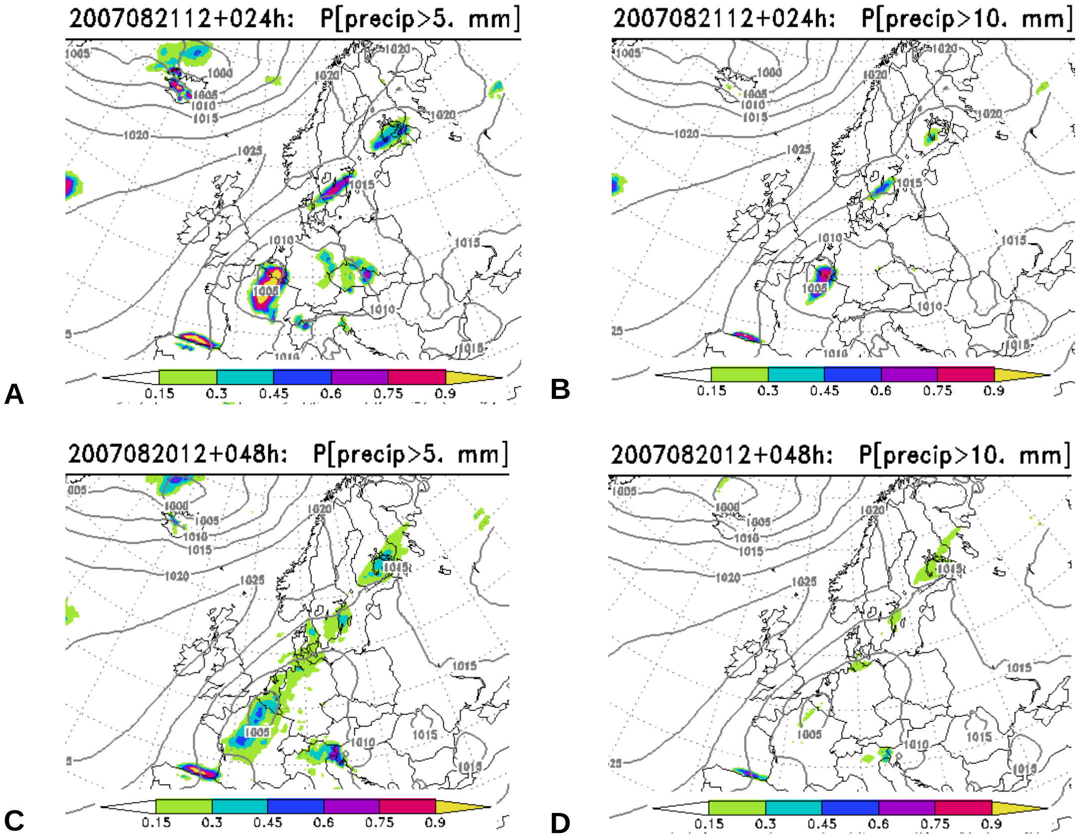

Figure 9: Forecasted probabilities of more than 5mm (left, A-C) and 10mm (right, B-D) precipitation accumulated between 22.08.2007 06-12 UTC, for forecast range 18-24h (upper) and 42-48h (lower). HIRHAM is used with RKKF cloud scheme, 0.2 degree resolution in domain shown in Fig. 1, and 40 levels. 3DVar analysis is used for the control forecast. Initial and lateral boundary perturbations are from the ECMWF EPS. The ensemble has 21 members, incl. the control. (K. Sattler)

It should be mentioned that important aspects of the storm were accounted for by 6h forecasts with other versions of HIRLAM (e.g. the Swedish), and also by the ECMWF 21h operational forecast, even though many other models either produced important position errors for the precipitation or missed to entirely. As an experiment we calculated 60h 21-member ensemble forecasts with HIRLAM every 12 hours starting a few days before the event, including a short spin-up for the 3D-Var data-assimilation for the HIRLAM control. The resolution was 0.2 degrees and 40 levels using the common integration domain in Fig. 1. Also ALADIN was used to calculate downscaled control forecasts (not shown), but due to technical obstacles a full ensemble could not be produced. (These obstacles are now solved.)

