Working Area Predictability

Progress Report

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Period:	Jan – Jun 2025
Date:	Sep 2025

Progress summary

The use of ensemble prediction systems in the national meteorological services of RC LACE is steadily increasing. In addition to products from the classical EPS (A-LAEF, C-LAEF, AROME-EPS), post-processed ensemble output is being applied more and more frequently. Consequently, significant effort is currently being dedicated to subject S6 of the RC LACE work plan – statistical EPS and user-oriented approaches. These methods include classical techniques such as analog-based and statistical post-processing, but also new developments in the field of artificial intelligence (AI), for example physics informed and data-driven machine learning nowcasting for the renewable energy sector. A novel approach to EPS, the Cascading Ensemble Method (CEM), is currently under development at IMGW in Poland. CEM adds new members dynamically during forecast computations, when forecast uncertainty increases. Its goal is to achieve results comparable to traditional methods but at lower computational cost.

So far, no major upgrades have been implemented in 2025 for the two operational EPSs running on the ECMWF HPC (A-LAEF and C-LAEF). However, improved systems are already in the testing phase. For A-LAEF, an upgrade from cy40t1 to cy46t1 is planned by the end of this year. This will also introduce a new upper-air spectral blending method and an enhanced multi-physics package.

A major upgrade of the C-LAEF system is scheduled for early 2026. The development of C-LAEF AlpeAdria (AA) has evolved into a joint initiative between Austria, Croatia, and Slovenia, involving both shared computational resources (SBUs) and manpower. The upgrade includes an updated model cycle (cy46t1), an increase in horizontal resolution from 2.5 km to 1 km, and substantial improvements in data assimilation (new observation types, EnVar), model error representation (SPP, flow dependency), dynamics setup, and post-processing (GRIB2). C-LAEF AA is designed as a continuous lagged ensemble with 16+1 members, providing eight runs per day with a lead time of 60 hours. An Esuite of C-LAEF AA has already been successfully tested during both winter and summer periods, with very 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. A lot of testing and tuning is currently ongoing in that topic.

Another important focus within RC LACE is the DEODE project, in which many members of the EPS community are actively involved. The project develops on-demand, configurable digital twin engines for forecasting environmental extremes. With DEODE, ensemble systems are moving into the hectometric scale (750 m), representing a significant step forward in 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 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

The operational suites on the ECMWF HPC in Bologna (A-LAEF and C-LAEF) have been running in the current setup for several years now. No big operational upgrades have been made so far in 2025, but the future systems are currently tested on Atos. For the A-LAEF system a cy46t1 Esuite with some substantial upgrades (e.g. implementation of upper-air spectral blending, new ALARO-1 multi-physics, etc.) has been set up and launched under the TC user zla2 on June 12. At the moment only the control member is run to warm up the assimilation cycle for a prompt operational switch.

In course of the DEODE project first test runs with a mini ALARO-EPS (5+1 members) on 750m resolution coupled in ECMWF ENS have been made. No progress has been made on the implementation of SURFEX and ALARO-EPS due to the leave of the main contributor Martin Bellus.

For C-LAEF a complete 1km ensemble has been running for a winter (January - February 2025) and summer period (June – August 2025). The summer test period consisted of a continuous lagged ensemble with 8 full ensemble runs per day. Intensive verification showed a general quite good performance. However, a lot of tests and optimizations (longer time step, new ICE3 scheme, etc.) had to be made to make the EPS affordable. The work on C-LAEF AlpeAdria (new name) is a joint cooperation between the RC LACE countries Austria, Slovenia and Croatia. The goal is to put C-LAEF AlpeAdria into operations at the beginning of 2026.

The reanalysis of C-LAEF (2.5km version) for the 2012-2021 period has been finished in summer 2025. It is planned to be extended up to the current year 2025.

The operational AROME-EPS in Hungary has been upgraded to cy46t1 in February 2025 and the work on the introduction of model perturbations (SPP) is currently ongoing.

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

No major operational upgrades have been made for A-LAEF so far in 2025, only some minor changes (upgrading of GRIB2 tables, debugging of blending task crashes, implementing solutions for potential share library issues). Currently, a lot of testing with the new cy46t1 version of A-LAEF is ongoing.

The planned upgrade consists beside a general cycle upgrade (from cy40t2 to cy46t1) also upgraded Clim files based on ECOCLIMAP v2.6 and updated PGD fields (e.g. orographic roughness, vegetation roughness, subgrid orographic characteristics for GWD and LZOTHE=.F.) – Figure 1.

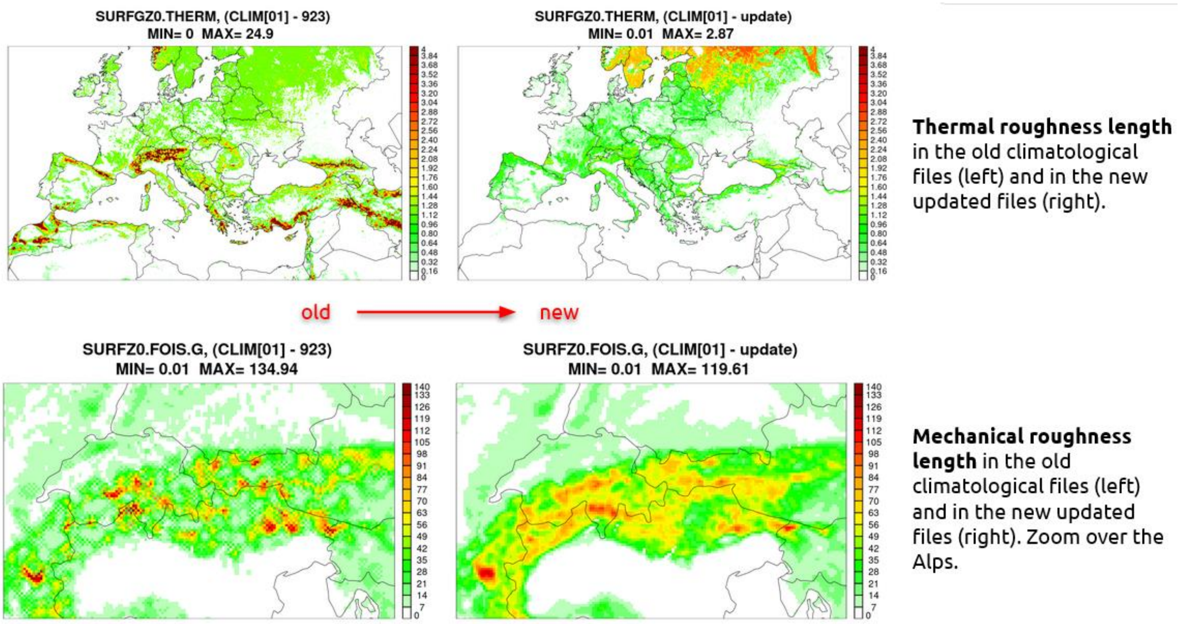


Figure 1: New clim files for A-LAEF Esuite including updated roughness length fields.

The leadtime of the new A-LAEF system has been extended to 78 hours (from 72h) and a GRIB2 inline FPOS is used including new parameters (e.g. precipitation types, lightnings, simulated radar reflectivity, etc.). Furthermore, the upgraded A-LAEF version consists of a completely new ALARO-1 multi-physics cluster (Figures 2 and 3).

	cluster / member	phys01	phys02	phys03	phys04
		00,01,05,09,13	02,06,10,14	03,07,11,15	04,08,12,16
	namelist parameter	oper	double	oper	double
		EL0		EL1	
limits for hail/graupel classification in precip.type	RDHAIL1	2.8	2.4	2.8	2.4
	RDHAIL2	7.5	6.5	7.5	6.5
mixing length	CGMIXLEN	EL0	EL0	EL1	EL1
PBL height based on TKE profile	LPBLH_TKE	F	F	T	T
PBL height limit	XMAXLM	0.	0.	5000.	5000.
TOUCANS (EL1 tunings)	ETKE_C0SHEAR	0.5	0.5	0.35	0.35
	ETKE_DTHETA_S1	-5.0	-5.0	-2.5	-2.5
	ETKE_DTHETA_S2	2.0	2.0	1.0	1.0
	ETKE_R2SIM	0.2	0.2	0.1	0.1
Lopez evaporation	LEVAPLOP	F	T	F	T
roughness impact of snow via snow height	LZ0SNOWH	F	T	F	T

Figure 2: New A-LAEF (CY46T1+) physics clusters setup 1/2.

	cluster / member	phys01	phys02	phys03	phys04
		00,01,05,09,13	02,06,10,14	03,07,11,15	04,08,12,16
critical RH profile tuning for radiation cloudiness	HUCREDRA	0.42	0.46	0.42	0.46
autoconversion to rain	RAUTEFR	0.5E-03	0.8E-03	0.5E-03	0.8E-03
autoconversion to snow	RAUTEFS	2.E-03	1.E-03	2.E-03	1.E-03
flash diagnostics	RCFLASH1	16.76	22.29	16.76	22.29
variation of exp-random cloud overlap in radiation	RDECRD1	10000.	8000.	10000.	8000.
	RDECRD2	20000.	215000.	20000.	215000.
liquid/ice partition for cloud condensate	RDTFAC	1.00	0.75	1.00	0.75
max. evaporation rate for rain	REVASXR	0.	7.E-07	0.	7.E-07
critical liquid w.c. for liquid cloud w. autoconv.	RQLCR	3.E-04	4.E-04	3.E-04	4.E-04
snow fraction	WCRIN	4.0	10.0	4.0	10.0
ratio of mechanical roughness length to obstacle height	RZ0_TO_HEIGHT	0.13	0.1	0.13	0.1
	FACRAF	10.0	3.6	10.0	3.6
wind diagnostics (TKE vs friction velocity)	LRAFTKE	F	T	F	T
	LRAFTUR	T	F	T	F

Figure 3: New A-LAEF (CY46T1+) physics clusters setup 2/2.

The A-LAEF upgrade also contains a surface SPPT scheme of ISBA surface prognostic fields which have been phased to cy46t1 (Figure 4). At each time step in grid-point space, stochastic perturbations are applied to the physics tendencies of surface fields (7 fields in total). Direct perturbations of deep soil prognostic fields, such as deep soil temperature or moisture, were intentionally avoided. They naturally undergo much slower temporal changes, exhibiting a delayed response compared to the surface parameters.

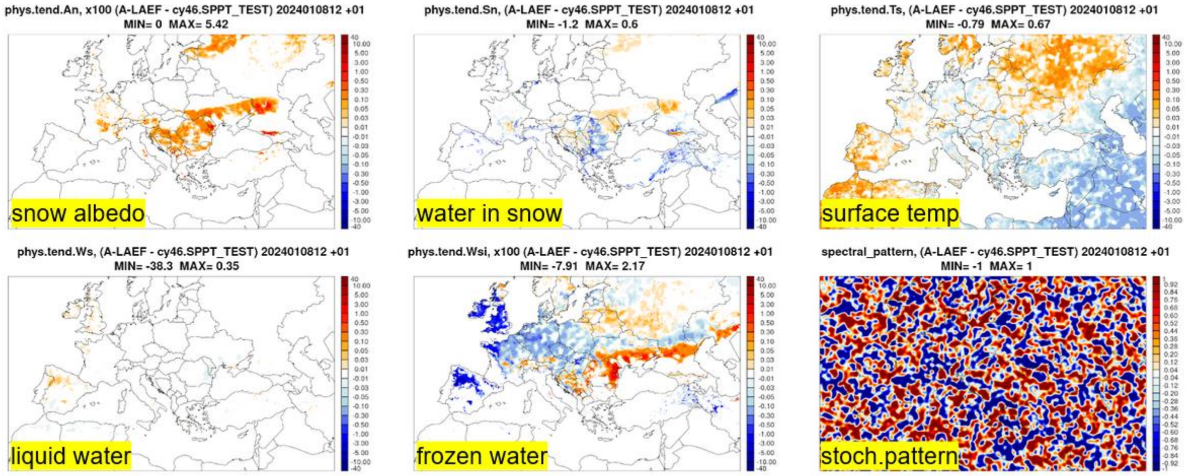


Figure 4: Surface SPPT of A-LAEF surface prognostic fields.

