Working Area Predictability

Progress Report

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Period:	Jan – Jun 2024
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Progress summary

The three ensemble prediction systems currently operated in RC LACE (A-LAEF, C-LAEF, AROME-EPS) are running smoothly and provide probabilistic information to forecasters and users in all RC LACE countries. They have shown a strong additional benefit during several severe weather situations in this year.
No major upgrades have been made so far in 2024, but new and improved systems are currently in test phase. For A-LAEF an upgrade from cy40t1 to cy46t1 is planned for the end of the year, C-LAEF and AROME-EPS are intended to be upgraded to newer versions in 2025. The A-LAEF upgrade also includes a new upper-air spectral blending method and an upgraded version of the multiphysics package. The switch of the C-LAEF system to its successor C-LAEF1k comprises beside an upgrade in the model cycle (cy43t2 to cy46t1) also an increase of the horizontal resolution from 2.5km to 1km and some substantial improvements in data assimilation (new observation types, EnVar), model error representation (new SPP, flow dependency), dynamics setup and post processing (grib2). An Esuite of C-LAEF 1k has been successfully tested during a winter and summer test period and verification scores are very promising. Slovenia and Croatia have decided to join the C-LAEF1k project by contributing SBUs and manpower. Further expansions of C-LAEF 1k (more long runs, longer leadtimes, more members) are planned in the near future by running in a continuous lagged ensemble mode.

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

A lot of people working in the EPS area of RC LACE are also involved in phase II of the Destination Earth project of the European Commission where on-demand configurable digital twin engines for forecasting of environmental extremes at the sub-km scale are planned (DEODE). With this project we might enter the hectometric scale with our ensemble systems.

Scientific and technical main activities and achievements, major events

S1 Subject: Preparation, evolution and migration

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

The originally planned topics for 2024 were:

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

The operational suites on the ECMWF HPC in Bologna (A-LAEF and C-LAEF) are generally running very smoothly and stable. No big operational upgrades have been made so far in 2024, 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, upgrade of multiphysics, etc.) has been setup and tested for some case events. For C-LAEF a complete 1km ensemble has been running for a winter (December 2023 - January 2024) and summer period (June – September 2024). Intensive verification showed a general quite good performance, but also some deficiencies (e.g. too less convection over mountainous areas) have been found which resulted in some adaptations in the dynamics setup. Intensive cooperation between the RC LACE countries Austria, Slovenia and Croatia has been initiated with the scope of a common C-LAEF 1k system in the future.

First tests have also been made with an upgraded ALARO-EPS system at 1km coupled in the A-LAEF system.

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

C-LAEF for Turkey is running continuously on Atos since March 2024, but it has not yet been shared with the forecaster. The performance is currently verified and it is expected to become operational at the end of 2024. The model resolution is 1.7 km with 72 vertical levels, a lead time of 24 hours and the domain is the same as for the operational AROME model.

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

The operational AROME-EPS system has not undergone any upgrade in 2024 so far but it is planned to go for cy46t1 at the beginning of 2025 together with an introduction of model perturbations (SPP).

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

No major upgrades have been made for A-LAEF so far in 2024, only some minor changes have been made - e.g. ECPDS dissemination via fast Slovak Academic Network SANET => speed up by a factor of 6-8). A-LAEF data have also been prepared for Kempelen Institute of Intelligent Technologies (KInIT) for the period 2022-2024 as training data for AI/ML app development. Currently, a lot of testing with the new cy46t1 version of A-LAEF is ongoing.

New ALARO-1 physics clusters for A-LAEF cy46t1:

An upgrade of A-LAEF multiphysics at cy46t1 has been tested during a 2-week RC LACE stay of Martin Bellus (supervised by Jan Mašek) in Prague from 7 to 19 January 2024. Four different physics clusters (Figures 1 and 2) for the A-LAEF system based on the latest ALARO-1 development at model cycle cy46t1 have been set up and tested. It must be noted that a substantial part of this code is generally not available in the cy46t1 export version (nor in the later bugfixes). It includes some add-ons back-phased from newer cycles cy48t3 and cy49t1. New physics clusters have also been successfully combined with the stochastic perturbation of the physics tendencies for ISBA surface prognostic fields. This code has been locally phased to the cy46t1 as well. Such configuration is capable of producing qualitatively comparable results to those of the operational version (for tested cases). Moreover, it provides new interesting diagnostic fields and should also offer better physics. Apart from the case studies, it is expected to carry out a more complex comparison of statistical scores for the new system vs the old one, for a reasonably long verification period (however, this might be difficult due to the computational costs and limited SBUs for research). After the finalization of the upgrade of all A-LAEF components (e.g. ESDA, post-processing), the new system should become operational in Q3/2024.

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

Validation of EL0 vs EL1 mixing length parameterization

Two versions of the mixing length parameterization and PBL height computation have been implemented and validated in an A-LAEF Esuite on CY46T1 on Atos at ECMWF (Figure 3). EL0 mixing length computation (Geleyn-Cedilnik) with the PBL height calculations using weak capping inversion method and EL1 mixing length computation (revised Bougeault-Lacarrère with the inclusion of a shear member) with the PBL height computation based on vertical profile of TKE.

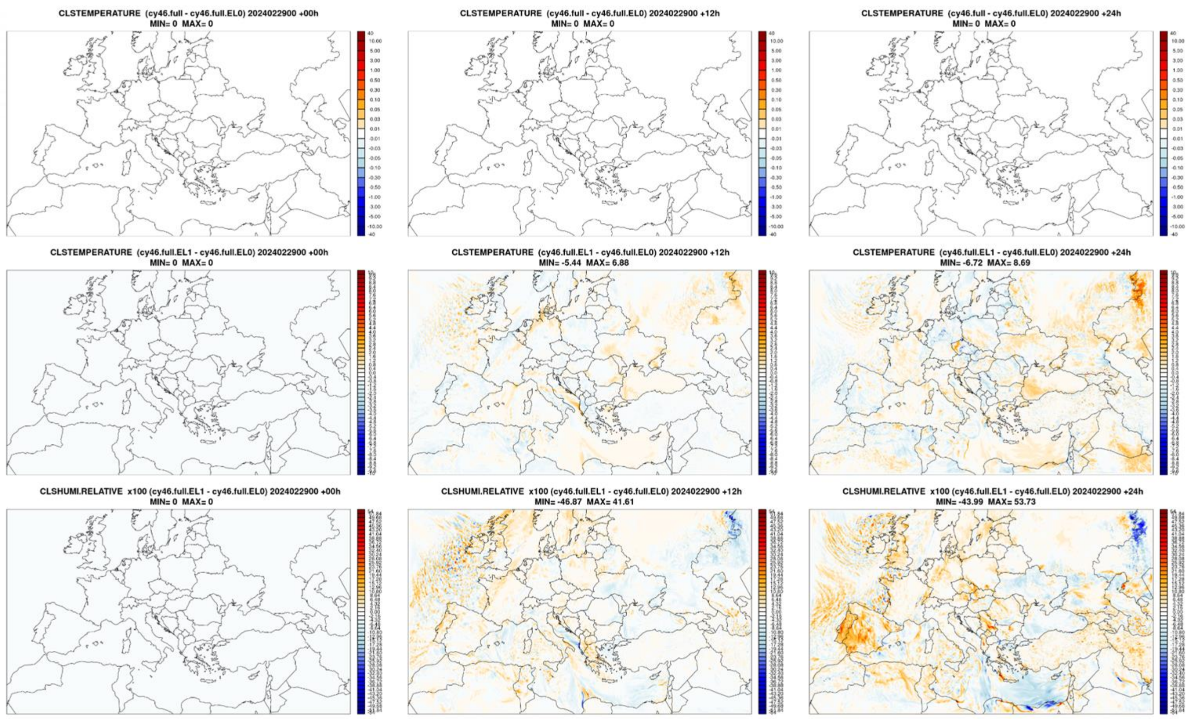


Figure 3: Validation of code changes (first row for temperature) and sensitivity tests (second row for temperature and third row for 2m relative humidity) of EL0 and EL1 mixing length parameterizations in A-ALEF cy46t1 for a test case in February 2024.

Figure 3 shows validation results of the code upgrade in A-LAEF CY46T1. The first row shows that the code upgrade works properly – no differences in 2m temperature when EL0 is activated in both experiments. When E1 is activated the differences in 2m temperature (second row) and 2m relative humidity (third row) are increasing with lead time.

Validation of Esuite (CY46t1+) vs operational A-LAEF system (CY40t1)

The operational A-LAEF suite is still running on cy40t1 – the planned upgrade to cy43t2 or cy46t1 has been postponed in the past years several times due to missing resources. In the first half of 2024 a cy46t1 Esuite of A-LAEF has been set up on the ECMWF HPC. The performance of the system has been analyzed for several case studies showing a quite good forecast quality (Figures 4 and 5). The implementation of a full A-LAEF CY46T1+ parallel suite under the new TC user zla2@Atos/ECMWF has not yet been finished – there is still an issue within the assimilation cycle for c701 in AN mode while QC step works well.

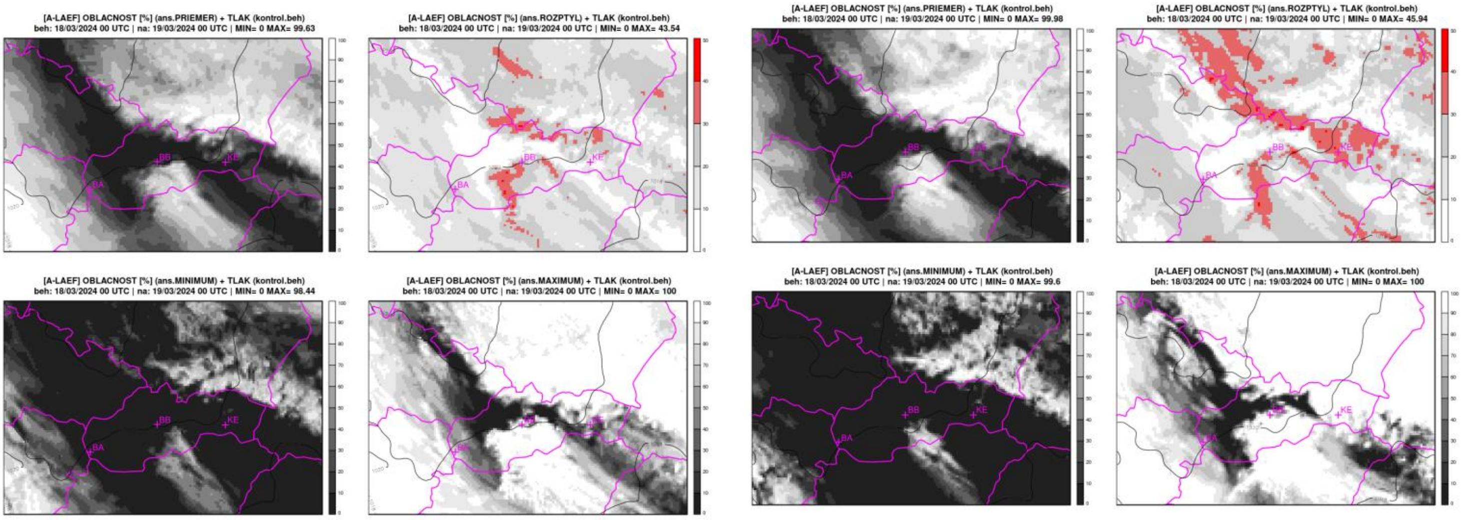


Figure 4: EPS mean, spread, min, max of total cloudiness based on March 18 2024 00 UTC run (+24h) for cy40t1 (left) and cy46t1 (right).

