Working Area Predictability

Progress Report

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Period:	Jul – Dec 2024
Date:	Mar 2025

Progress summary

Three ensemble prediction systems are currently operated in RC LACE – the common A-LAEF system and the two convection-permitting AROME based EPS C-LAEF (Austria) and AROME-EPS (Hungary).
No major upgrades on the operational systems have been made in 2024, but new and improved systems are currently in test phase. For A-LAEF an upgrade from cy40t1 to cy46t1 is planned soon, C-LAEF and AROME-EPS are intended to be upgraded to newer versions in 2025. The A-LAEF upgrade also includes a new upper-air spectral blending method and an upgraded version of the multiphysics package. The switch of the C-LAEF system to its successor C-LAEF 1k comprises beside an upgrade in the model cycle (cy43t2 to cy46t1) also an increase of the horizontal resolution from 2.5km to 1km and some substantial improvements in data assimilation (new observation types, EnVar), model error representation (new SPP, flow dependency), dynamics setup and post processing (grib2). It will be operated as a continuous lagged ensemble providing 8 EPS runs per day with 60 h forecasting range. An Esuite of C-LAEF 1k has been successfully tested during a winter and summer test period and verification scores are very promising. Slovenia and Croatia have joined the C-LAEF 1k project by contributing SBUs and manpower. Further expansions of C-LAEF 1k (more members, combination with AI technologies, etc.) are planned in the near future.

The main research topics in the EPS area of RC LACE are currently the improvement of the model error representation by SPP and the statistical post-processing of EPS data. The latter one comprises classical approaches (e.g. analog-based post-processing, statistical post-processing), but also new approaches in the area of artificial intelligence (AI). For example physics informed and data-driven machine learning nowcasing for the PV and wind power sector.

A lot of people working in the EPS area of RC LACE are also involved in phase II of the Destination Earth project of the European Commission where on-demand configurable digital twin engines for forecasting of environmental extremes at the sub-km scale are planned (DEODE). In phase II it is planned to run limited area ensemble systems on the hectometric scale (750 m) on demand.

Scientific and technical main activities and achievements, major events

S1 Subject: Preparation, evolution and migration

Description and objectives: Maintain and monitor the operational suites of A-LAEF and C-LAEF running on ECMWF's HPC and the AROME-EPS running at the HPC at HungaroMet. Migration and implementations to new HPCs, operational upgrades, new cycles, optimizations and tunings.

The originally planned topics for 2024 were:

- ❑ A-LAEF and C-LAEF: Maintenance/monitoring of operational EPSs on ECMWF's HPC in Bologna, upgrades
- ❑ A-LAEF: Implementation of SURFEX for ALARO-EPS
- ❑ A-LAEF: Development of an ALARO-based convection-permitting EPS coupled to ECMWF-ENS and A-LAEF
- ❑ C-LAEF: C-LAEF 1k for Slovenia and Croatia, extension of domain, data provision, product generation, R&D, pre-operational status
- ❑ C-LAEF: New HPC at GeoSphere Austria – migration, tests for C-LAEF 1k
- ❑ C-LAEF: Migration of SPP code to export version of cy49t1 (cooperation with Ulf Andrea – stay in Innsbruck)
- ❑ AROME-EPS: Optimization and tuning of convection-permitting ensemble system on HPC at HungaroMet
- ❑ AROME-EPS: Introduction of model perturbations (SPP) in operational AROME-EPS

A-LAEF and C-LAEF have been running on the ECMWF HPC in Bologna for several years now. Beside some short interruptions due to technical problems at the HPC they are running very stable. No big operational upgrades have been made in the second half of 2024, the focus of the work in S1 was placed on the development and testing of the new ensemble systems and Esuites (e.g. new A-LAEF, C-LAEF 1k, ALARO-EPS) which should become operational in the near future.

For the A-LAEF system a cy46t1 Esuite with some substantial upgrades (e.g. implementation of upper-air spectral blending, upgrade of multiphysics, etc.) has been set up under the new time-critical user zla2 at the Atos HPC of ECMWF. This Esuite has been tested for several case studies (e.g. storm Boris in September).

The work on an ALARO-EPS system coupled in ECMWF-ENS is progressing well. Mini ensembles (6+1 members) on 1 km and 750 m resolution with new multi physics and stochastic physics have been tested for various case studies. The coupling of ALARO-EPS in A-LAEF has started with the setup of an ecFlow suite on Atos. Due to missing resources this has not been tested so far. No progress has been made in the implementation of SURFEX in the ALARO-EPS.

In a cooperation with Pau Escriba from the Spanish Meteorological Agency AEMET new Clim files for different gSREPS operational domains (e.g. antarctica, iberia, canarias) have been prepared for their ALARO ENS.

The new 1km version of the C-LAEF system (C-LAEF 1k) has been running continuously for a summer (July – September 2024) and a winter period (January, Februar 2025). Verification showed a general quite good performance, but also some deficiencies (e.g. too less convection over mountainous areas) have been found which resulted in some adaptations in the dynamics setup. Intensive cooperation between the RC LACE countries Austria, Slovenia and Croatia has been initiated with the scope of a common C-LAEF 1k system in the near future.

The delivery of the new HPC at GeoSphere Austria has been postponed for several times, but in June 2024 it has been finally delivered. Testing and migration of NWP models to the new HPC have started in autumn 2024 and in January 2025 it was put into operations.

C-LAEF for Turkey is running continuously on Atos since March 2024. The performance is currently verified and it is expected to become operational soon. The model resolution is 1.7 km with 72 vertical levels, a lead time of 24 hours and the domain is the same as for the operational AROME model.

During a 1-week stay in Innsbruck Ulf Andrae (SMHI) and Clemens Wastl worked on the porting of the SPP code to the cy49t1 IAL code. In this context parts of the code have also been rewritten to be ready for GPUs (cooperation with Meteo France).

The operational AROME-EPS system in Hungary has not undergone any upgrade in 2024 due to missing resources but it is planned to be upgraded to cy46t1 in February 2025.

❑ Topic 1: Upgrade of A-LAEF on ECMWF's HPC

No major operational upgrades have been made for A-LAEF in 2024 but some work has been dedicated to the development of a cy46t1 based A-LAEF Esuite under the new time-critical user zla2 at the Atos HPC in Bologna. This upgrade contains a new ALARO-1 multiphysics scheme which has been developed and tested during a stay of Martin Belluš in Prague in the beginning of 2024. The new configuration is able to deliver qualitatively comparable results to the operating version for tested cases. Moreover, it provides some new interesting diagnostic fields (e.g. precipitation type).

The new A-LAEF cy46t1 Esuite has been tested for several case studies including a massive flooding/storm event in Central Europe. Between September 13 and 16 2024 a low-pressure system named Boris brought record-breaking rainfall and extreme winds to Central Europe, resulting in severe flooding, blocked roads by fallen trees and damaged power lines. The most affected areas included eastern Austria, regions along the Czech-Polish border, and the western parts of Slovakia. The flooding caused extensive damage, and tragically, loss of lives was also reported. The forecast of the cy46t1 A-LAEF Esuite has been prolonged to 108h to depict the complete event (Figure 1). The synoptic situation was very well captured by the A-LAEF Esuite and the observed precipitation maxima of more than 400mm in lower Austria and near the Czech-Polish border have been indicated by the ensemble maximum.

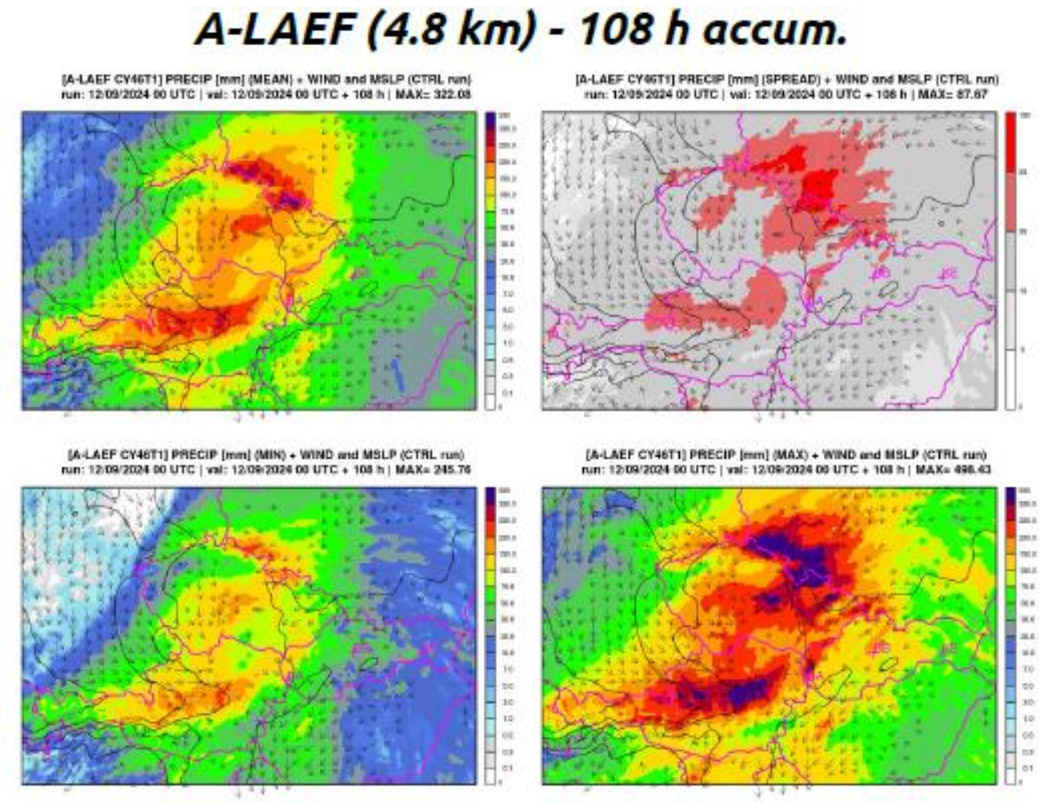

Figure 1: 108h accumulated precipitation of the A-LAEF cy46t1 Esuite for storm Boris initialized on September 13 2024 00 UTC. Ensemble mean, ensemble spread, ensemble minimum and maximum are shown in the 4 panels.

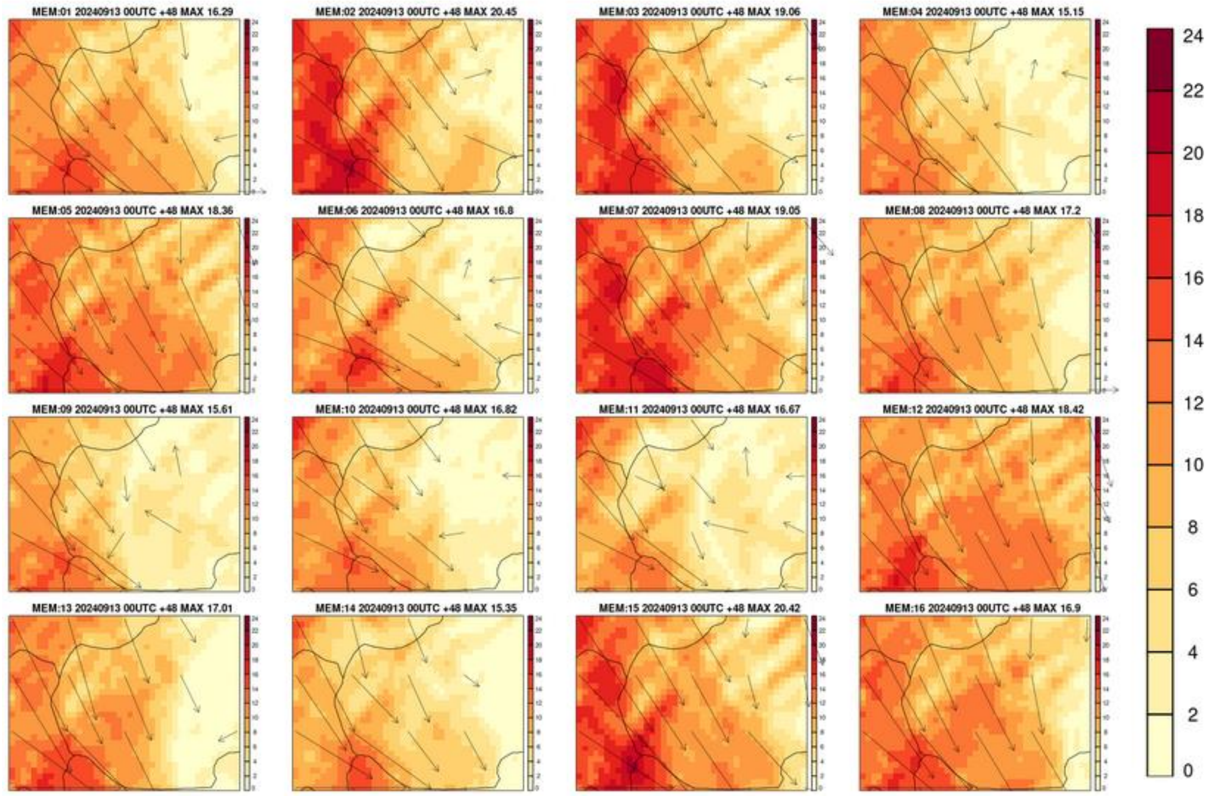

Figure 2: 10m wind forecast (+48 h) for 16 perturbed members of the A-LAEF cy46t1 Esuite initialized on September 13 2024 00 UTC.

Beside the massive precipitation amounts storm Boris also brought strong winds with more than 20 m/s due to orographic subsidence (mountain waves) behind the Little Carpathian (Figure 2).

Apart from the case studies, it was planned to carry out a more complex comparison of statistical scores between the cy46t1 Esuite of A-LAEF and the operational A-LAEF system, for a reasonably long verification period. This has been postponed because of a bug in the B-level parallelization of the c701 configuration (canari) in the assimilation cycle, which has been solved now. Furthermore some problems also appeared in the DFI step of spectral blending for a given combination of boundary conditions and first guess sources in the A-LAEF Esuite. After these long term test periods it is planned that the new full system including all upgrade components (e.g. ESDA, post-processing) should become operational in 2025.