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

The switch to the new CY46T1 A-LAEF version was originally planned for spring 2025, but due to the leave of the main contributor Martin Bellus it is at the moment unclear when this can be arranged. Since June 12th 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.

- ❑ **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 set up on the ECMWF HPC Atos. It consists of 6 perturbed + 1 unperturbed control and is run on a Slovakian domain with 750m grid resolution (Figure 5). The uncertainty simulation consists of an ALARO-1 multi-physics scheme and surface stochastic physics (SPPT), initial conditions and LBCs have been taken from the ECMWF ENS. The ecFlow suite is based on the A-LAEF scripting system. The system has been tested for several severe weather situations, e.g. the flooding event in September 2024 (storm Boris, see EPS report of 2024), a lee wave event on Christmas Eve 2024 and a freezing rain event in January 2025. The benefit of the higher resolution can be seen clearly in such situations (e.g. Figures 6 - 8).

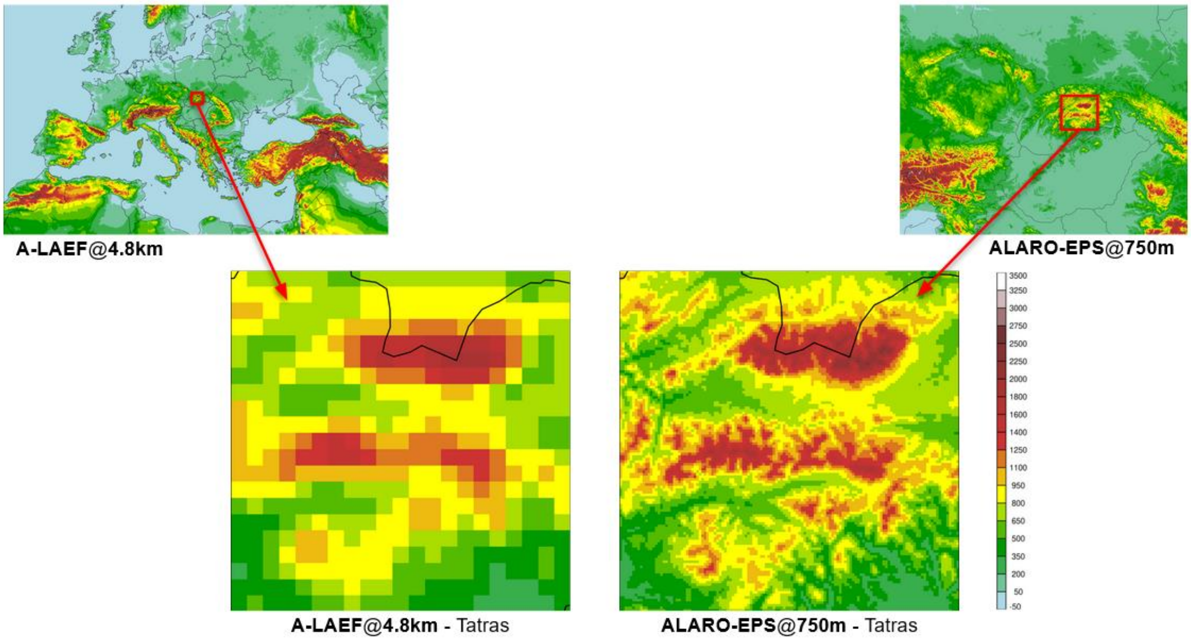


Figure 5: Comparison of the A-LAEF domain (left) and the ALARO-EPS domain (right).

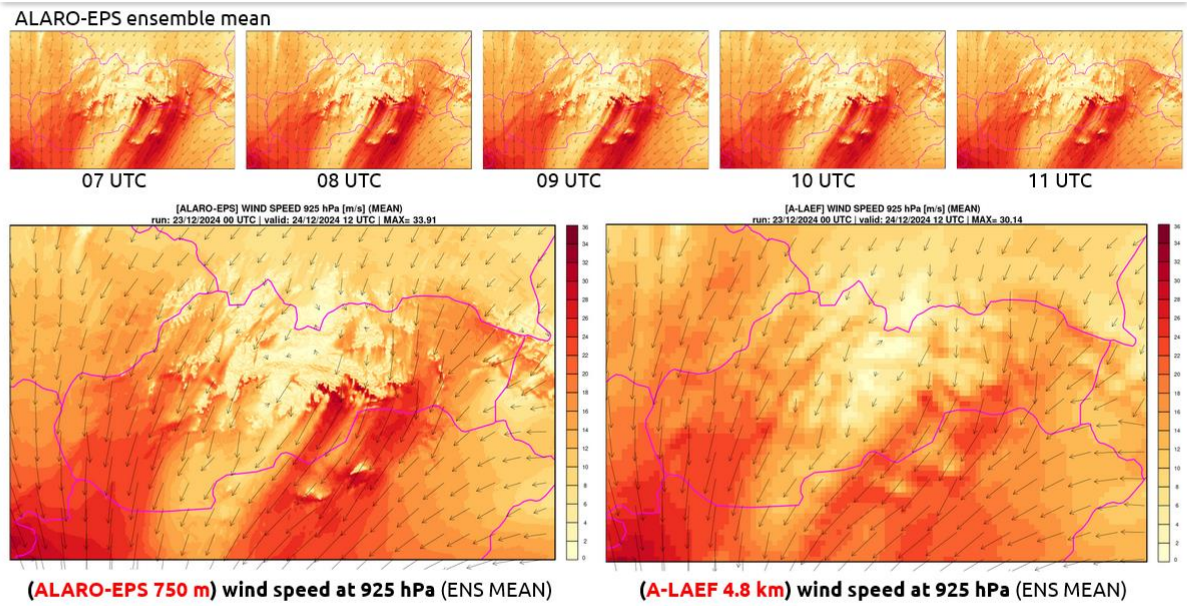


Figure 6: Wind speed at 925 hPa in ALARO-EPS (left) and A-LAEF (right) for a lee wave event on December 24, 2024.

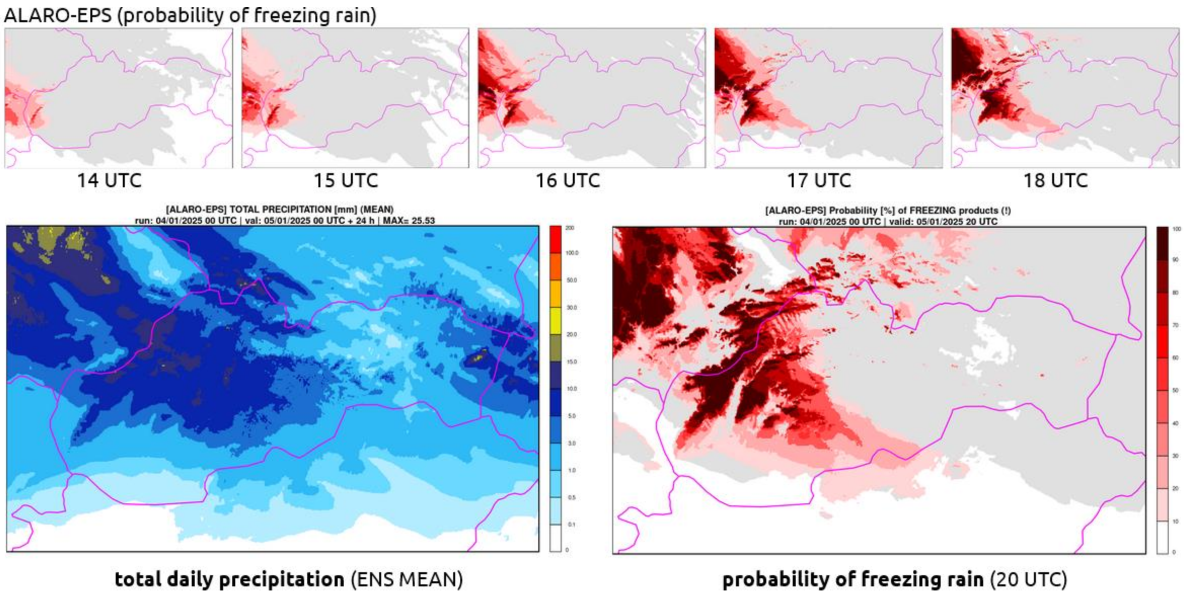


Figure 7: Probability of freezing rain and total daily precipitation of ALARO-EPS on January 5th, 2025.

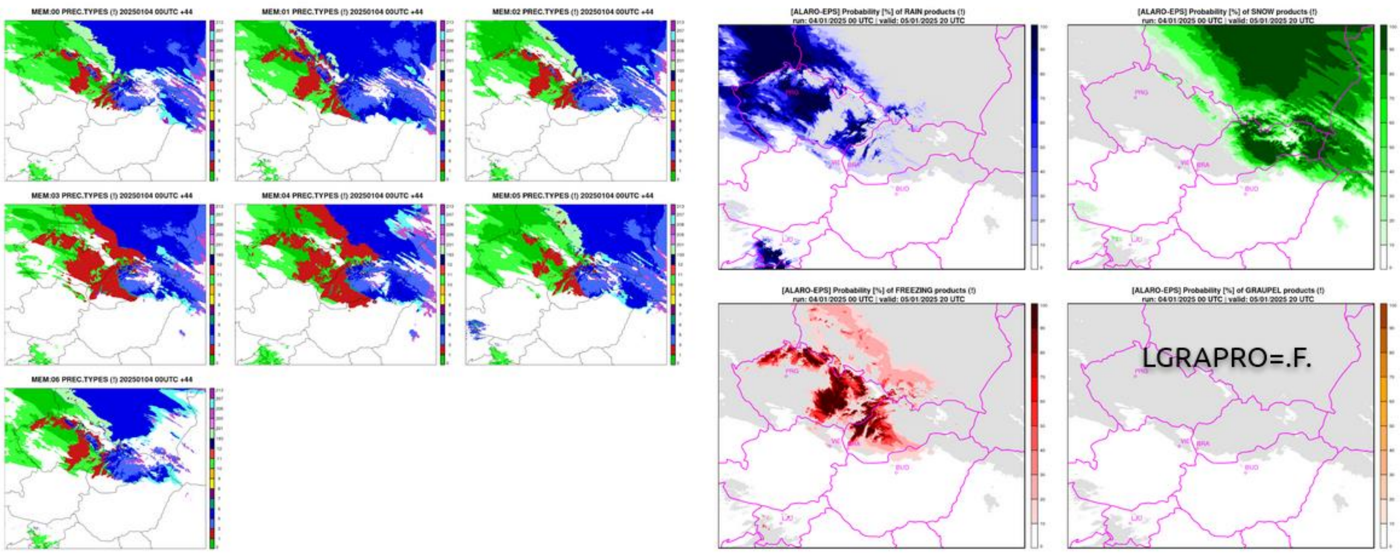


Figure 8: Precipitation types of ALARO-EPS on January 5th, 2025.

