Report on stay at ZAMG

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Stochastically perturbed physics tendencies of surface fields in ALADIN-LAEF system

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::Acknowledgement

I would like to acknowledge the whole local team at ZAMG for their hospitality. Special thanks to Christoph and Florian for the code consultations and technical support. It becomes more and more difficult to come up each time with a fresh and attractive acknowledgement, which doesn't really mean I'm not grateful enough to all of you.

::Foreword

Numerical weather prediction is generally affected by 2 main sources of errors. The first one is the uncertainty of initial conditions (or in case of LAM also the uncertainty of lateral boundary conditions) and the second one concerns the accuracy of the models themselves. Because the first type of the errors has been already tackled in ALADIN-LAEF system by the ensemble of surface data assimilations and upper-air spectral blending, here we address rather the model accuracy part. Although, multi-physics approach is also the way how to handle model uncertainty (and we use it successfully in ALADIN-LAEF operational version already for some time), the stochastic physics method presented in this report is a tool, which can randomly disturb the model tendencies computed by the physical parameterizations and hence addresses the model accuracy at its source. Moreover, we have used stochastic physics to perturb the surface prognostic fields, which is more or less the novelty in NWP.

::I. Stochastically perturbed parameterization tendencies

Stochastic parameterization techniques have been developed at ECMWF since the end of last century and now are widely used by many operational centres in their ensemble prediction systems. Formerly known simply as stochastic physics, the scheme based on the approach of Buizza, Miller and Palmer (1999) was later referred as BMP and finally revised under the name Stochastically Perturbed Parameterization Tendencies (SPPT), which better represents this class of model uncertainties. The j^{th} ensemble member's state at time T is defined as an integral of the following model equation:

$$\frac{\partial e_j}{\partial t} = A\left(e_j,t\right) + P'\left(e_j,t\right)$$

where A stands for the resolved non-parameterized processes (e.g. dynamics), while P' is perturbed tendency of the parameterized processes. In other words, P' represents the fluctuation around the grid-box averaged value P of physical parameterization tendency, hence describing the uncertainty of subgrid physical processes:

$$P'_j\left(e_j,t\right) = \left(1 + r_j(\lambda,\varphi,t)_{D,T}\right) P_j\left(e_j,t\right)$$

where r_j is uniformly sampled random number used for subdomain with the size D and constant over time T. That is to ensure space and time consistency of the perturbed fields.

In revised SPPT scheme, the random number is defined in more sophisticated way, using the Gaussian distribution with the zero average (to keep the model energy budget unchanged) and with the standard deviation σ. It is defined by a spectral pattern generator:

$$r = \sum_{mn} (\hat{r})_{mn} Y_{mn}$$

with the spectral coefficients $(\hat{r})_{mn}$ prescribed by an autoregressive process and Y_{mn}, the spherical harmonics in case of a global model or bi-Fourier functions in limited area model.

Finally σ, L and τ can shape the amplitude, structure and temporal change of the perturbations, where standard deviation σ (SDEV_SDT), spatial correlation scale L (XLCOR_SDT) and time correlation scale τ (TAU_SDT) - all in NAMSPSDT namelist, are tunable parameters. Resulting random number at each grid point follows the Gaussian distribution with the values from interval -2σ to +2σ.

::II. BMP (Buizza, Miller, Palmer) scheme vs new SPPT scheme

From practical point of view, the main difference between the original BMP scheme and revised SPPT is in the random patterns definition and their generation. While the first one approach divides the whole domain into regular, temporally and spatially constant lat-lon rectangles (see Fig.2, up), the second one generates rather chaotic patterns varying smoothly in space and time (see Fig.2, down). It is obvious, that the latter technique is more natural and less dangerous in creation of spurious, non-physical horizontal gradients in the perturbed physics fields.