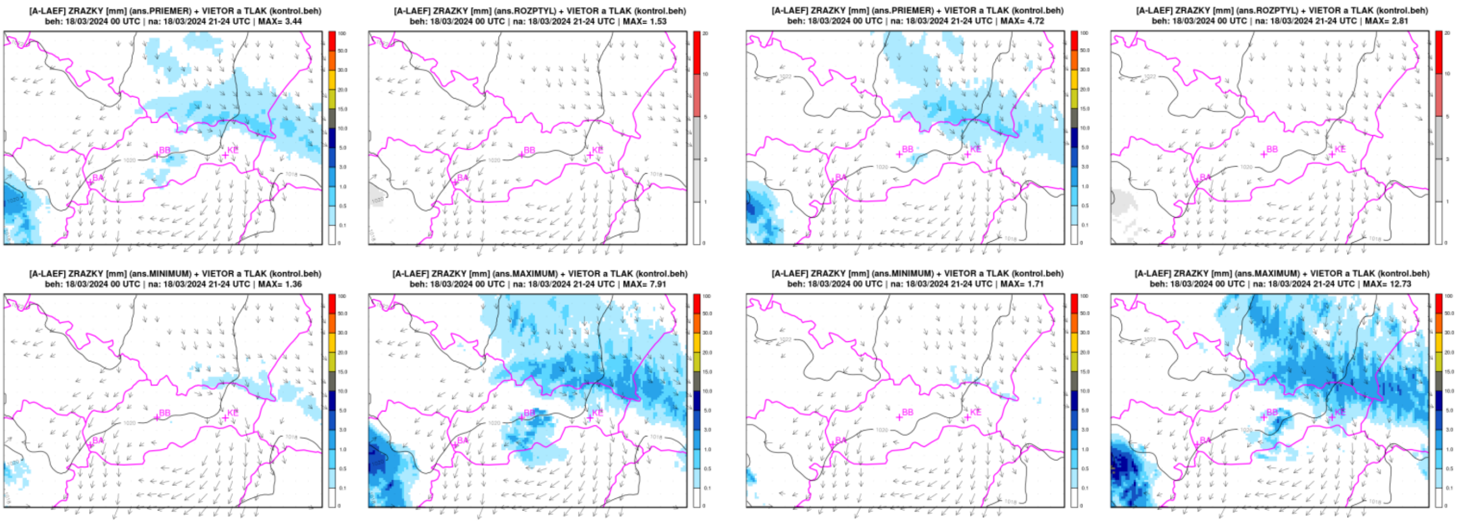


Figure 5: EPS mean, spread, min, max of 3h accumulated precipitation (+21h to +24h) based on March 18 2024 00 UTC run for cy40t1 (left) and cy46t1 (right).

- **Topic 2: Development of an ALARO-based convection-permitting EPS coupled to the regional ensemble A-LAEF**

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

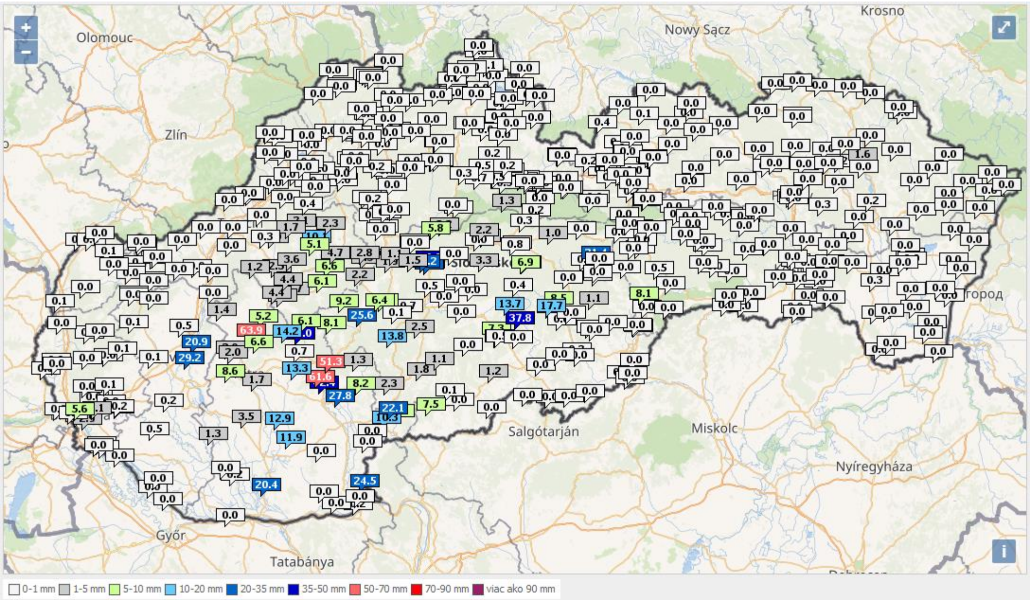


Figure 6: 24h precipitation measurements from all Slovak rain gauge stations on August 20, 2024.

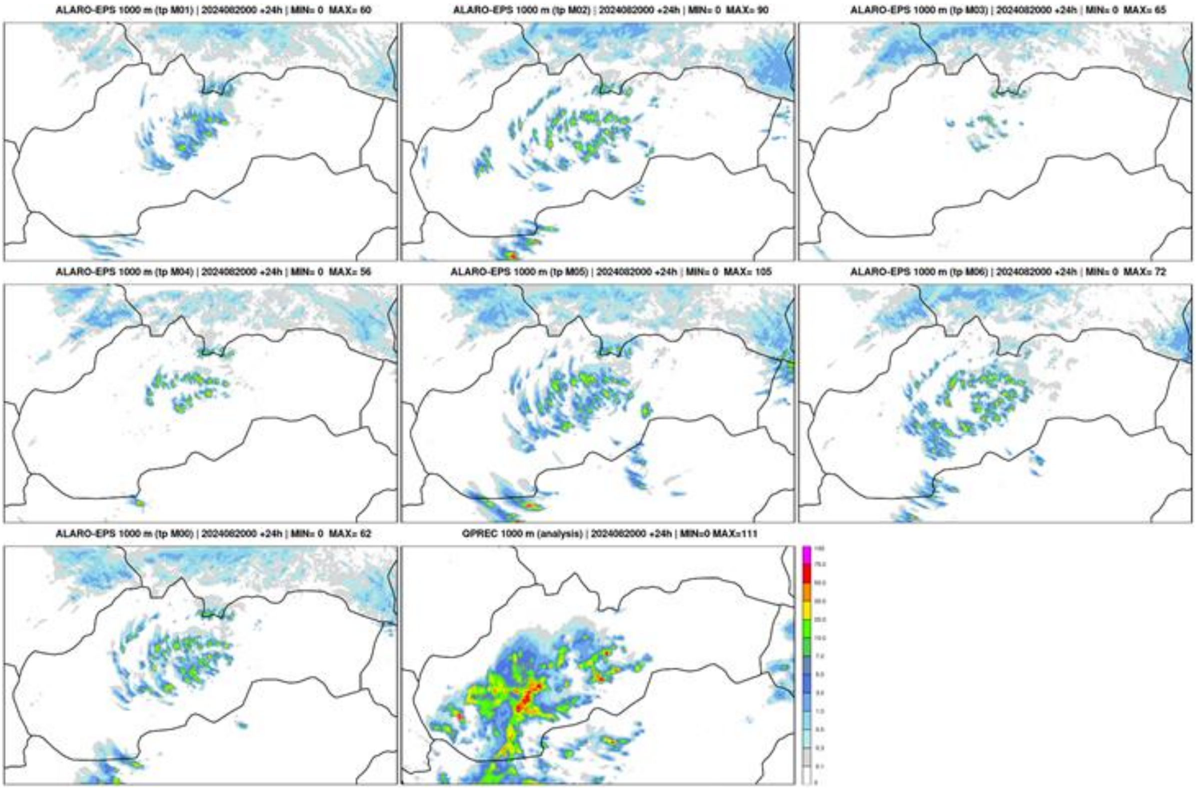


Figure 7: 24h accumulated precipitation for six perturbed ALARO-EPS members, along with one control run, and corresponding QPREC analysis based on Slovak RADAR and WS networks on August 20, 2024.

It has been tested for several case studies - as an example results of a severe weather situation at August 20, 2024 (when intense thunderstorms formed and moved across Slovakia) is shown in Figures 6 and 7. It was a relatively complex scenario, with storms spreading in a cascade due to outflows from earlier cells. The system originated in the

Low Tatras, with its movement predominantly from northeast to southwest, which is a rarely observed direction.

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

The operational C-LAEF system of Austria (cy43t2) is planned to be replaced by a 1km version on cy46t1 by the end of 2025. Slovenia and Croatia have joined this initiative by contributing SBUs and man power – Slovenian contributions focus mainly on data assimilation, Croatia is supporting in the area of model perturbations and post-processing. Currently a lot of testing and tuning is ongoing. The C-LAEF 1k ensemble consists of 16+1 members, where the 16 perturbed member are coupled with the first 16 ECMWF-ENS members, whereas the control run is coupled with the IFS deterministic run. A 3-hourly assimilation cycle is implemented with one long run per day, which is the 00 UTC run with a forecast range of +60h, while the other 7 runs only run up to 6 hours (for assimilation cycle, EnVAR). The control run is computed 4 times a day up to +60h. 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).

Single precision is used for configuration 001 including the usage of an I/O-server. The computing resources on ATOS for the 1km Esuite sum up to approximately 1.4 Mio SBU per day. The domain is more or less identical to the current operational C-LAEF system but it is planned to be expanded to the south to fulfill the requirements of Croatia (Figure 8). Croatian forecasters expressed the need for the whole Adriatic Sea to be included which means that the southern edge of domain needs to be, at least, at the Strait of Otranto. This domain extension has been prepared (climfiles, namelists, etc.) during the stay of Endi Keresturi in Vienna – first test runs have also been made. The additional costs are about +15%.