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

Austria has been running its operational AROME based (cy43t2) EPS C-LAEF on a 2.5km grid since 2019 on the ECMWF HPC. In the past years a lot of effort has been put into an essential upgrade of this system to 1km and cy46t1. Slovenia and Croatia have joined this initiative in the beginning of 2025 by contributing SBUs and man power. Slovenian contributions are mainly focusing on data assimilation, Croatia is supporting in the area of model perturbations and post-processing. This joint system is now officially called C-LAEF AlpeAdria (C-LAEF AA).

The C-LAEF AA ensemble consists of 16+1 members, where the 16 perturbed members 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 significantly towards the South compared to C-LAEF. Each country has its own post-processing domain. A common user name (zacs) and SBU account (claef-op) for Austria, Croatia and Slovenia have been created to share the development and the monitoring of the suite. The operationalization of C-LAEF AA is planned for the beginning of 2026.

To cover the extremely high computational costs, C-LAEF AA is operated in a continuous lagged ensemble mode. 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. By applying this method, we are able to 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). The output format of C-LAEF AA is grb2.

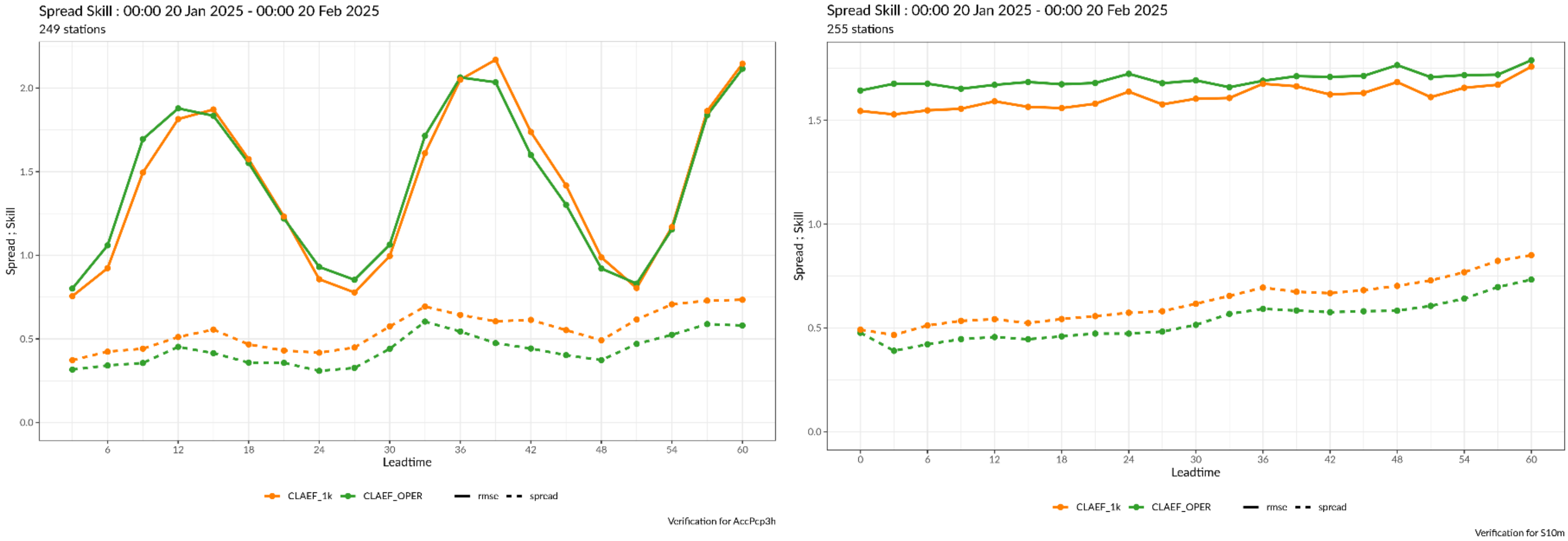


Figure 9: Spread (dashed) and skill (full) of 3h accumulated precipitation (left) and 10m wind speed (right) for C-LAEF (green) and C-LAEF AA (orange) in the winter test period 2025.

In 2025 the system has been extensively tested during a winter (Jan-Feb) and summer (Jun-Aug) test period. The suite has been generally running very stable with hardly no technical problems. The output has been provided to forecasters in Austria, Croatia and Slovenia (visual weather maps, meteograms). The full suite has been stopped end of August due to computational costs – only the control and the EnVar member are kept long till the end of the year.

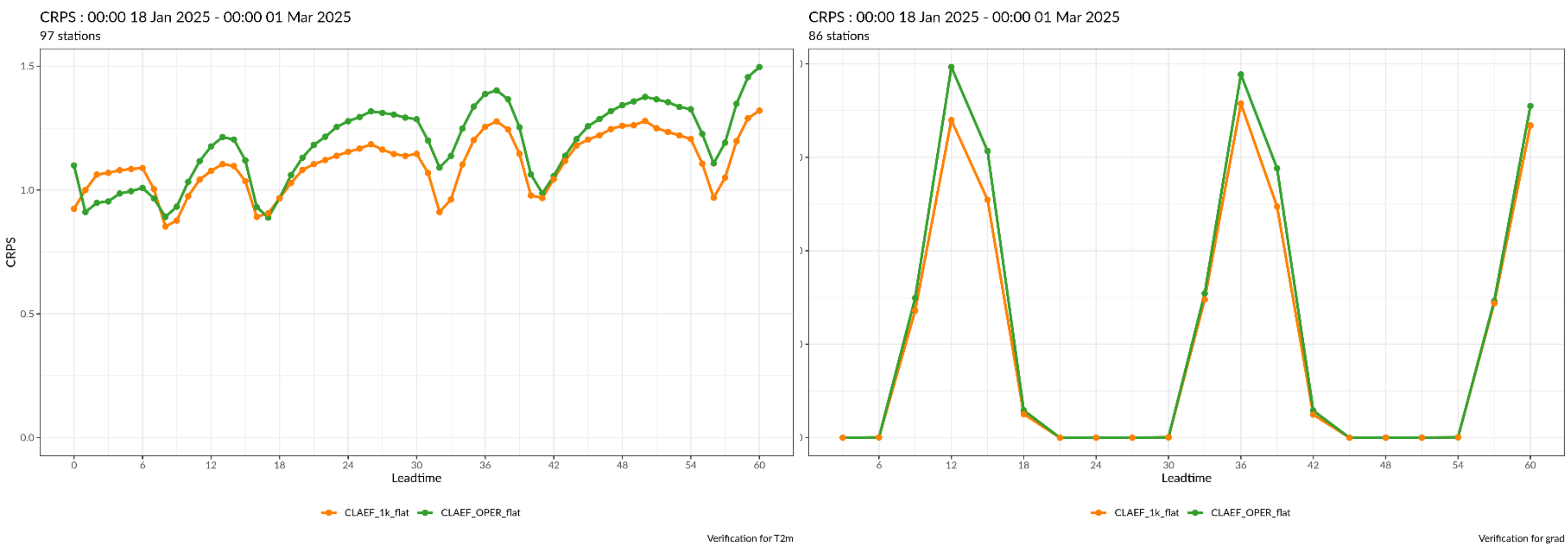


Figure 10: CRPS of 2m temperature (left) and global radiation (right) for C-LAEF (green) and C-LAEF AA (orange) in the winter test period 2025.

The performance of C-LAEF AA 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 AA is quite satisfying with score improvements for nearly all variables compared to the operational C-LAEF system.

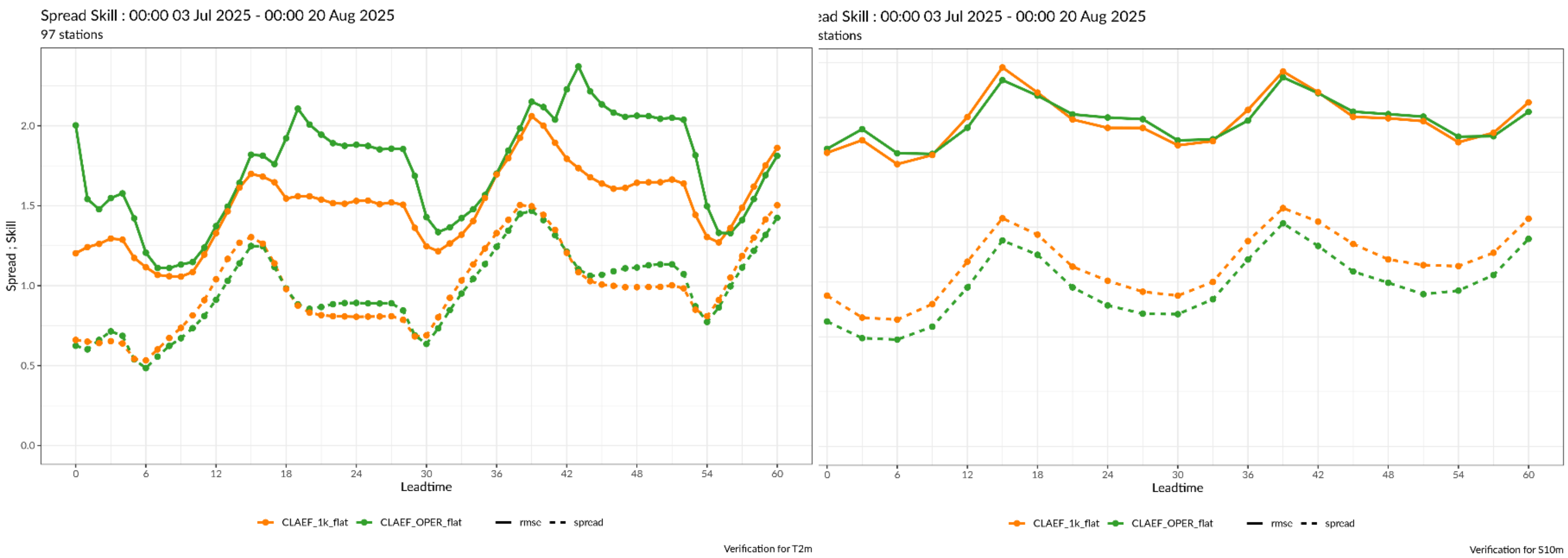


Figure 11: Spread (dashed) and skill (full) of 2m temperature (left) and 10m wind speed (right) for C-LAEF (green) and C-LAEF AA (orange) in the summer test period 2025.

The summer period has shown that despite some optimizations (NPROMA, FFTW, FPOS, etc.) the full EPS is still too expensive to be run in full operational mode in 2026. Therefore, a reduction of the timestep from 45s to 60s has been implemented and tested in a parallel suite during the summer test period. First tests were not very successful - the precipitation field over the Alps was negatively affected. A switch to the new ICE3 microphysics scheme (less time step dependent) helped in that context.

Figure 12: 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.

