

Working Area Predictability

Progress Report

Prepared by:	Area Leader: Clemens Wastl
Period:	Jul – Dec 2025
Date:	Mar 2026

Progress summary

The use of ensemble prediction systems within the national meteorological services of RC LACE continues to grow steadily. Alongside products from the classical EPS suites (A-LAEF, C-LAEF, AROME-EPS), post-processed ensemble output is being applied with increasing frequency. As a result, substantial effort is currently being invested in subject S6 of the RC LACE work plan – statistical EPS and user-oriented approaches. These methods encompass established techniques such as analog-based and statistical post-processing, as well as emerging developments in artificial intelligence (AI), including physics-informed and data-driven machine-learning nowcasting for the renewable-energy sector.

No major upgrades have been introduced in 2025 for the two operational EPSs running on the ECMWF HPC (A-LAEF and C-LAEF). However, improved versions are already undergoing testing. For A-LAEF, an upgrade from cy40t1 to cy46t1 has been postponed due to the departure of the main contributor Martin Bellus – it is now planned in 2026. This upgrade contains a new upper-air spectral blending technique and an enhanced multi-physics package.

A major upgrade of the C-LAEF system (to C-LAEF AlpeAdria, AA) is scheduled for June 2026. The development of C-LAEF AA has evolved into a joint initiative between Austria, Croatia, and Slovenia, combining shared computational resources (SBUs) and manpower. The upgrade includes a newer model cycle (cy46t1), an increase in horizontal resolution from 2.5 km to 1 km, and significant improvements in data assimilation (new observation types, EnVar), model-error representation (SPP, flow dependency), dynamics configuration, and post-processing (GRIB2). C-LAEF AA is designed as a continuous lagged ensemble with 16+1 members, producing eight runs per day with a lead time of 60 hours. An Esuite of C-LAEF AA has already been successfully tested during winter, summer and autumn periods, yielding highly promising verification results.

In Hungary, AROME-EPS was upgraded to cy46t1 in February 2025, the planned introduction of stochastic perturbations to represent model error (SPP) has been postponed to 2026. Extensive testing and tuning in this area are currently underway.

Another key focus within RC LACE is the DEODE project, in which many members of the EPS community are actively involved. The project aims to develop on-demand, configurable digital-twin engines for forecasting environmental extremes. With DEODE, ensemble systems are advancing into the hectometric scale (750 m), marking a significant step forward in both resolution and capability.

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 implementation to new HPCs, operational upgrades, new cycles, optimizations and tunings.

The originally planned topics for 2025 were:

- Maintenance/monitoring of operational EPSs (A-LAEF, C-LAEF) on ECMWF's HPC in Bologna, upgrades
- Development of an ALARO-based convection-permitting EPS coupled to ECMWF ENS and A-LAEF
- Implementation of SURFEX in ALARO-EPS
- Implementation of ENS BlendVar assimilation method in the A-LAEF system to improve the simulation of upper-air ICs uncertainty
- C-LAEF AlpeAdria for Austria, Slovenia and Croatia, continuous lagged ensemble, data provision, product generation, pre-operational status
- Reanalysis of C-LAEF for 2012 – 2021 period.
- Optimization and tuning of AROME-EPS on HPC at HungaroMet, upgrade to cy46t1
- Introduction of model perturbations (SPP) in operational AROME-EPS

A-LAEF and C-LAEF have been running in their current configuration for several years on the ECMWF HPC. No major operational upgrades have been introduced far in 2025, but the next-generation systems are currently being tested on the Atos platform.

For the A-LAEF system, an Esuite based on cy46t1 has been set up, incorporating several significant enhancements — including the implementation of upper-air spectral blending and the new ALARO-1 multi-physics package. This Esuite is running under the TC user *zla2*. At the moment, only the control member is being executed to spin up the assimilation cycle and prepare for a swift transition to operational status. This has been postponed due to the leave of the main developer, Martin Bellus.

As part of the DEODE project, the first test runs of a mini ALARO-EPS (6 + 1 members) at 750 m resolution, coupled to the ECMWF ENS, have been completed. No further progress has been made so far on the implementation of SURFEX in an ALARO-EPS system.

The C-LAEF AlpeAdria (C-LAEF AA) system — a joint collaboration between Austria, Slovenia, and Croatia — has been running continuously since 2024 as a two-member

ensemble (one control and one EnVar member). The system has undergone several rounds of tuning and upgrades, including adjustments to the dynamics configuration, truncation, time step, and physics optimization. A full ensemble with 16 + 1 members in lagged mode has been tested for winter (January–February 2025), summer (June–August 2025), and autumn (November 2025). Extensive verification indicates generally very good performance. Final refinements, such as further dynamics optimization, are currently underway, with the goal of bringing C-LAEF AlpeAdria into operations in June 2026.

The C-LAEF reanalysis (2.5 km version) for the period 2012–2021 was completed in summer 2025, and the dataset is now being extended to cover up to the year 2025.

In Hungary, the operational AROME-EPS was upgraded to cy46t1 at the beginning of 2025, and work on introducing stochastic model perturbations (SPP) is currently in progress.

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

No major operational upgrades have been implemented for A-LAEF in 2025; only minor adjustments have been carried out, such as updates to the GRIB2 tables, debugging of blending-task crashes, and solutions for potential shared-library issues. The planned major upgrade to cy46t1 has been postponed several times due to the departure of the main developer, Martin Bellus. At the moment it is unclear when this can be arranged. Since June a continuous Esuite (consisting of 1 control member) is running on ECMWF Atos HPC to warm up the assimilation cycle for a prompt switch to the new A-LAEF version.

The A-LAEF upgrade includes not only a general cycle transition from cy40t2 to cy46t1, but also an extension of the forecasting range from 72 to 78 hours. In addition, a GRIB2 inline FPOS is introduced, providing new parameters such as precipitation types, lightning, and simulated radar reflectivity.

The upgraded A-LAEF version also features a completely new ALARO-1 multi-physics cluster, updated Clim files based on ECOCLIMAP v2.6, a surface SPP scheme and revised PGD fields (including orographic roughness, vegetation roughness, and subgrid-scale orographic characteristics).

The new A-LAEF system has been successfully tested for some severe weather events, e.g. the storm Boris in 2024 (see EPS report from September 2025).

At present, teams from Poland, Czech Republic, Slovenia, and Croatia are in the process of taking over A-LAEF development and maintenance responsibilities from Slovakia.

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

Within the DEODE project, an ALARO-based mini-EPS has been implemented on the ECMWF HPC Atos system. It consists of 6 perturbed members plus 1 unperturbed control member and runs over a Slovak domain at 750 m horizontal resolution (Figure 1). The representation of uncertainty is achieved through an ALARO-1

multi-physics scheme combined with surface stochastic physics (SPPT). Initial conditions and lateral boundary conditions are taken from the ECMWF ENS. The ecFlow suite is derived from the A-LAEF scripting framework.

The system has been tested in several high-impact weather situations, including the September 2024 flooding event (storm Boris, see the 2024 EPS report), a lee-wave episode on Christmas Eve 2024, and a freezing-rain event in January 2025. The advantages of the higher resolution are clearly visible in these cases.

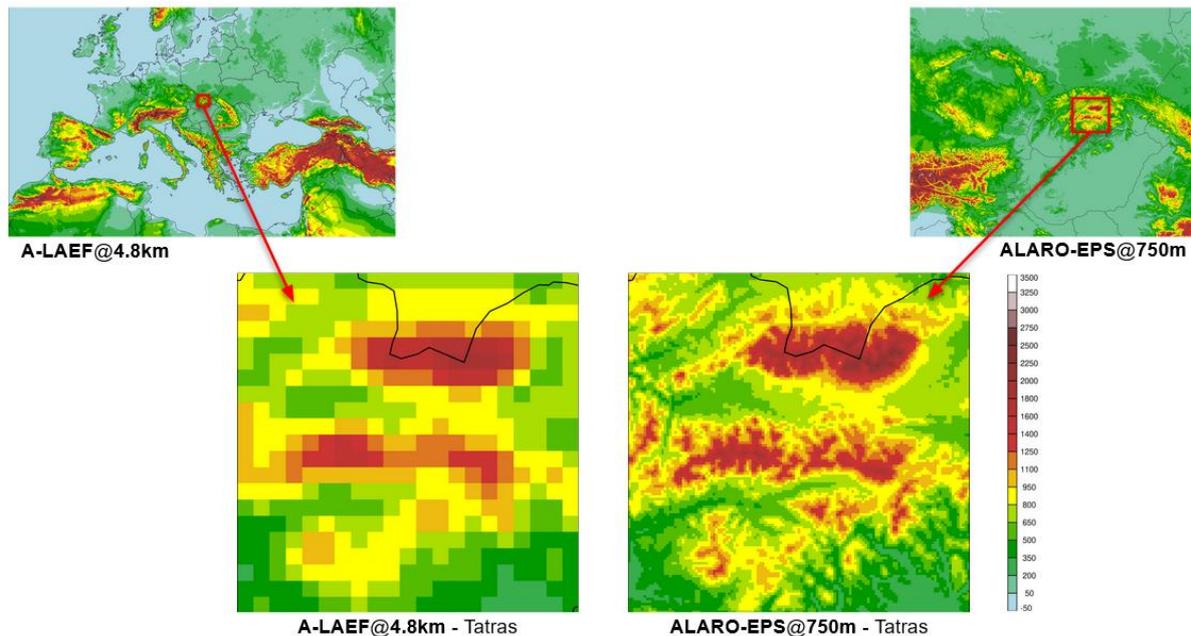


Figure 1: Comparison of the A-LAEF domain (left) and the ALARO-EPS domain (right).

Due to the lack of manpower in Slovakia, this task will probably not be continued in the future.

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

Austria has been operating its AROME-based EPS C-LAEF system (cy43t2) on a 2.5 km grid since 2019, using ECMWF's high-performance computing (HPC) resources. In recent years, significant efforts have been made to upgrade the system to a 1 km grid and cy46t1. Starting in early 2025, Slovenia and Croatia joined this initiative by contributing both computational resources (SBUs) and personnel. Slovenia's contributions mainly focus on data assimilation, while Croatia provides support in model perturbations, dynamics, and post-processing. This collaborative effort has resulted in the creation of the C-LAEF AlpeAdria (C-LAEF AA) system.