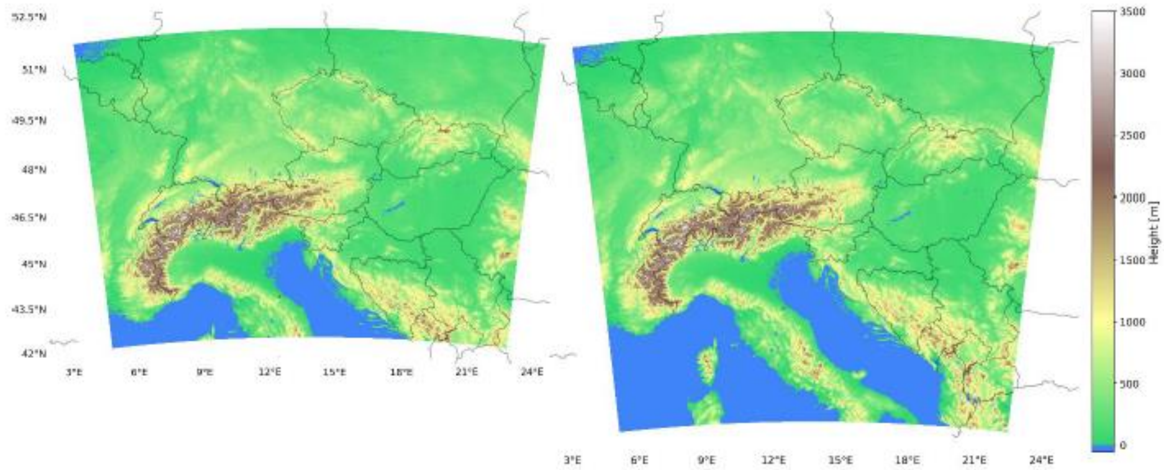


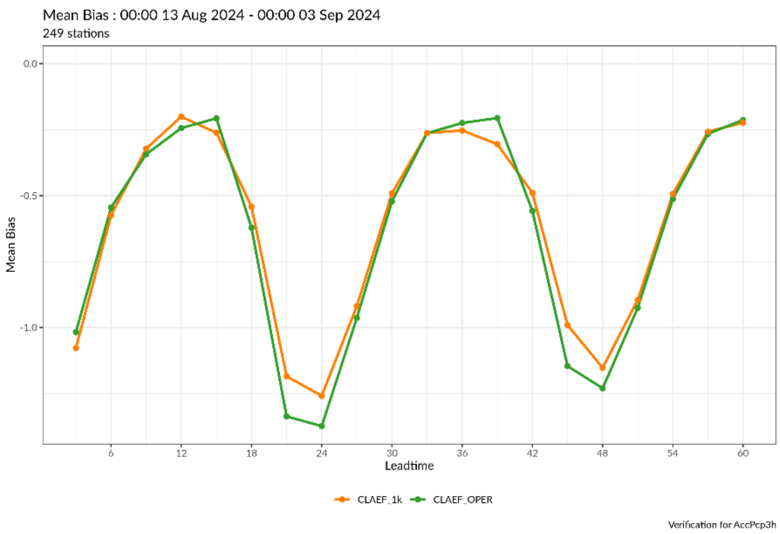
Figure 8: Domain extension of C-LAEF1k to the south.

A full C-LAEF1k has been running for a winter (December 2023 and January 2024) and summer period (June – September 2024). The suite is generally running very stable with hardly no technical problems. The output has been provided to forecasters in Austria (visual weather maps, meteograms), grb files and meteograms have also been shared with Slovenian and Croatian colleagues. The suite is planned to be stopped mid of September (except for the control run) and to be switched on again in December.

A number of bug fixes and new features were implemented in 2024 based on the intensive verification and the feedback of the users. The most important ones are:

- Addition of ceilometer observations in 3D-Var (Austrian stations only)
- Assimilation of radar data – fix from Slovenia
- Assimilation of GNSS observations
- Updated B-Matrix
- Switch off CANOPY scheme – adaptation of 2m diagnostics in Gelyn scheme
- Fixes in SPP scheme
- Adaptation of dynamics setup (switch off COMAD, switch on SLHD)
- Additional member using new EnVAR setup -> all members switched from spectral to grid point output

The performance of C-LAEF 1k is monitored continuously using HARP verification software. The following verification scores were calculated for approx. 250 stations over Austria. The overall performance of C-LAEF 1k is quite satisfying with score improvements for nearly all variables compared to the operational C-LAEF system. However, some problems were observed during daily monitoring and more detailed analysis. One big problem occurred in the summer season with a significant dry bias in C-LAEF1k over the Alps in the afternoon and evening hours in case of convection.



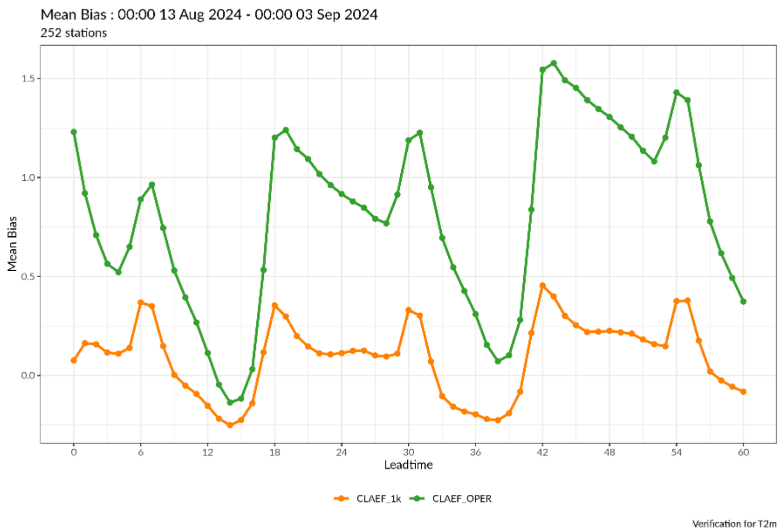


Figure 9: Mean Bias of 3h accumulated precipitation (left) and 2m temperature (right) for C-LAEF 1k (orange) and C-LAEF operational (green) for a test period in summer 2024.

A detailed investigation for some convective test cases showed that the new dynamics setting taken from Meteo France is the reason for that. Meteo France is using in their operational cy46t1 AROME version COMAD (Continuous MApping about Departure points) and SLHD (Semi Lagrangian Horizontal Diffusion) is switched off. Based on this bad test cases (convective precipitation was completely missing in C-LAEF1k over the mountains) we decided to use the same dynamics setting in C-LAEF 1k as in our operational C-LAEF system (SLHD turned on, COMAD switched off). More details about these tests can be found in the dynamics report.

Figures 9 and 10 show verification results of a two weeks period in August (after the last dynamics adaptation). For precipitation (Figure 9) there is a small improvement in C-ALEF1k, but for 2m temperatures the Bias is significantly reduced compared to the operational C-LAEF system. Also when looking on the probabilistic score CRPS in Figure 10, it is obvious that the C-LAEF1k system performs pretty well.

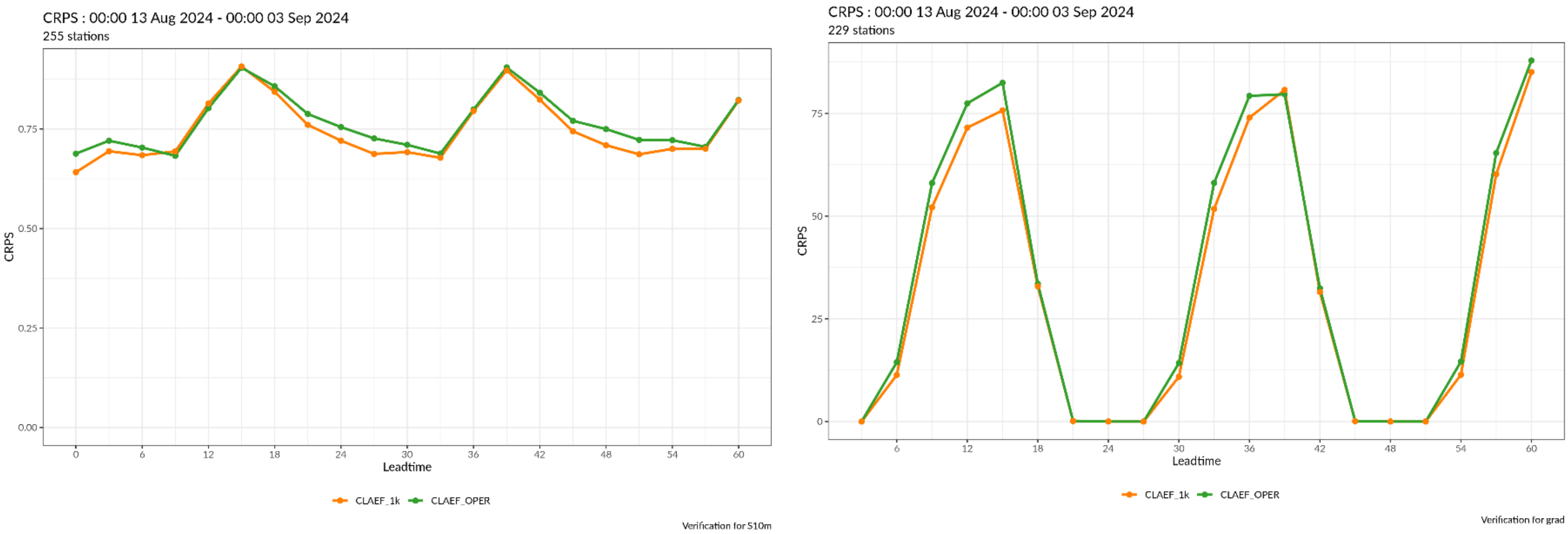


Figure 10: CRPS of 10m wind speed (left) and global radiation (right) for C-LAEF 1k (orange) and C-LAEF operational (green) for a test period in summer 2024

Some more tuning and testing is planned with C-LAEF1k, especially for the upcoming autumn and winter season. We will keep the control member running continuously, while we switch off the complete ensemble with the end of the summer season in September. It is planned to be reactivated in winter. One big topic is now the implementation of an Envar member, which has already been tested in 2023 (with some problems). The planned EnVar setup (based on cy48t3) uses in total 32 member as input, 16 members from the previous forecast and 16 members from the run before. The plan is now to keep the control member and an additional Envar member of 00, 06, 12 and 18 UTC run of C-LAEF1k long (+60h) for the rest of 2024 while the other members are short (+6h) just to keep the assimilation (with Envar) running. Further investigations for the best Envar setup are ongoing.

To expand the C-LAEF 1k system in the future (more runs, longer leadtimes, more members) a lagged ensemble approach has also been tested. In this mode 4 members + 1 control run of C-LAEF1k is run every 3h with an extended lead time of +69h, the rest of the members is kept short with +3h lead time. By combining the members of the 4 most recent runs (the oldest members are 9h old), a lagged ensemble with 16 +1 members can be created every 3h. This lagged ensemble has been running for a winter (February 2024) and summer (July 2024) period and verified with HARP. It is based on cy43t2 and on a 2.5km grid to have a fair comparison to the operational C-LAEF system. Figure 11 shows results of the summer period. For almost all parameters the scores of the lagged ensemble are equal or even better than for the classical ensemble. This is mainly due to an increase of ensemble spread based on the mixing of different initialization times of the members. The only small score degradation can be found for 2m temperature in the first 6 hours, where RMSE of the lagged ensemble a higher RMSE which results from members based on "old" data assimilation cycles.