Additionally, the distribution of perturbations has changed from the uniform to Gaussian one. The differences in their probability density functions (PDFs) and cumulative distribution functions (CDFs) are schematically shown on Fig.1. According to ECMWF's internal documentation, this change has to address the overprediction of heavy precipitation events.

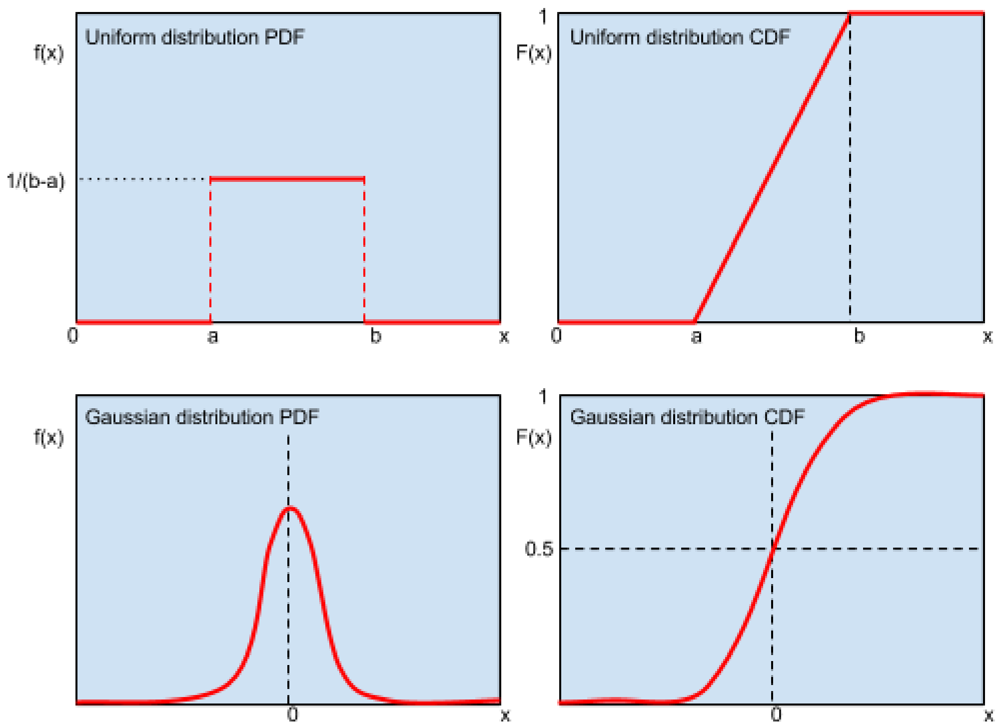

Fig 1: PDFs and CDFs of Uniform distribution (up) and Gaussian distribution (down).

