# THE ARPEGE/ALADIN LIMITED AREA ENSEMBLE PREDICTION SYSTEM: SENSITIVITY EXPERIMENTS USING GLOBAL SINGULAR VECTORS

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## Introduction

By perturbing the initial state of a numerical weather prediction (NWP) model it is possible to take into account the impact of the errors in the initial conditions (the fully exact description of the initial state is not achievable due to observation errors, errors in the data assimilation techniques, etc.). Then the model is integrated from these different initial conditions forming an ensemble of numerical weather predictions. The spread of this ensemble provides useful information on the predictability of the atmospheric state and on the probability of different weather events. One possible way to create such an ensemble is to use the singular vector method to perturb the initial conditions of the model. The aim is to find perturbations for a given initial state which grow most rapidly according to the chosen norm (e.g. total energy norm) focusing on a specific area (the optimization area) during a given time interval (optimization time). In this study sensitivity experiments were carried out in order to explore whether or not it is possible to optimize an existing global ensemble system (based on the French global NWP model ARPEGE) for Central Europe by changing only the optimization area and optimization time used for the global singular vector computations. With this purpose several optimization areas and times were defined and tested through case studies and longer test periods. Global ensemble forecasts were downscaled with a limited area NWP model (called ALADIN). Verification results show that the proper choice of the singular vector optimization domain and optimization time can increase the spread of the ensemble and (on average) improves the skill for the Central European area. This conclusion was found to be valid for the global forecasts and the limited area predictions (i.e. the simple downscaling of the global model) as well.

## Numerical weather prediction

While making numerical weather predictions, mathematical models are used to predict the future state of the atmosphere. These calculations can require the use of the most powerful supercomputers in the world. Forecasts are made by solving a set of partial differential equations, the so called primitive equations. These equations are nonlinear and are impossible to solve analytically. Because of their highly nonlinear nature, they are very sensitive to small errors in the initial conditions. This mean that small errors in the initial condition of a numerical weather prediction model can lead to huge errors in the forecast.

The problem is that the true state of the atmosphere cannot be known exactly. Because of the limited number of observations, their uneven spread around the globe and also the inevitable observation errors, there will always be some uncertainty in the initial conditions of the numerical weather prediction models.

## Ensemble prediction

One possible solution to the above mentioned problem is to run a set or, as usually called, an ensemble of forecasts, each started from a slightly different initial condition. The difference between these initial conditions has the same order of magnitude as the analysis error, thus they are equally likely realizations of the atmospheric state.

The ensemble members can be combined into an average forecast (the ensemble mean), or they can be used to compute the probabilities of different weather events. Another way to evaluate the ensemble system is to compute the spread of the members around the ensemble mean. The ensemble spread can give useful information about the predictability of the atmospheric state.

## The singular vector technique

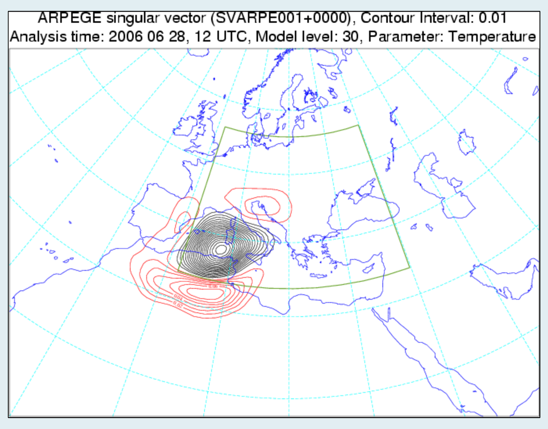
One possible way to create perturbed initial conditions for an ensemble system is to use the singular vector method. The aim is to find the most rapidly growing perturbations to a given atmospheric state. The problem can be formulated mathematically as an eigenvalue problem. To solve this problem several assumptions and choices are needed.

Main assumption:

- perturbations grow linearly in time ⇒ use of the tangent linear model

Choices:

- how to measure the size of a perturbation ⇒ choice of norms at initial and final time
- what region(s) to focus on ⇒ **optimization area(s)**
- between which two model layers to allow the perturbations to grow ⇒ vertical optimization
- how long to allow the perturbations to grow for ⇒ **optimization time**




*Leading singular vector calculated with the ARPEGE model for 28 June 2006, 12 UTC. The parameter presented here is temperature on model level 30. Contour interval is 0.01 Kelvin. The optimization area is shown in green and optimization time was 12 hours.*

The singular vectors are the perturbations with the greatest linear growth over the specified time interval for given norms and optimization areas. Different choices may lead to different sets of singular vectors. Once the singular vectors are computed they can be combined to generate the perturbed initial conditions of the numerical weather prediction model.