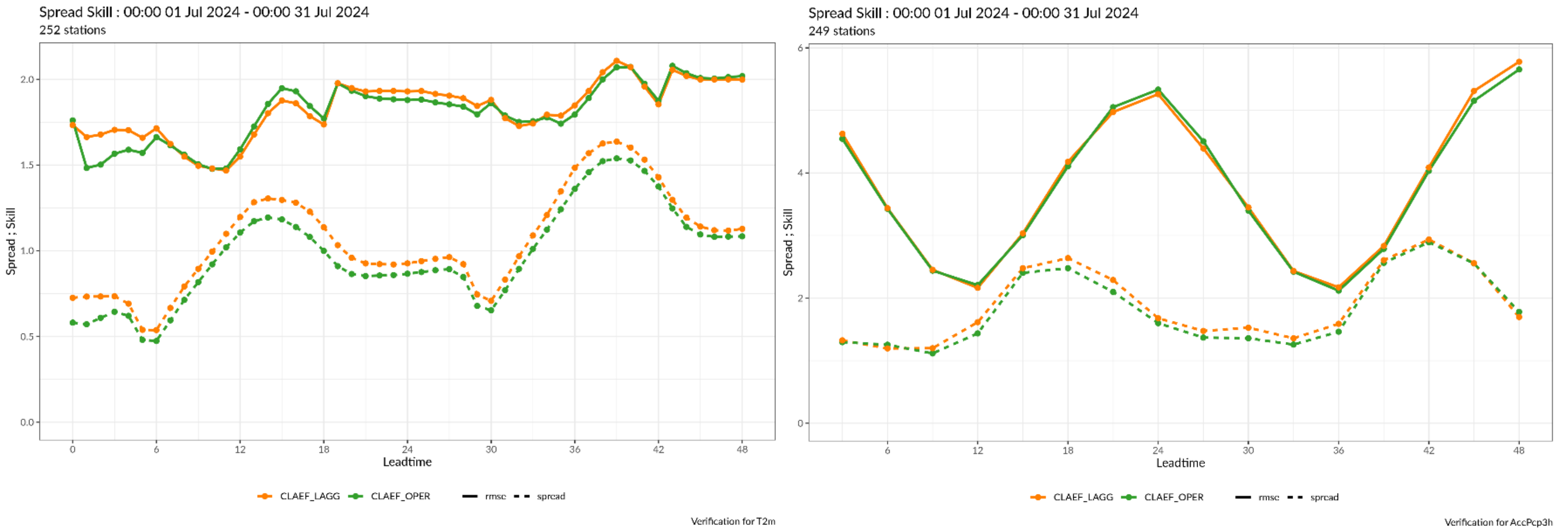


Figure 11: Ensemble spread (dashed) and RMSE (full) of 3h accumulated precipitation (left) and 2m temperature (right) for C-LAEF lagged (orange) and C-LAEF operational (green) for a test period in July 2024.

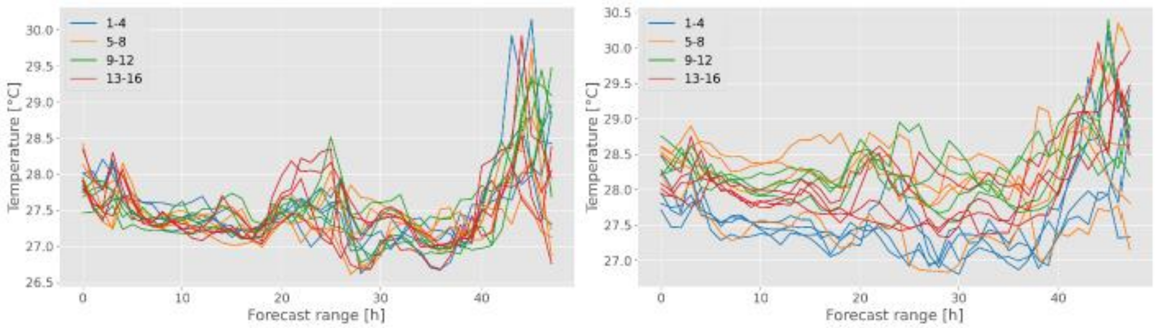


Figure 12: 2 m temperature at open sea for C-LAEF_oper (left) and C-LAEF_lag (right) for a test case in July 2024.

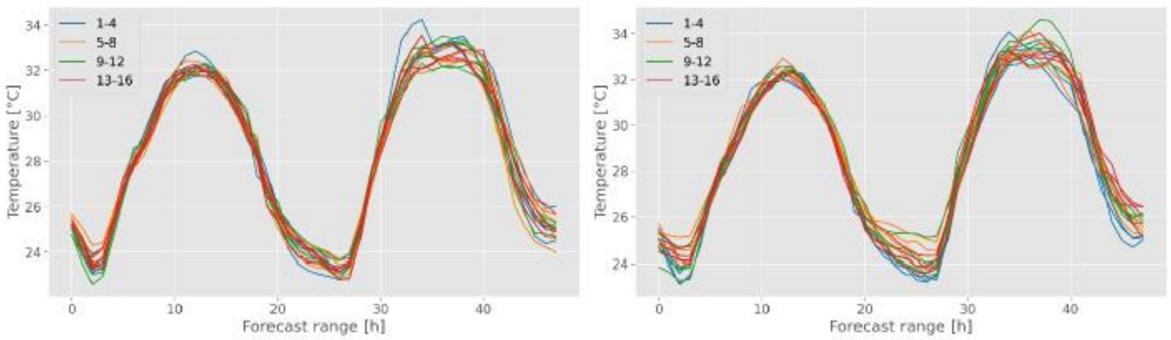


Figure 13: 2 m temperature Zadar for C-LAEF_oper (left) and C-LAEF_lag (right) for a test case in July 2024.

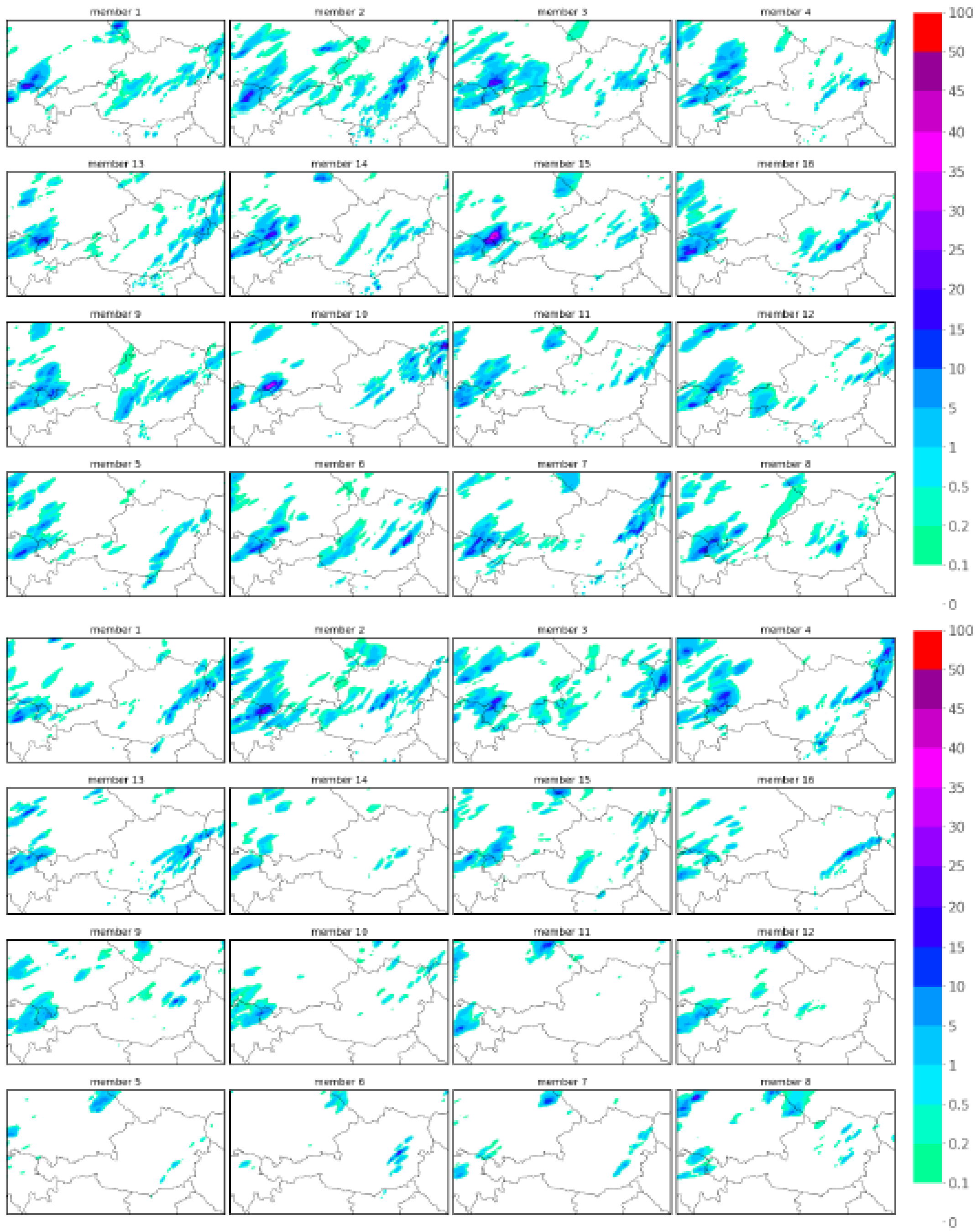


Figure 14: All ensemble members for C-LAEF_oper (up) and C-LAEF_lag (down) at forecast lead time of 4 h. Members are sorted by age from top (newest) to bottom (oldest).

To find any evidence of clustering (which is sometimes mentioned as the biggest caveat of a lagged ensemble) Endi Keresturi investigated a case study (11 July 2024) of the lagged ensemble during his stay in Vienna. The results in Figure 12 and 13 indicate that the clustering is mostly not present, and when it is, it is at the beginning of the forecast. The situations where clustering is present: (1) 2 m temperature over the open sea (Figure 12). In this case, the clustering is obvious, and it comes from different SST used by older members (SST is not assimilated, it is taken from

ECMWF). Coastal locations and islands can then be affected but the intensity of clustering is reduced (Figure 13 shows an example of a coastal location). (2) Precipitation spatial distribution. Figure 14 shows spatial precipitation plots for all members of the ensemble for C-LAEF_oper and C-LAEF_lag at the beginning of the forecast (+4 h). It can clearly be seen that members do cluster, but with larger lead time, this clustering disappears (not shown). To some extent, this can also be seen in total cloudiness fields.

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

The delivery of the new HPC at GeoSphere Austria has been delayed for several times in the past but finally on 5 June 2024 it arrived in Vienna. It is a HPE CRAY XD2000, 100 Nodes, AMD EPYC 9654 96-Core Processor. It has been finally accepted at 17 July 2024. At the moment only early users are allowed to enter the system. Migration of AROME-Aut is currently ongoing. There are still stability issues, so no regular model forecast is possible at the moment.