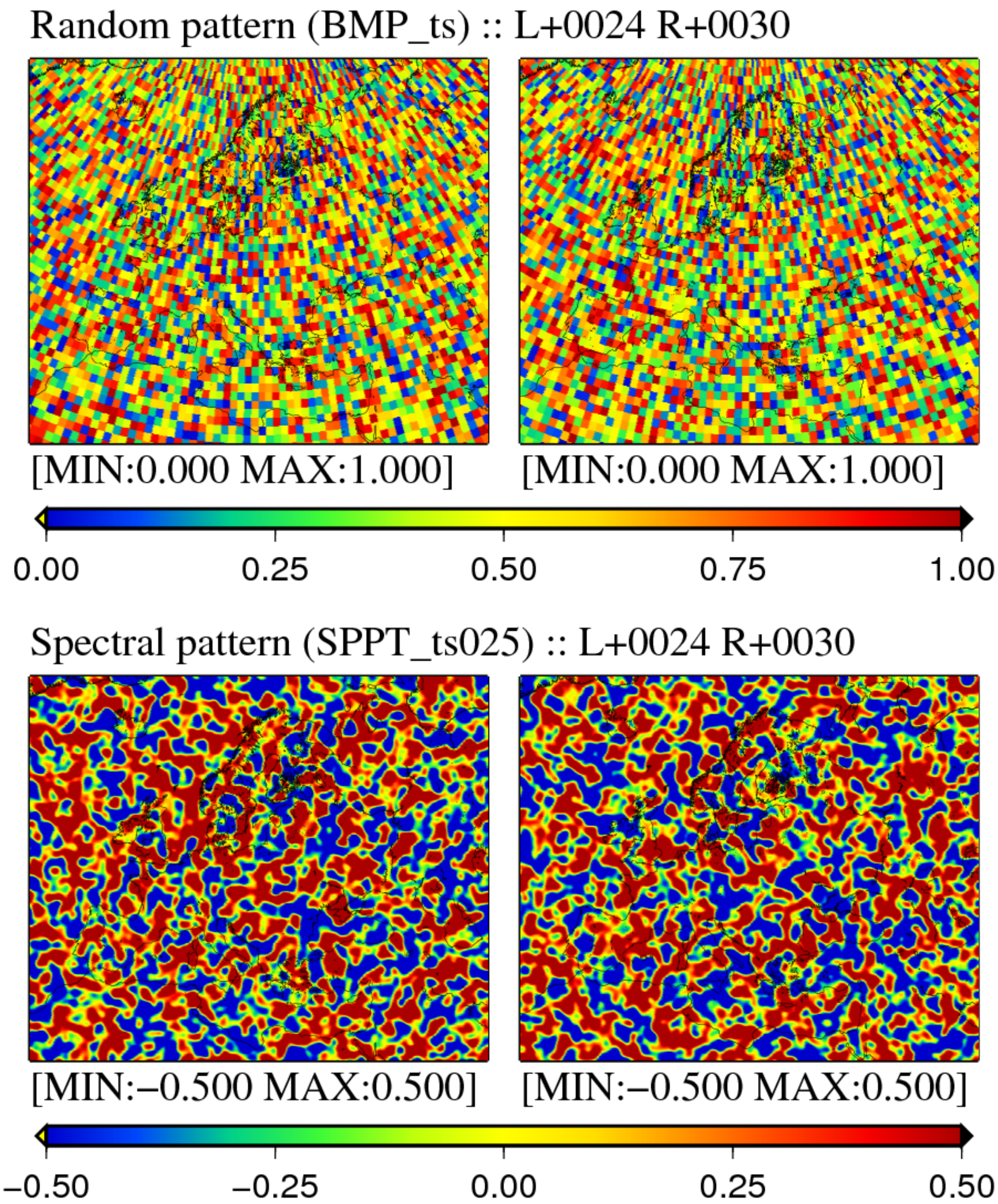

Fig 2: Random pattern generated by former BMP scheme with horizontal correlation given by boxes of 1x1 deg size (up) and corresponding random spectral pattern generated by revised SPPT scheme for σ=0.25, spatial correlation L=500 km and time correlation τ=2h (down).

In the following picture (Fig.3), one can see how the spectral patterns generated by new SPPT scheme are dependent on the tuning parameters like spatial correlation. The sensitivity to chosen XLCOR_SDT namelist parameter is obvious. Different "sizes" of random patterns could be used for representing the global or limited area model uncertainties and the appropriate physics scales. The spatial correlation of the perturbations expressed in the picture is intentionally magnified to see the effect clearly.