- ❑ **Topic 2: Development of an ALARO-based convection-permitting EPS coupled to ECMWF-ENS and A-LAEF**

An ALARO-EPS (coupled in ECMWF-ENS) ecFlow suite with 1 km spatial resolution and 87 vertical levels has been implemented under the user sk2 at the ECMWF HPC Atos, covering Slovakia and the surrounding regions. This suite aims to provide experience with convection-permitting ensembles on kilometric scales, focusing on the coupling of such systems and simulating their uncertainties using ALARO multi-physics combined with stochastic physics. The insights gained will contribute to the development of a convection-permitting ALAR-EPS at SHMU coupled to A-LAEF.

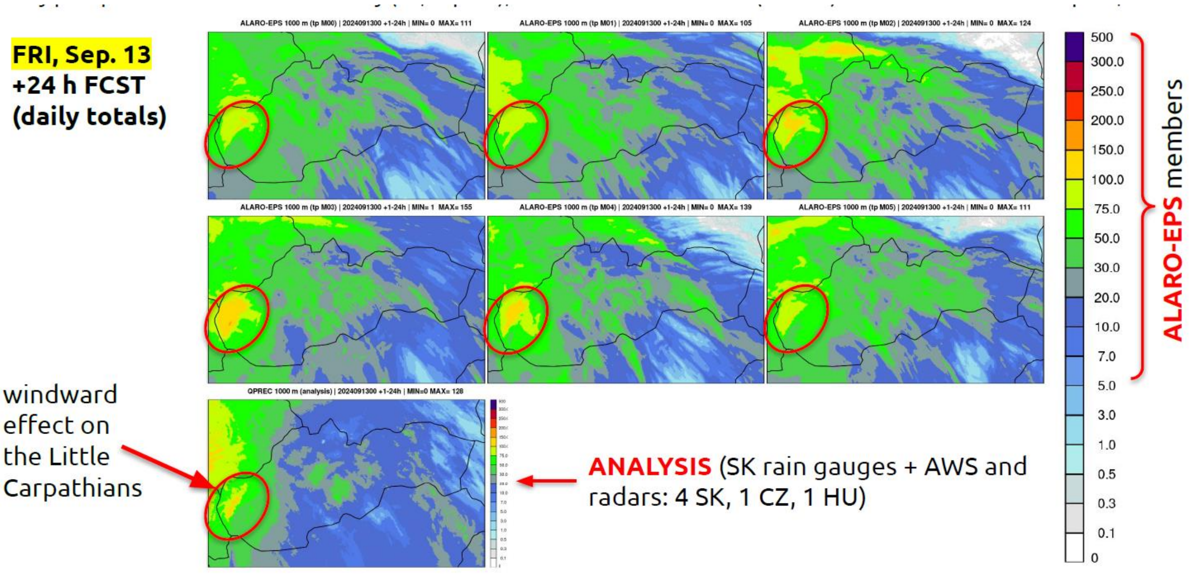

Figure 3: 24h accumulated precipitation for storm Boris (September 13 00 UTC – September 14 00 UTC) in the 6 members of ALARO-EPS. The last panel shows the analysis based on a combination of rain gauges and radar data. Forecast initialized on September 13 00 UTC.

First tests with a mini ALARO-EPS (6+1 members) have been made on 1 km for the storm Boris event in September 2024 (Figures 3 and 4). The high resolution ALARO-

EPS is able to show increased precipitation amounts due to orographic lifting on the windward side of the Little Carpathians (150–300 mm).

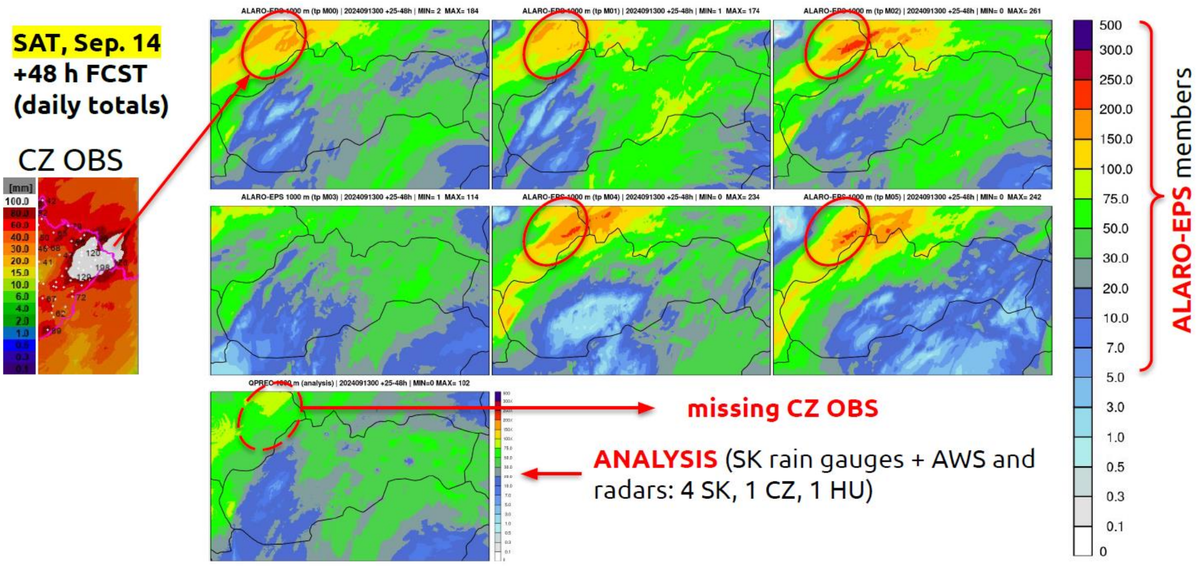

Figure 4: 24h accumulated precipitation for storm Boris (September 14 00 UTC – September 15 00 UTC) in the 6 members of ALARO-EPS. The last panel shows the analysis based on a combination of rain gauges and radar data. Forecast initialized on September 13 00 UTC.

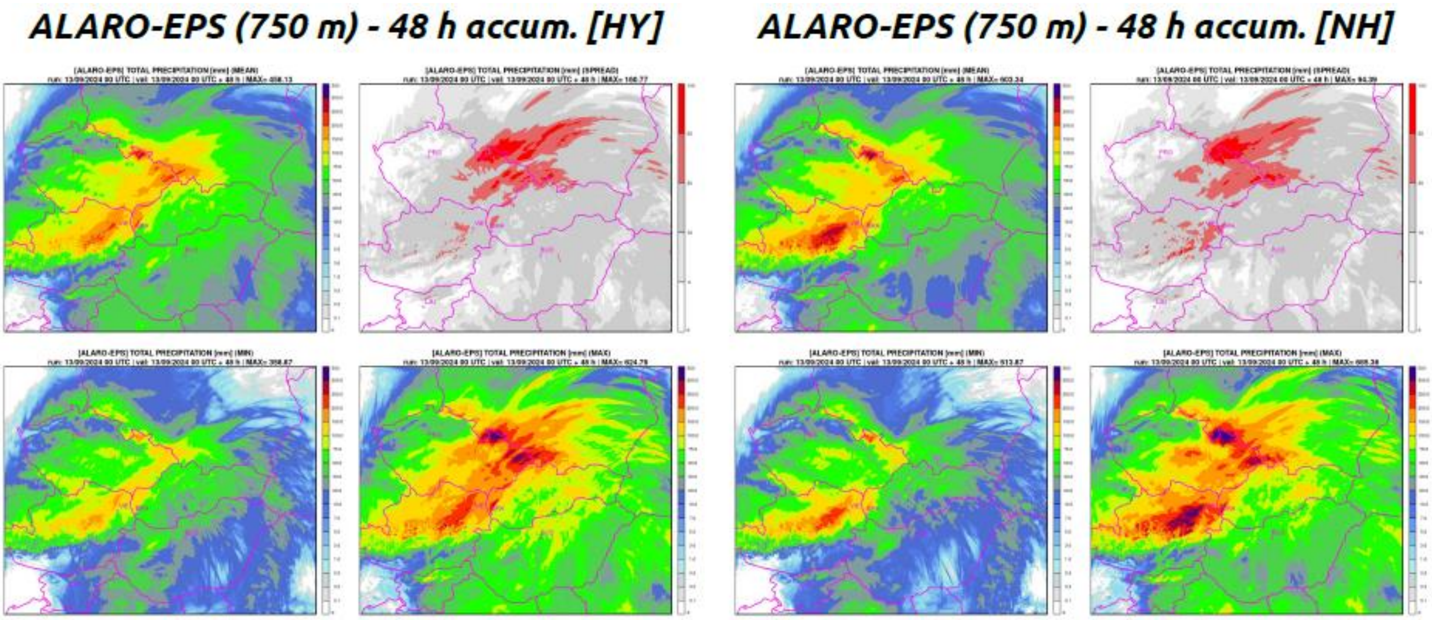

Figure 5: 48h accumulated precipitation for storm Boris (September 13 00 UTC – September 15 00 UTC) of ALARO-EPS on 750m in a hydrostatic (left) and non-hydrostatic (right) configuration. Ensemble mean, ensemble spread, ensemble minimum and maximum are shown in the 4 panels each. Forecast initialized on September 13 00 UTC.

For this Boris case the ALARO-EPS has also been run on increased resolution of 750m in a hydrostatic and non-hydrostatic configuration including the new ALARO multiphysics and surface stochastic physics (Figure 5). The non-hydrostatic version is producing significantly higher precipitation amounts over the mountains compared to the hydrostatic configuration. Some more tuning is planned on the optimized settings for this high resolution ensembles. The benefit of the increased resolution can also be seen when looking on the wind waves behind the Little Carpathians in Figure 6. The 1 km version is producing much sharper structures and higher wind speeds in the orographic waves.

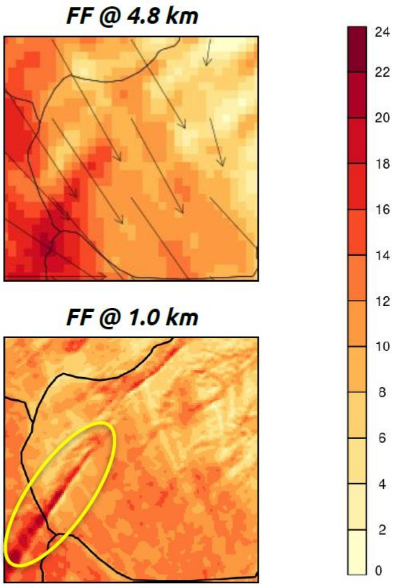

Figure 6: Comparison of 10 wind speed on September 15 00 UTC 2024 for a specific member in A-LAEF on 4.8 km resolution (top) and ALARO-EPS on 1.0 km resolution (bottom). . Forecast initialized on September 13 00 UTC.

- **Topic 3: Upgrade of C-LAEF to 1km – test suites, optimizations, verification**

The operational C-LAEF system of Austria (cy43t2) is planned to be replaced by a 1 km version on cy46t1 by the end of 2025 (C-LAEF 1k). Slovenia and Croatia have joined this initiative by contributing SBUs and man power – Slovenian contributions focus mainly on data assimilation, Croatia is supporting in the area of model perturbations and post-processing. In 2024 a lot of testing and tuning has been made. The C-LAEF 1k ensemble consists of 16+1 members, where the 16 perturbed member are coupled with the first 16 ECMWF-ENS members, whereas the control run is coupled with the IFS deterministic run. A 3-hourly assimilation cycle is implemented with using new types of observations (e.g. radar, GNSS, ceilometer, etc.). Single precision is used for configuration 001 including the usage of an I/O-server and a time step of 45 sec. Due to the cooperation with Slovenia and Croatia, the domain has been extended towards the South (Figure 7). To handle different post processing domains for the partners, some adaptations have been made in the ecFlow suite of C-LAEF 1k. Currently some preparation work is ongoing for the switch to grb2 output and an option for ccsds-packing. A common user name (zacs) and SBU account (claef-op) for Austria, Croatia and Slovenia has been created to share the development and the monitoring of the suite.

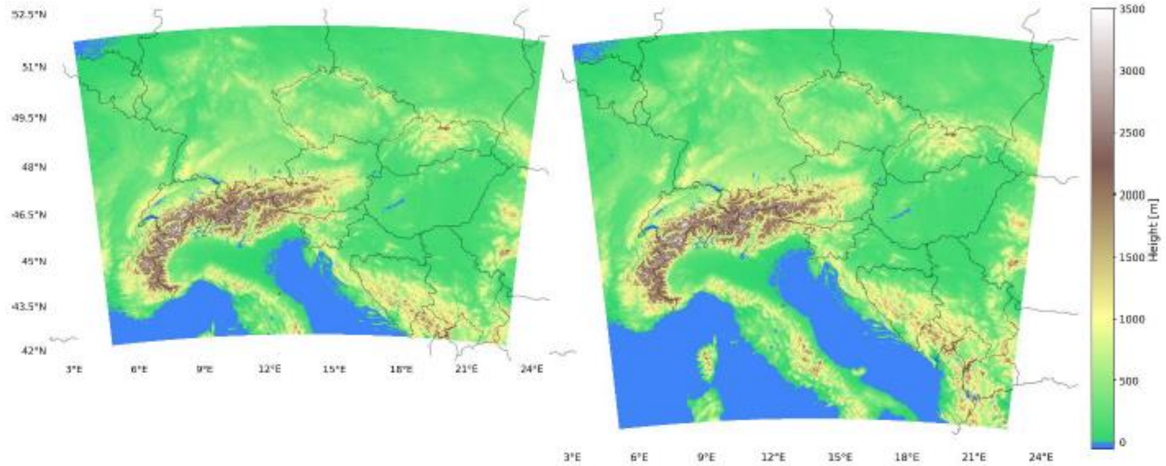

Figure 7: Domain extension of C-LAEF 1k to the south.