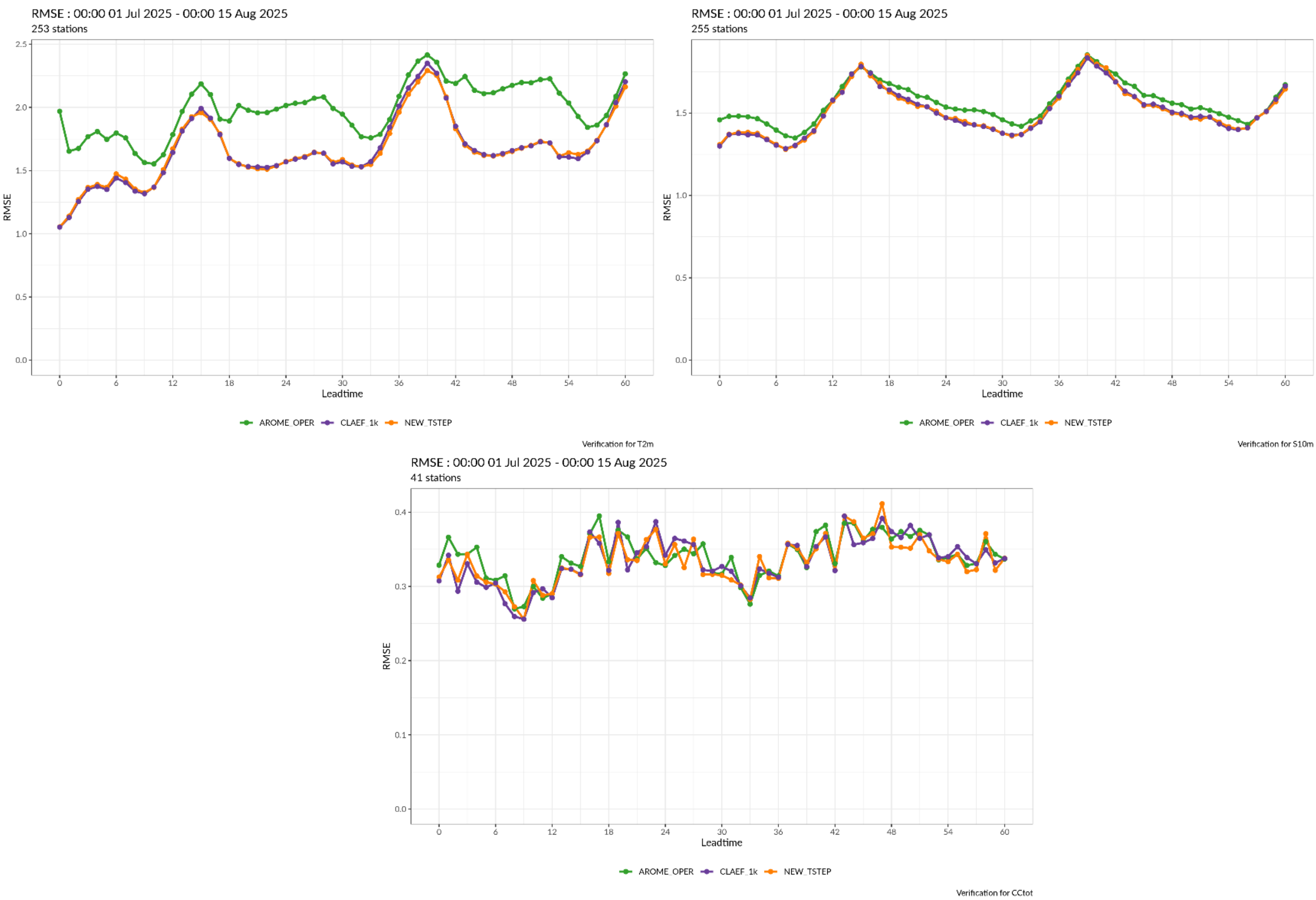


Figure 13: RMSE of T2m, S10m and total cloudiness for C-LAEF oper (2.5km, green), C-LAEF AA with tstep=45s (purple) and C-LAEF AA with tstep=60s (orange) for the summer test period July 1st – August 15th.

The scores in Figure 13 are based on the summer test period (July 1st – August 15th) and show hardly now score degradation in the 60s C-LAEF AA version (orange) compared to the 45s version (purple). The 3D data assimilation system of C-LAEF AA should be based completely on EnVar in the future. However, for the moment we still face some issues with EnVar (stability, bad scores for some situations, more details in S3) and therefore some more testing is necessary (see subject S3 and DA report). For the operational start of C-LAEF AA it is planned to use classical 3DVar.

- ❑ **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.

ARA is primarily based on dynamical downscaling of European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 dataset (with a spatial resolution of 31km) by applying "Application of Research to Operations at Mesoscale" (AROME) non-hydrostatic limited area model to a destination spatial resolution of 2.5km. With the aid of the three-dimensional variational assimilation (3DVAR) system in AROME and the Convection-permitting Limited Area Ensemble Forecasting system (C-LAEF), observations from multiple sources, such as, satellites, radiosondes, aircraft, wind profiler etc. are assimilated to reconstruct a ten member ensemble with spatially, temporally, and physically consistent 3D and 2D atmospheric fields.

In addition to enhanced spatial resolution this reanalysis provides essential climate variables (ECVs) that can be aggregated at hourly, sub-daily, daily, and monthly scale. Furthermore, an uncertainty estimate from the ensemble has been created and made publicly available. The application potential for this dataset is enormous.

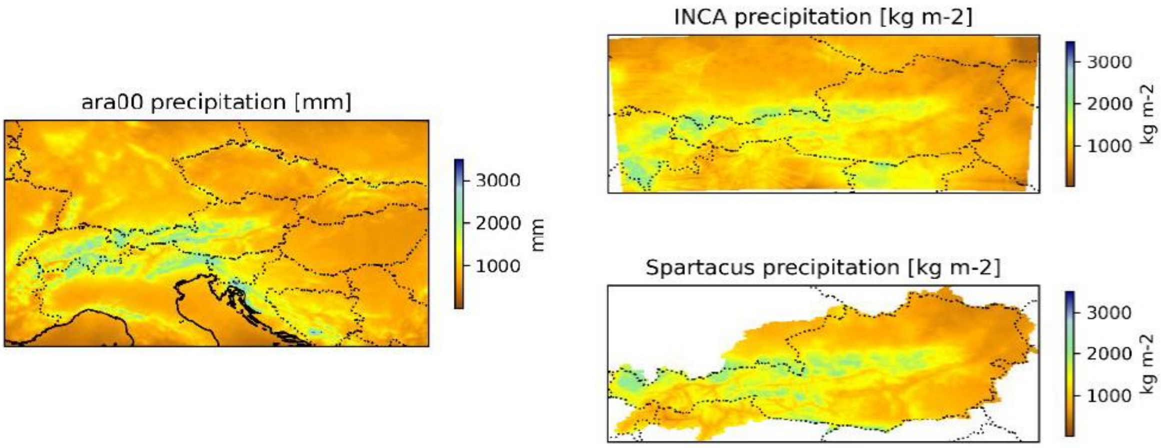
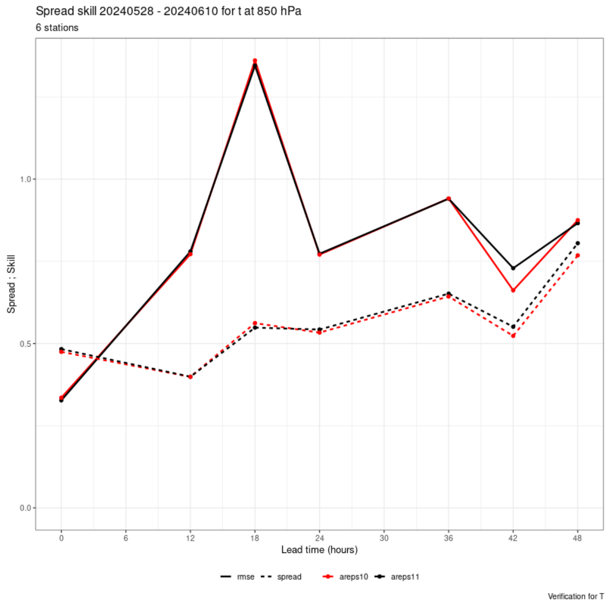


Figure 14: Evaluation of the ARA long-term accumulated precipitation climatology (left) against INCA analysis (upper panel) and SPARTACUS (lower panel).

The ARA dataset has been compared with two independent independent high-quality reference analyses:
INCA (Integrated Nowcasting through Comprehensive Analysis): A high-resolution, radar-gauge blended analysis system providing a accurate representation of observed precipitation.
SPARTACUS (Spatiotemporal Reanalysis Dataset for Climate in Austria): A in-situ observations based climatological analysis product, valued for its long-term consistency.
The comparison of annual mean temperatures shows that ARA is able to reproduce the large-scale climatological pattern reasonably well, with colder conditions over the Alps and warmer lowlands to the east. However, a systematic warm bias is evident for the high elevated regions. For precipitation (Figure 14), ARA demonstrates skill in replicating the correct spatial patterns of precipitation, including the location of maxima relative to topography and the spatial gradients between wet and dry regions. However, a systematic wet bias in the ARA model is observed.

- ❑ **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 on February 24th 2025. The operationalization of SPP in AROME-EPS has been postponed due to some personnel restructuring – Gabriella Nagy left HungaroMet in summer 2024 and the new colleague (Zsofia Szalkai) did start in January 2025 (for more details see S2). The Hungarian team studied the impact of 1 additional ensemble member in AROME-EPS. As the “HRES” forecast and the ensemble control forecast of ECMWF will be unified from November, also the deterministic AROME and the control forecast of AROME-EPS will be merged. This opens the possibility to add one more member to the ensemble using the same amount of the computing capacity (so to have 11+1 members in the future instead of the current 10+1 members). At the same time, the operational ensemble predictions in Hungary run using the full power of the operational HPC, 22 nodes in total (2 nodes per member). This kind of capacity distribution started to get vulnerable due to the recent amortization of the HPC and having 2 extra nodes for HPC problems would ensure more reliability. Therefore, the Hungarian team investigated with an experiment which strategy should be followed: to add one more member to the ensemble for better representation of the forecast uncertainty or to keep the 10+1 member to provide a slightly more safe environment for the operational runs.To judge the impact of involving one more member in the ensemble, the application of 11 versus 10 members has been compared in AROME-EPS for the period from 28th May to 10th June 2024. Differences between the results of the two sets were minor for the surface and for the upper level parameters (Figure 15) as well, the spread slightly increased in the 11-member version. As a conclusion it was decided that it is not worth to introduce one new EPS member, because it does not improve the performance of the ensemble significantly.



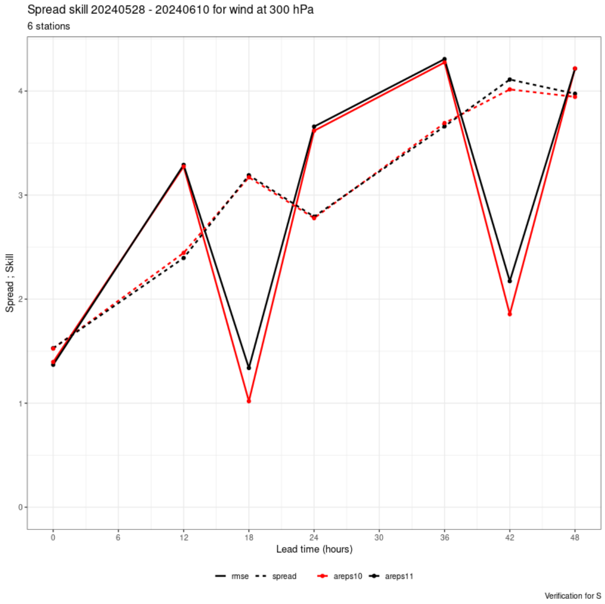


Figure 15: Ensemble spread and RMSE of ensemble mean for temperature (K) at 850 hPa (left) and for wind speed (m/s) at 300 hPa (right) for the AROME-EPS runs with 10 (red) and 11 members (black).