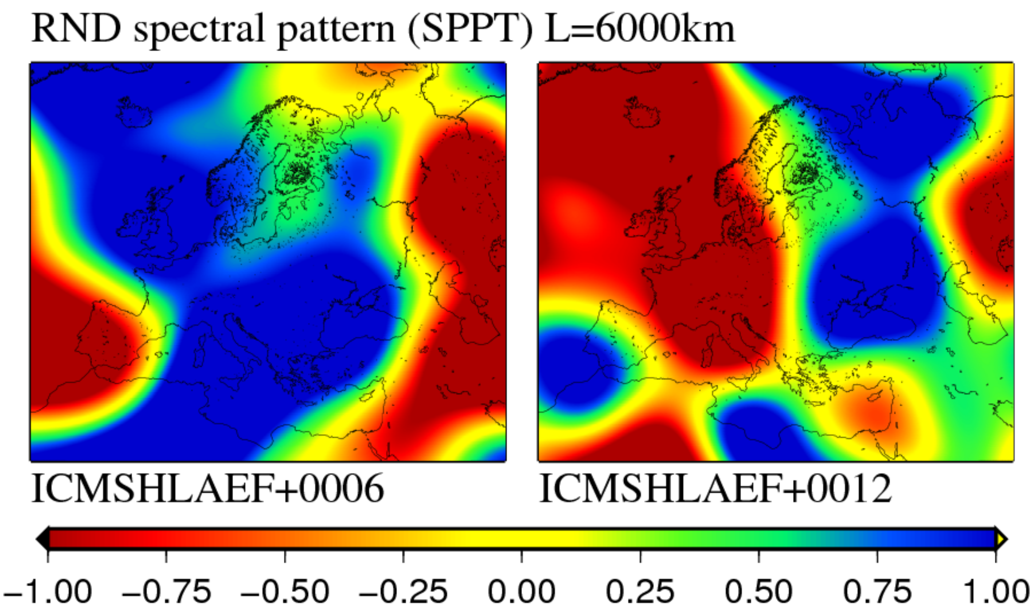

Fig 3: An example of random spectral pattern generated by revised SPPT scheme for σ=0.5, spatial correlation L=6000 km and time correlation τ=2h. The time difference between the left and right image is 6 hours.

::III. Implementation of SPPT for ISBA fields in ALADIN-LAEF

The original BMP scheme had used unique random numbers to perturb differently each of the prognostic fields like temperature, wind components and specific humidity. This multivariate approach has changed to univariate in revised SPPT scheme, moreover only the prognostic fields on vertical model levels were disturbed. Additional function was implemented into the equation to force perturbation size to become zero near the surface and the model top. This change was made in order to avoid model instability. We have kept the idea of univariate Gaussian distribution, but perturbed only the following seven surface prognostic fields (instead of the four upper air prognostic variables):

- surface temperature
- liquid soil water content
- frozen soil water content
- snow albedo
- snow reservoir water content
- snow density
- water intercepted by vegetation

We intentionally skipped the perturbation of deep soil prognostic fields (e.g. deep soil temperature), because such fields are naturally changing very slowly in time and their disturbance could be contradictory due to their slow response. On the other side, we found the perturbation of (skin) surface prognostic fields very important for generating enough spread for screen-level variables in LAM EPS.

In order to create those perturbations, new model routine *sppten_isba.F90* was introduced and called in the ALADIN code from *mf_phys.F90* routine just after the computation of physics tendencies of surface variables in *cptends.F90* and before the final computation of the changes of surface prognostic variables in *cpwts.F90*.

mf_phys: *cptends* ⟶ *sppten_isba* ⟶ *cpwts*

A straightforward modification of the physics tendencies is performed in new *sppten_isba.F90* routine without any boundary and security checks (e.g. oversaturation treatment, etc.), because this is already done within the final computation of the overall surface fields physics tendencies in *cpwts.F90* routine.

general code in sppten_isba:
$X'_s = (1+r) * X_s$ where X'_s is perturbed surface physics tendency, X_s is the original unperturbed value and r is random number (for σ=0.25 it is from the interval <-0.5, 0.5>)

Here is the list of all perturbed surface physics tendencies with their code names:

local variable	global variable	denotation	name (tendency of)
ZTDTS	PTENTS	T_s	surface temperature
ZTDWS	PTENWS	W_s	liquid water
ZTDWSI	PTENWSI	W_{si}	frozen water
ZTDWL	PTENWL	W_r	water on leafs
ZTDSNS	PTENSNS	S_n	water in snow
ZTDALBNS	PTENALBNS	A_n	snow albedo
ZTDRHONS	PTENRHONS	ρ_n	snow density