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

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

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

In order to have a common code base to work with where both AROME and HARMONIE-AROME works, the CY49T2 version used in DEODE was chosen. This branch contains modifications done by the HARMONIE-AROME system group allowing the version to run without breaking the functionality of AROME and ALARO. The code base used was https://github.com/destination-earth-digital-twins/IAL/tree/dev-CY49T2h_deode and it was possible to compile the code with both

CMake and, after some minor modifications, with gmkpack. Another aspect that is important for the cooperation. The natural choice for the runtime environment was the DEODE scripting as both parties are involved in the project and since it provides a common ground for intercomparison and cooperation.

At the end of the stay not all SPP parameters have been implemented, but it is planned to be finished in autumn to be ready for the CY50T1 phasing.

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

No operational changes in the operational AROME-EPS system at HungaroMet have been made so far in 2024. However, some potential upgrades are currently tested and are planned to become operational at the beginning of 2025. These plans comprise the introduction of SPP into AROME-EPS (see subject 2 in this report) and the upgrade to cy46t1.

Efforts: 7.5 PM (planned 20.0 PM total in 2024)

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

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

Planned stays:

1. Martin Bellus (4 weeks at CHMI) – A-LAEF upgrade (multi-physics); 2 weeks completed (8-19 January 2024)

Status: Ongoing, on time.

S2 Action/Subject/Deliverable: Model perturbations

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

The originally planned topics for 2024 were:

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

The A-LAEF topic (stochastic perturbation of fluxes instead of tendencies) is delayed because Martin Bellus could not make his stay in Vienna due to personal reasons. He worked instead on an enhanced model uncertainty simulation by stochastically perturbing ISBA surface prognostic fields. Main work in this action S2 in 2024 has therefore been spent on the continuation of the work on SPP in C-LAEF and AROME-EPS. While the scheme is already running operationally in Austria (since September 2023), it has been tested experimentally in Hungary. After the remote stay of Gabriella Tóth in 2023 where she made all the coding and some first tests, she continued to work on this topic in 2024. After fixing some bugs during the EPS working week in January 2024 in Budapest she optimized the setup and made some long verification tests. It is planned to become operational with a big upgrade of AROME-EPS to cy46t1 beginning of 2025.

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

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

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

Endi Keresturi implemented and assessed during his previous stays the general behavior of FD-SPP and its impact on the C-LAEF behavior, which was found to be beneficial, especially for ensemble spread. However, no long-term verification was done which is necessary to make a final judgement about the method. This has been the topic of another stay of Endi Keresturi in Vienna in 2024 (24 June – 19 July).

The first part of his stay was spent on revising the original FD-SPP implementation in C-LAEF1k cy46t1 which was coded without paying attention to ARPEGE/IFS coding norms (link) or recommended Fortran optimizations. Most of the corrections concerned the changes in variable names, usage of array syntax (:), variable allocations, loops structure and removal of unnecessary commented lines.

The second part was the verification of the long term runs of C-LAEF with FD-SPP (February & June 2024). The original FD-SPP was implemented to C-LAEF1k cy46t1, but the operational C-LAEF is on 2.5 km and cy43t1. In order save billing units (SBUs) and to have a fair comparison with the standard SPP implementation in the operational C-LAEF system on 2.5km, FD-SPP was phased back to cy43t1 for the long-term verification of the new perturbation scheme. The goal was to assess the added value of FD-SPP perturbations in C-LAEF. For this reason, two experiments were defined: a) C-LAEF_oper – operational C-LAEF configuration on 2.5 km and cy43t1 using regular SPP and b) C-LAEF_FD – configured the same as C-LAEF_oper except that FD-SPP has been used instead of standard SPP.

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

Results for February are generally positive (Figures 15 and 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 (Figure 16). Results for June (Figure 17) are unexpectedly more neutral. Increase in spread is only visible for TC, while it is neutral for other variables. RMSE is decreased for WS and is neutral for other variables. CRPS is decreased for WS and slightly for TC. Bias is improved for WS and neutral for other variables.

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

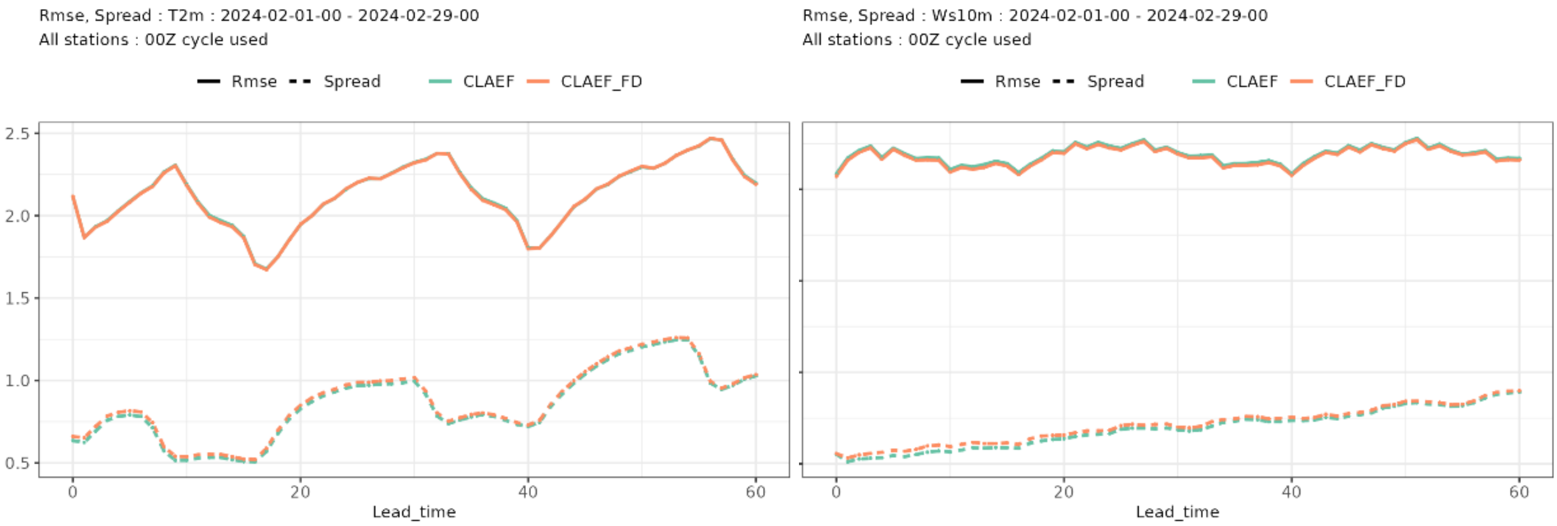


Figure 15: RMSE (solid) and spread (dashed) for C-LAEF_oper (blue) and C-LAEF_FD (orange) for February 2024 averaged over Austrian stations. T2m is shown in the left panel, the right one shows 10m wind speed.

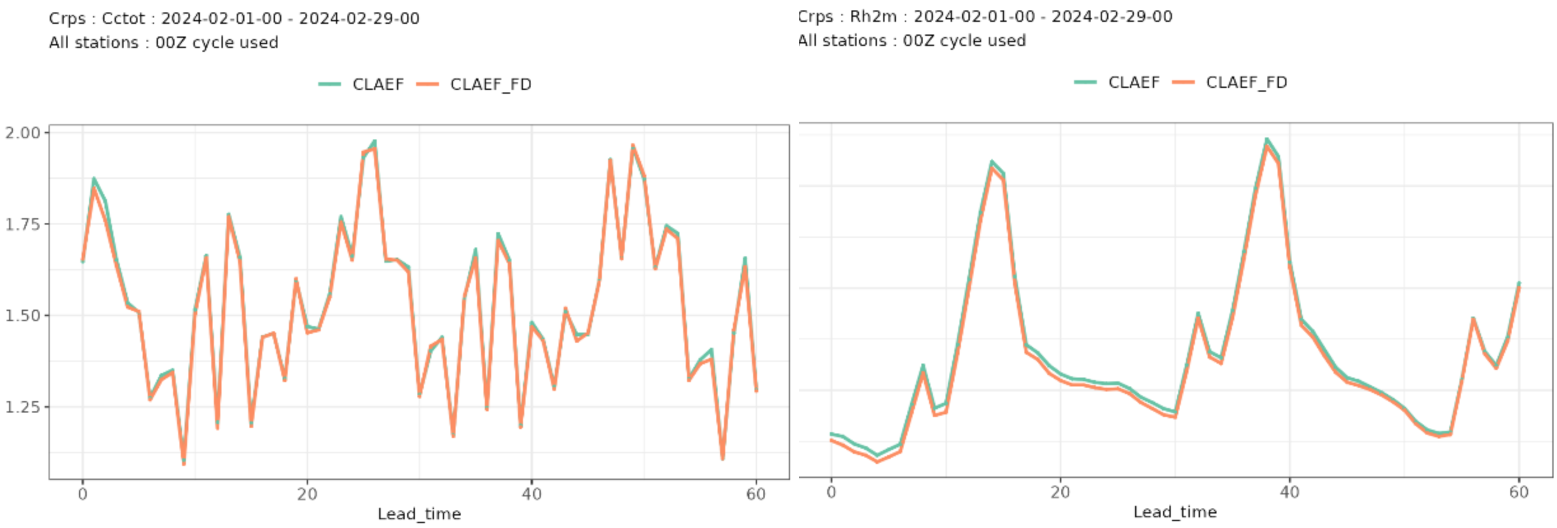


Figure 16: CRPS for C-LAEF_oper (blue) and C-LAEF_FD (orange) for February 2024 averaged over Austrian stations. Total cloudiness is shown in the left panel, the right one shows 2m relative humidity.

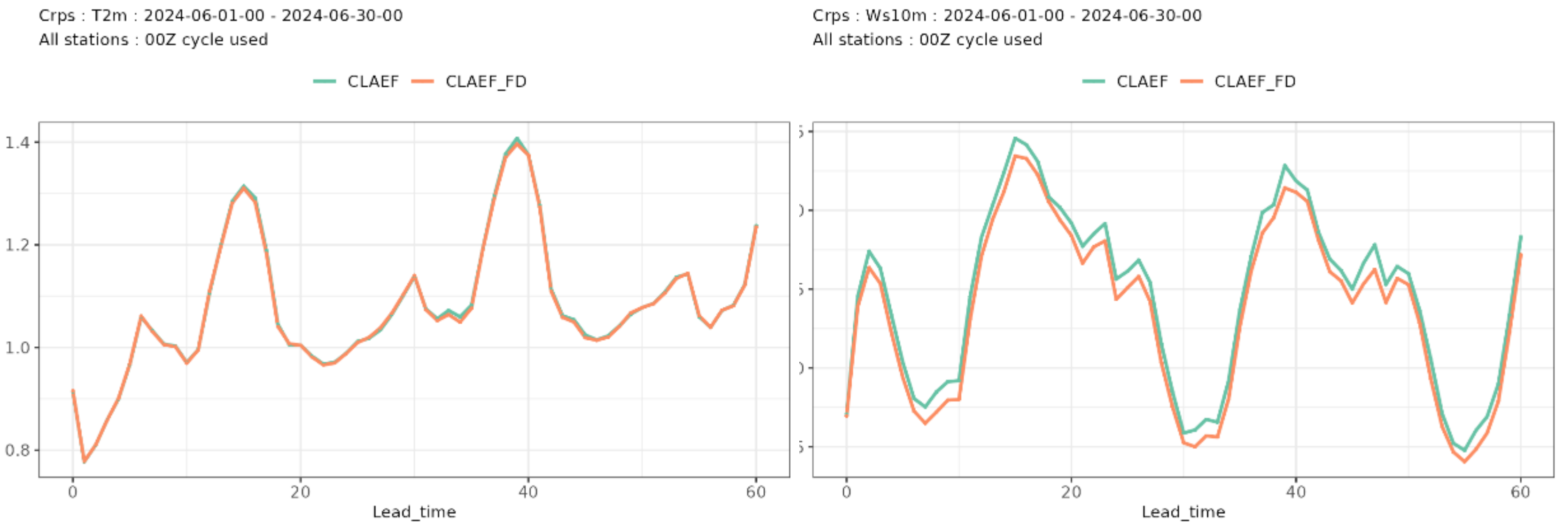


Figure 17: CRPS for C-LAEF_oper (blue) and C-LAEF_FD (orange) for June 2024 averaged over Austrian stations. T2m is shown in the left panel, the right one shows 10m wind speed.