Efforts: 10.25 PM (planned 18.0 PM total in 2025)

Contributors: Martin Belluš (SHMU), Katalin Jávorné-Radnóczi and Zsófia Szalkai (HungaroMet), Clemens Wastl, Florian Weidle (GeoSphere Austria)

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 SHMU) – Development of an ALARO-based convection-permitting EPS coupled to A-LAEF
2. Martin Belluš (4 weeks at CHMI) – A-LAEF upgrade

Status: Ongoing, mostly 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 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 “stochastic perturbation of fluxes instead of tendencies” is delayed and it is not yet clear if it can be continued due to the leave of the main contributor Martin Bellus. Some work for the model error representation in A-LAEF has been spent on the upgrade of the ALARO-1 multi-physics clusters and on the implementation of a surface SPPT scheme in ISBA (see S1 for more details).

Main work in action S2 in 2025 has so far been spent on SPP in C-LAEF and AROME-EPS. While the scheme is already running operationally in Austria (since September 2023), it has been tested intensively in Hungary. It is planned to become operational in 2026 after some more tuning of the perturbation scales.

SPP has also been implemented to the new C-LAEF AA ensemble of Austria, Croatia and Slovenia on cy46t1. After some tuning of the perturbation scales to the 1km resolution it is now ready for operations. It is planned that the SPP perturbations should also be implemented to the dynamics part of the model – a first parameter (SLWIND) has been successfully tested. Within the DEODE project the SPP code has been phased to cy50.

The work on flow-dependent model perturbations has also proceeded very well in 2025. After implementing the code and testing it for some longer periods, a publication summarizing the results has been submitted to QJRMS in June 2025.

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

Endi Keresturi developed and implemented a flow dependent SPP scheme (FD-SPP) for C-LAEF during several stays in the past years. After testing the scheme for some case studies, he was running a complete C-LAEF ensemble for a winter (February 2024) and summer (June 2024) test period.

Results for February are generally positive (Figure 16). 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. Results for June are unexpectedly more neutral. Increase in spread is only visible for total cloudiness, while it is neutral for other variables. RMSE is decreased for wind speed and is neutral for other variables. CRPS is decreased for wind speed and slightly for total cloudiness. Bias is improved for wind speed and neutral for the other variables.

All the verification results have been summarized in a publication “Introducing a flow-dependent stochastically perturbed parameterizations scheme” which has been submitted to QJRMS in June 2025.

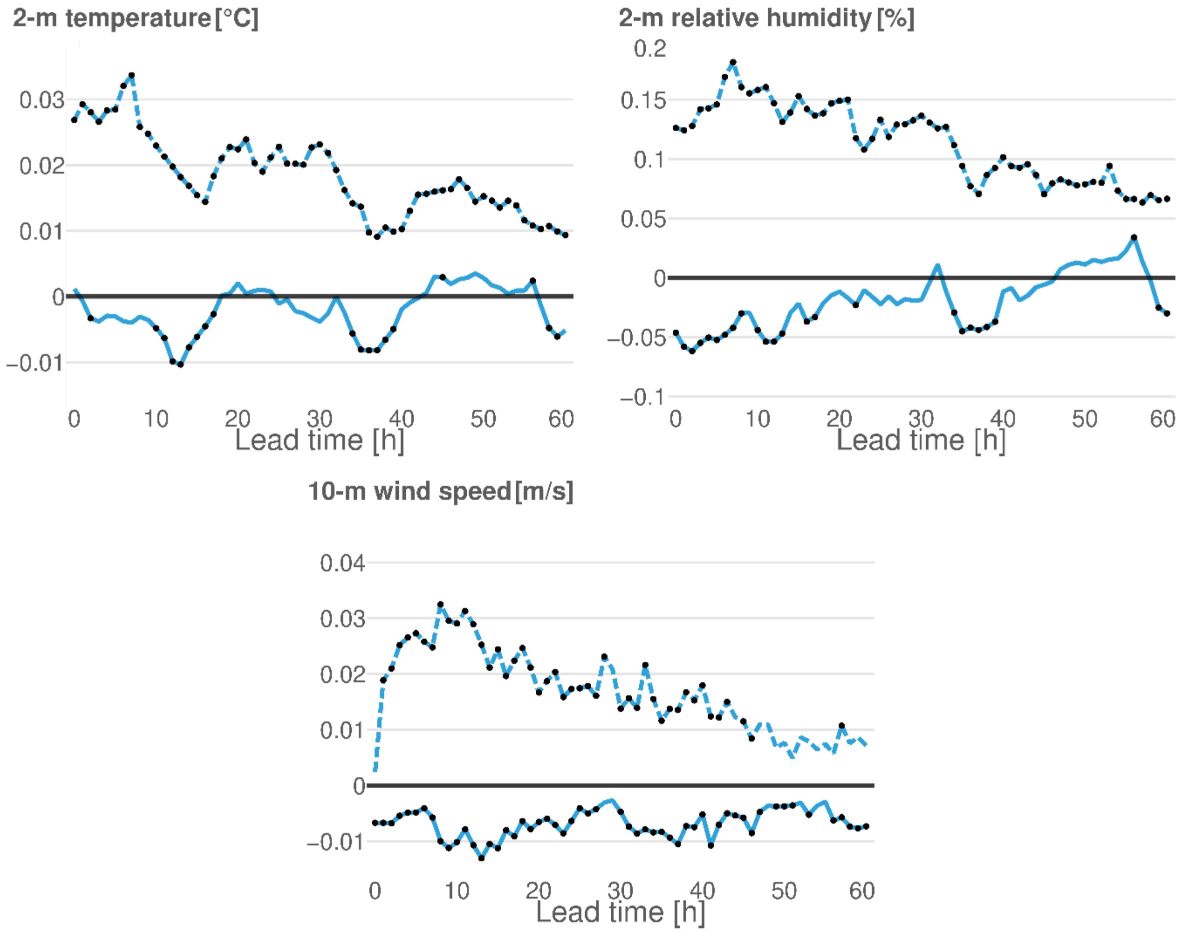


Figure 16: RMSE of the ensemble mean (solid) and spread (dashed) of flow dependent SPP relative to SPP for February 2024. Variable names are denoted above each subplot. Lead times with statistically significant differences are marked with black bullets.

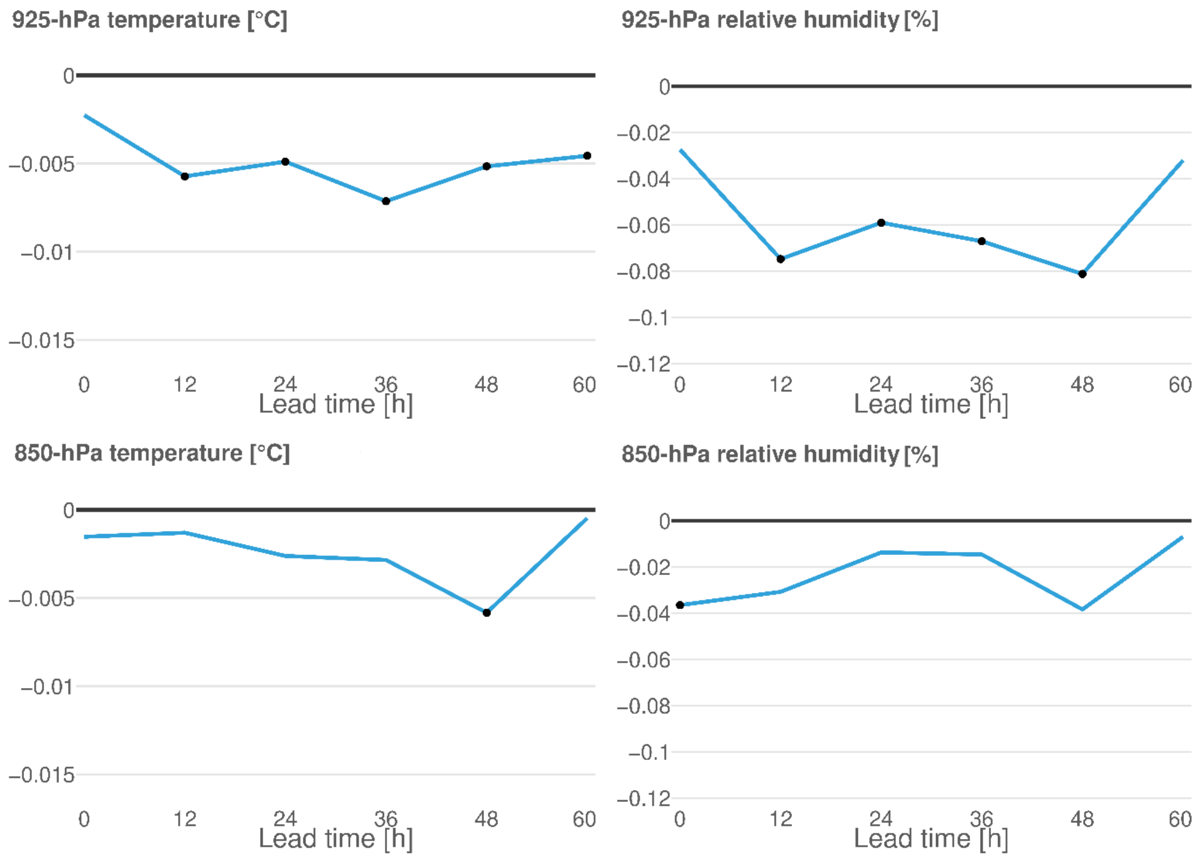


Figure 17: CRPS of FD-SPP relative to SPP for February 2024. Variable names are denoted above each subplot. Lead times with statistically significant differences are marked with black bullets.

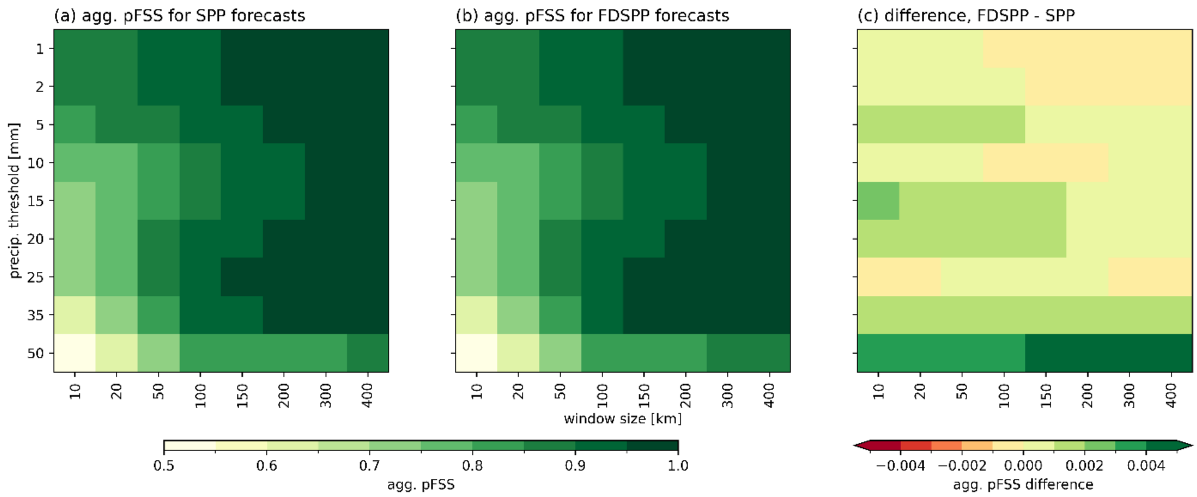


Figure 18: Monthly aggregated pFSS for (a) SPP, (b) FD-SPP and (c) FDSPP – SPP. Precipitation thresholds are shown on the y-axis, while neighbourhood sizes are shown on the x-axis.