The C-LAEF AA ensemble consists of 16+1 members: the 16 perturbed members are coupled with the first 16 members of the ECMWF Ensemble, while the control member is coupled with the IFS deterministic model. A 3-hourly assimilation cycle is implemented, incorporating new types of observations such as radar, GNSS, and

ceilometers. The system operates in single precision (configuration 001), utilizing an I/O server and a 45-second time step. The perturbation methods used include the SPP scheme for model perturbations, Ensemble-JK, EDA, and surface EDA for initial condition perturbations, as well as an external surface perturbation scheme (pertsurf). The output format of C-LAEF AA is GRIB2. Thanks to the collaboration with Slovenia and Croatia, the domain has been expanded to the south compared to the original C-LAEF system, with each country managing its own post-processing domain. A shared username (zacs) and SBU account (claeiop) have been created to facilitate the joint development and monitoring of the system. The operational launch of C-LAEF AA is planned for June 2026.

Test period & verification:

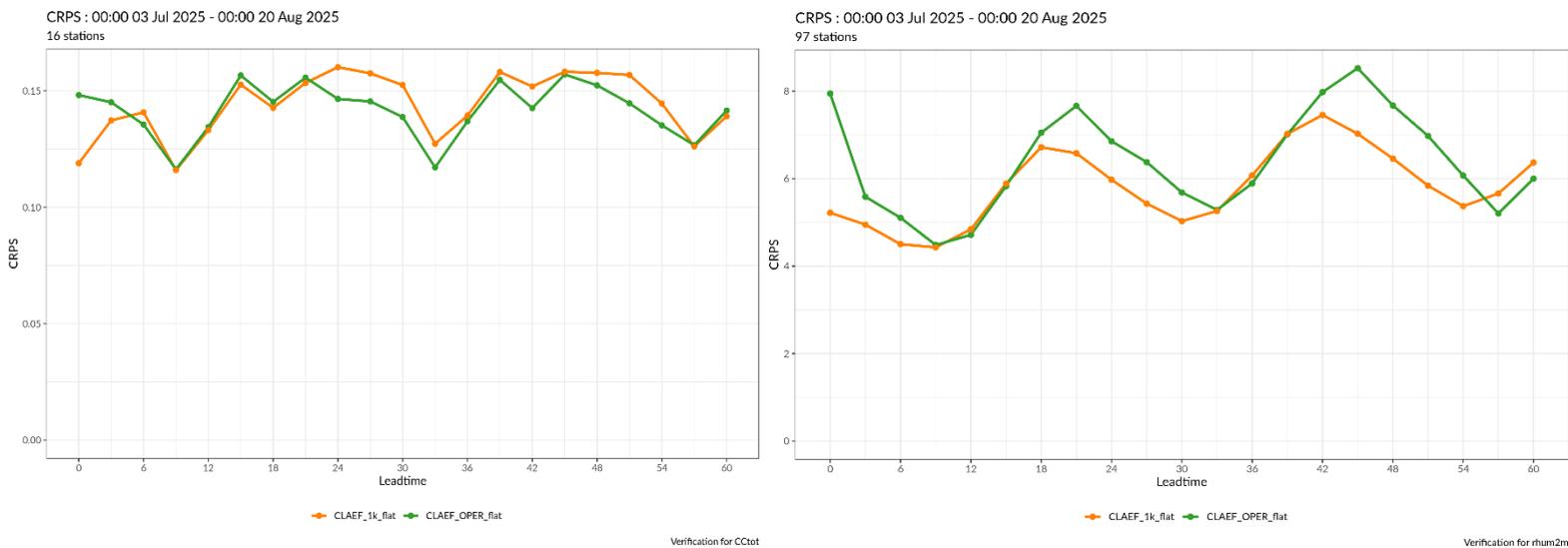


Figure 2: CRPS of total cloudiness (left) and 2m relative humidity (right) for C-LAEF (green) and C-LAEF AA (orange) in the summer test period 2025.

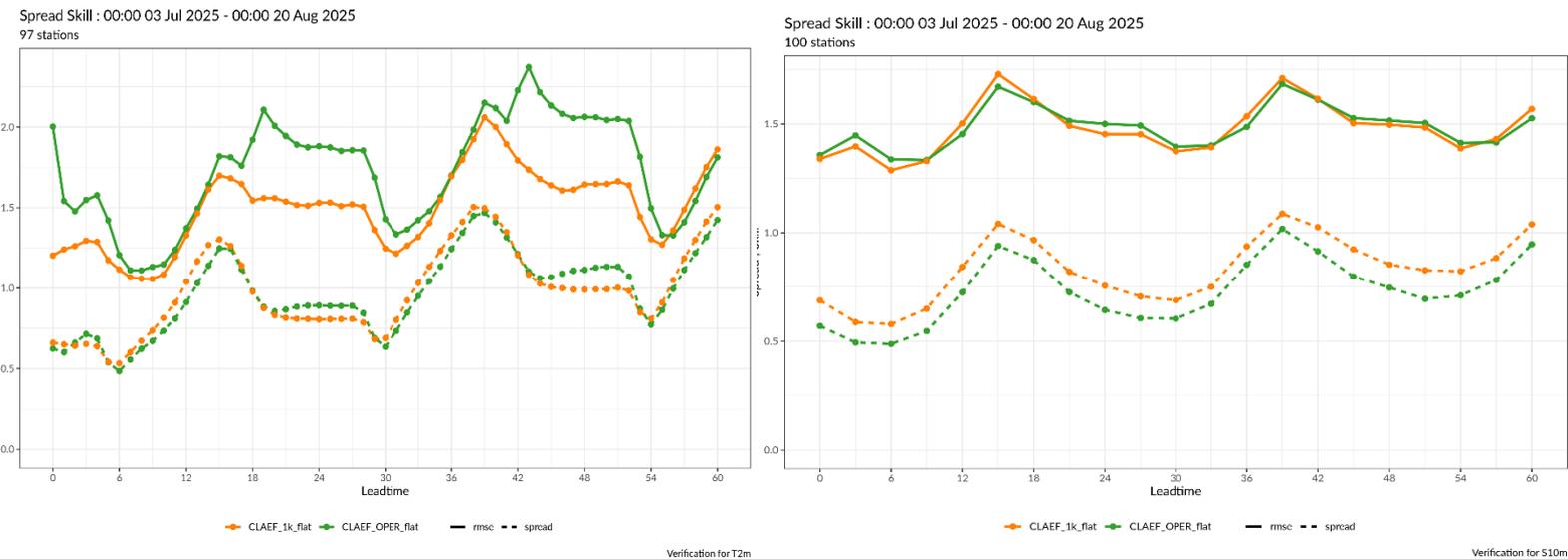


Figure 3: Spread (dashed) and skill (full) of 2m temperature (left) and 10m wind speed (right) for C-LAEF (green) and C-LAEF AA (orange) in the summer test period 2025.

In 2025, the C-LAEF AA system was extensively tested during three dedicated periods: winter (January–February), summer (June–August), and autumn (November). Throughout these campaigns, the suite ran very reliably, with virtually no technical issues. Output products were provided to forecasters in Austria, Croatia, and Slovenia, including visual weather maps and meteograms. The performance of C-LAEF AlpeAdria has been continuously monitored using HARP verification. The verification scores presented were computed for approximately 250 stations across Austria. Overall, C-LAEF AlpeAdria performs very well, showing improvements for nearly all variables compared with the operational C-LAEF system (Figures 2 and 3).

Timestep:

The summer test period revealed that, despite several optimizations (NPROMA, FFTW, FPOS, etc.), the full EPS remains too computationally expensive to run in full operational mode in 2026. As a result, the timestep was increased from 45 s to 60 s and tested in a parallel suite during the summer campaign. Initial results were not encouraging, as the precipitation field over the Alps deteriorated noticeably. Switching to the new ICE3 microphysics scheme - which is less sensitive to timestep changes - proved beneficial in this context.