After operationalization (end of 2025) the system will provide a full 16 + 1 member ensemble 8 times a day with a forecasting range of +60 h. The perturbation methods include the SPP scheme for model perturbations, Ensemble-JK, EDA and surface EDA for initial condition perturbations and an external surface perturbation scheme (pertsurf). To cover the extremely high computational costs, C-LAEF 1k is run in a continuous lagged ensemble mode (Figure 8). This means that for each run only 4 members (plus the unperturbed control member) are computed over an extended forecasting range of +69 h whereas the remaining 12 members are kept short (+6 h) just for the assimilation cycle (including Envar). In the post processing (after the creation of the grib files) the members of the most recent 4 runs are combined (modification of grib headers, etc.) to get a full 16 + 1 member ensemble with 60 h forecasting range every 3 hours. This means that the oldest members of the ensemble are 9 hours old.

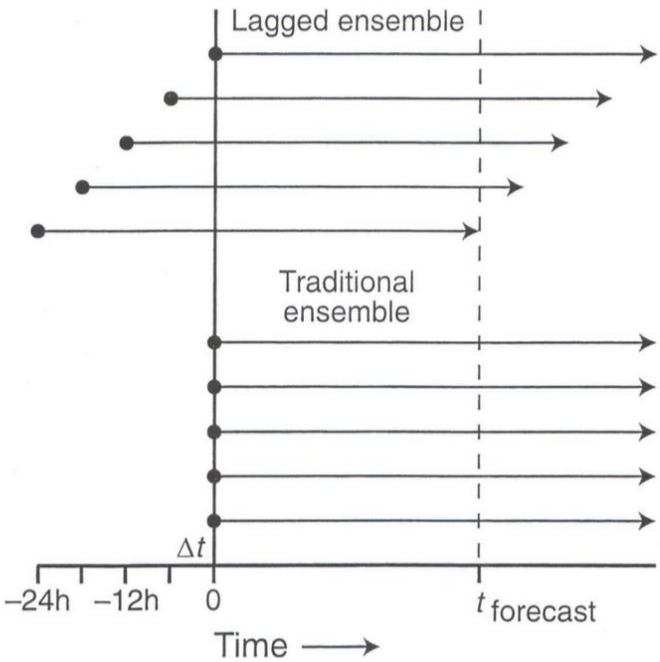

Figure 8: Schematic illustration of a continuous lagged ensemble after Warner et al., 2011.

This lagging approach has been intensively tested in 2024 and the scores are comparable or even slightly better compared to the classical EPS (Figure 9).

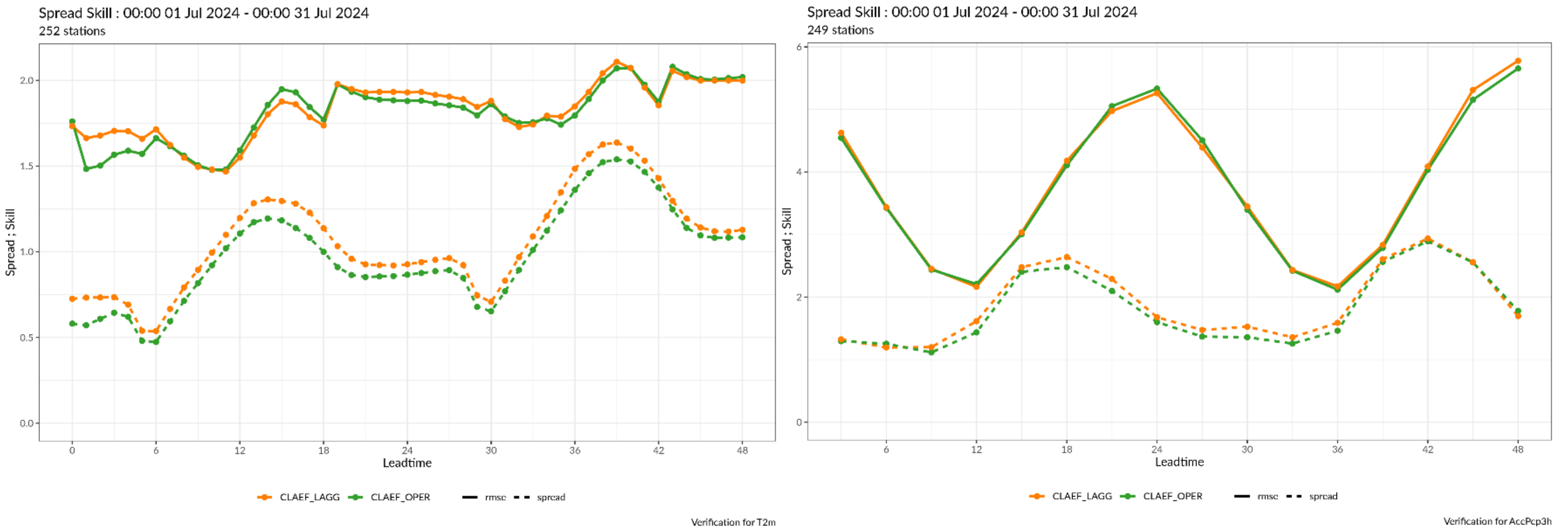

Figure 9: Ensemble spread (dashed) and RMSE (full) of 3 h accumulated precipitation (left) and 2m temperature (right) for C-LAEF lagged (orange) and C-LAEF operational for July 2024.

The full C-LAEF 1k has been running for a summer (July – September 2024) and a winter test period (January - February 2025). The performance of C-LAEF 1k is monitored continuously using HARP verification software. The following verification scores were calculated for approx. 250 stations over Austria. The overall performance of C-LAEF 1k is quite satisfying with score improvements for nearly all variables compared to the operational C-LAEF system. However, some problems were observed during the convective season in 2024 resulting in a significant dry bias in C-LAEF 1k over the Alps in the afternoon and evening hours in case of convection. A detailed investigation for some convective test cases showed that the new dynamics setting taken from Meteo France was the reason for that. Meteo France is using in their operational cy46t1 AROME version COMAD (Continuous MApping about Departure points) and SLHD (Semi Lagrangian Horizontal Diffusion) is switched off. Based on this bad test cases (convective precipitation was completely missing in C-LAEF 1k over the mountains) we decided to use the same dynamics setting in C-LAEF 1k as in our operational C-LAEF system (SLHD turned on, COMAD switched off). The switch was done mid of August 2024 and resulted in a significant score improvement.

Figures 10 and 11 show verification results of a two weeks period in August (after the last dynamics adaptation). For precipitation (Figure 10) there is a small improvement in C-ALEF1k, but for 2m temperatures the Bias is significantly reduced compared to the operational C-LAEF system. Also when looking on the probabilistic score CRPS in Figure 11, it is obvious that the C-LAEF 1k system performs pretty well.

Figures 12 and 13 show some verification scores of C-LAEF and C-LAEF 1k for the winter period (January – February 2025).

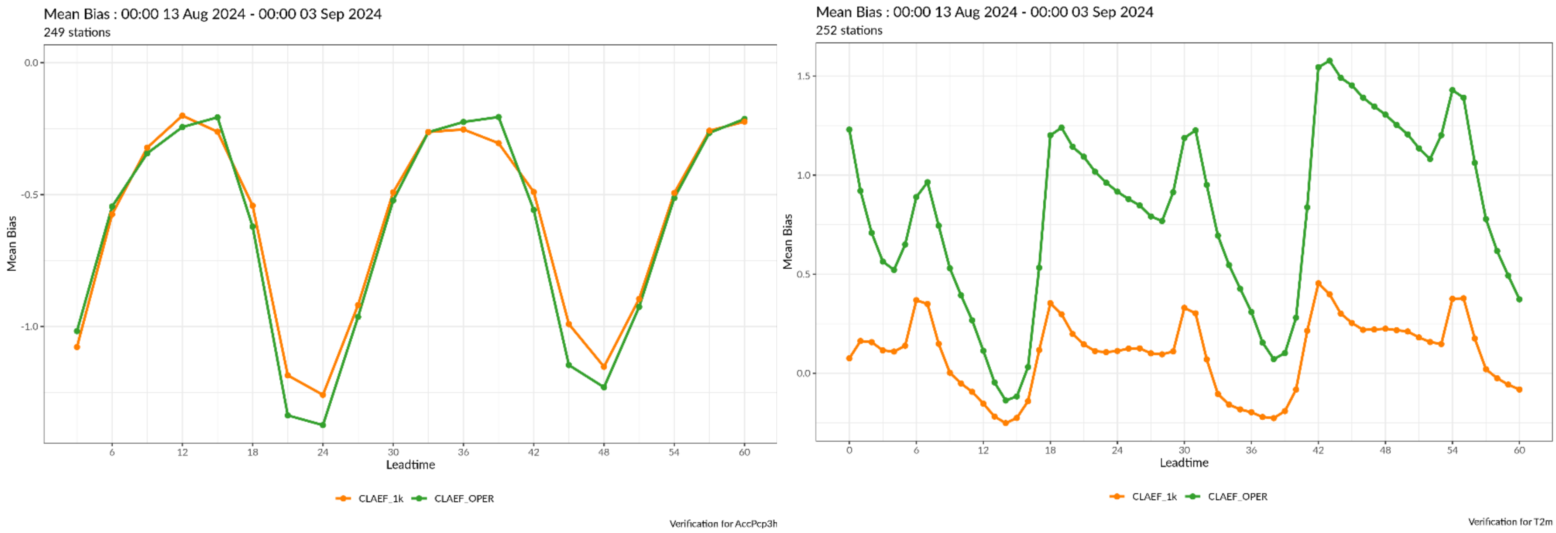

Figure 10: Mean Bias of 3 h accumulated precipitation (left) and 2m temperature (right) for C-LAEF 1k (orange) and C-LAEF operational (green) for a test period in summer 2024.

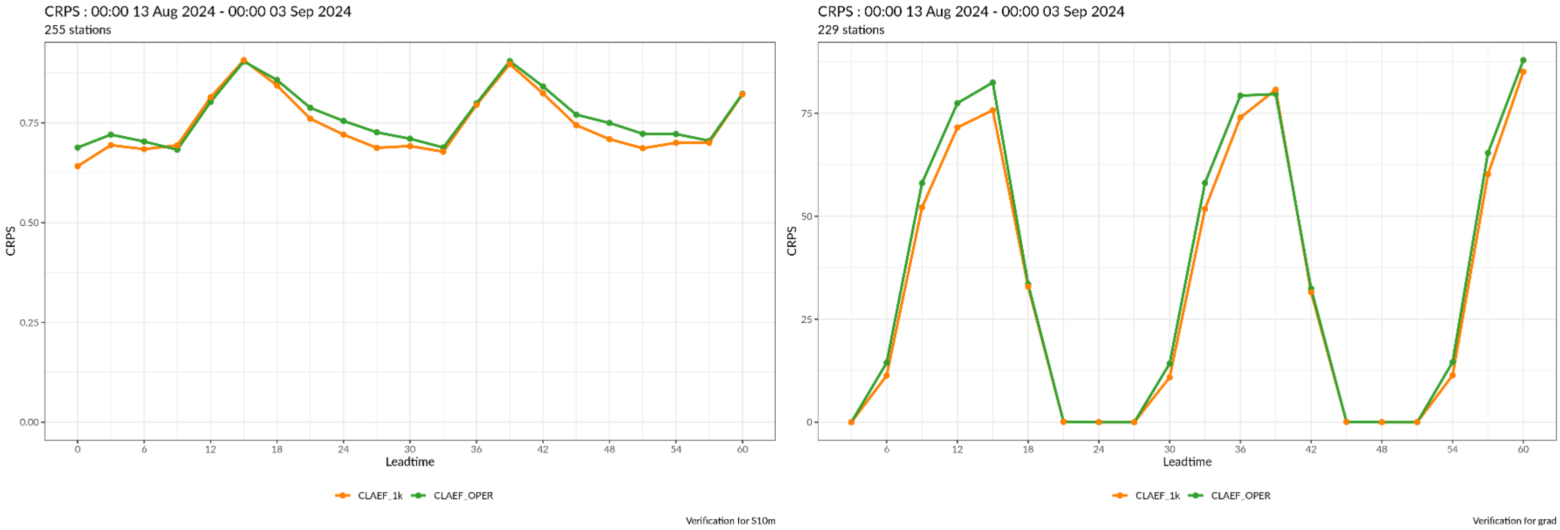

Figure 11: CRPS of 10m wind speed (left) and global radiation (right) for C-LAEF 1k (orange) and C-LAEF operational (green) for a test period in summer 2024.

In the future we want to bring more flow dependency into our EPS and therefore we are planning to replace 3Dvar in C-LAEF 1k with Envar. Therefore an additional Envar control member has been added to C-LAEF 1k (member 17). It is based on cy48t3 and uses in total 32 member as input, 16 members from the previous forecast and 16 members from the run before. First verification results are promising – some details on that are given in subject S3.