The SPPT scheme has to be initialized by the following namelist. For its correct operation it is important to have a unique seed number (NSEED_SDT) for each ensemble member, otherwise the pseudo-random perturbations would be equal to each other, resulting in zero ensemble spread. That is the reason why namelist is created dynamically by the LAEF application.

```
&NAMSPSDT
  LRDPATINIT_SDT=.F.,
  LSPSDT={LSPSDT},
  LWRITE_ARP=.F.,
  NSEED_SDT={MEMB},
  SDEV_SDT(1)=0.25,
  TAU_SDT(1)=7200.,
  XLCOR_SDT(1)=500000.,
/
```

To technically verify new code functionality and correctness we have compared the original (unperturbed) and modified (perturbed by SPPT) physics tendencies. In the following pictures (Fig.4 and 5) one can see the physics tendency of Surface Temperature for the different forecast lengths (more importantly for the different part of a diurnal cycle, because the size and direction of such tendency is actually a function of the sun height and the total energy balance between the surface and adjacent air layer).

The unperturbed reference run is compared to two different perturbation strengths (σ=0.25 and σ=0.10). It can be easily concluded, that the polarity of physics tendency is not affected by SPPT (it stays negative in the afternoons, while positive in the morning hours) and its structure well corresponds to the perturbation size. The higher the perturbation, the more structured the field is and with bigger extreme values.

Another logical test was to compare new SPPT with the old BMP scheme implemented in ALADIN-LAEF system by Jian Tang and Fan Xia in 2011 (for more details see their RC LACE reports). However, this was never used operationally because of the technical problems resulting into model blow up if the Surface Temperature tendency was perturbed together with all the other surface fields. After correcting some coding bugs, we managed to recreate the BMP scheme for the surface in ALADIN-LAEF and run it without crashing the model.

One can see the comparison of Surface Temperature perturbation generated by BMP and by SPPT on Fig.6. It is obvious, that the patterns generated by BMP suffer by already mentioned geographical layout, where the same values are constant for regular lat/lon rectangles - hence unphysical gradients are created on their borders (visible mainly in north Africa). While corresponding perturbation by SPPT (for σ=0.10 and L=500km) has similar distribution of the patterns over the ALADIN-LAEF integration domain with comparable extreme values (except the suspicious negative values over Greenland and Iceland, which are present only in BMP experiment). At the same time, SPPT is not spoiled by spatially constant unphysical gradients of perturbed fields.

Furthermore, in the pictures (Fig.7 and 8) one can see the perturbation generated by SPPT scheme for the other surface variables like Surface Liquid Water, Surface Ice, Surface Snow and again Surface Temperature. The perturbation patterns correspond well to the real distribution of the appropriate fields (a spring case is shown, therefore snow and ice related patterns are present only in the mountains or high latitudes). This at least technically confirms the correct implementation of the SPPT perturbation scheme for the surface variables in ALADIN-LAEF system.