❑ Topic 2: Implementation of model perturbations (SPP) in AROME-EPS

HungaroMet started in 2023 with testing Stochastically Perturbed Parametrizations (SPP) scheme on an experimental basis on selected parameters from the physical parametrization. After some tuning of the setup a winter and summer period have been calculated based on cycle 43t2.

In spring 2025, HungaroMet worked on a practical course with applied mathematician students of Loránd Eötvös University Budapest. The topic was to assess the impact of the individual perturbations of SPP parameters using AROME-EPS cy43t2 during a two weeks period in May/June 2024. Three parameters (Table 1) were perturbed one by one with SPP with seven ensemble members of each experiment set. The three parameters have been selected since they have a large effect on the meteorological variables (Wimmer et al., 2021). The experimental setup (resolution, domain, etc.) was the same as in the operational AROME-EPS. The two weeks have been chosen as it was an eventful time period with convective weather events. Results have been verified using Harp.

Table 1: The selected parameters for SPP perturbation

Parameter	Description	Effects on met. variables
VSIGQSAT	constant for subgrid condensation	precipitation, cloudiness, global radiation
XCED	constant for dissipation of turbulent kinetic energy	wind, precipitation, humidity, temperature
RCRIAUTC	rain autoconversion threshold	precipitation

The perturbation of XCED has not been successful, this indicates some errors in the program code. The perturbation of the two other parameters had the expected effects on meteorological variables, the forecast improved. This impact was larger than in the case when ten parameters were perturbed together (see the report for 2024). This may be attributed to the interaction between the parameters.

Taking the experiment with unperturbed XCED as a reference (no SPP, orange), we can notice in Figure 19 that the perturbations of VSIGQSAT (green) and RCRIAUTC (pink) have improved the CRPS values of the precipitation forecasts. The errors have a peak in the afternoons (at 15 and 39 hours lead times) caused by much precipitation accompanying an upper level cold vortex and the frontal zone of two cyclones (Figure 20).

The perturbation of VSIGQSAT and RCRIAUTC have improved the forecast, slightly reduced the RMSE values and increased the spread along the forecast range (Figure 21 for total cloud cover).

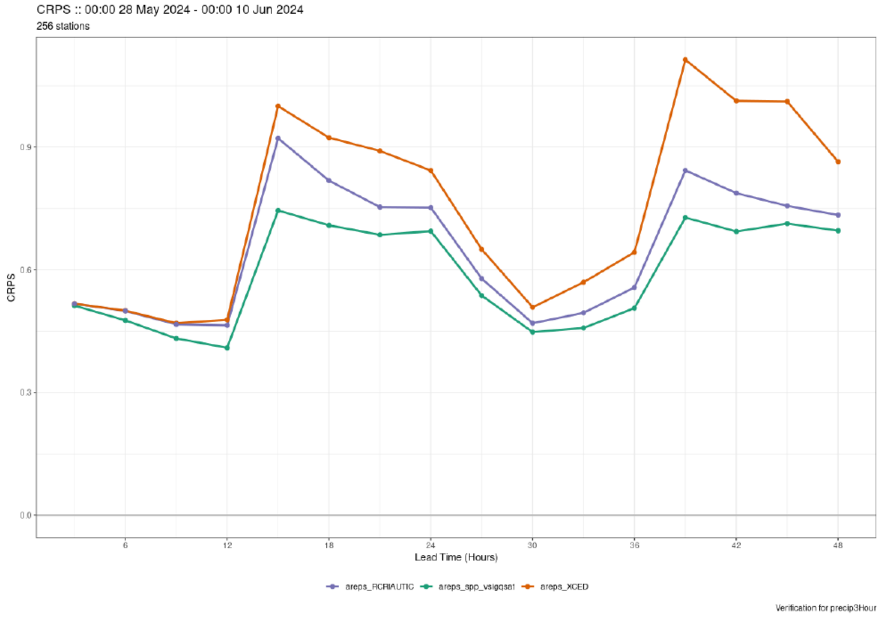


Figure 19: CRPS for the reference run without SPP (orange), the experiment with perturbed RCRIAUTC (pink) and VSIGQSAT (green) for 3h precipitation (mm) as a function of lead time (h) based on the 00 UTC AROME-EPS runs in the period from 28th May to 10th June 2024.

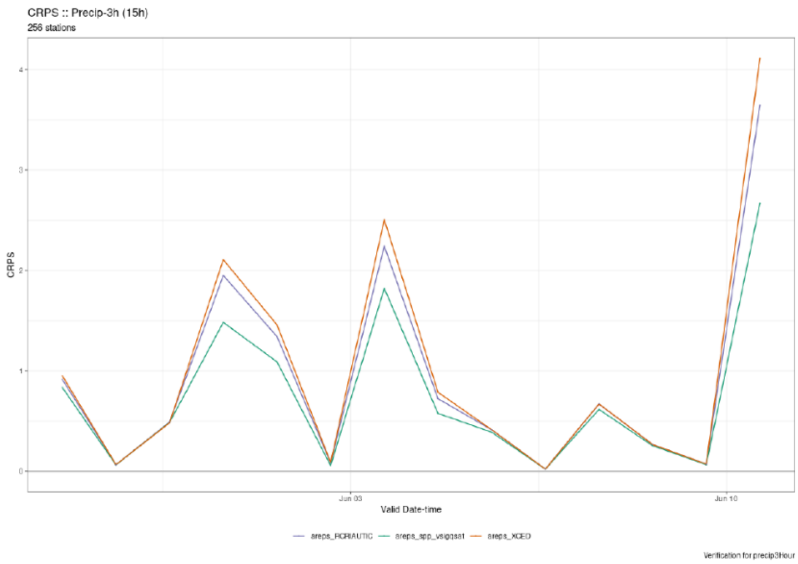


Figure 20: CRPS for the reference run without SPP (orange), the experiment with perturbed RCRIAUTC (pink) and VSIGQSAT (green) for 3h precipitation (mm) between 12 and 15 UTC as a function of validity time based on the 00 UTC AROME-EPS runs from 28th May to 10th June 2024.

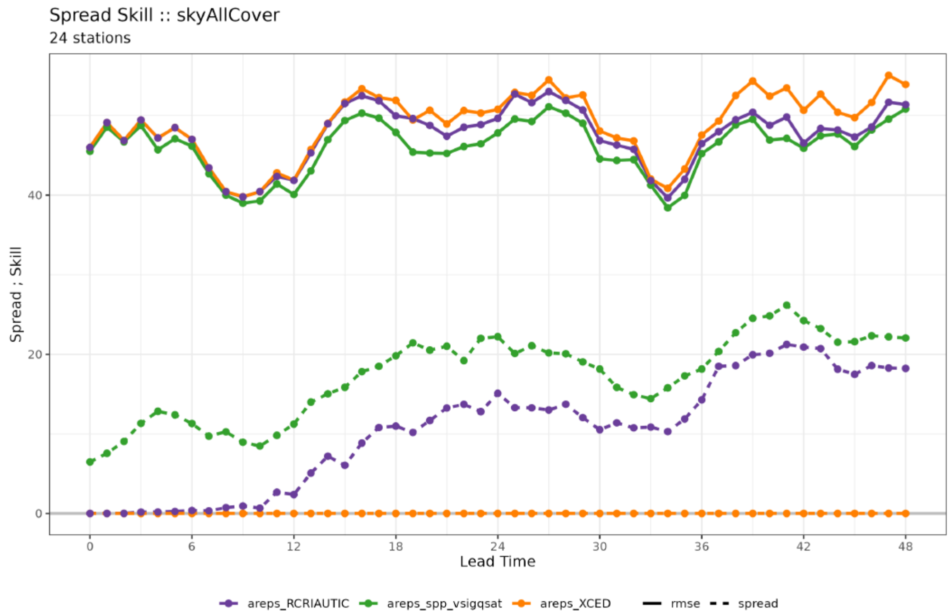


Figure 21: Ensemble spread and RMSE of ensemble mean for no SPP (orange), the experiment with perturbed RCRIAUTC (pink) and VSIGQSAT (green) for total cloud cover (%) as function of lead time (h) based on 00 UTC AROME-EPS runs in the period from 28th May to 10th June 2024. Note that there are only 24 stations with cloud cover measurements in Hungary.

The individual perturbations had a positive effect on the forecast of temperature, relative humidity, wind speed and global radiation. The improvement due to the perturbation of VSIGQSAT was higher, although it did not cure the U-shape of the rank histograms completely (Figure 22).

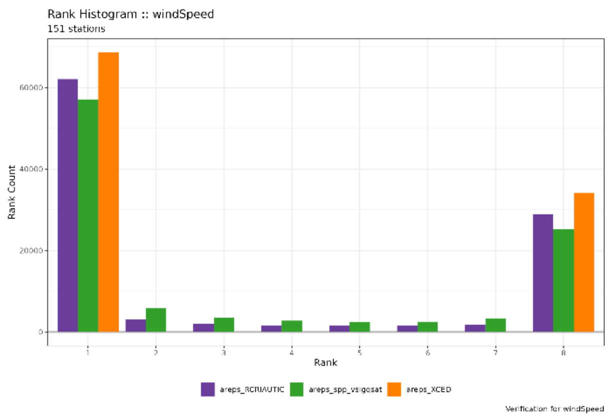


Figure 22: Rank histogram of 10 m wind speed for SPP (orange), the experiment with perturbed RCRIAUTC (pink) and VSIGQSAT (green) aggregated for all lead times based on 00 UTC AROME-EPS runs in the period from 28th May to 10th June 2024.

This analysis was based on AROME-EPS in cy43t2, but in February 2025 the operational AROME-EPS has been upgraded to cy46t1 (without model error representation). In a next step the SPP code has been phased to cy46t1 based on the version from GeoSphere Austria. A bug in the perturbation of the turbulence parameter XCTP has been fixed in that context. Some more testing and optimizations have to been made on SPP in AROME-EPS before it becomes operational.

Efforts: 8.5 PM (planned 6.0 PM in total in 2025)

Contributors: Martin Belluš (SHMU), Clemens Wastl (GeoSphere Austria), Endi Keresturi (DHMZ), Katalin Jávorné Radnóczi, 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

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 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.

The A-LAEF topic is delayed because of the leave of the main contributor Martin Bellus – it is unclear at the moment when this could be arranged.

For C-LAEF AA the work on EnVar is currently ongoing. An Envar member has been introduced to the C-LAEF AA system with the winter test period in January/February 2025. This member is continuously running since then and is verified using HARP. The statistical scores are quite good (Figure 23, 24), but we encountered some stability issues due to observation perturbations. Therefore, the inflation factor had to be increased (less weight to observations). For some selected cases, the EnVar member did not perform pretty well which has to be investigated in more detail. Nevertheless, the long-term goal is that EnVar will replace the classical 3Dvar in C-LAEF AA in the future. The work on EnVar in C-LAEF AA is a joint cooperation between Austria and Slovenia, more details on that work can be found in the data assimilation report.