In this study sensitivity experiments were carried out to explore whether or not it is possible to optimize an existing global ensemble system (based on the French global NWP model ARPEGE) for Central Europe by changing only the **optimization area** and **optimization time** used for the global singular vector computations. With this purpose several optimization areas and times were defined and tested through case studies and longer test periods. Global ensemble forecasts were downscaled (i.e. used as initial and lateral boundary conditions) with a limited area NWP model (called ALADIN).

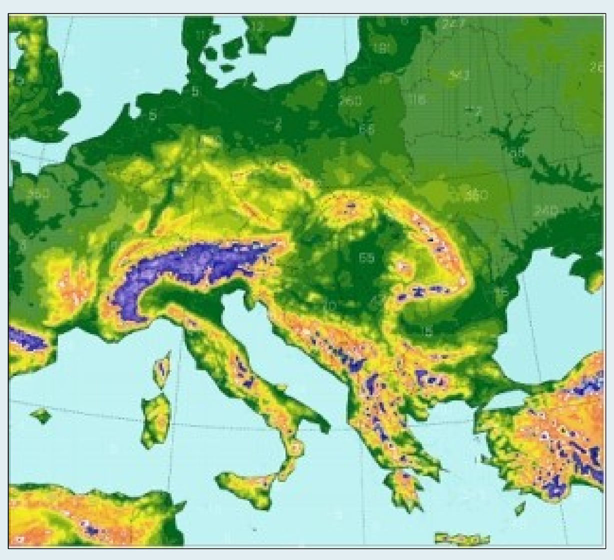
## Description of the applied models

For the experiments the ARPEGE/ALADIN model family was used.

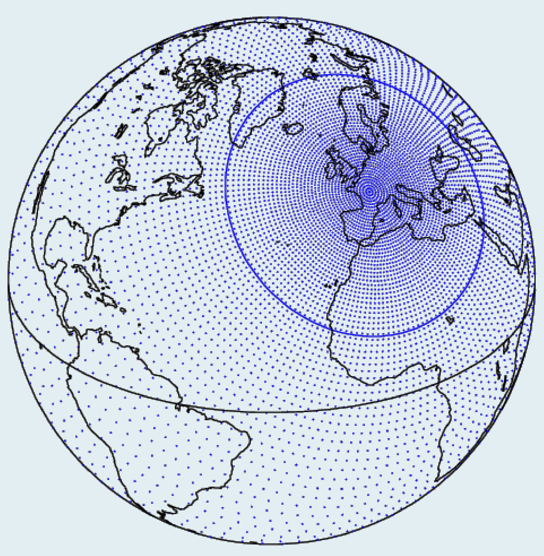
The **ARPEGE** global model is operationally used by the French Meteorological Service (Météo-France). The ARPEGE model has a special feature, the so called stretching, which enables the application of a variable resolution grid, i.e. higher horizontal resolution in the area of interest and lower resolution on the other side of the globe.

Based on the ARPEGE model a global short-range ensemble prediction system (called **PEARP**) was built. The system is running operationally at Météo-France once a day at 18 UTC, up to 60 hours since June, 2004. The perturbations used in this ensemble system are generated by the singular vector technique. Targeted singular vectors are computed using an optimization time of 12 hours with a low resolution over a limited area including Western Europe and the northern part of the Atlantic Ocean. In this way perturbations have the greatest impact in the area of interest (i.e. Western Europe, particularly France). The perturbations are computed by the linear combination of the first 16 targeted singular vectors. The PEARP system has 11 members (10 perturbed members started from different initial conditions + 1 control member, which is started from the unperturbed initial condition) and has an approximately 25 km horizontal resolution over Europe.

The limited area member of the ARPEGE/ALADIN model family is the **ALADIN** model. It has been developed by an international team with French leadership and it is used in the operational work at the Hungarian Meteorological Service. In our experiments the model was used with a horizontal resolution of 12 km and with 37 vertical levels. Integrations were performed for a 60 hours forecast range on a domain covering large part of Continental Europe. Initial and lateral boundary conditions were provided by the members of the ARPEGE ensemble system.