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

HungaroMet started in 2023 with testing Stochastically Perturbed Parametrizations (SPP) scheme on an experimental basis on selected parameters from the physical parametrization. Gabriella Tóth implemented the scheme during her stays in 2023. The first local application of SPP in the Hungarian AROME-EPS was a two-week-long winter-time experiment at the end of 2023. The results were presented in the ACCORD-EPS Working Week in January 2024. After examining the settings together with the participants, the experiment was rerun, considering their recommendations. With the new setup a winter and summer period have been calculated based on cycle 43t2 – consistent to the operational Hungarian AROME-EPS.

In the results of the original winter-time experiment (1 – 14 December 2023), the spread did not change due to the effect of the applied SPP. On the one hand, the temporal length scale, which determines the temporal change of the stochastic pattern, was defined too short (τ=1h). On the other hand, every EPS-member used the same SPG pattern, which should have been different for each member. Furthermore, SPP was not added to the data assimilation to see its pure impact on the forecast. Considering these aspects, the settings were modified with a temporal length scale of τ=6h (21600 s) and an extension of EDA with SPP. A different seed was defined for each EPS member, to apply individual stochastic pattern. Thereby different SPP effect on every single EPS member was achieved. Each day included a 48-hour long forecast at 00 UTC, and the EDA was cycled in every 3 hours. The first forecast was preceded by 10 days long spin up period. 10 parameters were perturbed, using lognormal distribution. The unperturbed values of the individual parameters were following the suggestion of Meteo-France (Wimmer et al., 2022), same way as in the first experiment. Only one exception was taken for the snow auto conversation threshold (RCRIAUTI), for which a higher value was used operationally

(RCRIAUTI=1*10-3), as the default value causes unrealistically much snow in the Hungarian AROME-EPS.

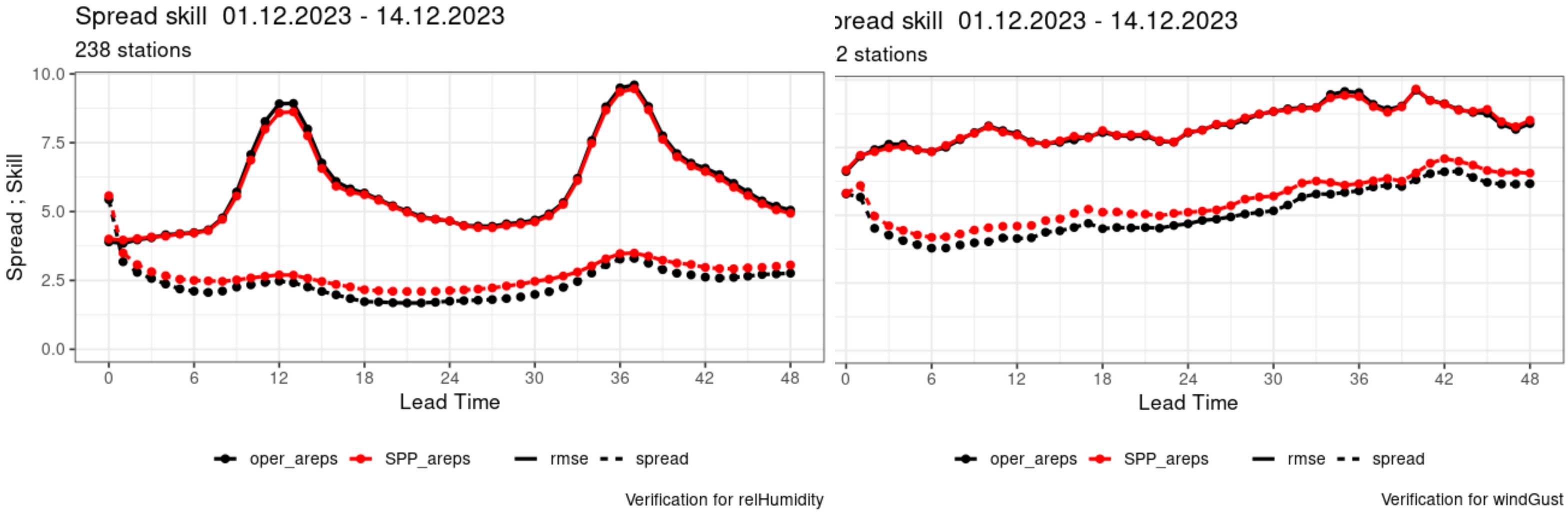


Figure 18: Ensemble spread and RMSE of ensemble mean for 2m relative humidity (left) and 10m wind gust (right) as function of lead time (h); 01-14.12.2023 00UTC.

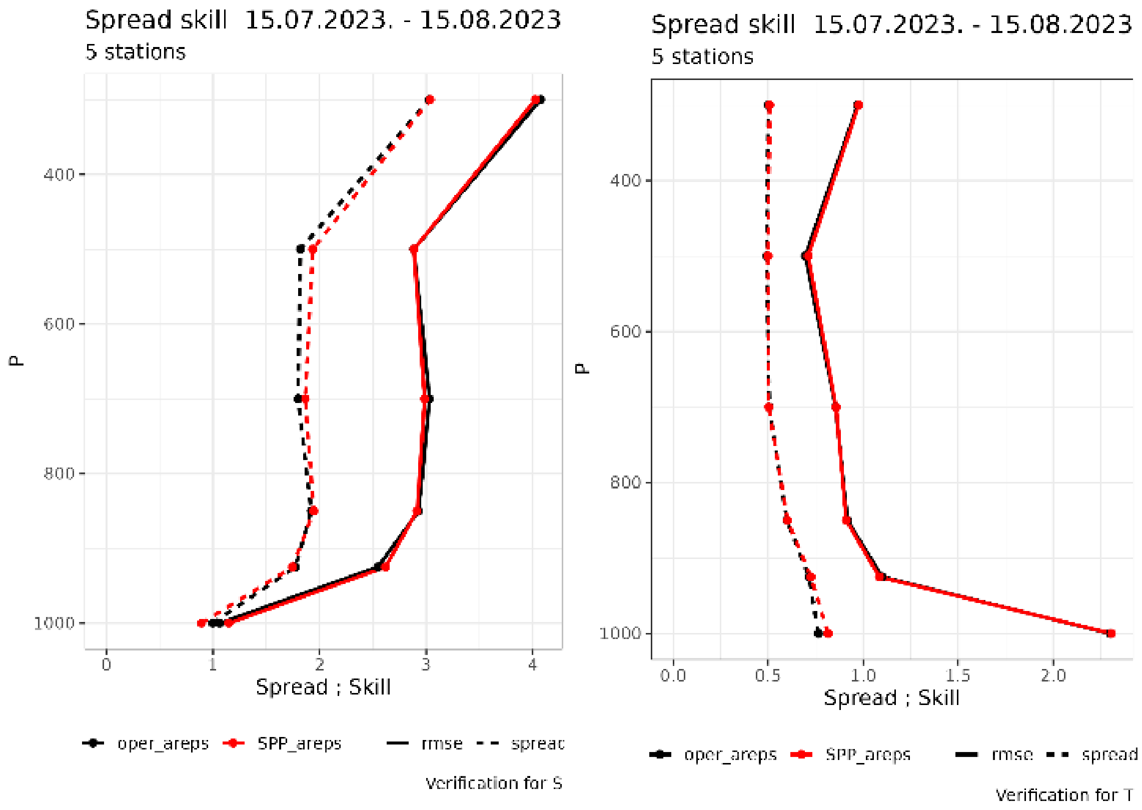


Figure 19: Ensemble spread and RMSE of ensemble mean for wind speed (left) and temperature (right) at different vertical levels; 15.07.2023 – 15.08.2023 00 UTC + 24h

The results of the winter-time experiment show the effect of SPP (Figure 18). The increase of the forecast spread is observable in the surface variables and on the lowest model levels in the upper-air variables. There is a small increase of the mean bias for the 10-meter wind speed, 10-meter wind gust, and cloud cover during night time. However, the cloud bias is doubtful, because there were some inconsistencies in the cloud amounts observed by ceilometers in Hungary until the beginning of 2024.

The testing process continued with a one-month-long summer-time experiment between 15.07. and 15.08.2023, after a 10-day spin-up period. The parameterization perturbation settings were all kept from the winter-time experiment. In comparison with the winter-time experiment, the results generally showed less, but slightly positive impact on the surface. The small increase in the mean bias of cloud cover remained in the summer-time period as well (observation inconsistencies). The upper-air ensemble scores reflect neutral impact on most model levels, but there is a mix of slightly positive and negative effect in the variables on the lowest model levels, especially in case of the wind speed (Figure 19).

The effect of SPP on spread is observable in the precipitation field as well. A case study was made on 22.07.2023, when a shallow cyclone affected the weather in the Central-European region, and caused intensive precipitation in the southern part of Hungary. SPP caused generally higher intensity of precipitation (Figure 20), while the reference run, which only includes EDA, sometime indicated the precipitation over a larger area, but with less intensity. The spatial location was better estimated in case of higher intensity precipitation.