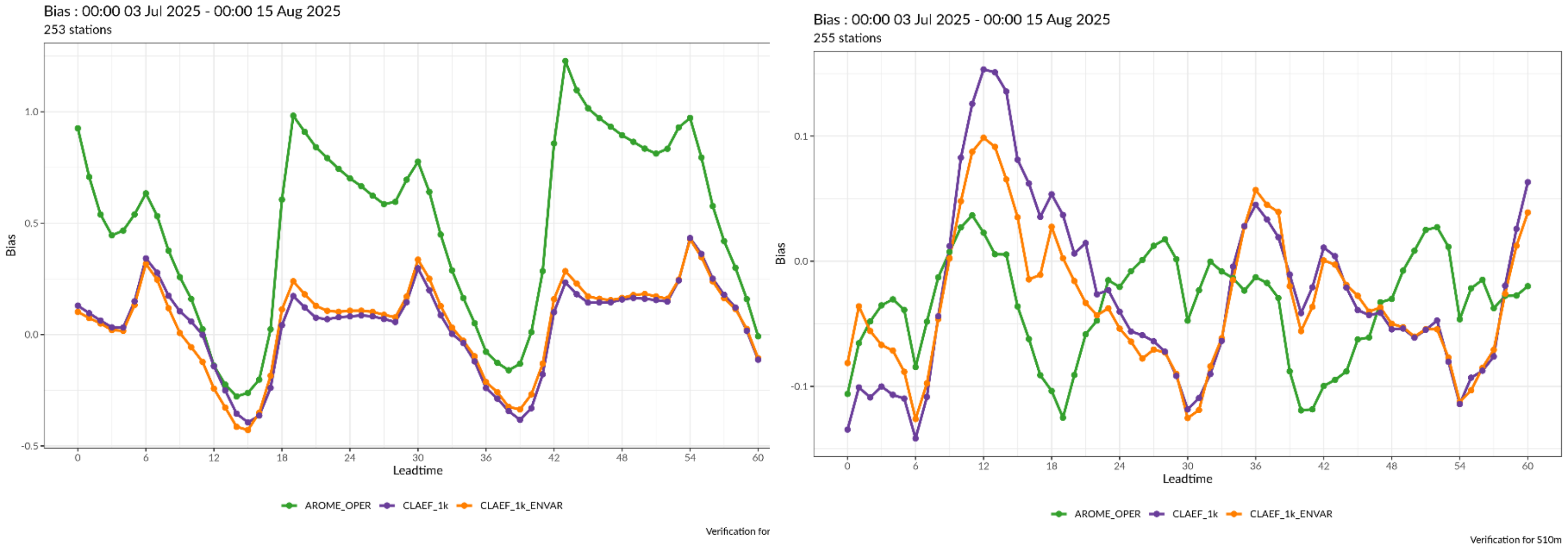
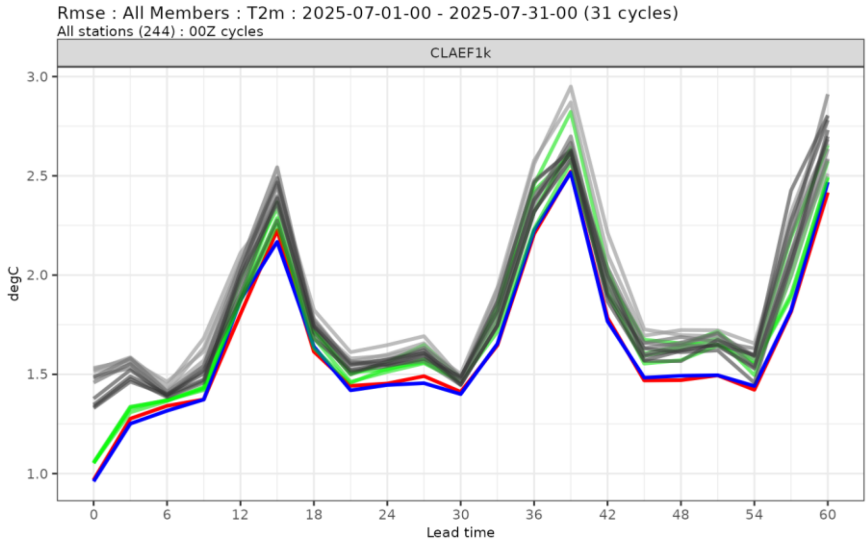


Figure 23: BIAS of 2m temperature (left) and 10m wind speed (right) of C-LAEF 2.5km (green), C-LAEF AA (purple) and C-LAEF AA with EnVar (orange) for the summer test period in 2025.



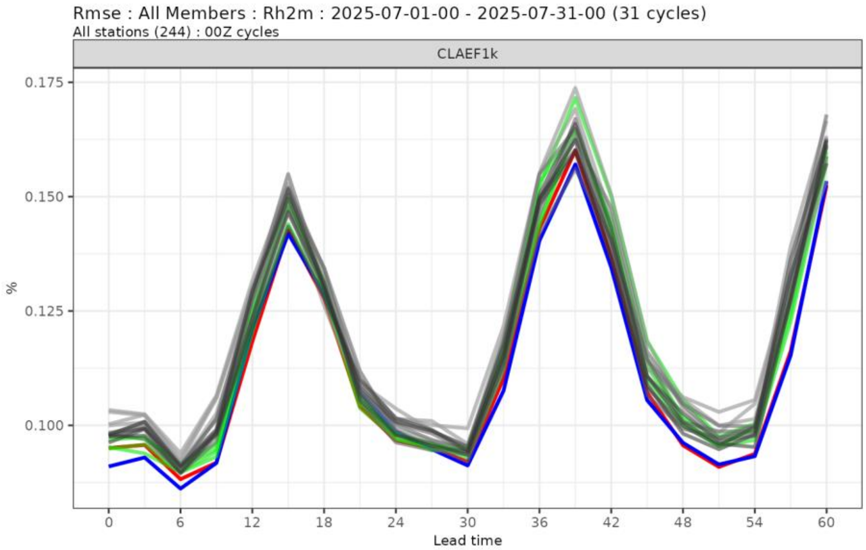


Figure 24: RMSE of T2m and Rh2m for all C-LAEF AA members. Ctrl in red, Envar in blue, „real“ members in green, lagged members in gray.

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

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, HungaroMet); EPS documentation

Planned stays:

Status: Ongoing. Delay because of leave of Martin Bellus.

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 implemented to the new C-LAEF AA system. Hungary is planning to add such a scheme into their AROME-EPS system in 2026.

The focus in the future will be put on implementing SPP perturbations to SURFEX, as it is already tested in ACCORD.

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

Contributors: Clemens Wastl, Daniel Deacu (GeoSphere Austria), Zsofia 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 has already been tested technically in the past with 903. Within the DEODE project an ALARO based mini EPS has been set up on the ECMWF HPC Atos, coupled with ECMWF ENS. It consists of 6 perturbed + 1 unperturbed control and is run on a Slovakian domain with 750m grid resolution. The system has already been tested successfully for several case studies in 2024 and 2025. The next step is to couple this ALARO EPS with the A-LAEF system.

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

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 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: focus on solar radiation and wind
- 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 become increasingly important in recent years with new technologies and artificial intelligence (AI). Several countries in LACE are working in that area. Croatia has switched the focus from analog based wind speed post-processing to irradiance nowcasting with AI (SHADEcast model). Prediction of solar radiation is a topic where also Austria (Multivariate Spatio-Temporal Neighbourhood Ensemble Method) and Hungary (AROME-EPS, EMOS) are involved. GeoSphere Austria is also working on the generation of ensemble members by deep learning algorithms.

Poland has continued the work on 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 statistical post-processing of EPS data

HungaroMet continued to tune the AROME-EPS EMOS postprocessing using data from groups of similar stations. The work is motivated by the fact that in the operational version of EMOS, data from different parts of Hungary are used together, and consequently the improving effect of the postprocessing is not optimal (sufficient) for all stations. The aim is to provide post-processed forecasts for any selected location that improve the CRPS score of the raw EPS as much as possible. To achieve this, the observation stations were classified considering their certain properties and chose "similar ones" for the (regional) EMOS runs. Similarity was quantified based on model error (CRPS) characteristics, incoming solar radiation climatologies (derived from observation data) or geographical distance, based on Lerch and Baran (2017).

A meteorologist student has been involved in the work to make experiments for the period of August to October 2023, involving radiation measurements from a private company for more than 100 stations, besides 35 HungaroMet stations. The test period was chosen because of the availability of the partner´s measurements and the large differences between measured and forecasted photovoltaic electricity production. Test experiments were run for three target locations to improve the CRPS characteristics. Because the partner´s pyranometers are tilted to the south, the data was recalculated to the horizontal plane, using the position of the sun, and empirical correlation between the diffuse fraction of radiation and sky clearness index.

Using data of “similar” stations (based on model error characteristics) in EMOS can improve the performance of the EMOS method significantly for a target station with respect to the other operational configuration. Partner measurements (i.e. from a private company) were only involved in tests based on geographical distance. Their involvement does not necessarily improve CRPS. In addition, when focusing only on the first day of the forecast, a seven days shorter (i.e. 24-day) training period and/or using more stations’ data, could also improve the postprocessing performance for most target stations. An example can be seen in Figure 25, which shows CRPS and bias for Sármellék (located near the Lake Balaton). In this case the weakest scores belong to 6 additional (5 partner and one HungaroMet), geographically nearest stations and 31 days training period, while the best one are produced using data of 8 similar (based on error-metrics similarity) HungaroMet stations, with 24 days training period. Average improvement for this station with respect to CRPS of the raw EPS was 5.2% in the former, and 16.6% in the latter case. It is planned to continue the work with testing the method involving more stations and a more recent period.

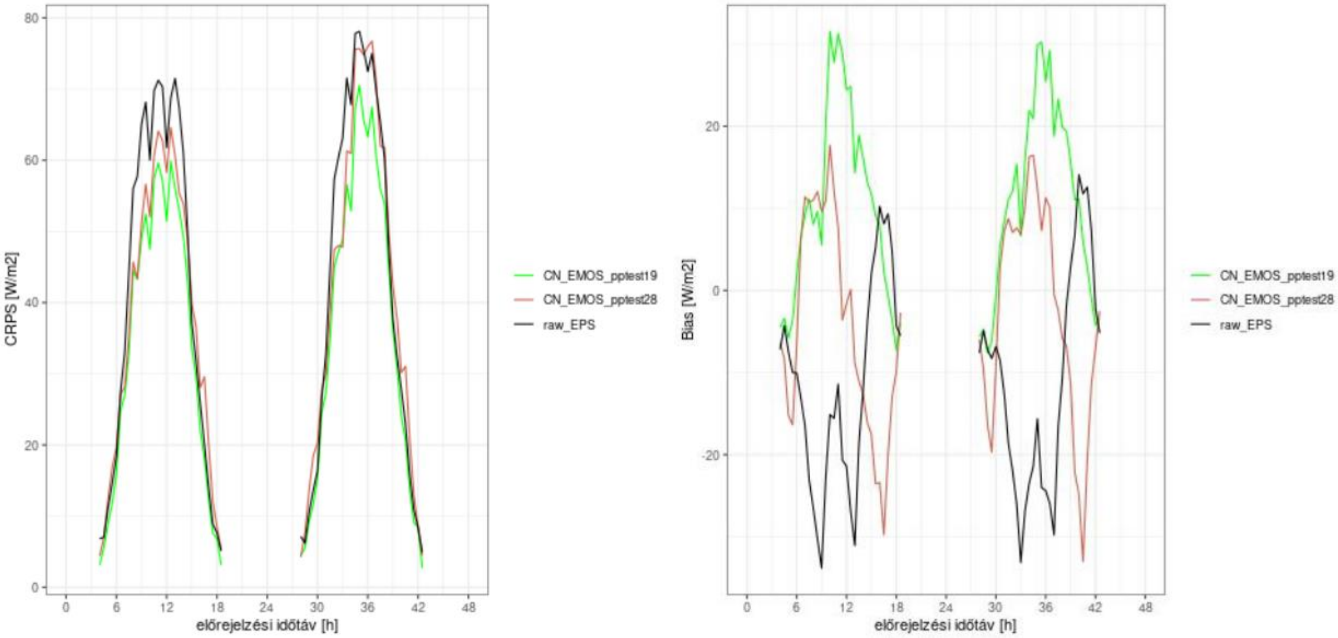


Figure 25: CRPS (left) and bias (both in W/m2) (right) of radiation ensemble.