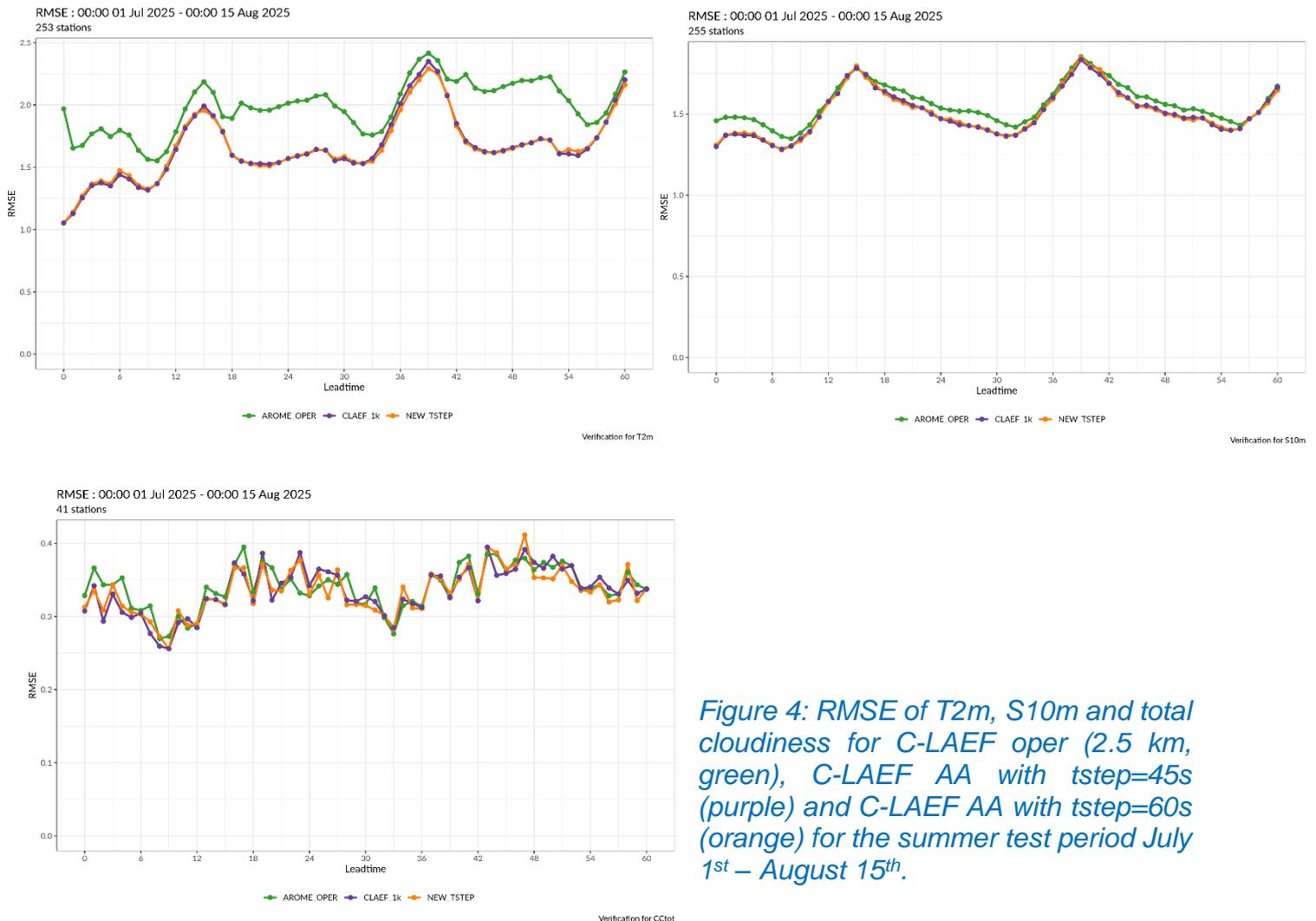


Figure 4: RMSE of T2m, S10m and total cloudiness for C-LAEF oper (2.5 km, green), C-LAEF AA with timestep=45s (purple) and C-LAEF AA with timestep=60s (orange) for the summer test period July 1st – August 15th.

The scores shown in Figure 4 are based on the summer test period (July 1–August 15) and indicate virtually no degradation in the 60 s C-LAEF AlpeAdria configuration (orange) compared with the 45 s version (purple). Based on these results, the timestep was increased to 60 s in autumn 2025. However, the first windy situations in autumn revealed stability issues with this setup, including numerous SMILAG trajectories going underground and several crashes caused by trajectories out of the atmosphere. As a result, the timestep had to be reverted to 45 s in December.

Lagged Ensemble:

To manage the high computational demands, C-LAEF AA operates in a continuous lagged ensemble mode. In the first version (until autumn 2025) the lagged ensemble was created in a way with 1 unperturbed control and four perturbed members (computed over an extended forecast range of +69 hours), while the remaining 12 members were kept short (+6 hours) and were used solely for the assimilation cycle, including EnVar. After the creation of the GRIB files in post-processing, the members from the four most recent runs were combined (including modifications to GRIB headers) to generate a complete 16+1 member ensemble with a 60-hour forecast range every three hours. In this approach the oldest members of the ensemble were 9 hours old. The test period in summer 2025 has shown that the SBU consumption of this approach was too high, so we switched to a setup with 3 perturbed members (+69 hours) every run and additionally use old control runs (extended forecasting range of +72 hours). We compared the performance of the two setups during a 3 weeks period in July 2025, the results are shown in Figures 5 and 6.

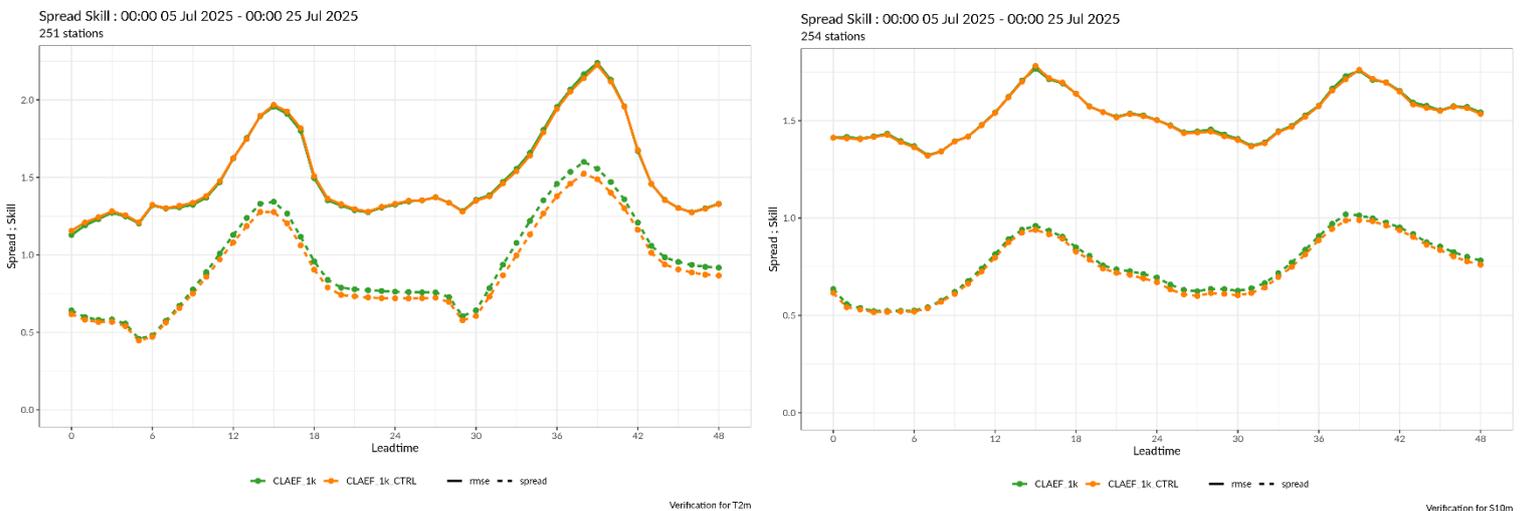


Figure 5: Spread (dashed) and skill (full) of 2m temperature (left) and 10m wind speed (right) for a lagged ensemble with 4 (green) and 3 (orange) perturbed members in a summer test period in 2025.

There is a slight degradation of ensemble spread when using 3 perturbed members instead of 4, but there is no impact on RMSE and only a very small impact on CRPS. Considering these results and the fact that the new methods saves about 10% of the SBUS, we decided to go for this new approach in 2026.

CRPS : 00:00 05 Jul 2025 - 00:00 25 Jul 2025
251 stations

CRPS : 00:00 05 Jul 2025 - 00:00 25 Jul 2025
251 stations

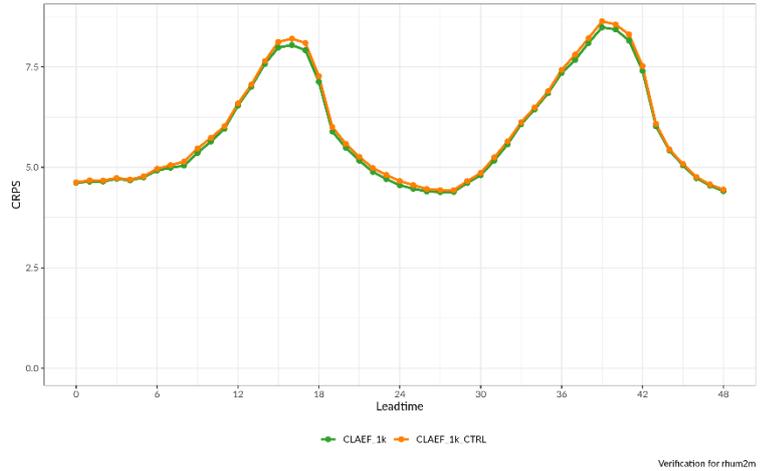
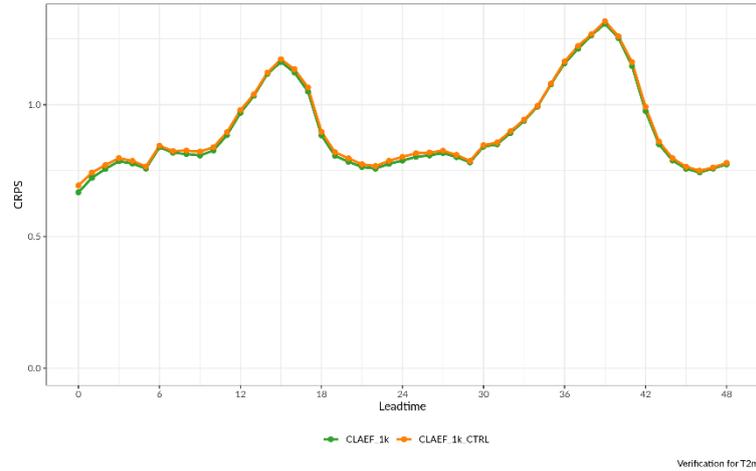


Figure 6: CRPS of 2m temperature (left) and 2m relative humidity (right) for a lagged ensemble with 4 (green) and 3 (orange) perturbed members in a summer test period in 2025.