*The integration domain of the ALADIN limited area model*



*The stretched grid of the ARPEGE model.*

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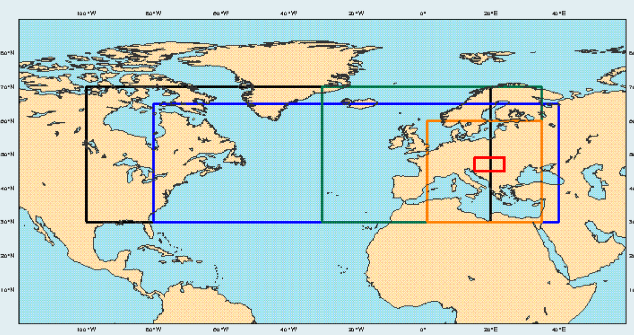
## Sensitivity experiments with the ARPEGE/ALADIN ensemble system – Experimental setup

Experiments were performed to investigate the sensitivity of global singular vector computations in terms of optimization domain and optimization time. Global (ARPEGE) ensemble members were downscaled with the limited area model ALADIN. The experimentation consisted of individual case studies, 10 days (in summer) and 32 days (in winter) continuous tests.

The five different optimization domains used for the global SV computations were the following:

- Domain 1: Atlantic Ocean and Western Europe (as in an earlier version of PEARP)
- Domain 2: Atlantic Ocean and Western Europe (as in the present PEARP system)
- Domain 3: Europe and some of the Atlantic Ocean
- Domain 4: nearly whole Europe
- Domain 5: a slightly bigger area than Hungary



*The five different target domains. Black: domain 1, blue: domain 2, green: domain 3, orange: domain 4, red: domain 5.*

Two different optimization times were used: 12 hours (as in the PEARP system) and 24 hours.

Based on the results of case studies and a 10 days continuous test it was decided to perform a longer (~30 days) experiment. On the one hand the operational PEARP members were downscaled with the ALADIN model, and on the other hand an experimental ARPEGE ensemble system was built. The only difference between this experimental system and PEARP was in the choice of singular vector optimization domain and optimization time. As optimization area Domain 3 was used (see the picture above), the optimiaztion time was chosen as 24 hours. In the PEARP system Domain 2 is used as singular vector optimization area and the optimiaztion time is 12 hours. The experimental set was also downscaled with the ALADIN model.

## Sensitivity experiments with the ARPEGE/ALADIN ensemble system – Results

### Short description of the applied verification methods

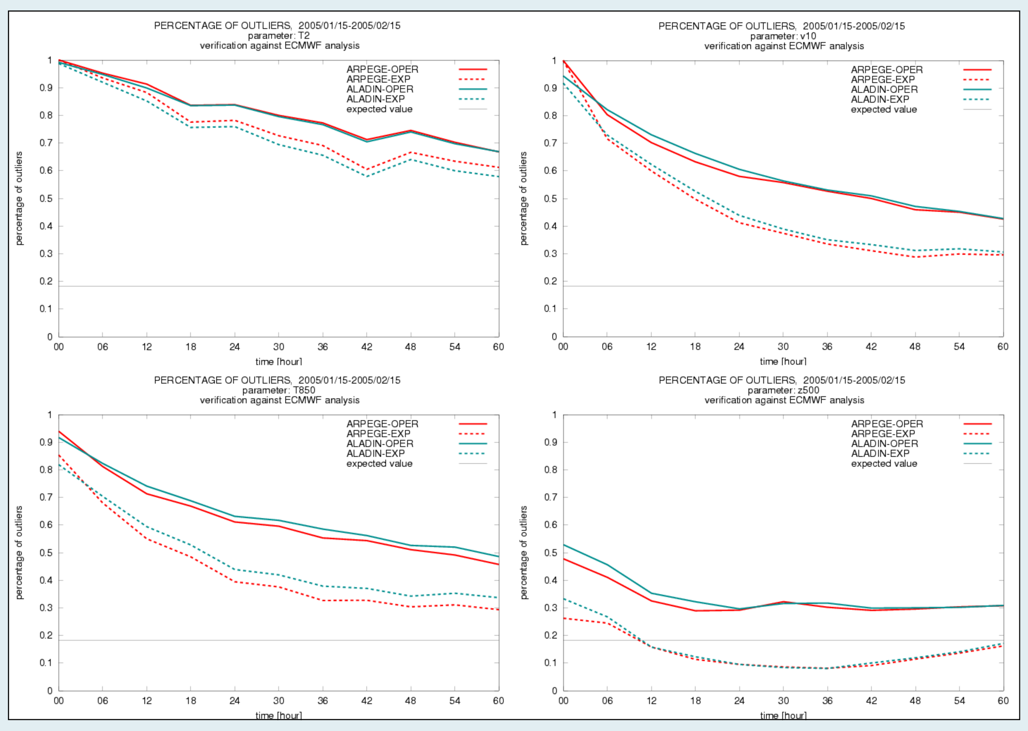
In a perfect system the verifying analysis/observation is equally likely to lie between any two sorted members of the ensemble, including the cases when it lies outside (on either side) the interval defined by the sorted ensemble members. This can be transformed into a diagram called Talagrand diagram. If the system is perfect, the distribution is flat. The **percentage of outliers** is the sum of the two outermost intervals of the Talagrand diagram. In the ideal case the percentage of outliers is equal to 2×1/(number of ensemble members+1), which is around 0.2 in the case of a 10 member ensemble system.