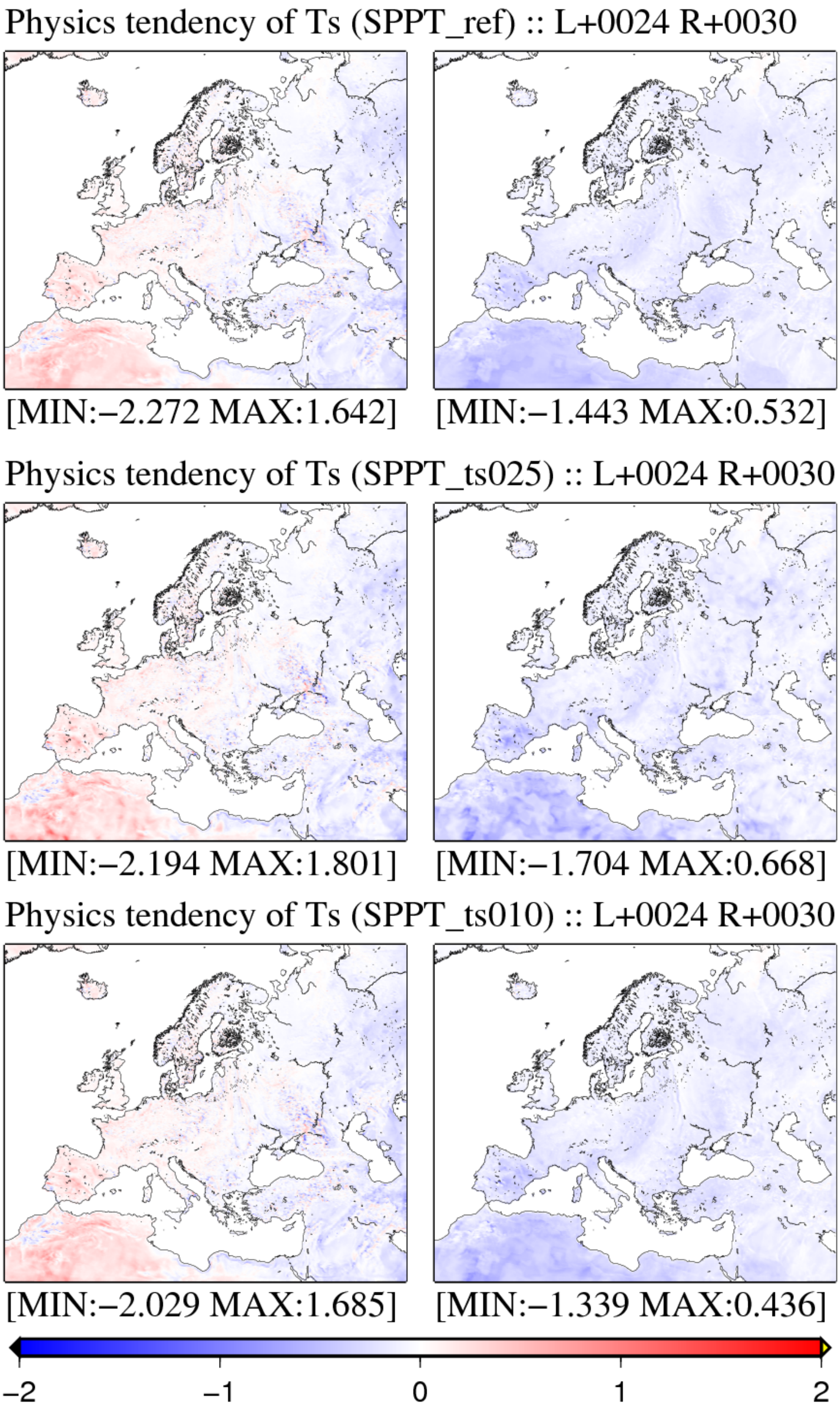

Fig 4: Physics tendency of Surface Temperature at 12:00 and 18:00 (12 UTC run) for the unperturbed reference (top), perturbed with SPPT scheme σ=0.25, L=500km, τ=2h (middle) and perturbed with SPPT scheme σ=0.10, L=500km, τ=2h (bottom).