Dynamics optimizations:

Effect of Dynamics Changes on 12-h Accumulated Precipitation (T+12 – T+24)

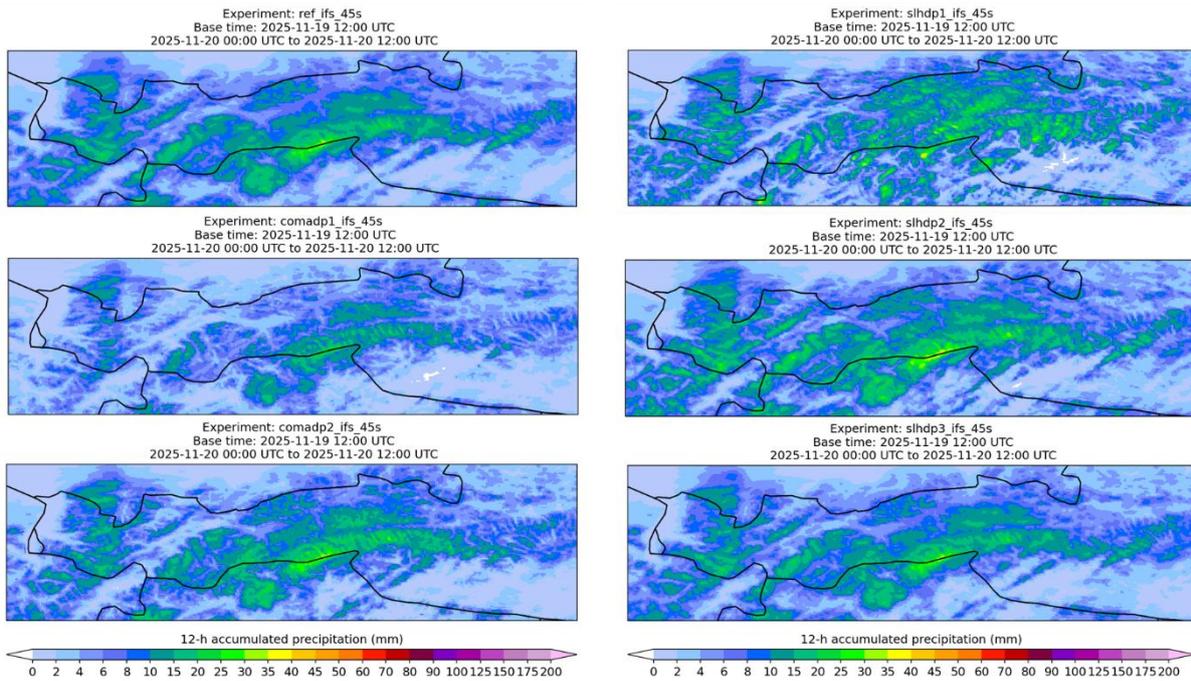


Figure 7: Test case with precipitation overestimation in the Alps (November 20, 2025). Upper left: Reference experiment (pre-operational C-LAEF, SLHD), upper right: no SLHD for GFL, middle left: COMAD (Meteo France setup), middle right: SLHDEPSH 0.08 -> 0.01, lower left: COMAD (not for YQ), lower right: SLHDKMAX 6 -> 1.

The constant monitoring and verification of the C-LAEF AA suite has offered that there is a tendency to overestimate precipitation in the Alpine regions in winter. A positive BIAS is also present in the 2.5 km version, but it is even stronger in C-LAEF AA on 1 km. Intensive testing for some selected winter cases has shown that the dynamics settings are not very well tuned for the 1 km resolution. Further testing over longer periods and an extensive report is planned for the next reporting period of LACE in September 2026.

EnVar:

Looking ahead, the 3D data assimilation system of C-LAEF AlpeAdria is intended to rely entirely on EnVar. At present, a parallel EnVar member is continuously run on the ECMWF HPC. The performance (see subject S3 and DA report) is pretty good, but during the summer there have been some cases when this member did not perform well. Further testing is therefore required. For the operational launch of C-LAEF AlpeAdria, the plan is to use the classical 3DVar system in the first version.

❑ **Topic 4: Reanalysis of C-LAEF for 2012 – 2021 period**

In course of the ARA (High resolution Austrian Re-analysis ensemble with AROME) project at GeoSphere Austria a first of its kind high resolution (2.5 km) reanalysis ensemble dataset for Austria has been created. It provides a detailed (2D and 3D) information on the state of atmosphere in Austria from 2010 – 2021 – see EPS report of September 2025. This ARA dataset is now being extended to cover up to the year 2025.

❑ **Topic 5: AROME-EPS: Optimization and tuning of convection-permitting ensemble system on HPC at HungaroMet**

The Hungarian AROME-EPS has been upgraded from cy43t2 to cy46t1 in February 2025. In the current version of AROME-EPS no representation of the model error is done. The plan is to include the stochastically perturbed parameterization scheme (SPP) in a next step. In 2025 the SPP scheme has been successfully implemented and intensively tested in AROME-EPS. At the moment a lot of tuning and optimization is ongoing (see subject S2 for more details) and the goal is to put SPP into operations end of 2026.

Efforts: 18.5 PM (planned 18.0 PM)

Contributors: Martin Belluš (SHMU), Katalin Jávorné-Radnóczy and Zsófia Szalkai (HungaroMet), Clemens Wastl, Florian Weidle, Brigitta Goger (GeoSphere Austria), Jadwiga Róg (IMGW), 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. Jadwiga Róg (4 weeks at DHMZ) – Development of an ALARO-based convection-permitting EPS coupled to A-LAEF – postponed to 2026
2. Martin Belluš (4 weeks at CHMI) – A-LAEF upgrade: Canceled

Status: Ongoing, some delays for the A-LAEF topics.

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 2025 were:

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

The topic of "stochastic perturbation of fluxes instead of tendencies" has been delayed, and it is currently uncertain whether it will continue due to the departure of the main contributor, Martin Bellus. However, some progress has been made on the model error representation in A-LAEF, particularly on upgrading the ALARO-1 multi-physics clusters and implementing a surface SPPT scheme in ISBA.

SPP has been integrated into the pre-operational version of the C-LAEF AA ensemble using cy46t1. A lot of tuning of SPP parameters on hectometric scales has been done within the DEODE project. Future plans include applying the SPP perturbations to the model's dynamics component, with the first parameter (SLWIND) successfully tested. As part of the DEODE project, the SPP code has been phased to cy50.

There has been little progress on flow-dependent model perturbations in the second half of 2025. A paper summarizing the results was submitted to QJRMS in June 2025 but was rejected, requiring significant revisions before resubmission. Meanwhile, the flow-dependent SPP code has been implemented in a separate branch of the DEODE system, with plans to integrate it into cy50.

A considerable amount of work has gone into the implementation and optimization of SPP within the Hungarian AROME-EPS. It is expected to become operational in 2026 after further fine-tuning of the perturbation scales.

Topic 1: Implementation of model perturbations (SPP) in AROME-EPS

HungaroMet began testing the Stochastically Perturbed Parametrizations (SPP) scheme in 2023 on an experimental basis, focusing on selected parameters from the different physical parametrizations. Previous studies (e.g., Lang et al., 2021; Wastl et al., 2019; Wimmer et al., 2021) did not provide clear guidance on the optimal number or specific parameters to perturb. Ideally, parameters with high uncertainty and those influencing various levels or geographical areas should be perturbed together.

Following the successful technical implementation of SPP in AROME-EPS, HungaroMet ran an experiment from July 1–14, 2025, perturbing all available 10 parameters (see Table 1), and running 6 perturbed members along with 1 control member. Compared to the baseline run without stochastic perturbations, some improvements were observed in global radiation and mean sea level pressure. However, the impact was generally minor in most cases (see Figure 8). Notably, the effect was stronger when three parameters were perturbed individually, suggesting that the neutral overall impact might result from interactions among the ten parameters. Based on these findings, it appears that perturbing fewer parameters could be more effective.

Table 1: 10 SPP parameters implemented in AROME-EPS in Hungary.

Name of the parameter	Description	CMPERT	Unperturbed Value
VSIGQSAT	constant for sub grid condensation	0.4	0.02
RSWINHF	short-wave inhomogeneity factor	0.05	1
RLWINHF	long-wave inhomogeneity factor	0.04	1
XCTP	constant for temperature and vapour pressure correlations	0.3	4.65
XCEP	constant for wind-pressure correlations	0.2	2.11
XCED	constant for dissipation of TKE	0.2	0.85
XCMF	closure coefficient at the bottom level	0.1	0.065
XFRACZ0	coefficient for the orographic drag	0.15	10
RCRIAUTI	snow auto conversion threshold	0.2	$1 * 10^{-3}$
RCRIAUTC	rain auto conversion threshold	0.02	$0.5 * 10^{-3}$

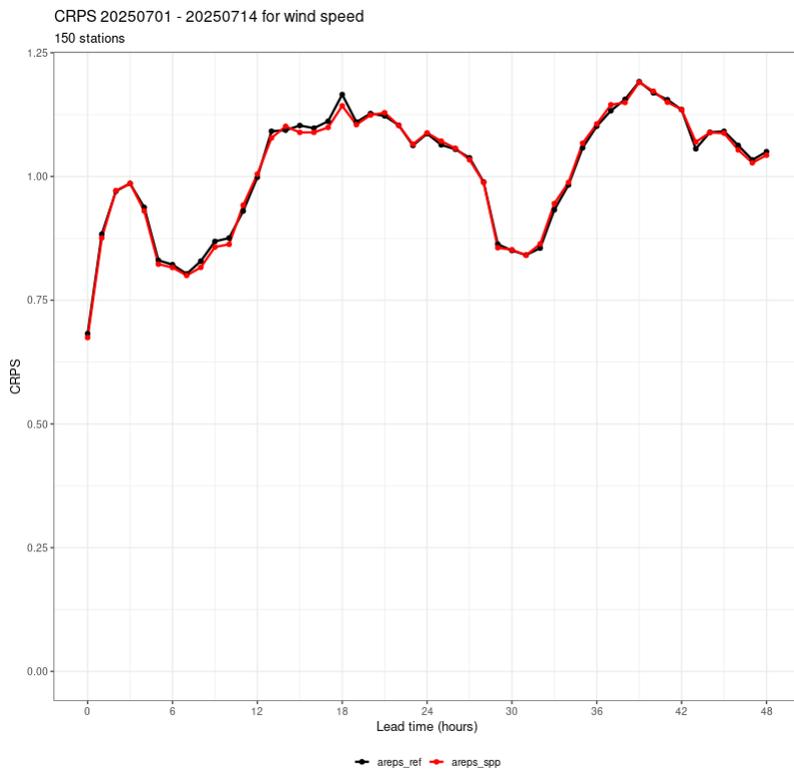


Figure 8: CRPS for 10m wind speed (m/s) as function of lead time (h), based on AROME-EPS; with 10 perturbed parameters (red) and without SPP (black); 1–14 July 2025 00 UTC.