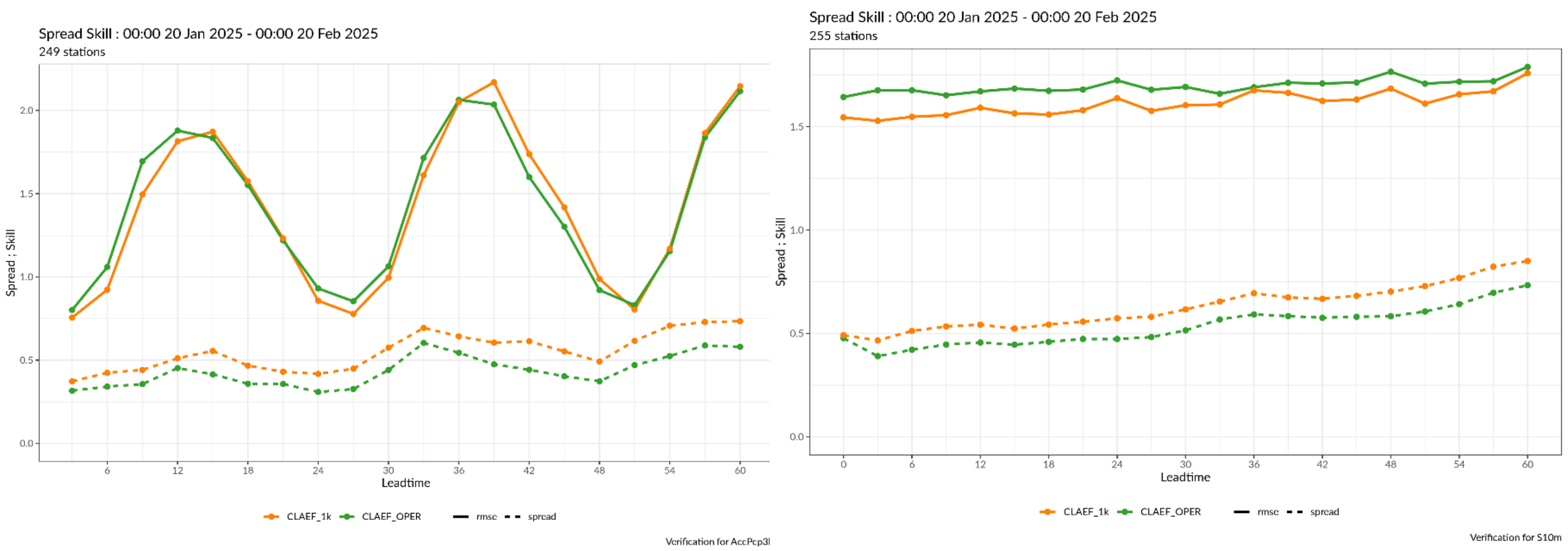

Figure 12: Spread (dashed) and skill (RMSE, full) of 3 h accumulated precipitation (left) and 10 m wind speed for C-LAEF 1k (orange) and C-LAEF operational (green) for a test period in winter 2025.

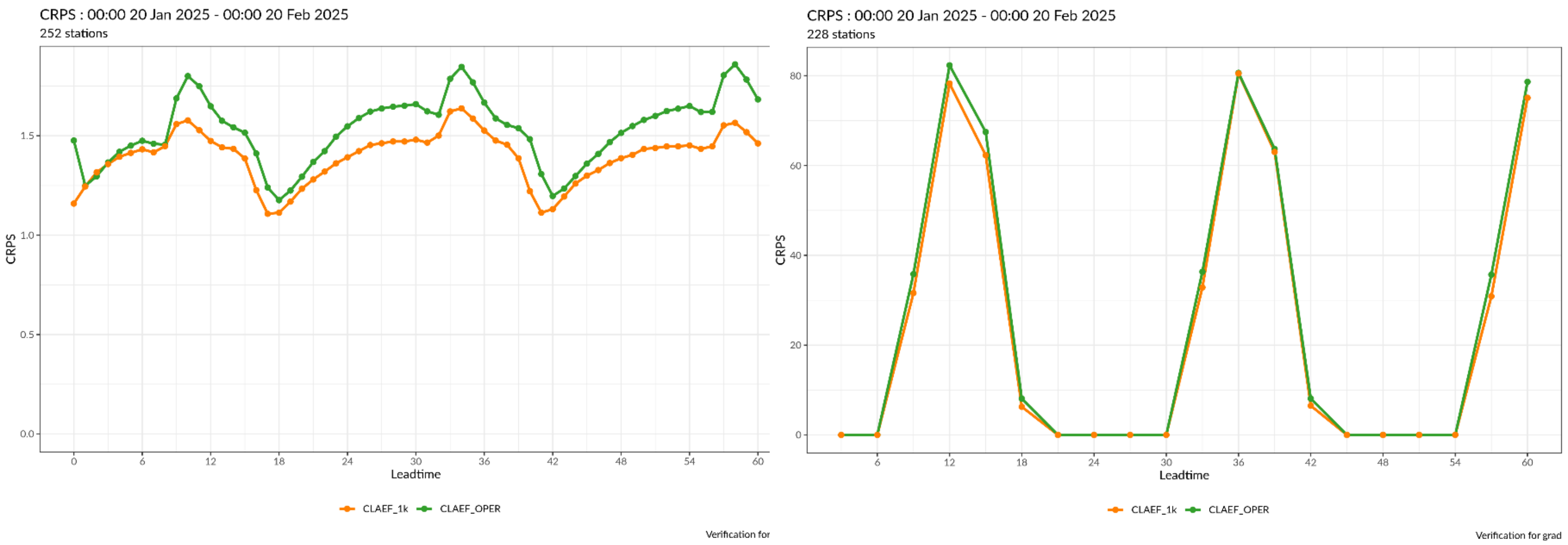

Figure 13: CRPS of 2 m temperature (left) and global radiation (right) for C-LAEF 1k (orange) and C-LAEF operational (green) for a test period in winter 2025.

The C-LAEF 1k suite is generally running very stable with hardly no technical problems (except there are general problems on the Atos HPC). The grib output and some products (visual weather maps, meteograms) have been provided to forecasters in Austria, Croatia and Slovenia. The full ensemble will be stopped after the winter test period (March 2025) to save SBUs and it is planned to be switched on for another summer period in July/August 2025. The control member and the additional Envar member are operated continuously in 2025. The final operationalization of the new C-LAEF 1k system is foreseen for the end of 2025.

❑ Topic 4: New HPC at GeoSphere Austria – migration, tests for C-LAEF 1k

The delivery of the new HPC at GeoSphere Austria has been delayed for several times in the past but finally on 5 June 2024 it arrived in Vienna. It is a HPE CRAY XD2000, 100 Nodes including 2 Fat-Nodes, AMD EPYC 9654 96-Core Processor. It has been finally accepted at 17 July 2024. Early users had access starting from August 2024 onwards, in October GeoSphere Austria started to migrate the operational AROME-AUT and AROME-RUC systems to the new HPC. They have been running as parallel suites from October 2024 till January 2025. The official operational switch has been made on January 15 and the old HPC has been switched off on January 31 2025.

❑ Topic 5: C-LAEF: Migration of SPP code to export version of cy49t1 (cooperation with Ulf Andrea – stay in Innsbruck)

The Stochastically Perturbed Parameterization (SPP) scheme is an important part in the representation of model uncertainty. SPP is operationally used as model error representation in several ensembles of the ACCORD consortium: E.g. in HarmonEPS (MetCoOp), DINI-EPS (UWC-W), C-LAEF (Austria) and tested in other systems as well (e.g. AROME-EPS of Hungary, etc.). It is also used operationally in the IFS system of ECMWF. The original SPP code has been developed by Ollinaho et al. (2019) at ECMWF and it has been adapted to the AROME based systems of HarmonEPS and C-LAEF by Ulf Andrea and Clemens Wastl. As a large part of the methods, and code, are shared between AROME and HARMONIE-AROME there was the idea to increase the practical cooperation and create a common SPP code version during a stay of Ulf Andrae at Innsbruck.

In CY49 there are several changes that require some extra attention. One part is the rewritten setup procedure, a development that has been driven by ECMWF but discussed and agreed with the LAM community. The second part is the externalization of the MESO-NH physics into the PHYEX project and the ongoing work of making the physics ready for running on GPU processors. Parts of the HARMONIE-AROME setup was introduced in CY49T1 and CY49T2 but e.g. the pattern generator SPG had been removed, without any notification of concerned parties, and has been reintroduced on top of CY49T2. None of the SPP parameters for AROME had been introduced in CY49 prior to the visit.

In order to have a common code base to work with where both AROME and HARMONIE-AROME works, the CY49T2 version used in DEODE was chosen. This branch contains modifications done by the HARMONIE-AROME system group allowing the version to run without breaking the functionality of AROME and ALARO. The code base used was https://github.com/destination-earth-digital-twins/IAL/tree/dev-CY49T2h_deode and it was possible to compile the code with both CMake and, after some minor modifications, with gmkpack. The natural choice for the runtime environment was the DEODE scripting as both parties are involved in the project and since it provides a common ground for intercomparison and cooperation.

At the end of the stay not all SPP parameters have been implemented, the rest could be finished in autumn 2024. Currently some testing is ongoing to be ready for the CY50T1 phasing in 2025.

- **Topic 6: AROME-EPS: Optimization and tuning of convection-permitting ensemble system on HPC at HungaroMet**

No operational changes in the operational AROME-EPS system at HungaroMet have been made in 2024 because of some personell restructuring – Gabriella Nagy left HungaroMet in summer 2024 and the new colleague (Zsofia Szalkai) did not start before January 2025. However, some work has been spent on the preparation of the upgrade of AROME-EPS from cy43t2 to cy46t1 in the first half of 2024 (see EPS report of September 2024). Cy46t1 is planned to become operational in February 2025.

Efforts: 13.5 PM (planned 20.0 PM)

Contributors: Martin Belluš (SHMU), Katalin Jávorné-Radnóczi and Gabriella Nagy (HungaroMet), Clemens Wastl, Florian Weidle, Christoph Wittmann (GeoSphere Austria), Endi Keresturi (DHMZ)

Documentation: Reports on stays and case studies (on webpage); papers submitted to scientific journals; improvement of current regional ensemble system through the results and outcomes of R&D

Planned stays:

1. Martin Belluš (4 weeks at CHMI) – A-LAEF upgrade on multi-physics (reduced to 2 weeks completed, January 8 – 19 2024)

Status: Ongoing, on time.

S2 Action/Subject/Deliverable: Model perturbations

Description and objectives: Research and development concerning model perturbations in the three EPSs within RC LACE. Study ways to represent uncertainty in the atmospheric models itself and how to best incorporate this into the models.

The originally planned topics for 2024 were:

- ❑ A-LAEF: Stochastic perturbation of fluxes instead of tendencies in order to preserve the energy balance in perturbed model.
- ❑ C-LAEF: Introduction of new parameters in SPP – dynamics parameters; testing
- ❑ C-LAEF: Development of flow-dependent model perturbations
- ❑ AROME-EPS: Add model perturbations to AROME-EPS at HungaroMet. Work on SPP, tests, verification, optimization

The A-LAEF topic (stochastic perturbation of fluxes instead of tendencies) has been postponed because of missing resources of Martin Belluš. The main work in this action S2 in 2024 has therefore been spent on the continuation of the work on SPP in C-LAEF and AROME-EPS. While the scheme is already running operationally in Austria (since September 2023), it has been implemented and tested in Hungary and should have been become operational end of 2024. However, due to the leave of the main contributor (Gabrielly Nagy) from HungaroMet this action has been postponed to 2025 with the start of a newcomer (Zsofia Szalkai).

In Austria SPP has also been implemented to the new C-LAEF 1k ensemble on cy46t1. During the EPS working week in Budapest the dynamics parameter SLWIND has been implemented, but it has not yet been tested so far. A new version of the SPP code has been introduced by ECMWF in cy49t2. Ulf Andrea and Clemens Wastl phased the ACCORD AROME SPP code and prepared everything to become part of the upcoming cy50 (see subject S1 of this report)

The work on flow-dependent model perturbations has also proceeded very well in 2024. After implementing the code during a RC LACE stay of Endi Keresturi at GeoSphere Austria in October 2023, a C-LAEF test suite with flow dependent SPP was running for a winter (February 2024) and summer (June 2024) test month. During another stay in Vienna (June 24 – July 19, 2024) Endi Keresturi worked on some code adaptations and did some verification. Results are promising, but some tuning will be necessary before a final operationalization.

❑ Topic 1: C-LAEF: Development of flow-dependent model perturbations

Endi Keresturi implemented and assessed during his previous stays the general behavior of FD-SPP and its impact on the C-LAEF system, which was found to be beneficial, especially for ensemble spread. However, no long-term verification was done at that time which is necessary to make a final judgement about the method.

This verification has been the topic of another stay of Endi Keresturi in Vienna in 2024 (24 June – 19 July). The first part of his stay was spent on revising the original FD-SPP implementation in C-LAEF 1k cy46t1 which was coded without paying attention to ARPEGE/IFS coding norms (link) or recommended Fortran optimizations. Most of the corrections concerned the changes in variable names, usage of array syntax (:), variable allocations, loops structure and removal of unnecessary commented lines.

The second part was the verification of the long term runs of C-LAEF with FD-SPP (February & June 2024). The original FD-SPP was implemented to C-LAEF 1k cy46t1, but the operational C-LAEF is on 2.5 km and cy43t1. In order save billing units (SBUs) and to have a fair comparison with the standard SPP implementation in the operational C-LAEF system on 2.5km, FD-SPP was phased back to cy43t1 for the long-term verification of the new perturbation scheme. The goal was to assess the added value of FD-SPP perturbations in C-LAEF. For this reason, two experiments were defined: a) C-LAEF_oper – operational C-LAEF configuration on 2.5 km and cy43t1 using regular SPP and b) C-LAEF_FD – configured the same as C-LAEF_oper except that FD-SPP has been used instead of standard SPP.

Verification has been performed separately for February 2024 and June 2024 and separately for surface and upper air variables. Variables used in verification are the following: Temperature (T), wind speed (WS), wind gusts (WG), total cloudiness (TC), relative humidity (RH), dewpoint temperature (Td), geopotential height (Z) and mean sea level pressure (MSLP). Different domains/verification packages were used for Austria (HARP) and Croatia (own package).

Results for February are generally positive (Figures 14 and 15). Ensemble spread is slightly increased for all variables and all lead times. Impact on RMSE is more neutral and slightly positive for some variables and some lead times. Impact on CRPS is also positive (Figure 15). Results for June (Figure 16) are unexpectedly more neutral. Increase in spread is only visible for TC, while it is neutral for other variables. RMSE is decreased for WS and is neutral for other variables. CRPS is decreased for WS and slightly for TC. Bias is improved for WS and neutral for other variables.

The reason for this is unclear especially because, during summer, model physics is more active. It might be that SPP in C-LAEF is not properly tuned for the convective season, and therefore has less impact during the summer. In order to confirm this, an additional experiment has been run – without using SPP at all. Unfortunately, it was possible to run only one day in the winter and summer period, respectively, because the ECMWF coupling files have not been stored for the whole test months. The results show that SPP in C-LAEF is significantly less (2-3 times) active during the summer for surface variables while for vertical levels, differences were much smaller.