- ❑ **Topic 2: Work on EPS post-processing by different machine learning (ML) methods: focus on solar radiation and wind**

Iris Odak went for a stay to GeoSphere Austria in spring 2025 (April 14th – May 17th) to gain some expertise on nowcasting with AI methods. The focus of this stay has been switched from wind speed post-processing (several stay reports in the past years on analog based wind post processing) to irradiance nowcasting with AI. As a first step, 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 PyTorchmodulesand 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.

The expected use is, of course, wider and should include NWP data. 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.

Another stay on that area is planned for autumn 2025 (Ivan Vujec) at GeoSphere Austria dealing with NWP postprocessing using neural networks.

Also at GeoSphere Austria a lot of work is ongoing in the area of AI. Within the EnergAIze project climate and weather models have been combined with physics-informed AI to tackle challenges in the energy transition. A critical component of this work is the development of 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 renewable energy meteorological applications. The core builds the dynamically and empirical-statistical downscaled cases, which are enhanced by 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, the multi-model ensemble and a more AI-enhanced ensemble generation method, "ensemble generation #1" are included. Ensemble datasets generated within EnergAIze are built upon downscaled simulations from CMIP6 historical runs using COSMO, and WRF, as well as EPISODES (using CERRA as target dataset), enhanced through a multi-parameter spatio-temporal neighborhood ensemble method. These datasets are designed to serve diverse renewable energy applications across wind, solar, and hydropower use cases under historical and future climate conditions. To ensure their utility, representativeness, and transferability, a standardized set of meteorological parameters is required. These parameters fall into three primary categories:

Core Atmospheric Variables – essential for representing physical conditions across spatial and temporal scales.

Energy-Relevant Derived Variables – tailored specifically to energy system needs.

Metadata and Configuration Information – supporting transparency, reproducibility, and quality control.

The work builds upon statistical ensemble generation methods, regional climate model ensembles, and the ML-based ensemble generator to create a comprehensive multi-method approach suitable for both research and operational applications.

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 interference has been tested. The model itself is trained as 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.

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

IMGW in Poland has continued the work on the new ensemble technology CEM (Cascading Ensemble Method). CEM is adding new members of any type of ensemble forecasts, not at the beginning of the forecast as it is usually done, but during the computations of forecasts, 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. It can forecast 20 atmospheric variables, 5 of which are on the surface level. Timestep between each forecast is 6 hours, with a 0.25° spatial resolution, and the result is a 720x1440 grid point map of predicted values for each variable. The model used recently is a modified version of FourCastNet, installed on the ACK Cyfronet computing center supercomputer Athena. We create an ensemble forecast, and the number of ensembles rises 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 (here called ENS) were evaluated with CEM by running a month of forecasts using Nvidia's AI-driven global model FourCastNet (0.25 x 0.25 degree grid) and then comparing them to global data from WMO synoptic stations. The testing period was January 2023, with each run starting at 00:00 UTC and lasting 120 hours or 20 timesteps. CEM has the ensemble count increase from 1 to 256, doubling up until timestep 8. In ENS, the model maintains the same number of ensembles through the entire forecast (256 ensembles). Two variables were chosen for consideration: air temperature at 2m height (for which the graphics are presented here), and pressure at sea level.

The results in Figure 26 show that the CEM method has consistently rising spread values throughout the entire run, resulting in spread bigger than ENS for every timestep but the first. For bias and RMSE the most notable difference is the varying amplitudes between the methods. Errors are most likely tied to the diurnal cycle of the variable. For example, bias reaches maximum around local noon and minimum around local 6 am (Figure 27). The amplitude of values is larger for the ENS method, while for CEM the diurnal cycle of the errors has less extreme oscillations and the run smooths out over time, which leads to the difference between methods growing between timesteps. CRPS sees a great difference in growth between the methods (Figure 27). The ENS run has rapid growth for the first 6 timesteps before slowing down. For CEM, the values grow slowly and consistently without the initial jump, leading to a much lower CRPS overall.

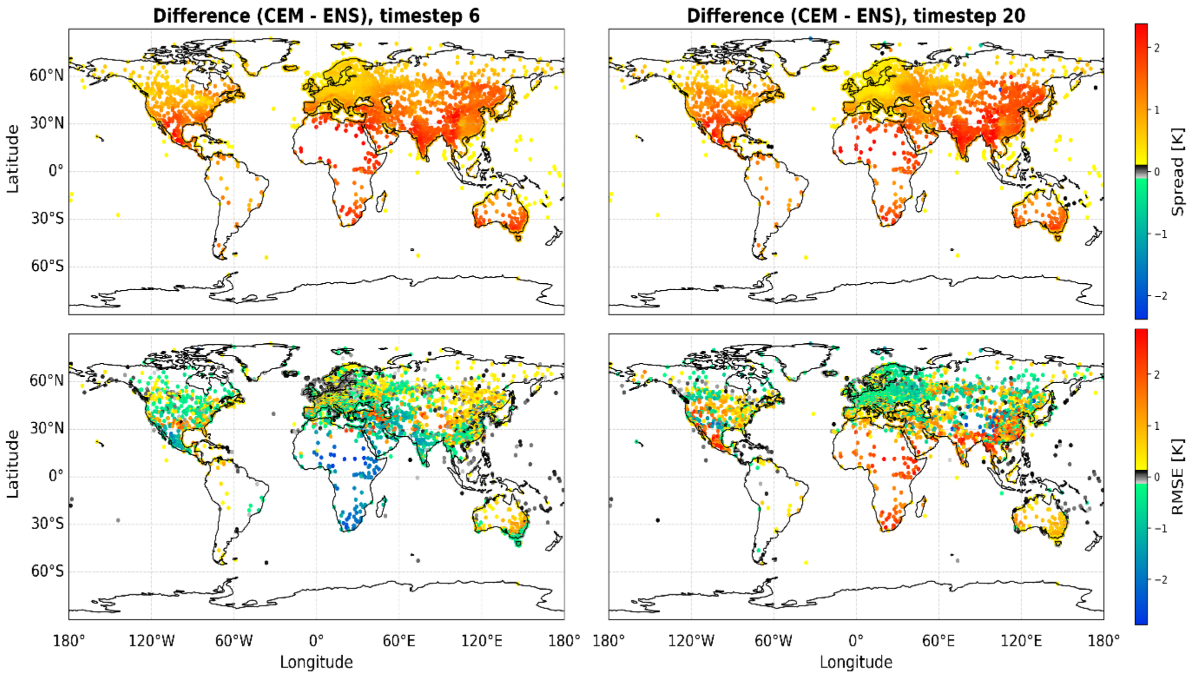


Figure 26: Difference maps of both methods for spread and RMSE.

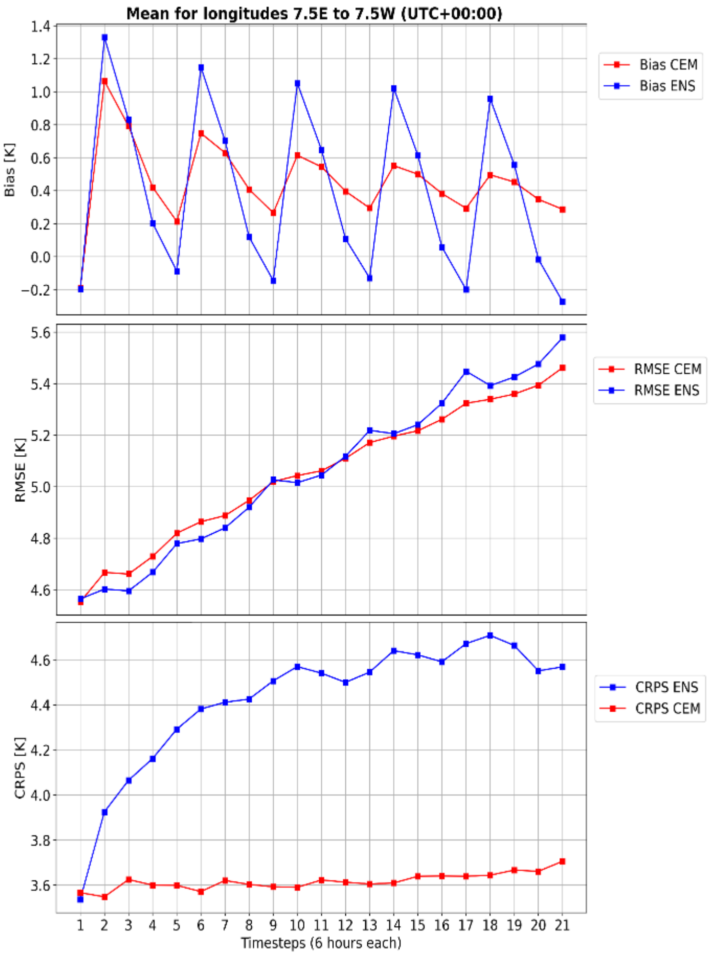


Figure 27: Mean bias, RMSE and CRPS progression through timesteps for a 15 deg wide area.

Efforts: 7.5 PM (planned 12.0 PM in total in 2025)

Contributors: Iris Odak, Ivan Vujec (DHMZ), Alexander Kann, Irene Schicker (GeoSphere Austria), Katalin Jávorné-Radnóczi (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

Publications

E. Keresturi, C. Wastl, P. Scheffknecht, F. Weidle, C. Wittmann, 2025: Introducing a flow-dependent stochastically perturbed parameterizations scheme, submitted to QJRMS.

M. Šinger, M. Belluš, L. Méri, 2025: Floods in September 2024 – Part 1: Synoptic and mesoscale analysis using global, regional and sub-kilometric ensemble forecasting systems, Meteorologický časopis, 28/2025-1, Doi: 10.62699/mj28.1x.38

G. Szalontainé, B. Tóth, G. Szépszó, D. Lancz, K. Jávorné Radnóczi, L. Magyar, H. Tóth, S. Oláh, D. Tajti, 2025: Implementation of AROME/HU cy46t1 model version with modified town fraction. ACCORD Newsletter 7, 16-22.

RC LACE supported stays – 1 PM in first half of 2025

Until now (September 2025) only one stay has been realized in 2025 in the EPS area of RC LACE: The stay of Iris Odak (4 weeks at GeoSphere Austria, April 14th – May 17th) on ML based post-processing methods. Two stays are planned for autumn 2025 at GeoSphere Austria: Ivan Vujec should work on NWP postprocessing using neural networks and Endi Keresturi should continue with flow dependent SPP in C-LAEF AA.

The stay of Martin Bellus can not be realized because of his leave from SMHU in July 2025. Furthermore, the planned stay of Jadwiga RóG at SHMU to work on an ALARO-based convection-permitting EPS coupled to A-LAEF is also questioned because of this reason.

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

Subject	Manpower		RC LACE		ACCORD	
	plan	realized	plan	realized	plan	realized
S1: Preparation, evolution and migration	18	10.25	2	0	0	0
S2: Model perturbations	6	8.5	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	7.5	2	1	0	0
Total:	38	26.75	5	1	0	0

References

Lerch, S. and Baran, S. (2017): Similarity-based semilocal estimation of postprocessing models. Appl. Statist. 66, Part 1, 29–51

Wimmer, M., Raynaud, L., Descamps, L., Berre, L. and Seity, Y. (2022): Sensitivity analysis of the convective-scale AROME model to physical and dynamical parameters. Quarterly Journal of the Royal Meteorological Society, 148, 920–942.