Based on personal communication, it seems that perturbing only one parameter per parametrization scheme is the most effective approach. To test this, HungaroMet conducted an experiment for the same period, perturbing only five parameters as outlined in Table 2, running 6 perturbed members and 1 control member. Compared to the baseline run without stochastic parameter perturbation, the impact was minimal, as seen in Figure 9. In some cases, the perturbations led to systematic biases compared to the control member, such as the wind gusts between 15 and 30-hour lead times shown in Figure 10. However, for certain variables, like cloud cover, the forecast was improved when SPP was applied, as illustrated in Figure 11.

Based on these findings, a new experiment is planned, replacing the RCRIAUTC parameter with the XFRACZ0 from the surface scheme. Additionally, winter-time experiments and case studies are also on the agenda.

Table 2: The 5 SPP parameters perturbed in the 5SPP experiment.

Name of the parameter	Parametrisation scheme	Unperturbed value
VSIGQSAT	Microphysics	0.02
RSWINHF	Radiation	1
XCED	Turbulence	0.85
XCMF	Convection	0.065
RCRIAUTC	Microphysics	$0.5 \cdot 10^{-3}$

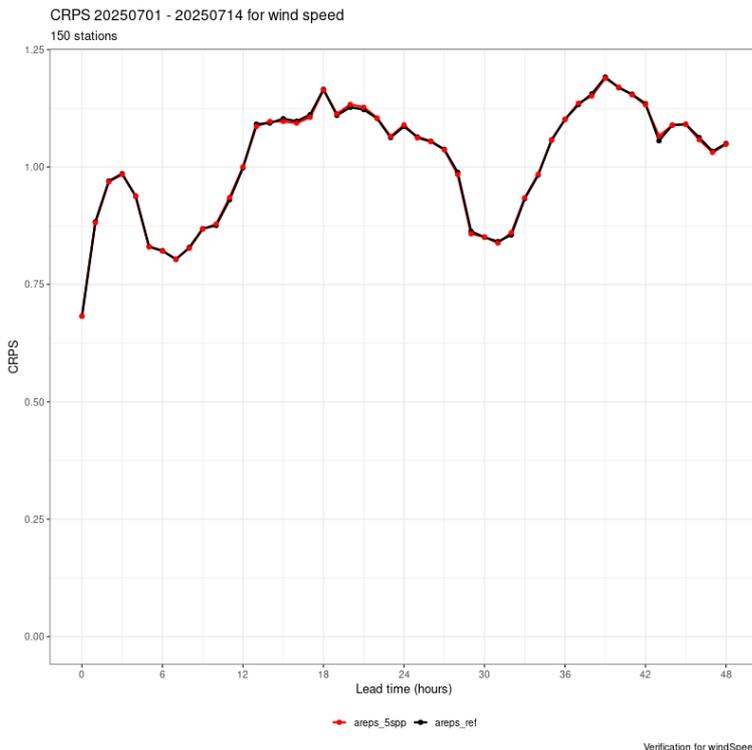
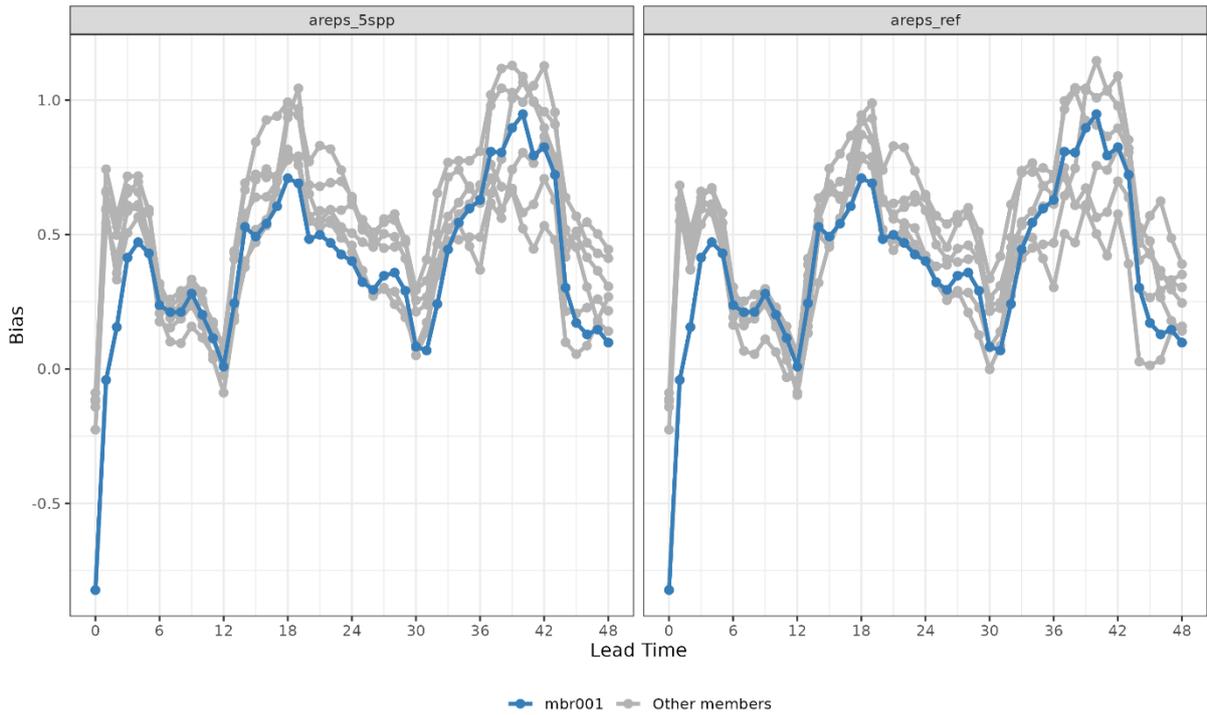


Figure 9: CRPS of 10m wind speed (m/s) as function of lead time (h) based on AROME-EPS with 5 perturbed parameters (red) and without SPP (black); 1–14 July 2025 00 UTC.

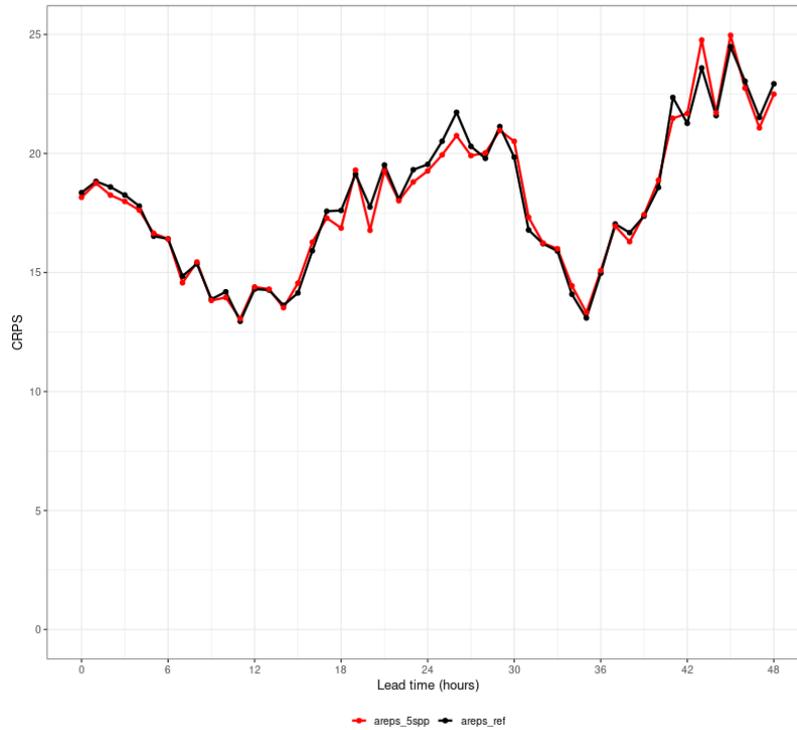
Bias :: 00:00 01 Jul 2025 - 00:00 14 Jul 2025
141 stations



Verification for windGust

Figure 10: Bias of 10m wind gusts (m/s) as function of lead time (h) based on the control member (blue) and 6 perturbed members (grey) of AROME-EPS with 5 perturbed parameters (left) and without SPP (right); 1–14 July 2025 00 UTC.

CRPS 20250701 - 20250714 for cloud cover
22 stations



Verification for skyAllCover

Figure 11: CRPS of cloud cover (%) as function of lead time (h) based on AROME-EPS with 5 perturbed parameters (red) and without SPP (black); 1–14 July 2025, 00 UTC.