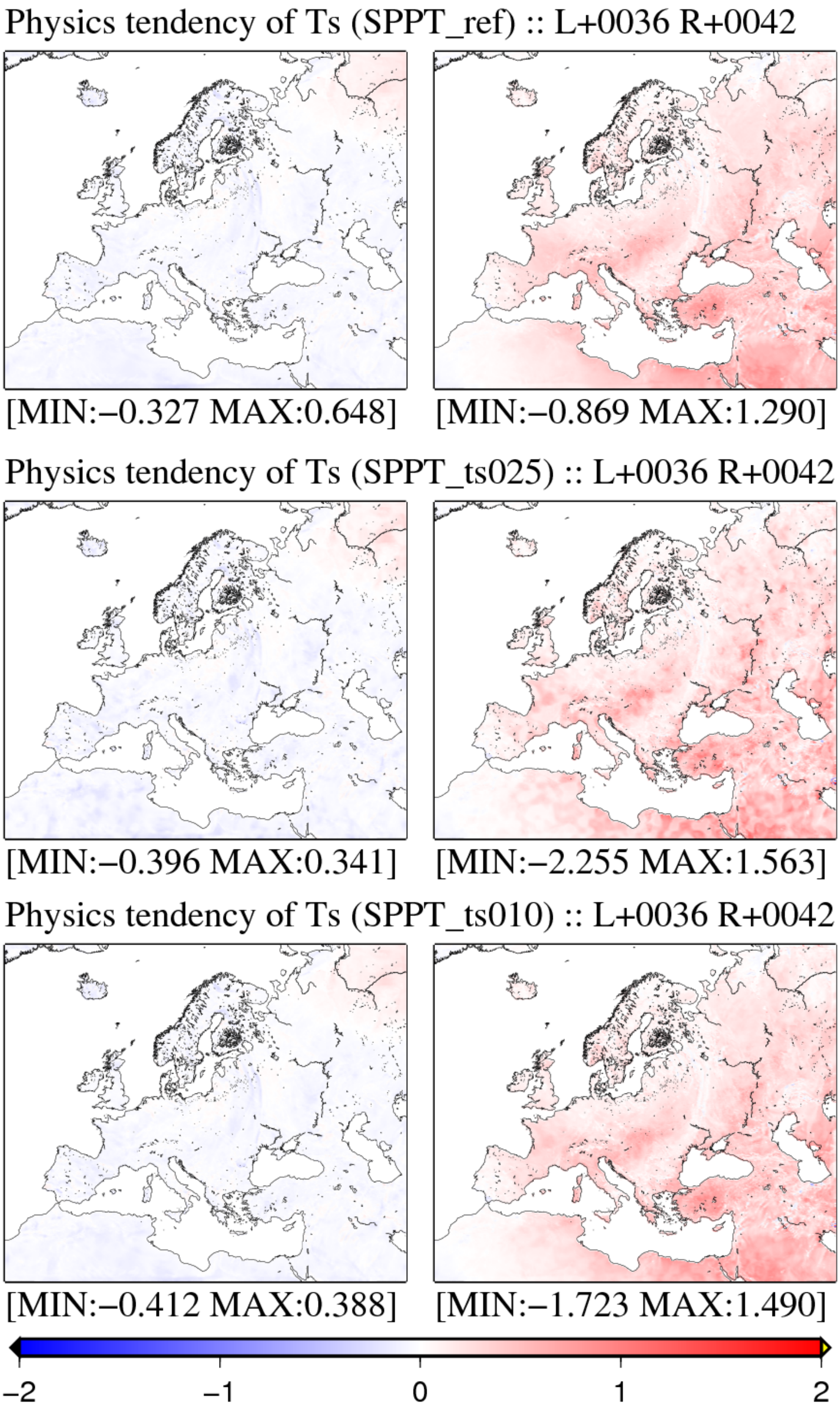

Fig 5: Physics tendency of Surface Temperature at 00:00 and 06:00 (12 UTC run) for the unperturbed reference (top), perturbed with SPPT scheme σ=0.25, L=500km, τ=2h (middle) and perturbed with SPPT scheme σ=0.10, L=500km, τ=2h (bottom).