In the end of 2024 a paper about flow dependent SPP has been prepared based on this verification results. It is planned to be submitted in spring 2025.

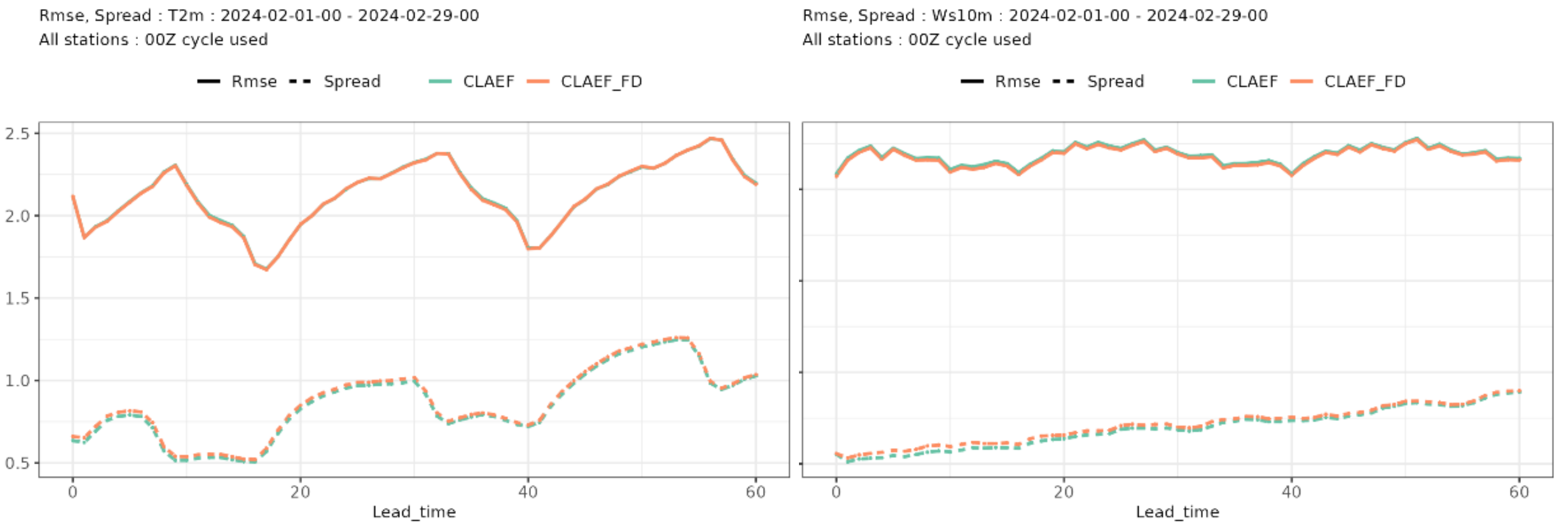

Figure 14: RMSE (solid) and spread (dashed) for C-LAEF_oper (blue) and C-LAEF_FD (orange) for February 2024 averaged over Austrian stations. T2m is shown in the left panel, the right one shows 10m wind speed.

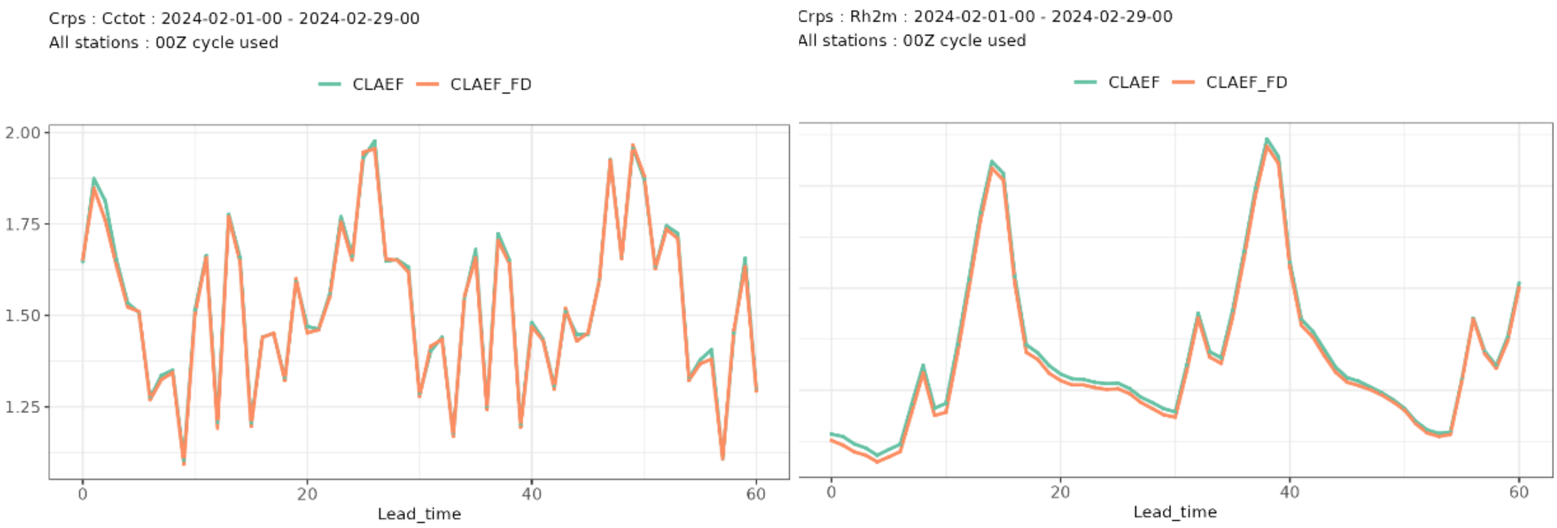

Figure 15: CRPS for C-LAEF_oper (blue) and C-LAEF_FD (orange) for February 2024 averaged over Austrian stations. Total cloudiness is shown in the left panel, the right one shows 2m relative humidity.

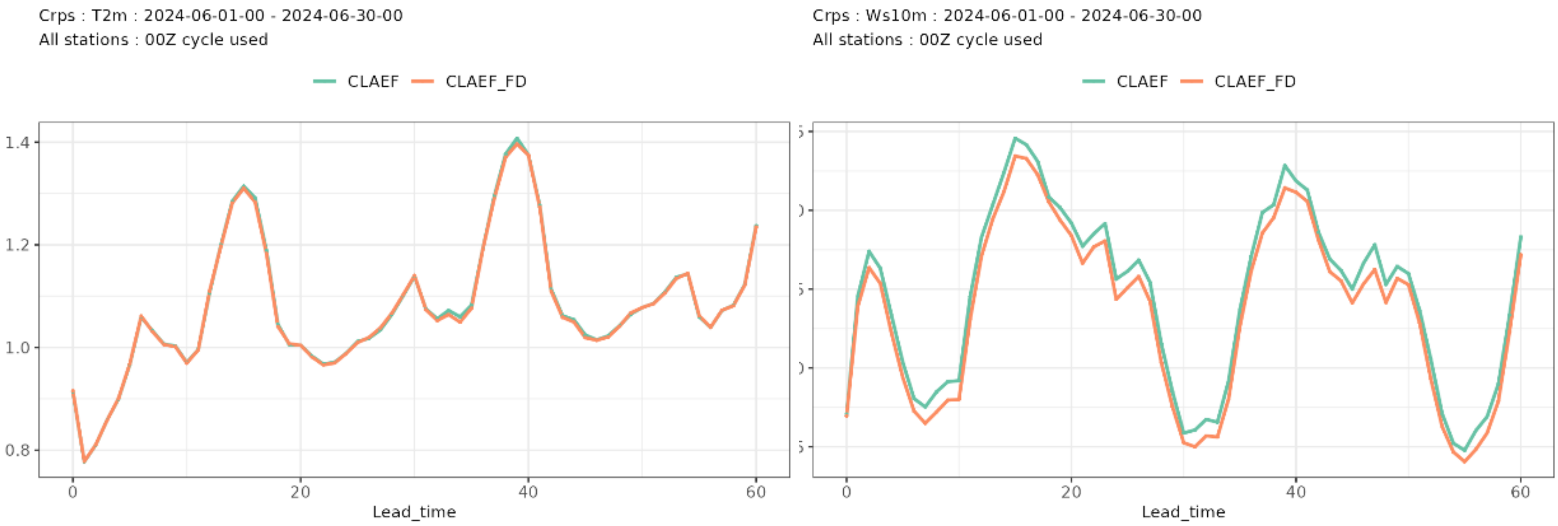

Figure 16: CRPS for C-LAEF_oper (blue) and C-LAEF_FD (orange) for June 2024 averaged over Austrian stations. T2m is shown in the left panel, the right one shows 10m wind speed.

❑ Topic 2: AROME-EPS – implementation of model perturbations (SPP)

HungaroMet started in 2023 with testing Stochastically Perturbed Parametrizations (SPP) scheme on an experimental basis on selected parameters from the physical parametrization. Gabriella Nagy implemented the scheme during her stays in 2023. After some problems with the setup and following modifications, the scheme worked as expected and it was tested during a winter and a summer period (Figure 17 and 18). The tests were carried out in AROME-EPS based on cy43t2.

The increase of the forecast spread in winter (Figure 17) is observable in the surface variables and on the lowest model levels in the upper-air variables. There is a small increase of the mean bias for the 10-meter wind speed, 10-meter wind gust, and cloud cover during night time. However, the cloud bias is doubtful, because there were some inconsistencies in the cloud amounts observed by ceilometers in Hungary until the beginning of 2024.

In comparison with the winter-time experiment, the results of the summer period (Figure 18) generally showed less, but slightly positive impact on the surface. The small increase in the mean bias of cloud cover remained in the summer-time period as well (observation inconsistencies). The upper-air ensemble scores reflect neutral impact on most model levels, but there is a mix of slightly positive and negative effect in the variables on the lowest model levels, especially in case of the wind speed (Figure 18).

The effect of SPP on spread is observable in the precipitation field as well. A case study was made on 22.07.2023, when a shallow cyclone affected the weather in the Central-European region, and caused intensive precipitation in the southern part of Hungary. SPP caused generally higher intensity of precipitation, while the reference run, which only includes EDA, sometime indicated the precipitation over a larger area, but with less intensity. The spatial location was better estimated in case of higher intensity precipitation.

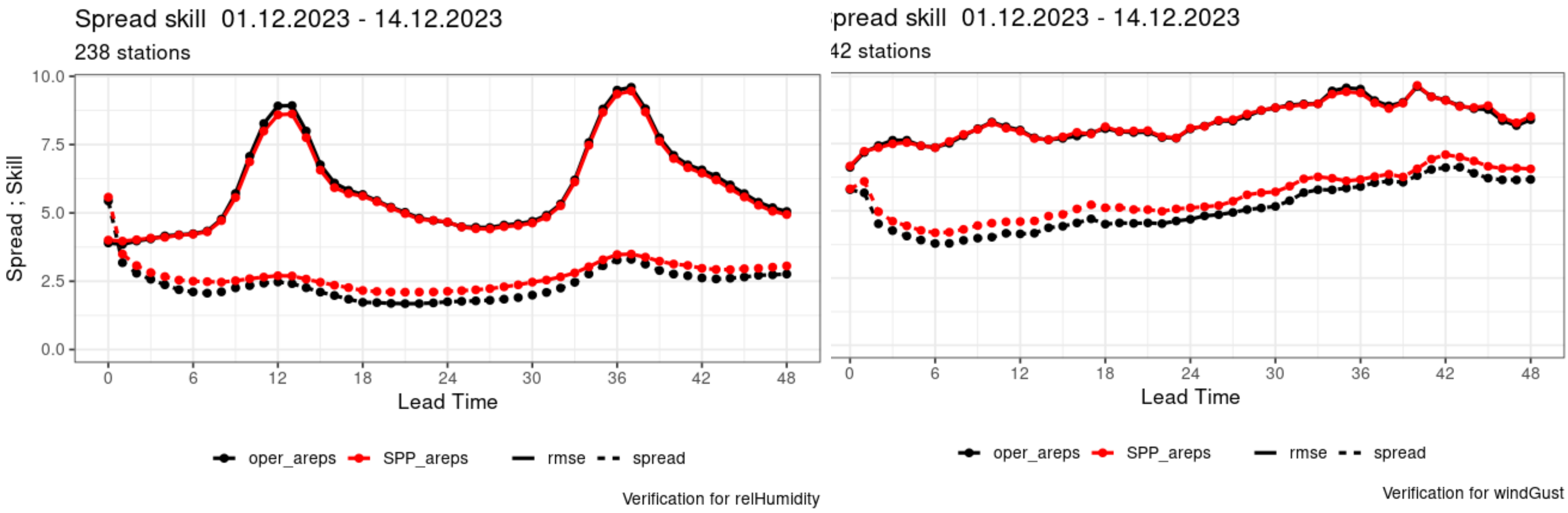

Figure 17: Ensemble spread and RMSE of ensemble mean for 2m relative humidity (left) and 10m wind gust (right) as function of lead time (h); 01-14.12.2023 00UTC.