Efforts: 11.0 PM (planned 6.0 PM in total in 2025)

Contributors: Martin Belluš (SHMU), Clemens Wastl (GeoSphere Austria), Endi Keresturi (DHMZ), Katalin Jávorné Radnóczy, Zsófia Szalkai (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 at GeoSphere Austria) – flow dependent SPP perturbations/C-LAEF AA – postponed to 2026

Status: Ongoing; some delays in the A-LAEF topics

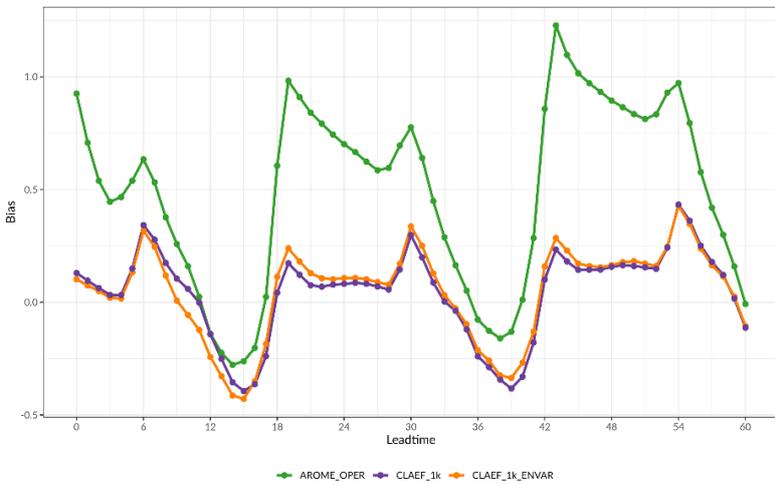
3 Action/Subject: Initial condition perturbations

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

The originally planned topics for 2025 were:

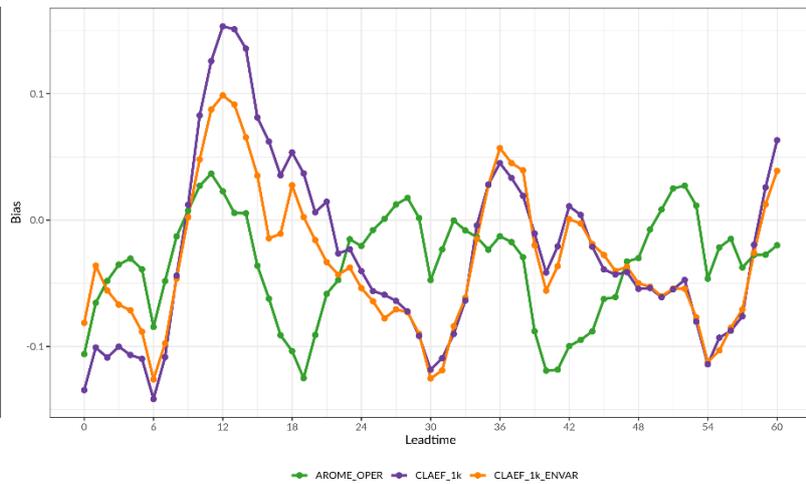
- Preparation of flow-dependent B-matrix for local 3DVar assimilation systems based on ALARO CMC using A-LAEF operational outputs
- EnVar and Hybrid EnVar in C-LAEF to create initial conditions for ensemble members. Test what perturbations are suitable and perform the best.

Bias : 00:00 03 Jul 2025 - 00:00 15 Aug 2025
253 stations



Verification for T2m

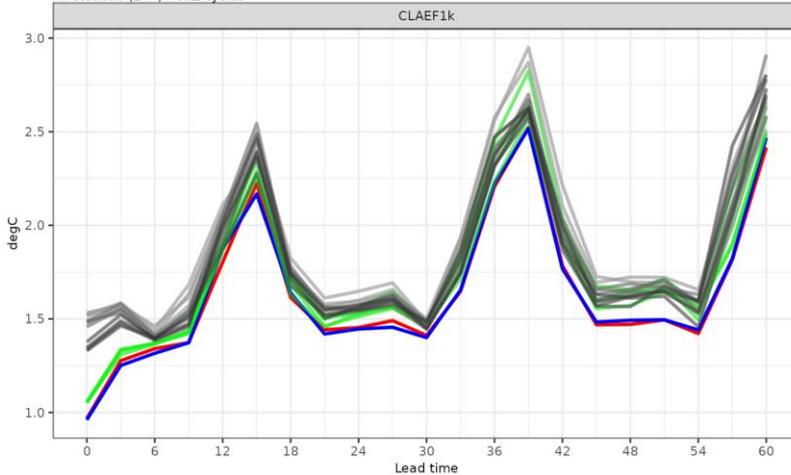
Bias : 00:00 03 Jul 2025 - 00:00 15 Aug 2025
255 stations



Verification for 10m

Figure 12: BIAS of 2m temperature (left) and 10m wind speed (right) of C-LAEF 2.5 km (green), C-LAEF AA (purple) and C-LAEF AA EnVar (orange) in summer 2025.

Rmse : All Members : T2m : 2025-07-01-00 - 2025-07-31-00 (31 cycles)
All stations (244) : 00Z cycles



Rmse : All Members : Rh2m : 2025-07-01-00 - 2025-07-31-00 (31 cycles)
All stations (244) : 00Z cycles

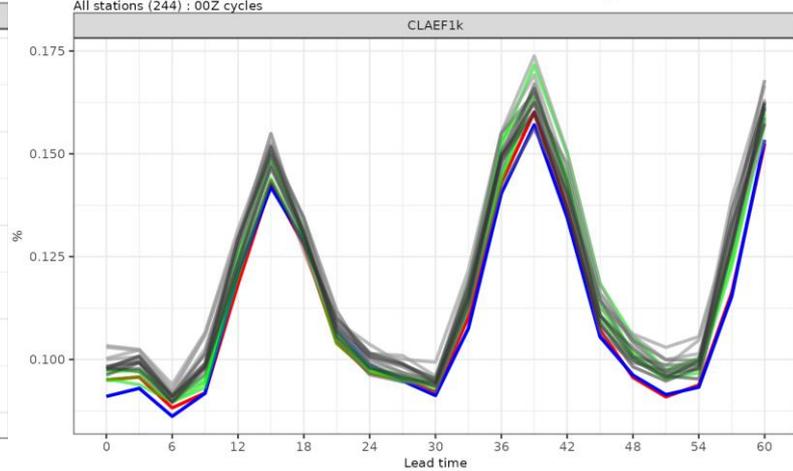


Figure 13: RMSE of T2m and Rh2m for all C-LAEF AA members in the summer test period. Ctrl in red, Envar in blue, „real“ members in green, lagged members in grey.

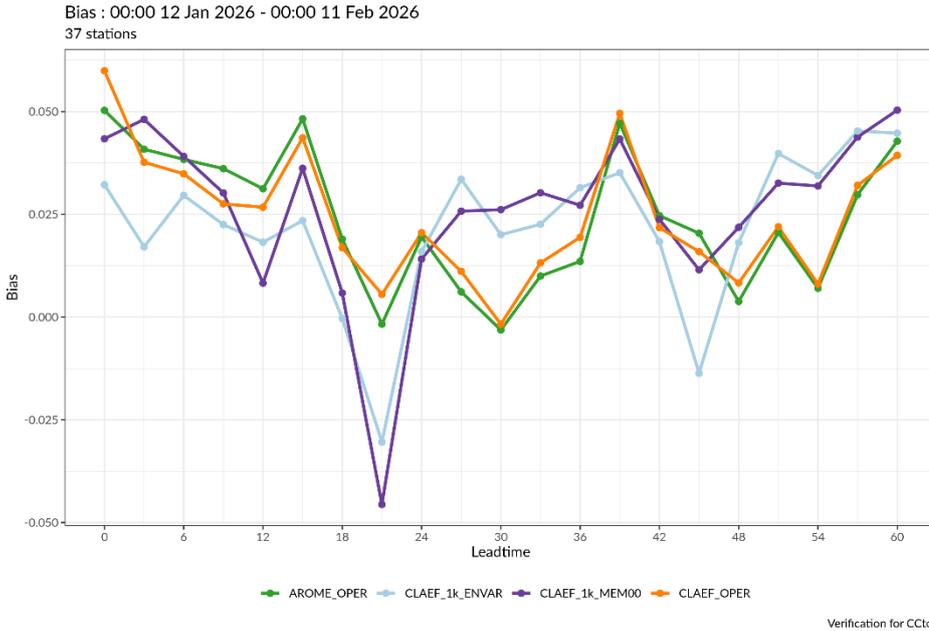


Figure 14: BIAS for total cloudiness of AROME 2.5 km (green), C-LAEF ctrl 2.5 km (orange), C-LAEF AA Ctrl (purple) and C-LAEF AA EnVar member (light blue).

The A-LAEF topic is delayed because of the lack of manpower at SHMU – it is unclear at the moment when this could be arranged.

Work on the EnVar system for C-LAEF AlpeAdria is currently ongoing. An EnVar member was introduced into the C-LAEF AA suite during the winter test period in January/February 2025. This member has been running continuously since then and is being evaluated using HARP verification. The statistical scores are generally very good (Figures 12–14), but some stability issues have been observed due to perturbed observations in summer. As a result, the inflation factor had to be increased, reducing the weight given to observations. Another issue appeared when we switched to 60s timestep for some time in autumn 2025. There were stability issues when 001 of C-LAEF Alpe Adria was initialised with 3D-EnVar and extended timestep of 60s. This was solved by applying IAU with a short IAU window during 001.

For several convective cases in summer, the EnVar member performed noticeably worse than the 3DVar member. Further investigations have shown that the problem was in the radar assimilation that delivered quite deviating results from 3D-Var MASTERODB solutions. This was caused by not properly set NOTVAR namelist switches in Screening (both Reflectivity and relative humidity have to be active, otherwise pseudo relative humidity values are incorrect). Finally, it was reported by Maud Martet that perturbations could lead to negative RH and >100% RH pseudo radar observations. This could be cured by small modification in pertobs/uncorr.F90 where sigma_o is linearly reduced to 0 if RH extends 90% or is below 10% (in the perturbation only). This adaptation still needs to be tested in the future.

Despite these challenges, the long-term objective remains to replace the classical 3DVar with EnVar in C-LAEF AA. The EnVar development for C-LAEF AA is a joint effort between Austria and Slovenia; additional details are provided in the data assimilation report.

Efforts: 0.0 PM (planned 1.0 PM in total in 2025)

Contributors: 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, HungaroMet); EPS documentation

Planned stays:

Status: Ongoing. Delay because missing resources in Slovakia

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 2025 were:

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

An externalized surface perturbation scheme is currently used operationally in C-LAEF (pertsurf) and has also been implemented to the new C-LAEF AA system. Hungary is planning to add a surface perturbation scheme to AROME EPS in the near future. Zsafia Szalkai started to work on SURFEX SPP during the EPS working week in Vienna in October 2025. It is planned that this work will be continued during a stay in 2026.

Efforts: 0.0 PM (planned 1.0 PM in total in 2025)

Contributors: Clemens Wastl, Daniel Deacu (GeoSphere Austria), Zsafia Szalkai (HungaroMet)

Documentation:

Planned stays:

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 2025 were:

- No topics planned.