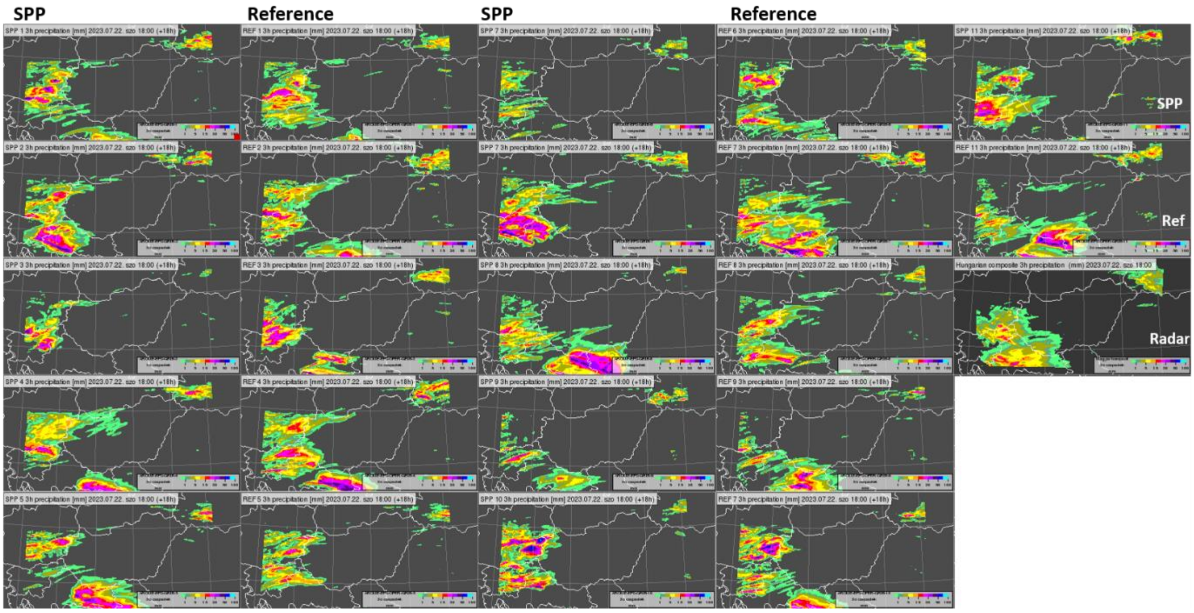


Figure 20: Precipitation amount between 15 and 18 UTC based on 11 ensemble members of forecasts on 22.07.2023. 00 UTC using SPP, without SPP (reference), and Hungarian radar data

Both the summer-time and the winter-time SPP experiments in the Hungarian AROME-EPS were carried out with cycle 43t2. In the next steps (in the beginning of 2025), an upgrade to cycle 46t1 in the AROME-EPS is planned together with a new version of the SPP code. SPP is planned to be become operational in cy46t1 after testing together of a single precision mode.

Efforts: 5.75 PM (planned 6.0 PM in total in 2024)

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

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

Planned stays:

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

Status: Ongoing; mostly in time

3 Action/Subject: Initial condition perturbations

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

The originally planned topics for 2024 were:

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

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

For C-LAEF the work on EnVar is currently ongoing. After some adaptations and debugging, it is planned that an EnVar based member will be added to the C-LAEF1k suite in September as second control. The work on EnVar in C-LAEF 1k is a joined cooperation between Austria and Slovenia, more details on that work can be found in the data assimilation report.

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

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

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

Planned stays:

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

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

4 Action/Subject: Surface perturbations

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

The originally planned topics for 2024 were:

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

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

However, there is some research ongoing in ACCORD on this topic where they adapt the SPP scheme to be used in surfex. So in the future this might be interesting for RC LACE as well.

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

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

Documentation:

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

Status: Delayed

5 Action/Subject: Lateral boundary condition perturbations

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

The originally planned topics for 202 were:

- No topics planned.

The coupling of the local convection-permitting EPS in Slovakia with A-LAEF has already been tested in 2022 with 903. In 2024 an ALARO-EPS ecFlow suite with a 1 km spatial resolution and 87 vertical levels has been implemented on Atos, covering Slovakia and the surrounding regions. This suite aims to provide experience with convection-permitting ensembles on kilometric scales, focusing on the coupling of such systems and simulating their uncertainties using ALARO multi-physics combined with stochastic physics. The system has been tested for some case studies in 2024. The insights gained will contribute to the development of a convection-permitting system at SHMU.

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

Contributors: Martin Belluš (SHMU)

Documentation:

Planned stays:

Status: Ongoing

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

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

The originally planned topics for 2024 were:

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

A lot of work is currently ongoing in this topic. The work on analog-based post-processing is planned to be continued during a stay of Iris Odak Plenkovic at GeoSphere Austria in autumn 2024. The idea is to try some other variables besides wind for post-processing as a next step. Radiation would be a logical choice since GeoSphere Austria has a lot of experience with post-processing of radiation. Additionally it would be good to test other machine learning methods besides analogs, because some of them could provide additional benefit.

Post-processing data of the operational A-LAEF and ECMWF ENS (daily averages/extremes/totals + regridding/interpolation) are used at SMHU for drought research purposes (in cooperation with the climate service department) by computing a probabilistic Standardized Precipitation and Evapotranspiration Index (SPEI).

At GeoSphere Austria the post-processing based on standardized anomaly model output statistics (SAMOS) has been expanded by not only providing mean and spread of a fitted distribution but also producing members which are consistent in space and time (Ensemble Copula Coupling, ECC). Beside that a lot of work is ongoing in providing very localized, post processed forecasts (nowcasts and intra-day forecasts) for the PV and hydro power sector.

- **Topic 1: Postprocessing of operational A-LAEF and ECMWF ENS data for a probabilistic computation of SPEI**

The drought research and monitoring has been an important and discussed topic in the recent years, because of frequent occurrence and strong intensity of droughts. SHMU monitors the meteorological and soil drought since 2015. The Standardized Precipitation and Evapotranspiration Index (SPEI) is used for evaluation of drought in Slovakia, utilizing a floating window with accumulation period of 30 days.

The SPEI index is designed to account for both precipitation and potential evapotranspiration (PET) when assessing drought conditions, thereby capturing the primary effect of rising air temperatures on water demand. Given the significant uncertainty inherent in precipitation forecasts, it was decided to calculate SPEI in a probabilistic manner (Figure 21, in cooperation with the Climate Service Department).

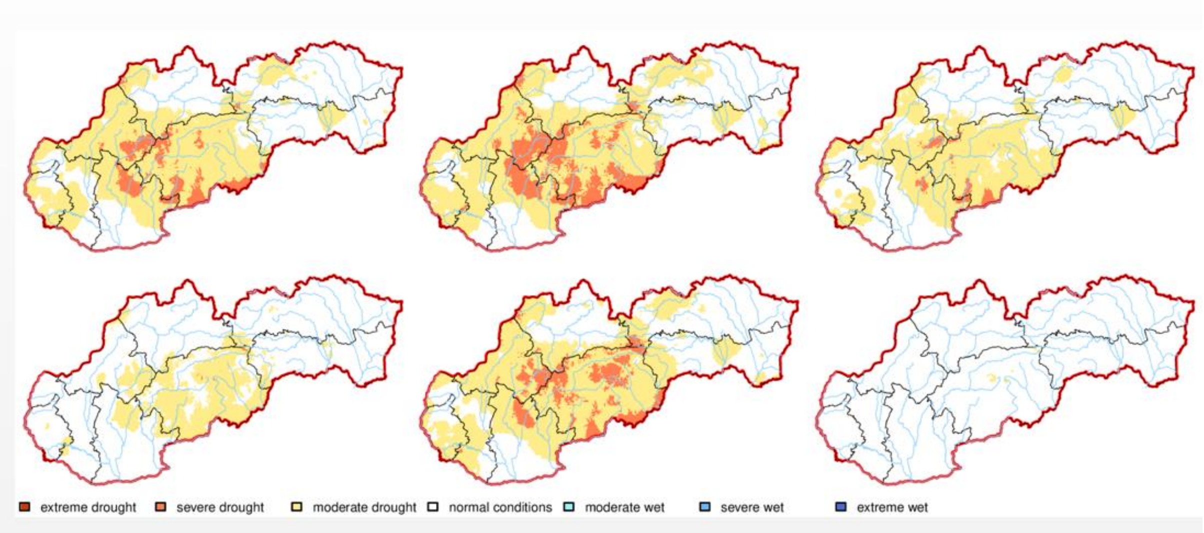


Figure 21: An example of SPEI forecast uncertainty (from left to right: mean, 10 and 90 percentiles) 3 days ahead based on A-LAEF EPS (top) and 7 days ahead based on ECMWF ENS (bottom). EPS inputs are from 2024-08-15 00 UTC model runs.

- **Topic 2: Work on statistical post-processing of EPS data at Geosphere Austria**

The post-processing based on standardized anomaly model output statistics (SAMOS) only produces mean and spread of a fitted distribution lacking the characteristic members of any EPS system, which are consistent in space and time. Aiming to generate members from the SAMOS system, the space and time correlations are taken from the numerical weather prediction (NWP) model.

In this case, the information from the control and first 16 members of the ECMWF ensemble forecasts are retrieved, following the idea of the C-LAEF members. In theory, all 51 members from the raw forecasts could be used but to reduce the amount of data for incorporating the forecasts into the operational workflow, the amount of members is reduced. C-LAEF could be used instead of ECMWF as NWP, but, in order to keep a coherent space-time structure for lead times up to +96 h lead time, ECMWF is used to not have a break in the structure coherency after the C-LAEF forecast horizon. The basic idea of reconstructing the structure is called Ensemble Copula Coupling (ECC). Figure 22 provides an example of ECC based on SAMOS and ECMWF ensemble. Panels b) and c) show the post-processed SAMOS forecast at lead time +12 h with the mean in b) and the standard deviation in c). Panel a) is the INCA analysis as the truth at that corresponding time step. Panels d) to f) depict the members 1, 9 and 17 as example of the raw ECMWF forecasts and panels g) to i) the corresponding SAMOS members after ECC.

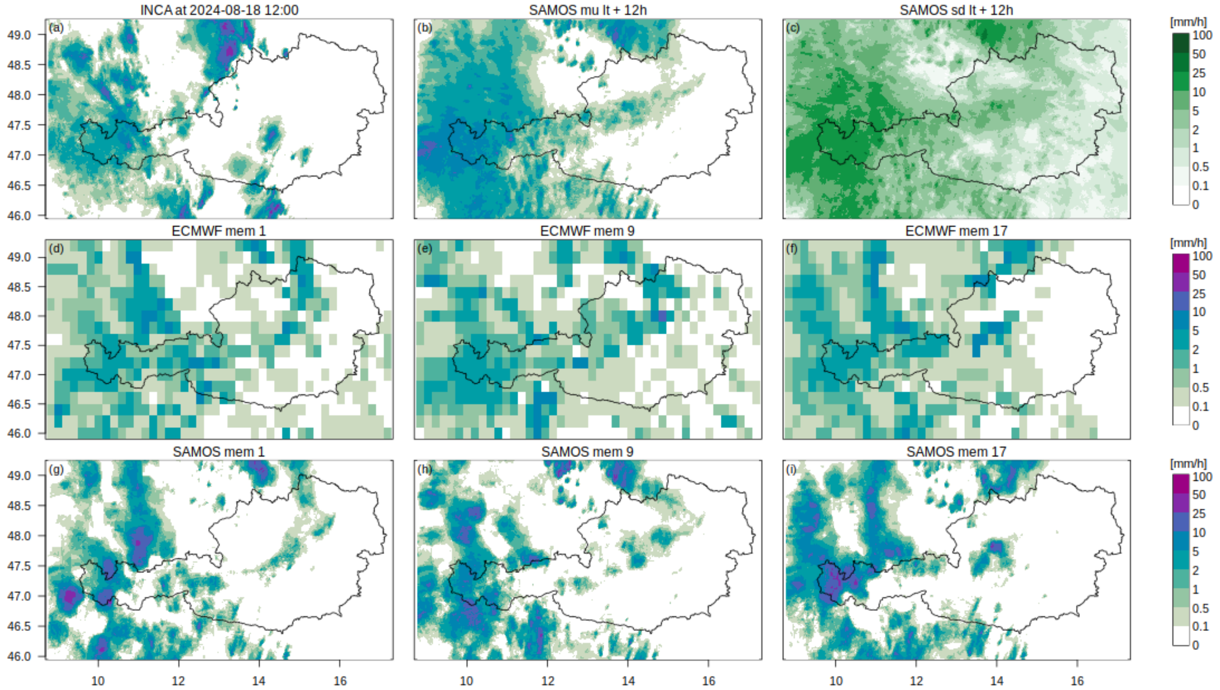


Figure 22: Ensemble copula coupling (ECC) based on SAMOS and ECMWF ensembles.