Fig. 9 shows estimated probabilities for precipitation between 6 and 12 UTC for 1-day and 2-day forecasts. Even though the amounts forecasted are considerably smaller than those estimated from radar echoes, the forecasted probabilities well in advance should provide good reasons for avoiding the kind of unpleasant surprise that the weather forecasters were taken by.

HIRLAM was run with both RKKF and Straco cloud schemes, and only the version with RKKF produced precipitation of considerable amounts in approximately the right area. In Fig. 4 it is shown that using stochastic physics in HIRLAM, increases the precipitation amounts for some ensemble members, regardless of operational cloud scheme. See in particular inside the circle in Fig. 4B. Unfortunately, the amounts are also increased considerably in many other areas. The potential operational use of stochastic physics in GLAMEPS depends on careful validation.

Acknowledgements This summarizes a presentation by T. Iversen in the ECMWF Workshop on Ensemble Prediction in Nov. 2007. All co-authors have provided invaluable input, but the main text is written by T. Iversen. Other active GLAMEPS collaborators include Alexander Deckmyn, Jose Antonio Garcia-Moya, Carlos Santos, Roeland Stappers, and Ole Vignes. Andras Horanyi was central since the start. Scientific and technical discussions with Martin Leutbecher, ECMWF, are gratefully acknowledged.

7. References

Anthes, R.A., Y.H. Kuo, D.P. Baumhefner, R.M. Errico, and T.W. Bettge, 1985: Predictability of mesoscale motions. Issues in atmospheric and oceanic modelling. In *Advances in Geophysics: Part B, Volume 28.* Eds. B. Saltzman and S. Manabe. Academic Press, Orlando, USA.

Barkmeijer, J., R. Buizza, and T.N. Palmer, 1999: 3D-Var Hessian singular vectors and their potential use in the ECMWF Ensemble Prediction System. *Q. J. R. Meteorol. Soc*., **125,** 2333–2351.

Barkmeijer, J., T. Iversen, and T. N. Palmer, 2003: Forcing singular vectors and other sensitive model structures. *Q. J. R. Meteorol. Soc.*, **129**, 2401-2423.

Bishop, C. H. and Z. Toth, 1999: Ensemble transformation and adaptive observations. *J. Atmos. Sci.*, **56**, 1748-1765.

Bishop, C. H., B.J. Etherton, and S. J. Majundar, 2001: Adaptive sampling with the ensemble transform kalman filter. Part 1: theoretical aspects. *Mon. Wea. Rev.,* **129**, 420-436.

Boer, G.J., 1994: Predictability regimes in atmospheric flow. *Mon. Wea. Rev.*, 122, 2285–2295.

Bowler, N. E., 2006: Comparison of error breeding, singular vectors, random perturbations and ensemble Kalman filter perturbation strategies on a simple model. *Tellus*, **58A**, 538-548.

Buizza, R. 1994 Localization of optimal perturbations using a projection operator. *Q. J. R. Meteorol. Soc*., **120,** 1647–1681

Buizza, R., M.J. Miller and T.N. Palmer, 1999: Stochastic simulation of model uncertainties in the ECMWF Ensemble Prediction System. *Q. J. R. Meteorol. Soc*., **125,** 2887-2908.

Dalcher, A., E. Kalnay, and R. N. Hoffman, 1988: Medium range lagged average forecasts. *Mon Wea. Rev.*, **116**, 402-416.

Du, J., J. McQueen, G. DiMego, Z. Toth, D. Jovic, B. Zhou, and H. Chuang, 2006: New Dimension of NCEP Short-Range Ensemble Forecasting (SREF) System: Inclusion of WRF Members, Preprint,WMO Expert Team Meeting on Ensemble Prediction System, Exeter, UK, Feb. 6-10, 2006, 5 pp. [http://wwwt.emc.ncep.noaa.gov/mmb/SREF/reference.html]

Evensen, G., 1994: Sequential data assimilation with a nonlinear quasi-geostrophic model using monte-carlo methods to forecast error statistics. *J. Geophys. Res. –Oceans,* **99**, 10143-10162.