The coupling of a local convection-permitting EPS in Slovakia with A-LAEF was already tested technically in the past using cycle 903. Within the DEODE project, an ALARO-based mini-EPS has now been implemented on the ECMWF HPC Atos system, coupled to the ECMWF ENS. It consists of 6 perturbed members plus 1 unperturbed control member and runs over a Slovak domain at 750 m horizontal resolution. The system has already been successfully evaluated in several case studies during 2024 and 2025.

The next step would be to couple this ALARO-EPS with the A-LAEF system, but it is unclear at the moment when this could be arranged.

Efforts: 0.5 PM (planned 0.0 PM in total in 2025)

Contributors: Martin Belluš (SHMU)

Documentation:

Planned stays:

Status: Delay due to the leave of Martin Belluš.

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 2025 were:

- Work on statistical post-processing of EPS data (e.g. more flexible calibration methods, etc.)
- Work on EPS post-processing by different machine learning (ML) methods
- Investigation of (ensemble) foundation models for post-processing (point with extension to spatial)
- Generation of ensemble members by deep learning algorithms
- Cascading Ensemble Method (CEM)
- Development of new probabilistic products to meet users' requirements

This subject has gained increasing relevance in recent years due to advancements in new technologies and artificial intelligence (AI). Several LACE countries are actively working in this field. Croatia, for example, has shifted its focus from analog-based wind-speed post-processing to AI-driven irradiance nowcasting through the SHADEcast model.

Solar-radiation prediction is also being pursued in Austria, using the Multivariate Spatio-Temporal Neighbourhood Ensemble Method, and in Hungary, where AROME-EPS and EMOS are applied. GeoSphere Austria is additionally developing approaches for generating ensemble members with deep-learning algorithms.

Poland has continued its work on the Cascading Ensemble Method (CEM) using the global AI model Fourcastnet together with an ALARO-based EPS. CEM is an ensemble technique characterized by a continuously increasing number of members. A publication is currently in preparation.

Furthermore, Romania has indicated interest in this topic. A newcomer at Meteo Romania with a background in Automation and Computer Science is has started to work on the field of EPS post-processing by AI and wants to make a stay at GeoSphere Austria next year. Also Slovakia has shown interest in this topic.

- Topic 1: Work on statistical post-processing of EPS data**

HungaroMet improved AROME-EPS EMOS by grouping stations with similar characteristics instead of using nationwide data. Tests (Aug–Oct 2023) showed that using stations with similar error patterns significantly improves CRPS, while including private-company measurements based only on distance does not always help. Shorter training periods and more stations can further enhance day-1 forecasts. Further testing with more stations has started in the second half of 2025 (see area leader report of application and verification for more details).

In Austria the statistical post-processing with SAMOS is running operationally and is steadily being extended. Additional to that also some research on the post-processing with copula methods has been made. A research paper has been published on this topic at Quarterly Journal of the Royal Meteorological Society about “A new copula-based shuffling method for ensemble weather forecast post-processing”. The correction strategy for multivariate ensemble forecasts is usually a two-step process: first correcting the univariate forecasts, then restoring the multivariate dependence structure. The second step is typically handled with non-parametric methods, which can struggle when only limited historical data are available. Parametric alternatives — such as the Gaussian Copula Approach (GCA) — have theoretical benefits, but often yield poorly calibrated multivariate forecasts because they rely on random sampling of the corrected univariate margins. In this publication the new method COBASE (Copula-Based Shuffling of Ensemble) is introduced which keeps the flexibility of parametric modeling while mimicking non-parametric techniques through a rank-shuffling mechanism. This ensures both calibrated marginal distributions and realistic dependence structures. COBASE is evaluated on multi-site 2-m temperature forecasts from the ALADIN–LAEF ensemble over Austria, as well as on joint temperature and dew-point forecasts from ECMWF in the Netherlands. Across all test cases, COBASE consistently outperforms traditional parametric approaches like GCA and performs on par with leading non-parametric methods such as SimSchaake and ECC, with only minor performance differences. These findings show that COBASE is a strong and reliable option for multivariate postprocessing, effectively bridging parametric and non-parametric dependence reconstruction.

❑ **Topic 2: Work on EPS post-processing by different machine learning (ML) methods**

Iris Odak went for a stay at GeoSphere Austria in spring 2025 (April 14th – May 17th) to work on Machine Learning (ML) methods that can be used for the post-processing of several different meteorological parameters. The stay report was just recently published and therefore some results are shown here (for more details see the complete stay report on the RC LACE webpage).

With the growing demand for accurate solar energy predictions, there’s a need for advanced ML techniques that can analyze and predict weather variables with high precision. These predictions are crucial for optimizing renewable energy production, especially for solar power generation, which heavily depends on weather conditions such as temperature, cloud cover, and solar radiation. Even though former methods such as basic implementation of LSTM did show certain potential, especially after the fraction of daily/night hours is included as additional predictor, the result was only comparable to operational ALADIN-HR deterministic model. Additionally, the

increasing demand for post-processed visibility parameter is also becoming a factor to go for a more complex model and use more than station data. The natural next step was to consider available satellite data in order to develop a reasonable nowcasting model.

The idea was to try to make it work using a state-of-the-art SHADEcast model and satellite data. SHADECast is a modular deep generative nowcasting framework for satellite-based short-term forecasting of solar radiation, specifically Clear-Sky Index (CSI) fields. It is python based and freely available via GIT. SHADECast is structured into key modules, implemented as PyTorchmodules and combined into a training and inference pipeline. The core components are:

- Variational Autoencoder (VAE): Compresses CSI input into latent space.
- AFNO Nowcaster: Deterministic forecast module operating in latent space
- Latent Diffusion Model: Stochastic generator producing ensemble forecasts in latent space.
- Decoder: Transforms latent forecasts back into full-resolution CSI maps.

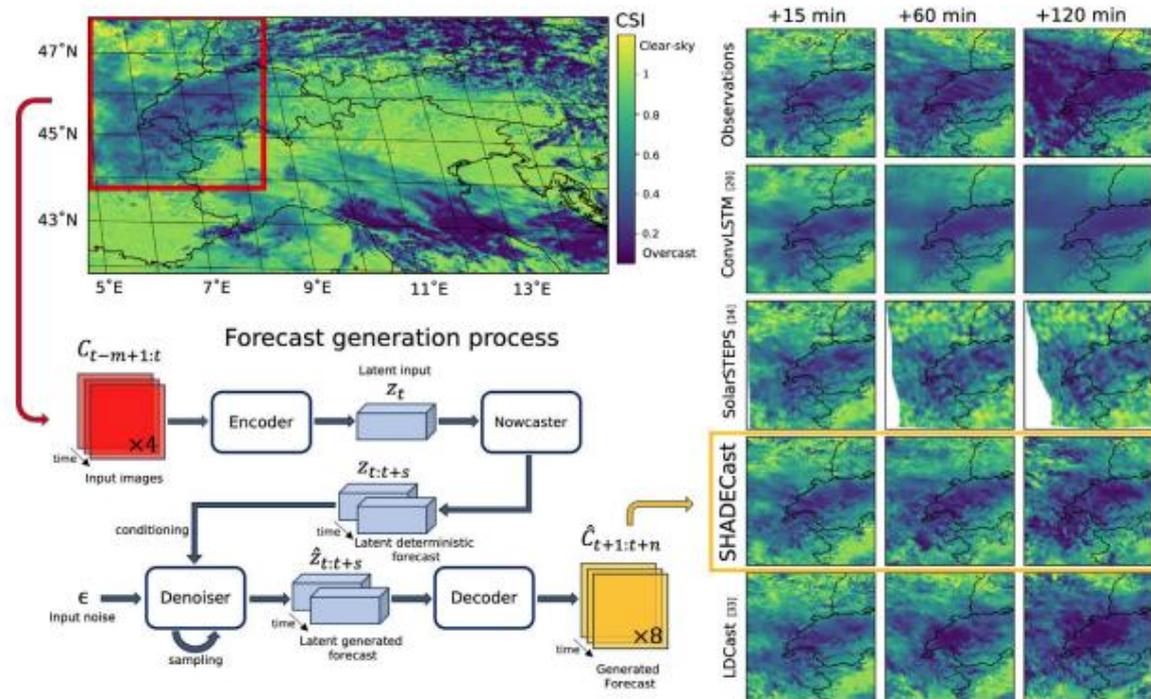


Figure 15: SHADECast forecast generation pipeline. Upper left panel: Example CSI field of 24 Feb. 2016 at 11:45 UTC. The red box highlights the region forecasted in the right panel. Lower left panel: SHADECast forecast generation pipeline. Right panel: Forecasts made by SHADECast (yellow box) and benchmark models for lead times up to 120 min. For SHADECast, LDCast and SolarSTEPS the ensemble member chosen is the one with the lowest average root mean squared error (RMSE). The first row shows the satellite-derived CSI fields.

The functionality of the SHADECast model is shown in Figure 15. The input CSI fields ($C_{t-m+1:t}$) are fed to the encoder, which projects the image sequence to the latent space, obtaining z_t . Then, the deterministic nowcaster forecasts the future

latent representation of the CSI fields ($z_{t+1:t+s}$), where s is the lead time in the latent space, which can differ from n due to data compression. The latent forecast is, then, fed to the denoiser together with Gaussian noise ϵ . The pseudo linear multi-step (PLMS) sampler employs the denoiser to generate an ensemble member. The decoder finally decompresses the latent ensemble forecast, obtaining $C_{t+1:t+n}$

This stay was a first step in that direction with the purpose to gain experience with radiation forecasting and products for solar in general. The SHADEcast model is not yet fully implemented, because it is a complicated model. The plan is to continue on this topic in the form of work at home institution (debugging, testing using satellites) and also in form of another research stay at GeoSphere Austria in 2026.