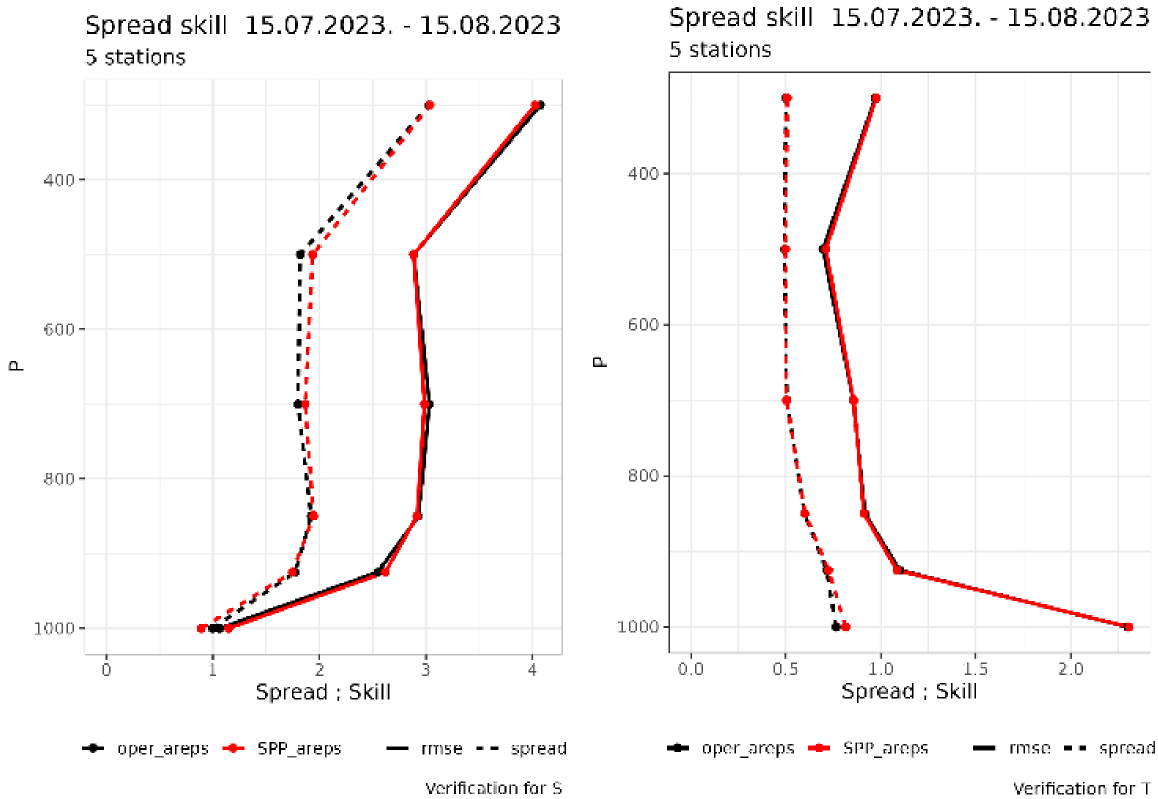

Figure 18: Ensemble spread and RMSE of ensemble mean for wind speed (left) and temperature (right) at different vertical levels; 15.07.2023 – 15.08.2023 00 UTC + 24h.

Not much work on this topic was done in the second half of 2024 because of the leave of Gabriella Nagy from HungaroMet. HungaroMet is planning an upgrade of AROME-EPS to cycle 46t1 in February 2025 and therefore also the SPP code needs to be phased to cy46t1. This should be done by a newcomer (Zsofia Szalkai). After some intensive testing SPP is planned to become operational end of 2025 in a single precision mode.

Efforts: 9.75 PM (planned 6.0 PM in total in 2024)

Contributors: Martin Belluš (SHMU), Clemens Wastl (GeoSphere Austria), Endi Keresturi (DHMZ), Gabriella Nagy (HungaroMet)

Documentation: papers published in scientific journals; convection-permitting ensemble systems for operational use (SHMU, GeoSphere Austria, HungaroMet); EPS documentation

Planned stays:

Endi Keresturi (4 weeks GeoSphere Austria) – flow dependent model perturbations (June 24 – July 19 2024)

Status: Ongoing; mostly in time

3 Action/Subject: Initial condition perturbations

Description and objectives: Research and development concerning initial condition perturbations in the three EPSs within RC LACE.

The originally planned topics for 2024 were:

- ❑ A-LAEF: Utilization of A-LAEF operational forecasts for flow-dependent B-matrix computation to be used in local assimilation cycles of RC LACE members.
- ❑ C-LAEF: The use of EnVar and Hydrid EnVar in C-LAEF 1k; development, implementation and testing

The A-LAEF topic is delayed because the planned stay of Martin Belluš at GeoSphere Austria could not be arranged so far (personal reasons). Therefore also the main work in this action had to be postponed.

Austria and Slovenia are working together on the implementation of Envar in the common system C-LAEF 1k. After some adaptations and debugging, an Envar based member has been added to the C-LAEF 1k suite in September as a second control member.

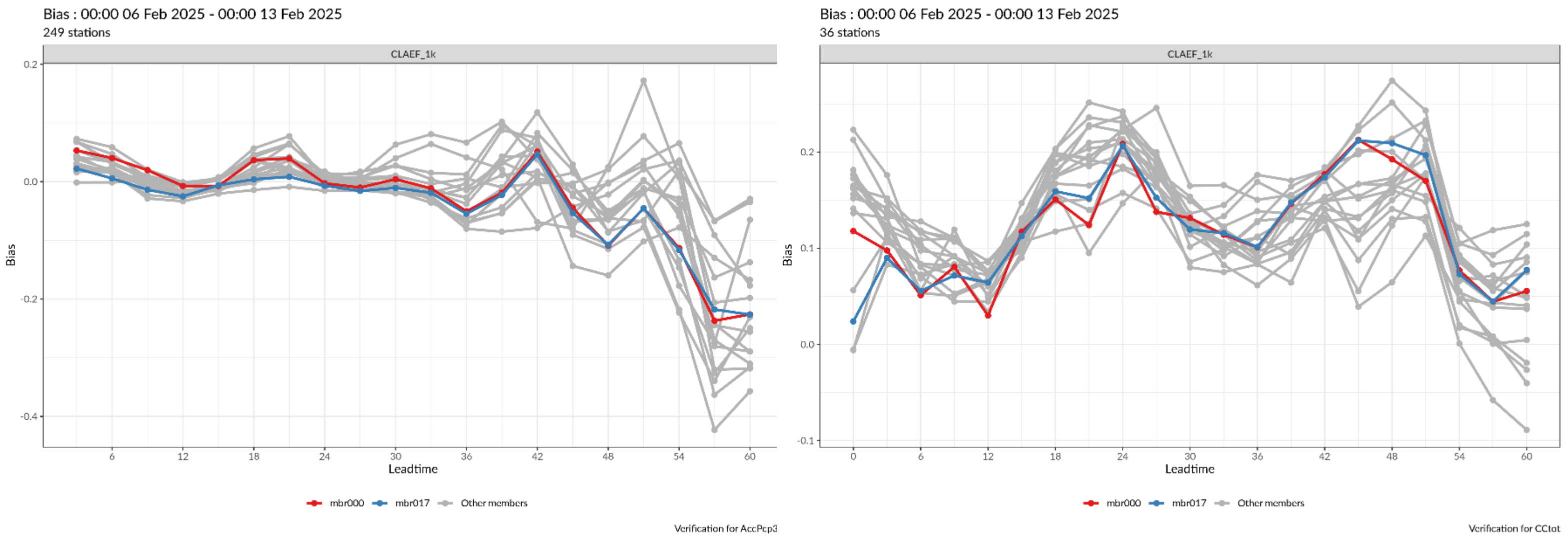

Figure 19: BIAS of 3 h accumulated precipitation (left) and total cloud cover (right) for all members of C-LAEF 1k during the test period in winter 2025. The 3Dvar member is given in red, the Envar member in blue.

Figures 19 and 20 show a comparison between the control (3Dvar, member 00) and the Envar member (member 17) for a test period in February 2025. The scores are generally very promising, especially in the first few hours. Further investigations and optimizations for the best Envar setup are ongoing, especially in connection with the continuous lagged ensemble. More details on the Envar work in C-LAEF 1k can be found in the data assimilation report.

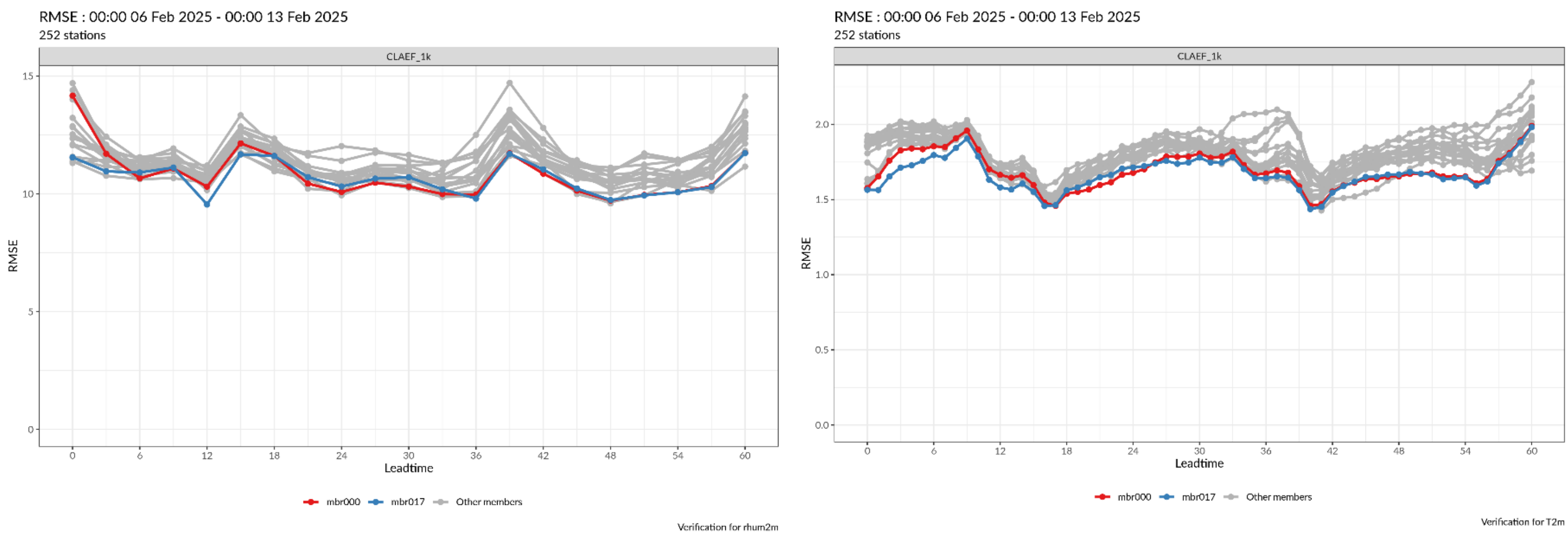

Figure 20: RMSE of 2m relative humidity (left) and temperature (right) for all members of C-LAEF 1k during the test period in winter 2025. The 3Dvar member is given in red, the Envar member in blue.

Efforts: 0.0 PM (planned 3.0 PM in total in 2024)

Contributors: Martin Belluš (SHMU), Florian Meier and Florian Weidle (GeoSphere Austria), Benedikt Strajnar (ARSO)

Documentation: papers published in scientific journals; convection-permitting ensemble systems for operational use (SHMU, GeoSphere Austria); EPS documentation

Planned stays:

1. Martin Belluš (4 weeks at GeoSphere Austria) – flow-dependent B-Matrix – postponed

Status: Ongoing. Delay because of postponed stay of Martin Belluš at GeoSphere Austria

4 Action/Subject: Surface perturbations

Description and objectives: Research and development concerning surface perturbations in the three EPSs within RC LACE.

The originally planned topics for 2024 were:

- ❑ C-LAEF and AROME-EPS: Implementation of surface perturbations in AROME-EPS; SPP in SURFEX, implementation testing, verification

An externalized surface perturbation scheme is currently used operationally in C-LAEF (pertsurf). Hungary was planning to add such a scheme into their AROME-EPS system during a RC LACE stay of Gabriella Nagy at Geosphere Austia in autumn 2024. Unfortunately, due to the leave of Gabriella from HungaroMet this has been cancelled.

There is some research on surface perturbations ongoing in ACCORD where they adapt the SPP scheme to be used in SURFEX. This is an interesting topic which will be addressed in RC LACE as well in the future.

Efforts: 0.0 PM (planned 2.0 PM in total in 2024)

Contributors: Clemens Wastl (GeoSphere Austria), Gabriella Tóth (HungaroMet)

Documentation:

Planned stays: Gabriella Nagy (4 weeks at GeoSphere Austria) – surface perturbations in AROME-EPS - cancelled

Status: Delayed

5 Action/Subject: Lateral boundary condition perturbations

Description and objectives: Research and development concerning lateral boundary condition perturbations in the three EPSs within RC LACE.

The originally planned topics for 202 were:

- ❑ No topics planned.

Some tests with coupling of the local convection-permitting ALARO-EPS in Slovakia within A-LAEF have already been made in 2023. In 2024 an ALARO-EPS ecFlow suite coupled in A-LAEF with a 1 km spatial resolution and 87 vertical levels has been implemented on Atos, covering Slovakia and the surrounding regions. This suite aims to provide experience with convection-permitting ensembles on kilometric scales, focusing on the coupling of such systems and simulating their uncertainties using ALARO multi-physics combined with stochastic physics. The insights gained will contribute to the development of a convection-permitting system at SHMU.

Efforts: 0.0 PM (planned 0.0 PM in total in 2024)

Contributors: Martin Belluš (SHMU)

Documentation:

Planned stays:

Status: Ongoing

6 Action/Subject: Statistical EPS and user-oriented approaches

Description and objectives: Research and development concerning statistical calibration of EPS data to reduce systematic errors; research and development of new products; user-oriented approaches to increase the reputation of EPS

The originally planned topics for 2024 were:

- ❑ A-LAEF: Continuation work on methods for analog-based post-processing of probabilistic fields on a regular grid
- ❑ ALL: Work on statistical post-processing of EPS data (e.g. new calibration methods)
- ❑ C-LAEF: Generation of ensemble members by deep learning algorithms
- ❑ C-LAEF: Extension of data-driven ML ensemble modelpoint nowcasting towards a hybrid (data-driven + NWP) and days-ahead system; extension of spatial nowcasting with physics-informed ML using NWP data for the days-ahead and looking into ensemble generation;
- ❑ ALL: Development of new probabilistic products to meet users requirements
- ❑ ALL: Development of decision-making criteria based on EPS for various users (e.g. hydrology, renewable energy, road safety, mountaineers, etc.)