**ROC** (Relative Operating Characteristics) diagrams give information about the skill of the forecast. Hit rate is plotted on the y axis, while false alarm rate is plotted on the x axis. The integral area under the ROC curve can be calculated to represent the skill of the forecast. An integral area of 1 represents perfect forecast, while an integral area less than 0.5 means that the forecast has no skill compared to the use of climatological statistics

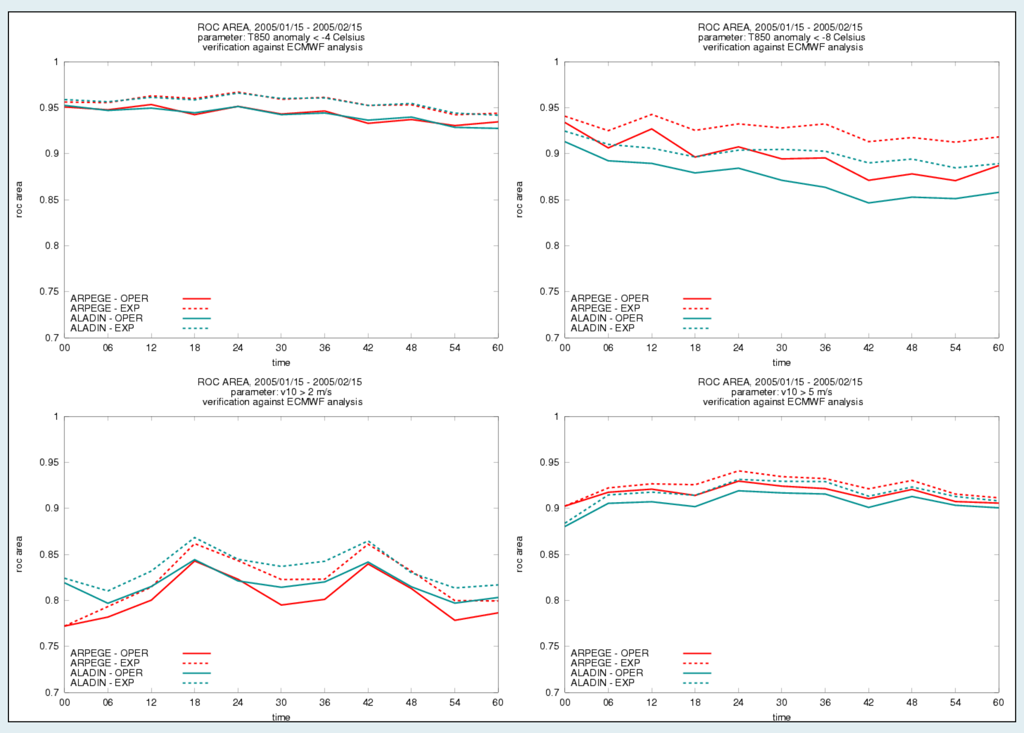
On average when an event is forecasted with a given probability, it should occur with the same frequency in the reality. On the **reliability diagram** the forecast probabilities are displayed along the x-axis and the observed frequencies for each forecast probability are on the y-axis. If the forecasted probabilities and the observed frequencies agree, the curve lies along the diagonal.