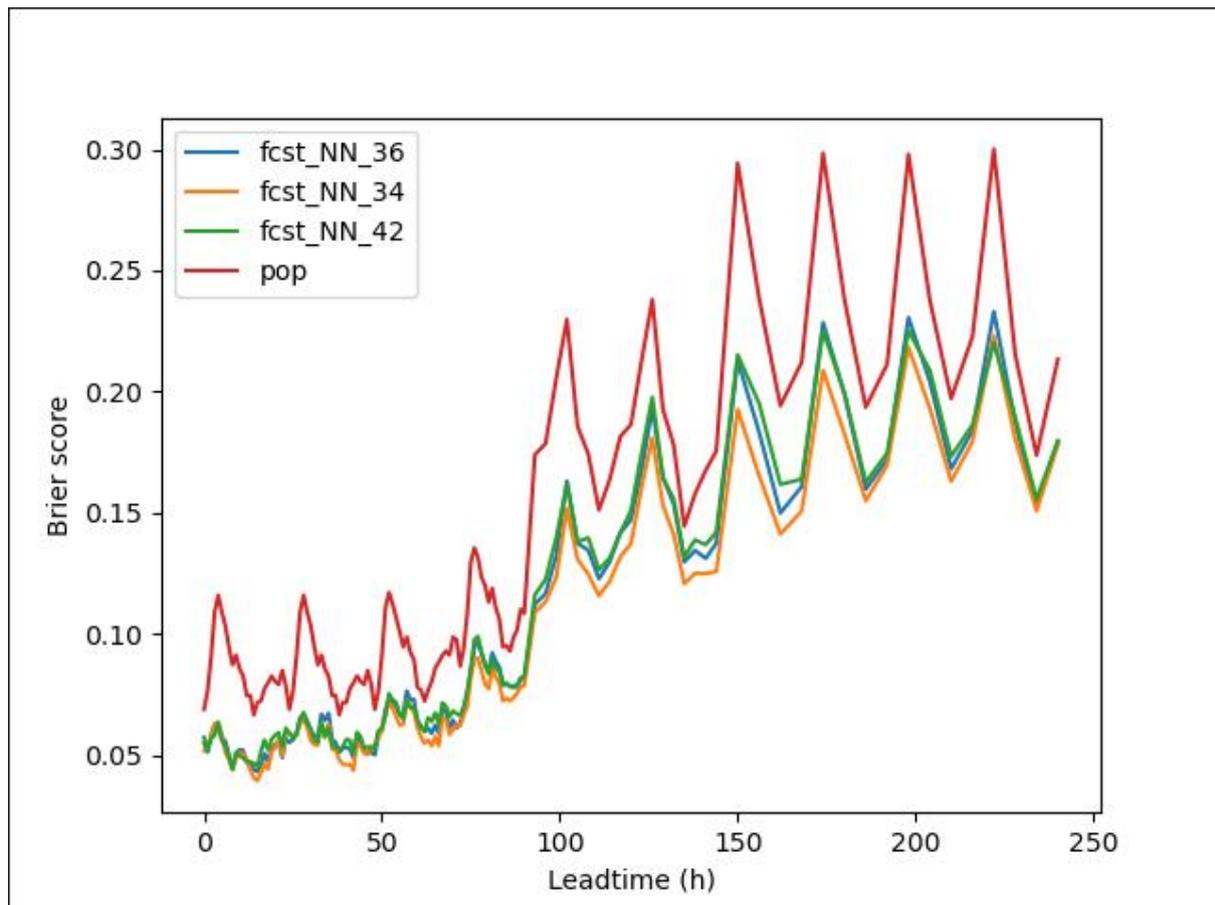


Figure 16: Brier score of the IFS Ensemble (red) and for several variations of the neural network approach for a test period in September 2024.

Another stay in that area was done by Ivan Vujec (DHMZ) in October (6th – 31st) 2025 at GeoSphere Austria dealing with rain NWP postprocessing using neural networks. The idea of this stay was to generate probabilistic forecasts of rain occurrence using the deterministic NWP runs. The Croatian and Austrian NWP models were used, and to increase the forecast duration, the information from ECMWF's IFS global model was also included. The post-processing was performed at the station locations, and the machine learning model used was a simple feed-forward neural network. Also, the transferability between the models was analyzed. In comparison to the IFS ensemble, the generated results show the potential of even the simplest neural

network architectures in such probabilistic cases (Figure 16). Several variations of the neural network models outperform the IFS ensemble, as indicated by better Brier scores. Further improvements are currently being pursued by incorporating additional time-lagged parameters.

At GeoSphere Austria some work has been spent on advanced ensemble generation methods that can provide reliable uncertainty quantification for renewable energy planning and operations. A multi-method ensemble generation system has been developed and implemented for meteorological applications. The core is a multi-parameter spatio-temporal neighbourhood ensemble generation method that generates physically consistent, spatially coherent ensemble forecasts specifically optimized for renewable energy applications (“baseline ensemble generation”). The baseline implementation successfully preserves cross-variable relationships critical for wind, solar, and hydropower applications while maintaining computational efficiency suitable for operational deployment. Additionally, a more AI-enhanced ensemble generation method, “ensemble generation #1” are included. The system has been validated using multiple case studies including precipitation storms, wind events, and solar energy scenarios, demonstrating realistic ensemble spread, proper calibration, and maintained physical relationships. The generated ensemble datasets have been made publicly available to support further research and operational applications in the renewable energy sector.

□ **Topic 3: Generation of ensemble members by deep learning algorithms**

GeoSphere Austria is currently working on the generation of ensemble members by deep learning algorithms. The technical installation and implementation of a diffusion-based model for emulating ensemble members (CorrDiff model) has been successful on the Leonardo HPC. Based on a mini ensemble the training and the inference has been tested. The model itself is trained in a two-step process: At the beginning a pre-training is done with ERA5 downscaling on C-LAEF reanalysis. In a second step the finetuning with downscaling of IFS-ENS members on C-LAEF is done. Due to lack of resources this method has been tested so far only for some selected cases. A much longer training dataset is required before it can be operationalized. This topic is planned to be continued in 2026.

□ **Topic 4: Cascading Ensemble Method (CEM)**

CEM (Cascading Ensemble Method) has been developed at IMGW in Poland and is an ensemble technology where members are added to an EPS during the integration of a model, when the uncertainty of forecasts starts to grow. Its aim is to achieve similar or better results compared to the traditional methods, but at a lesser computational cost and less storage usage.

CEM was tested first with the data-driven global weather forecasting model FourCastNet from Nvidia. It was trained on ERA5 reanalysis data, spanning the years 1979-2015. The CEM ensemble was created by increasing the number of members with the number of timesteps. For n timesteps, the final ensemble count is 2 to the n -th power. Different scores (BIAS, RMSE and CRPS) of the original ensemble forecasting method were evaluated with CEM by running a month of forecasts using

Nvidia's AI-driven global model FourCastNet and comparing to global data from WMO synoptic stations. The testing period was January 2023, with each run starting at 00 UTC and lasting 120 hours or 20 timesteps. CEM has the ensemble count increase from 1 to 256, doubling up until timestep 8. Two variables were chosen for consideration: air temperature at 2m height and pressure at sea level. CEM shows consistently rising spread values throughout the entire run, resulting in spread higher than the classical approach. BIAS and RMSE are comparable but the classical methods shows a much stronger diurnal cycle than CEM. CRPS sees a great difference in growth between the methods. The classical method shows rapid growth for the first 6 timesteps before slowing down, while for CEM the values grow slowly and consistently without the initial jump, leading to a much lower CRPS overall. At the moment a publication about CEM is in preparation at IMGW.

Efforts: 12.5 PM (planned 12.0 PM in total in 2025)

Contributors: Iris Odak, Ivan Vujec (DHMZ), Alexander Kann, Irene Schicker (GeoSphere Austria), Katalin Jávorné-Radnóczy (HungaroMet), Bogdan Bochenek, Jadwiga RóG (IMGW)

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

Planned stays

1. Iris Odak (April 14th – May 17th) – ML based post-processing methods
2. Ivan Vujec (October 6th – 31st) – Chance of rain NWP postprocessing using neural networks

Status: Ongoing, on time.

Activities of management, coordination and communication

- ❑ 44th LSC Meeting, 6-7 March 2025, Krakow
- ❑ 5th ACCORD All Staff Workshop 2025, March 31 – April 4 2025 (Zalakaros), online participation
- ❑ 45th LSC Meeting, 10-11 September 2025, Ljubljana
- ❑ 47th EWGLAM and 32nd SRNWP workshop, 22-25 September 2025, Norrköping
- ❑ 5th ACCORD EPS working week, 20-24 October 2025, Vienna
- ❑ EUMETNET SRNWP-EPS workshop, 25-27 November, Bologna

Publications

Flos, M., François, B., Schicker, I., Whan, K. & Perrone, E. (2026) COBASE: A new copula-based shuffling method for ensemble weather forecast postprocessing. Quarterly Journal of the Royal Meteorological Society, e70138. Available from: <https://doi.org/10.1002/qj.70138>

RC LACE supported stays – 2 PM in 2025

Two stays could be realized in the EPS area of RC LACE in 2025: The stay of Iris Odak (4 weeks at GeoSphere Austria, April 14th – May 17th) on ML based post-processing methods and the stay of Ivan Vujec (October 6th – 31st) in Vienna on NWP postprocessing using neural networks.

The stay of Martin Bellus (upgrade of A-LAEF) has been canceled because of his leave from SMHU in July 2025. The stays of Endi Keresturi in Vienna (flow dependent SPP) and Jadwiga Róg (A-LAEF) in Zagreb have been postponed to 2026.

Summary of resources [PM] – 2025 (Jan – Dec 2025)

Subject	Manpower		RC LACE		ACCORD	
	plan	realized	plan	realized	plan	realized
S1: Preparation, evolution and migration	18	18.5	2	0	0	0
S2: Model perturbations	6	11	1	0	0	0
S3: IC perturbations	1	0	0	0	0	0
S4: Surface perturbations	1	0	0	0	0	0
S5: LBC perturbations	0	0.5	0	0	0	0
S6: Statistical EPS and user-oriented approaches	12	12.5	2	2	0	0
Total:	38	42.5	5	2	0	0

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