A lot of work has been done in this subject in the second half of 2024. The work on analog-based post-processing has been continued during a stay of Iris Odak at GeoSphere Austria in autumn 2024 (September 16 – October 11). The topic was the implementation of different machine learning methods for radiation point-based post-processing.

At GeoSphere Austria some work has been spent on improving very localized, post processed ensemble nowcasts for the PV and wind power sector. Some progress could also been made in the area of creating ML based members for an extension of the C-LAEF ensemble at GeoSphere Austria. A Generative Adversarial Network (GAN) has been installed and currently data from C-LAEF reanalysis (2012 – 2021) are prepared to feed GAN.

Poland has initiated some work in that subject by testing a completely new approach (CEM, Cascading Ensemble Method) with the global AI model Fourcastnet and an ALARO EPS. CEM is an ensemble method with continuously increasing number of members.

- **Topic 1: Work on methods for analog-based post-processing of probabilistic fields on a regular grid**

During her stay in Vienna (September 16 – October 11 2024) Iris started to work on understanding and testing different machine learning (ML) methods in forecasting solar radiation. The used methods comprise k-Nearest Neighbors (kNN), Multivariate Adaptive Regression Splines (MARS), Bayesion Ridge Regression (BRR), Elastic Net (EN), Gradient Boosting Machine (GBM), Random Forest (RF) and Long Short Term Memory (LSTM). Very important for the modeling with ML methods is parameter tuning because they highly depend on the values of specific parameters, often referred to as hyperparameters. These parameters control the model's behavior during training, and tuning them allows the model to generalize better to unseen data, improving overall accuracy, reducing overfitting, and optimizing the computational resources required for training. Parameter tuning has been applied to the various methods mentioned above by automated approaches like GridSearchCV and RandomizedSearchCV.

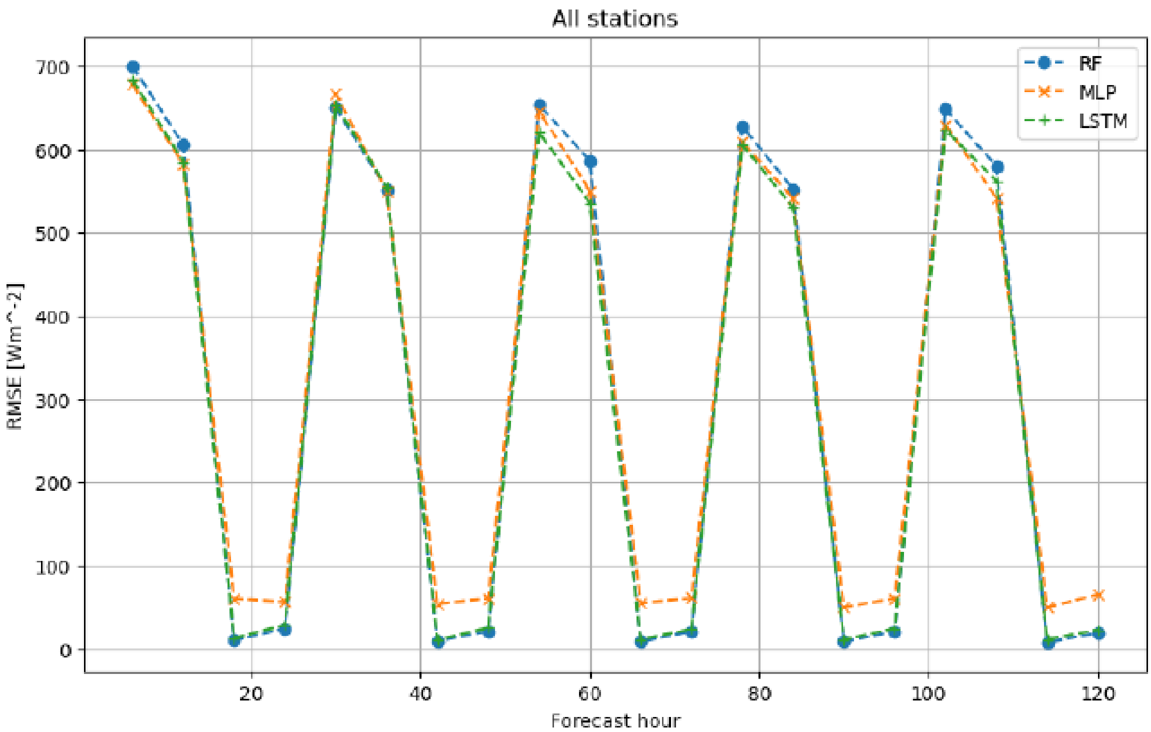

Figure 21: An example of the intercomparison of 3 trained ML models (RF, MLP and LSTM) for different forecast hours, across 15 locations in Austria averaged over 2 months (January and July).

Some preliminary results of this work are illustrated in the Figures 21-23. Figure 21 shows that the RMSE follows a recurring cycle with peaks at specific intervals (~24-hour periods), reflecting the diurnal cycle of solar radiation, which aligns with the typical daily variations in solar energy availability. For all models, RMSE decreases significantly after the initial peak of each cycle, indicating that the models perform better during periods with lower variability, such as during nighttime when solar radiation is minimal. The Random Forest model (blue line) exhibits consistently higher RMSE values compared to the Multi-Layer Perceptron (orange line) and Long Short-Term Memory model (green line), especially for the peaks of each cycle. In contrast, MLP and LSTM models show closer performance, with MLP marginally outperforming RF at certain points. Notably, LSTM tends to yield the lowest RMSE across the forecast horizon, which suggests its stronger capability in capturing temporal dependencies in the data.

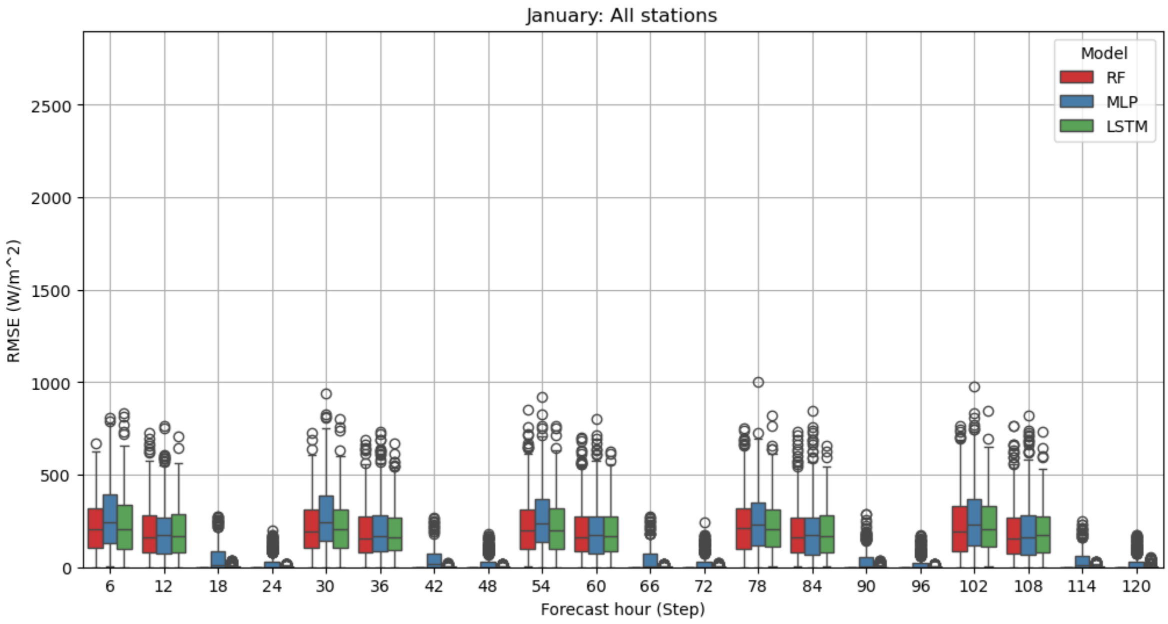

Figure 22: Intercomparison of different ML models' error distribution across 15 locations in Austria, depending on the forecast hour for January.

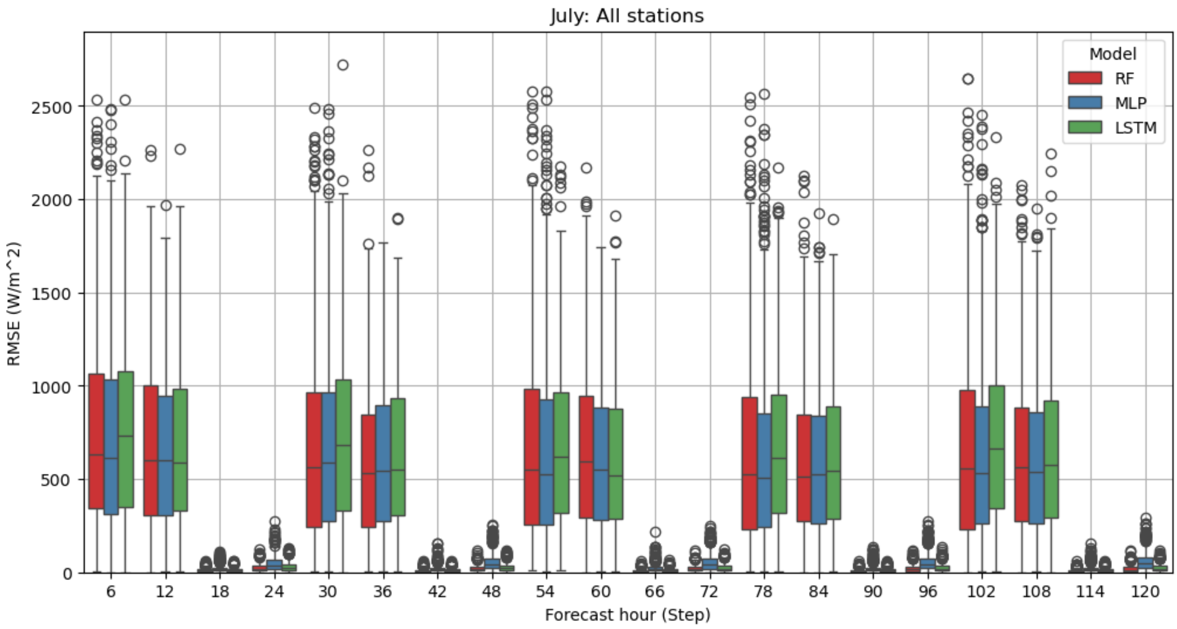

Figure 23: Intercomparison of different ML models' error distribution across 15 locations in Austria, depending on the forecast hour for July.

The improved performance of LSTM, likely due to its ability to effectively model time series, is evident even when the MultiOutputRegressor (MOR) was applied to nontime-series models such as RF and MLP. No exhaustive hyperparameter tuning has been done so far.

In January (Figure 22) the error distributions across forecast steps are relatively consistent, with most models showing similar performance throughout the day. The RMSE values are generally lower, which can be attributed to the shorter daylight hours and reduced solar radiation variability during the winter months.

In contrast, the results for July (Figure 23) show a clear increase in RMSE across most forecast steps, particularly during daylight hours. This heightened error can be attributed to increased solar radiation and the higher variability in weather patterns during the summer months. The differences between models remain small, with RF slightly underperforming in certain forecast steps compared to MLP and LSTM. The overall distribution of RMSE for each model is similar, but there is a more noticeable spread across stations in July compared to January.

All three models - Random Forest (RF), MLP, and LSTM - demonstrate comparable distributions, with only slight deviations between the models, suggesting that none stands out significantly in terms of error.

This work is planned to be continued during a new stay in Vienna in 2025.

- **Topic 2: C-LAEF: Extension of data-driven machine learning ensemble modelpoint nowcasting**

Also at GeoSphere Austria a lot of work is ongoing in the area of machine learning (ML). The increasing adoption of localized PV generation and the strong impact of atmospheric conditions on the generation necessitate accurate predictions of expected generation at a very local level allowing to better plan and schedule their network and power production in-feed. There is, thus, a need for providing very localized PV generation forecasts for the nowcasting and intra-day range issued hourly with a 15-minute temporal resolution. Uncertainty of the forecast needs to be accounted for using either quantile forecasts or ensembles.

To generate PV production nowcasts it is important to gather metadata information. This data consists of the approximate location of the PV sites, aggregated per transformer node or per region, and the respective kW peak rates. If it is possible to share location data, information on the installed PV panel type, azimuth and orientation are beneficial for good PV production forecasts. Additional to metadata, AI methods also need meteorological historical observation and forecast data. Observation data cover site specific observations, satellite data, and (re)analysis data are used as model input. Ideally, also historic production data of at least 2 years are available for the respective site or aggregation level. Static information such as topography and its derivatives (slope, orographic shadowing) is also necessary.

As there is not enough historic production data available, synthetic data is generated using different sets of granularity (length of historical data, available meteorological data, etc.) and, thus, providing already some uncertainty information. For the PV power prediction using AI tools the synthetic data are used as target and meteorological forecast model data are used as input features. Once this model is trained, it can be refined using the available historic production data and provide forecasts for the future. However, further refinement is needed and the longer the training data the better the forecast will get.

Several methods (IrradPhyDNet, PhyDNet, IrradianceNet, PFST-LSTM, Spatio Temporal Analogs) have been implemented and tested for the radiation nowcasting at GeoSphere Austria. The radiation nowcasting using IrradPhyDNet (Gfäller, 2023) has in the meantime been put into operations providing new daytime forecasts every 15 minutes on an Austrian domain and on a Pan-European Domain for DEODE. The ensemble version is currently in test phase and is planned to be put into operations soon.

Another interesting application area of AI based forecasts is the wind power sector, which is also very sensitive to short-term fluctuations of wind speed and direction. To exactly forecast wind ramping events - rapid changes in wind speed or direction across a wind farm which lead to large variability in power generation over short periods of time (Figure 24) – similar AI methods as for the radiation nowcasting can be applied. This work has been initiated within the Deode project and first results can be expected in 2025.