While SAMOS mean shows a rather smooth forecast, the SAMOS members are able to show individual cells of heavy precipitation. While ECMWF does have a much lower resolution, a similar to the observations spatial structure can be seen in the corresponding SAMOS member. With SAMOS we have now a calibrated forecast based on several NWPs to provide the best possible forecasts and with ECC we are able to produce consistent space-time scenarios for forecasters or other end-users operationally available.

❑ Topic 3: C-LAEF: Extension of data-driven machine learning ensemble modelpoint nowcasting

At GeoSphere Austria a lot of work is ongoing in the area of machine learning (ML). The increasing adoption of localized PV generation and the impact of atmospheric conditions on the generation necessitate accurate predictions of expected generation at a very local level allowing DSOs to better plan and schedule their network and power production in-feed. There is, thus, a need for providing very localized PV generation forecasts for the nowcasting and intra-day range issued hourly with a 15-minute temporal resolution. There is, too, a need for small hydropower plants as they react to runoff and especially flash floods very timely but also can serve compensation measure in case there is more/less PV generation than predicted. Furthermore, both PV and hydropower can aid a preparatory implementation for future operational decisions. For both RES types, uncertainty of the forecast needs to be accounted for using either quantile forecasts or ensembles.

To generate PV production and small hydropower production predictions an essential step is to gather metadata information. In case of PV production forecasting the metadata consists of the approximate location of the PV sites, aggregated per transformer node or per region, and the respective kW peak rates. If it is possible to share location data, information on the installed PV panel type, azimuth and orientation are beneficial for good PV production forecasts. For hydropower, ideally the exact location is known to generate the needed catchment information and retrieve the meteorological data feeding into the catchment. Furthermore, to convert rainfall-runoff data to power, a power curve is needed.

To generate very localized predictions of PV and hydropower with AI methods, meteorological historical observation and forecast data are needed (Figure 23). Observation data cover site specific observations, satellite data, and (re)analysis data. Ideally, also historic production data of at least 2 years are available for the respective site or aggregation level. Static information such as topography and its derivatives (slope, orographic shadowing), land-use and soil type (the latter two for hydrological modelling) are available for the small hydropower basin.

As there is not enough historic production data available, synthetic data is generated using different sets of granularity (length of historical data, available meteorological data, etc.) and, thus, providing already some uncertainty information. This is done for both PV and hydropower or hydropower + runoff of small river hydropower and incorporates Machine Learning as well as physical models and ML in case of hydropower.

For the PV and hydropower prediction using AI tools like random forest or an LSTM, the synthetic data are used as target and meteorological forecast model data are used as input features. Once this model is trained, it can be refined using the available historic production data and provide forecasts for the future. However, further refinement is needed and the longer the training data the better the forecast will get. For PV prediction, especially in the nowcasting range, using additionally satellite nowcasts as input can improve the predictions and add further information to the models.

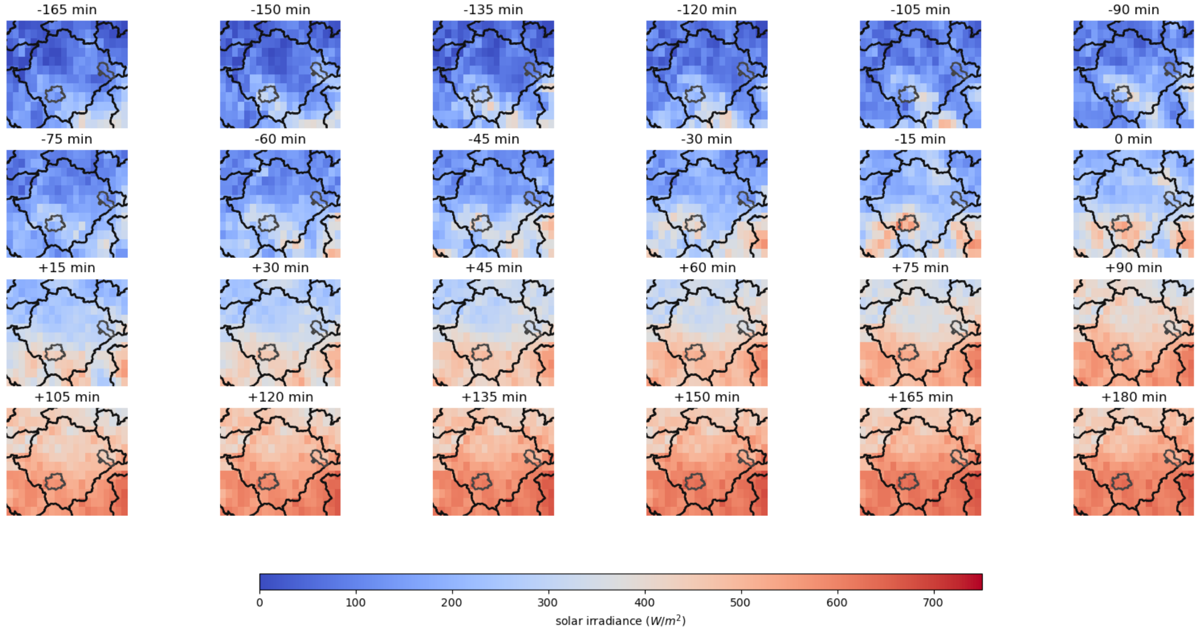


Figure 23: Forecast from 9:00 26.04.2023, upper two rows show ground truth satellite images, part of the input to the model, bottom two rows show the forecasted solar irradiance frames for the following three hours

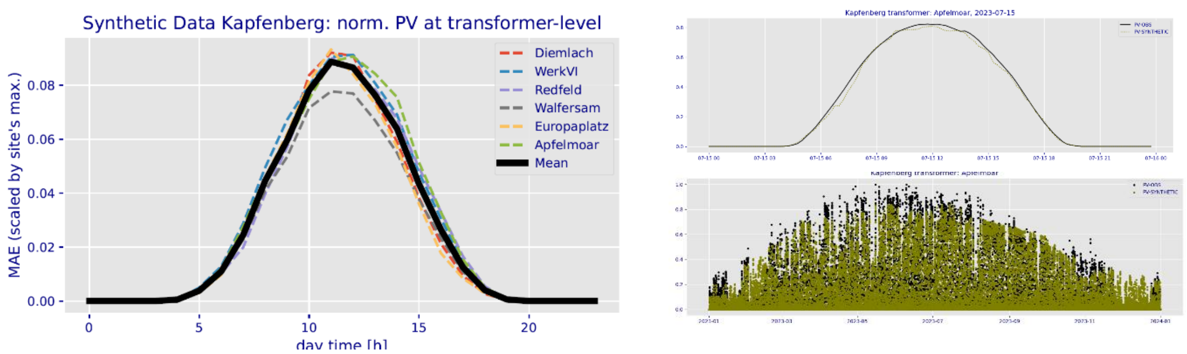


Figure 24: Synthetic data generation using a data driven approach in two steps, training and prediction, yielding promising and robust preliminary results by RF, stable using small amounts of training data and a highly diverse set of inputs. Result plots of synthetic PV production (scaled to [0,1]) by RF are shown for Kapfenberg's transformers given data of 2023 using 8-fold cross-validation (non-shuffled to avoid dependencies in time-adjacent observation) with time-series examples for transformer "Apfelmoar".

To convert both the solar irradiance nowcast (two methods available with different sets of input data and fitness for missing input values) and meteorological forecast/observations to power production several steps are carried out. Providing PV production forecasts with a high level of accuracy needs, too, historical data to calibrate a model and, if needed, correct historical synthetic PV production data for forecast model training and refinement (Figure 24).

Another essential part is, in close collaboration with the users, the visualisation of the forecast and the forecast data type so that integration into their workflow is as easy as possible. Using .csv-Files enables a direct inspection with a tool of choice and easy integration. Forecast and analysis plots can be adjusted as needed. For hydropower forecasting, an ensemble foundation model was investigated, too, with promising results.

Efforts: 4.5 PM (planned 11.0 PM in total in 2024)

Contributors: Iris Odak Plenković, Endi Keresturi, Ivan Vujec (DHMZ), Alexander Kann, Markus Dabernig, Irene Schicker (GeoSphere Austria), Martin Belluš (SHMU), Katalin Jávorné-Radnóczi (HungaroMet)

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

Planned stays: Iris Odak Plenković (4 weeks at GeoSphere Austria) - analog-based post-processing methods

Status: Ongoing, on time.

Activities of management, coordination and communication

- 3rd ACCORD EPS working week, 22 – 26 January 2024 (Budapest)
- 42nd LSC Meeting, 27-28 February 2024, Budapest
- 4th ACCORD All Staff Workshop 2024, 15 - 19 April 2024 (Norrköping), RC LACE EPS activities presented by Clemens Wastl
- 43rd LSC Meeting, 18-19 September 2024, Vienna

Publications

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

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

RC LACE supported stays – 1.5 PM in first half of 2024

Until now two stays have been realized in 2024 in the EPS area of RC LACE: The stay of Martin Bellus (2 weeks at CHMI in Prague in January) on the upgrade of multiphysics in A-LAEF and the stay of Endi Keresturi (4 weeks at GeoSphere Austria in Vienna in June/July) on flow dependent SPP for C-LAEF. The stay of Iris Odak Plenkovic (4 weeks at GeoSphere Austria) on the continuation of analog based post-processing is foreseen for autumn 2024, the stay of Gabriella Tóth on surface perturbations in AROME-EPS (4 weeks at GeoSphere Austria in November) has been cancelled due to the leave of Gabriella from HungaroMet.

Summary of resources [PM] – 2024 (Jan – Jun 2024)

Subject	Manpower		RC LACE		ACCORD	
	plan	realized	plan	realized	plan	realized
S1: Preparation, evolution and migration	20	7.5	1	0.5	0	0
S2: Model perturbations	6	5.75	1	1	0	0
S3: IC perturbations	3	0	1	0	0	0
S4: Surface perturbations	2	0	1	0	0	0
S5: LBC perturbations	0	0	0	0	0	0
S6: Statistical EPS and user-oriented approaches	11	4.5	1	0	0	0
Total:	42	17.75	5	1.5	0	0

References

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

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.