Fjørtoft, R. 1953: On the changes in the spectral distribution of kinetic energy for twodimensional, nondivergent flow. *Tellus,* 5, 225-230.

Frogner, I-L. and T. Iversen, 2001: Targeted ensemble prediction for northern Europe and parts of the North Atlantic Ocean. *Tellus*, 53A, 35–55.

Frogner, I-L. and T. Iversen, 2002: High-resolution limited-area ensemble predictions based on low-resolution targeted singular vectors. *Q. J. R. Meteorol. Soc.*, 128, 1321–1341

Frogner, I-L., H. Haakenstad, and T. Iversen, 2005: Limited area ensemble predictions at the Norwegian Meteorological Institute. *Q. J. R. Meteorol. Soc,* **132**, 2785–2808 doi: 10.1256/qj.04.178

Hagel, E. and A. Horanyi, 2007: The ARPEGE/ALADIN limited area ensemble prediction system: the impact of global targeted singular vectors. *Meteorologische Zeitschrift,* **16,** 653-663, DOI: 10.1127/0941-2948/2007/0251.

Hamill, T.M., C. Snyder, and R.E. Morss, 2000: A comparison of probabilistic forecasts from bred, singular vector, and perturbed observation ensembles. *Mon. Wea. Rev.*, **128**, 1835-1851.

Hersbach, H., Mureau, R., Opsteegh, J. D. and Barkmeijer, J. 2000. A short to early-medium range ensemble prediction system for the European area. *Mon. Wea. Rev*., **128**, 3501-3519.

Hoffman, R. and E. Kalnay, 1983: Lagged average forecasting, an alternative to Monte Carlo forecasting. *Tellus,* **35A**, 100-118.

Houtekamer, P.L. and H.L. Mitchell, 1998: Data assimilation using an ensemble Kalman filter technique. *Mon. Wea. Rev.,* **126**, 796-811.

Iversen, T., 2007: On the contribution of the HIRLAM EPS to GLAMEPS version 0. Hirlam Newsletter No. 52. (http://hirlam.org/open/publications/NewsLetters/52/)

Kain, J. S., and J. M. Fritsch, 1993: Convective Parameterisation for Mesoscale Models: The Kain-Fritsch scheme. In: *The representation of cumulus convection in numerical models.* Eds: K. A. Emanuel and D. J. Raymond. AMS Monograph, 46, 246p.

Legg, T. E. and K. Mylne 2004: Early Warnings of Severe Weather from Ensemble Forecast Information" *Wea. Forecasting*, **19**, 891-906.

Leutbecher, M., 2007, On the representation of initial uncertainties with multiple sets of singular vectors optimized for different criteria. *Q. J. R. Meteorol. Soc.* **133**, 2045–2056. DOI: 10.1002/qj

Leutbecher, M. and T. N. Palmer, 2008: Ensemble forecasting. *J. Comp. Phys.* 227, 3515-3539. doi:10.1016/j.jcp.2007.02.014

Lorenz, E. N., 1969: The predictability of a flow which possesses many scales of motion. *Tellus*, 21, 289-307.

Mahfouf, J.-F., 1999: Influence of physical processes on the tangent-linear approximation. *Tellus*, **51A**, 147-166.

Marsigli, C., Montani, A., Nerozzi, F., Paccagnella, T., Tibaldi, S., Molteni, F., Buizza, R., 2001: A strategy for High–Resolution Ensemble Prediction. Part II: Limited–area experiments in four Alpine flood events. *Quart. J. Roy. Meteor. Soc.*, 127, 2095–2115.

Marsigli, C., Boccanera, F., Montani, A., Paccagnella, T., 2005: The COSMO–LEPS ensemble system: validation of the methodology and verification. *Nonlinear Processes in Geophysics*, 12, 527–536.