Percentage of outliers diagrams for the ARPEGE and ALADIN ensemble systems for the period 2005/01/15 - 2005/02/15 for 2 meter temperature (T2), 10 meter wind speed (v10), 850 hPa temperature anomaly (T850) and 500 hPa geopotential height (z500). The solid red line is the operational PEARP forecast, dashed red line is the experimental ARPEGE ensemble (with modified singular vector optimization domain and optimization time), solid green line is ALADIN coupled with the operational PEARP members and dashed green line is ALADIN coupled with the experimental set. In the ideal case the percentage of outliers would be equal to 2*1/(ensemble members+1), which is around 0.2 for our system.

It was found that the change of the optimization domain and optimization time during the global singular vector computation could improve the system's ability to comprise the true state of the atmosphere. Looking at the percentage of outliers clear improvement can be seen especially for upper level parameters.



However, it is also clear that the simple downscaling of the global ensemble system with the ALADIN model does not yield significant improvements. For some parameters the ALADIN forecasts have better scores (e.g. 2 meter temperature), for others (e.g. 850 hPa temperature) the ARPEGE ones.

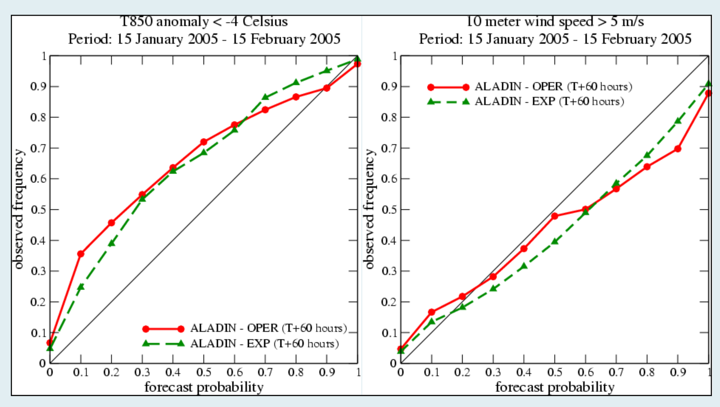


ROC area diagrams for the ARPEGE and ALADIN ensemble systems for the period 2005/01/15 - 2005/02/15 for 850 hPa temperature anomaly (T850) and 10 meter wind speed (v10). The solid red line is the operational PEARP forecast, dashed red line is the experimental ARPEGE ensemble (with modified singular vector optimization domain and optimization time), solid green line is ALADIN coupled with the operational PEARP members and dashed green line is ALADIN coupled with the experimental set. (The value of 1 represents perfect forecast, while a value less than 0.5 means the forecast has no skill compared to the use of climatological statistics.)

Changing the optimization domain and optimization time used for the global singular vector computations yields improvement for the 850 hPa temperature anomaly. The ROC area shows rather good scores for the -4°C threshold (without loss of quality with the integration time), however the relative improvement is higher for the -8°C threshold value. (The examined period was much colder than the average therefore the scores for T850 temperature anomaly higher than +4°C and +8°C are not shown.)

For the 10 meter wind speed the improvement is less significant compared to the 850 hPa temperature anomaly. However, the change of the optimization domain and optimization time yields clear improvement for this parameter as well. It is important to note that the quality of the ensemble system increases for stronger wind values which is an encouraging result, especially if one would like to represent correctly extreme events.

Reliability diagrams at T+60 hours for the experiments ALADIN-OPER (solid red line, circle symbols) and ALADIN-EXP (dashed green line, triangle symbols). Parameters: 850 hPa temperature anomaly < -4 Celsius (T850). 10 meter wind speed > 5 m/s (v10). Verification was performed against ECMWF analysis for the period 15 January 2005 - 15 February 2005.




In case of reliability diagrams we cannot come to a clear conclusion. In certain forecast steps and for certain forecast probabilities ALADIN-OPER performed better, in other cases ALADIN-EXP had better scores. It can be concluded however, that on average the experimental set at least kept the forecast quality.

## Conclusion and future plans

Verification results of the ARPEGE/ALADIN ensemble system show that the proper choice of the singular vector optimization domain and optimization time can increase the spread and (on average) improve the skill of the ensemble system for the Central European area. On the other hand the studied limited area ensemble system was found not to provide significant additional information with respect to the global one, therefore the computation of mesoscale initial perturbations for the limited area model might be desirable for a more efficient short-range ensemble system. The work with singular vectors computed with the limited area model ALADIN has already started.