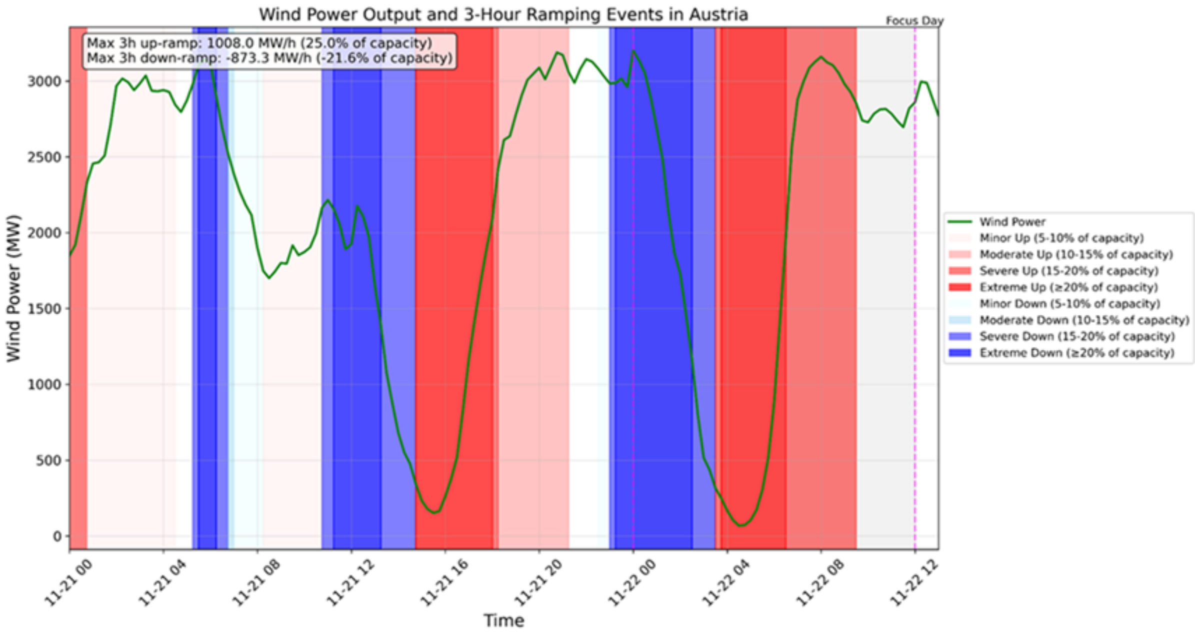

Figure 24: Wind power production (MW, green) and 3 h ramping events (blue down, red up) in Austria for a period in November 2024.

❑ Topic 3: Cascading Ensemble Method (CEM)

IMGW in Poland has initiated work in statistical EPS by developing a completely new approach in ensemble forecasting called Cascading Ensemble Method (CEM). The ensemble with CEM is created by increasing the number of members with lead time. It was tested first with the global AI Model Fourcastnet from Nvidia with 0.25 ° resolution and 10 days forecasting range. Figure 25 shows the verification scores of CEM and the unprocessed Fourcastnet model against ERA5. CEM with an increasing number of members (starting with 20 members, and adding 16 members each 6 hours, 256 members at the end of the forecast) shows better spread-skill-ratio and CRPS for 2m temperature than the standard system (starting with 256 members). This can also be seen in Figure 26. Beside the improved scores, the new approach is saving about 50 % of the computer power and disc usage. In a next step, the CEM method has also been applied to the ALARO 4km model of IMGW. An ensemble has been created by perturbing ALARO with Gaussian random noise and using the same LBC for all members. Figure 27 shows a comparison of a CEM ensemble with increasing number of members (starting with 1 member, and adding new members every 12 hours up to 30 members at +60 hours) with the standard ensemble (starting with 30 members) for a test case in February 2025. Spread in CEM is increasing faster with time then in case of the classical ensemble system. Further investigations and tuning of CEM is planned in 2025.

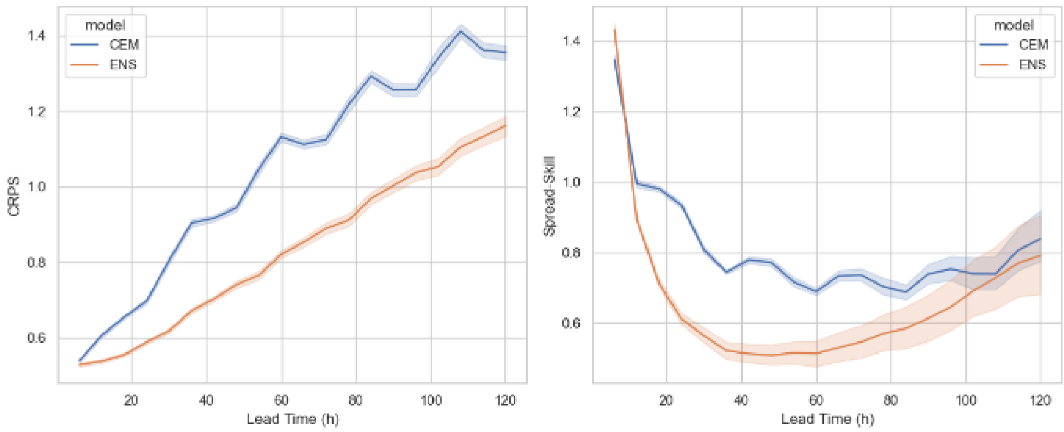

Figure 25: CRPS (left) and spread-skill ratio (right) of 2m temperature for standard Fourcastnet AI ensemble (red) and CEM (blue).

Efforts: 10.75 PM (planned 11.0 PM in total in 2024)

Contributors: Iris Odak, Ivan Vujec (DHMZ), Alexander Kann, Markus Dabernig, Irene Schicker (GeoSphere Austria), Martin Belluš (SHMU), Bogdan Bochenek and Jadwiga RóG (IMGW)

Documentation: papers published in scientific journals; convection-permitting ensemble systems for operational use (SHMU, GeoSphere Austria, HungaroMet); EPS documentation

Planned stays: Iris Odak (4 weeks at GeoSphere Austria) - analog-based post-processing methods (September 16 – October 11 2024)

Status: Ongoing, on time.

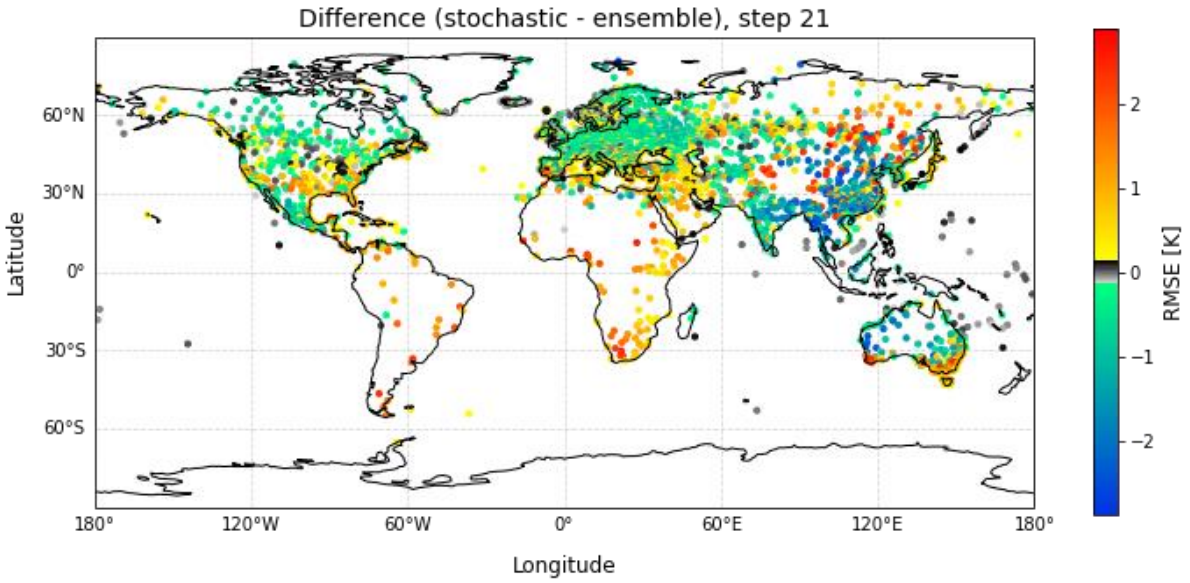

Figure 26: T2m verification against global synop data for the last timestep (+10 days). Colors show the RMSE difference between standard Fourcastnet ensemble and CEM. Green-blue colors indicate better results for the CEM method.

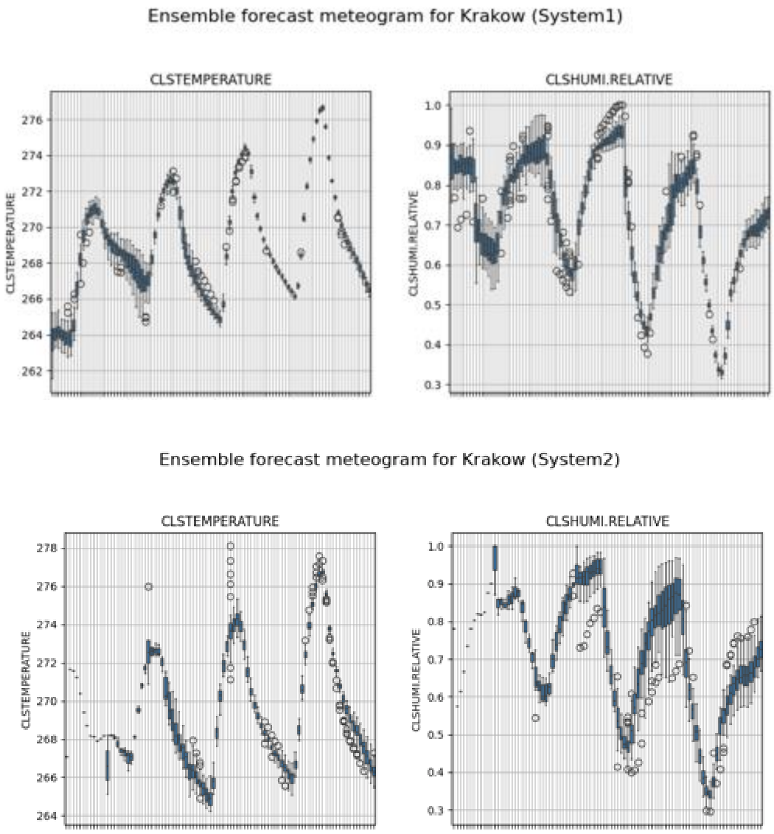

Figure 27: Ensgrams for 18th Feb 2025 for 2m temperature (left) and relative humidity (right) for the classical ensemble (top) and CEM (bottom).

Activities of management, coordination and communication

- 3rd ACCORD EPS working week, 22 – 26 January 2024 (Budapest)
- 42nd LSC Meeting, 27-28 February 2024, Budapest
- 4th ACCORD All Staff Workshop 2024, 15 - 19 April 2024 (Norrköping), RC LACE EPS activities presented by Clemens Wastl
- 43rd LSC Meeting, 18-19 September 2024, Vienna
- 4th ACCORD EPS working week, 25 – 29 October 2024 (Helsinki, online participation)
- 46th EWGLAM and 31st SRNWP Meeting (Prague), 30 September – 3 October 2024, RC LACE EPS activities presented by Clemens Wastl

Publications

Martin Belluš, 2024: Upgrade and validation of A-LAEF multiphysics based on the latest ALARO-1 code at cy46t1, Report on stay at CHMI, 07 – 19 January 2024, Prague, Czech Republic

Martin Belluš, 2024: "Regional ensemble prediction system A-LAEF", Weather - Climate - Water - Soil - Air and their interactions in the 3rd millennium: 1st Annual Poster Day of the Slovak Meteorological Society, Proceedings of Abstracts, ISBN 978-80-973051-1-6

Endi Keresturi, 2024: Flow dependent SPP in C-LAEF, Report on stay at GeoSphere Austria, 24 June – 19 July 2024, Vienna, Austria

Iris Odak, 2024: Machine learning methods for radiation point-based post-processsing, Report on stay at GeoSphere Austria, 16 September – 11 October 2024, Vienna, Austria

RC LACE supported stays – 2.5 PM in 2024

In 2024 3 stays could be realized in the EPS area of RC LACE: The stay of Martin Belluš (2 weeks at CHMI in Prague in January) on the upgrade of multiphysics in A-LAEF, the stay of Endi Keresturi (4 weeks at GeoSphere Austria in Vienna in June/July) on flow dependent SPP for C-LAEF and the stay of Iris Odak (4 weeks at GeoSphere Austria) on machine learning methods for radiation point-based post-processing. The stay of Gabriella Nagy on surface perturbations in AROME-EPS (4 weeks at GeoSphere Austria in November) has been cancelled due to the leave of Gabriella from HungaroMet. Another stay of Martin Bellus (4 weeks at GeoSphere Austria) on flow dependent B-matrix has been postponed due to missing resources.

Summary of resources [PM] – 2024

Subject	Manpower		RC LACE		ACCORD	
	plan	realized	plan	realized	plan	realized
S1: Preparation, evolution and migration	20	13.5	1	0.5	0	0
S2: Model perturbations	6	9.75	1	1	0	0
S3: IC perturbations	3	0	1	0	0	0
S4: Surface perturbations	2	0	1	0	0	0
S5: LBC perturbations	0	0	0	0	0	0
S6: Statistical EPS and user-oriented approaches	11	10.75	1	1	0	0
Total:	42	34	5	2.5	0	0

References

Gfäller, P. (2023): Evaluation of different techniques for solar irradiance nowcasting. Masterarbeit Universität Wien, DOI: 10.25365/thesis.73807

Ollinaho, P., Lock, S. J., Leutbecher, M., Bechtold, P., Beljaars, A., Bozza, A., Forbes, R. M., Haiden, T., Hogan, R. J. and Sandu, I. (2017): Towards process-level representation of model uncertainties: Stochastically perturbed parametrisations in the ECMWF ensemble. Quart. J. Roy. Meteor. Soc. 143, 408–422, https://doi.org/10.1002/qj.2931