Mladek, R., E. Hagel, and A. Horanyi, 2007: Singular vectors in the ALADIN model. LACE-report (http://www.rclace.eu/File/Predictability/2007/lace_report_budapest2007.pdf). Referred to in ALADIN Newsletter 32, 2007; Eds.: Bouttier, F. and C. Fisher. 109 pp.

Molteni, F., Buizza, R., Marsigli, C., Montani, A., Nerozzi, F., Paccagnella, T., 2001: A strategy for High–Resolution Ensemble Prediction. Part I: Definition of Representative Members and Global Model Experiments. *Quart. J. Roy. Meteor. Soc.*, 127, 2069–2094.

Molteni F, Buizza R, Palmer TN, Petroliagis T. 1996. The ECMWF ensemble prediction system: Methodology and validation. *Q. J. R. Meteorol. Soc.* **122**: 73–119.

Palmer, T. N., Barkmeijer, J., Buizza, R. & Petroliagis, T. 1997: The ECMWF Ensemble Prediction System. *Meteorol. Appl.*, **4:** 301–304.

Palmer, T. N., R. Buizza, M. Leutbecher, R. Hagedorn, T. Jung, M. Rodwell, F. Vitart, J. Berner, E. Hagel, A. Lawrence, F. Pappenberger, Y-Y. Park, L von Bremen, I. Gilmour, 2007, The Ensemble Prediction System - Recent and Ongoing developments. Tech. Memo. 540, 53pp. Available from ECMWF.

Rasch, P. J., and J. E. Kristjansson, 1998: A comparison of the CCM3 model climate using diagnosed and predicted condensate parameterizations. *J. Climatol.*, **11**, 1587-1614.

Raftery, A. E., T. Gneiting, F. Balabdaoui, and M. Polakowski, 2005: Using Bayesian model averaging to calibrate forecast ensembles. *Mon. Wea. Rev.*, **133**, 1155-1174.

Reynolds, C.A., R. Gelaro, T. E. Rosmond, 2005: A comparison of variance and total-energy singular-vectors. *Q. J. R. Meteorol. Soc.*, **131**, pp. 1955–1973 doi:10.1256/qj.04.132

Simmons, A. J., 1996: The skill of 500 hPa height forecasts. Proceedings of 1995 ECMWF seminar on Predictability. 19-68. Available from ECMWF, Shinfield Park, Reading, UK.

Stainforth, D. A., T. Aina, C. Christensen, M. Collins, N. Faull, D. J. Frame, J. A. Kettleborough, S. Knight, A. Martin, J. M. Murphy, C. Piani, D. Sexton, L. A. Smith, R. A. Spicer, A. J. Thorpe and M. R. Allen, 2005: *Uncertainty in predictions of the climate response to rising levels of greenhouse gases, Nature,* 433, pp.403-406,

Stappers, R. and J. Barkmeijer, 2007: Hirlam Singular Vectors. Hirlam Newsletter, No. 52. (http://hirlam.org/open/publications/NewsLetters/52/)

Stensrud D. J., H. E. Brooks, J. Du, M. S. Tracton, and E. Rogers, 1999: Using Ensembles for Short-Range Forecasting, *Mon. Wea. Rev.*, **127,** 433-446.

Undén, P., L. Rontu, H. Järvinen, P. Lynch, et al., 2002: HIRLAM-5 Scientific documentation. Available from SMHI, S-601 76 Norrköping, Sweden. 144pp.

Wang, X. and C. H. Bishop, 2003: A comparison of breeding and ensemble transform kalman filter ensemble forecast schemes. *J. Atmos. Sci.*, **60**, 1140-1158.

Wang, Y., T. Haiden, and A. Kann 2006: The operational Limited Area Modelling system at ZAMG: Aladin-Austria. *Österreichische Beiträge zu Meteorologie und Geophysik*, **37**, ISSN 1016-6254.