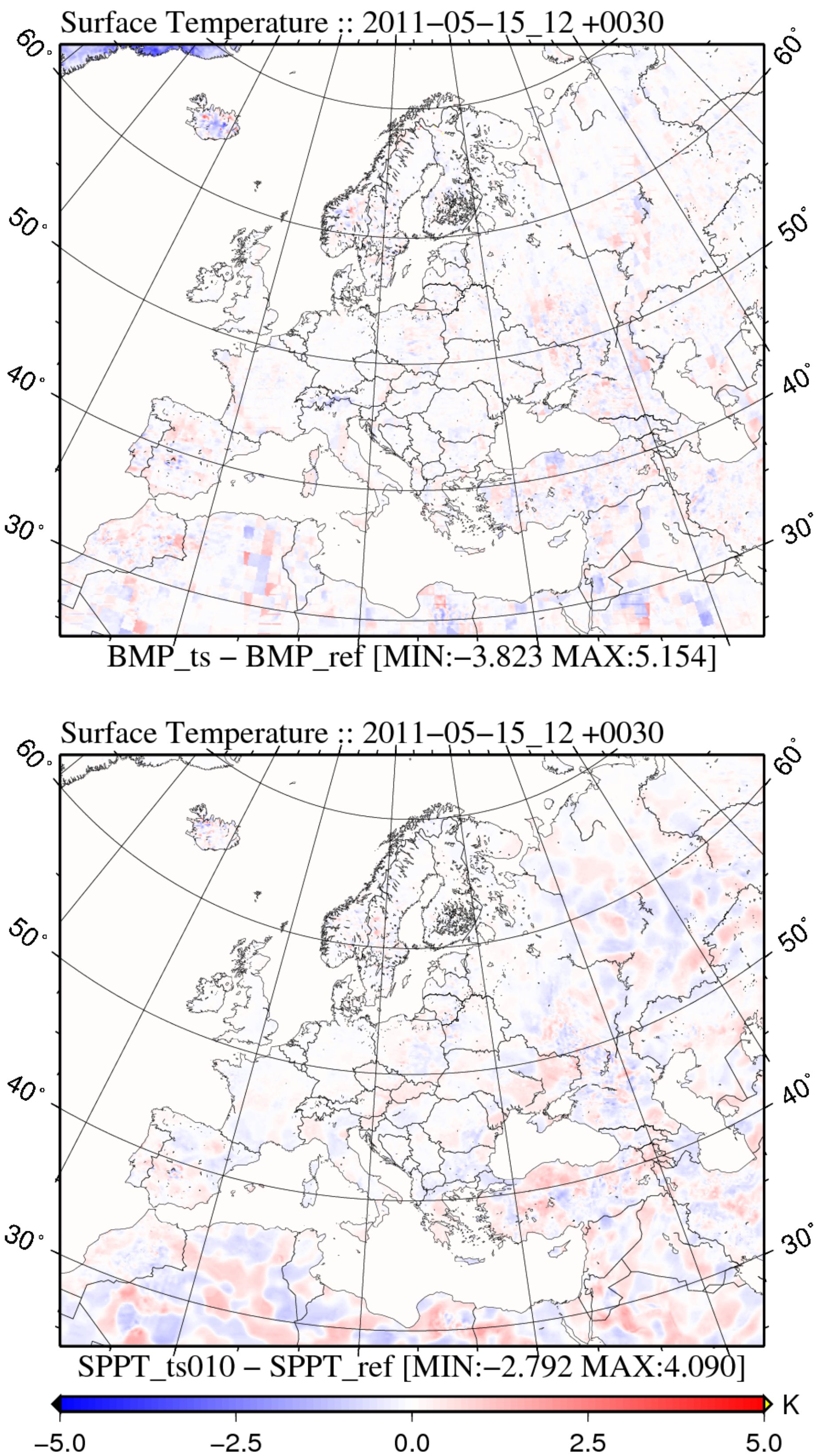

Fig 6: Departure from the unperturbed reference for the Surface Temperature after 30 hours of integration - BMP scheme (up) and new SPPT scheme (down) for one selected EPS member.

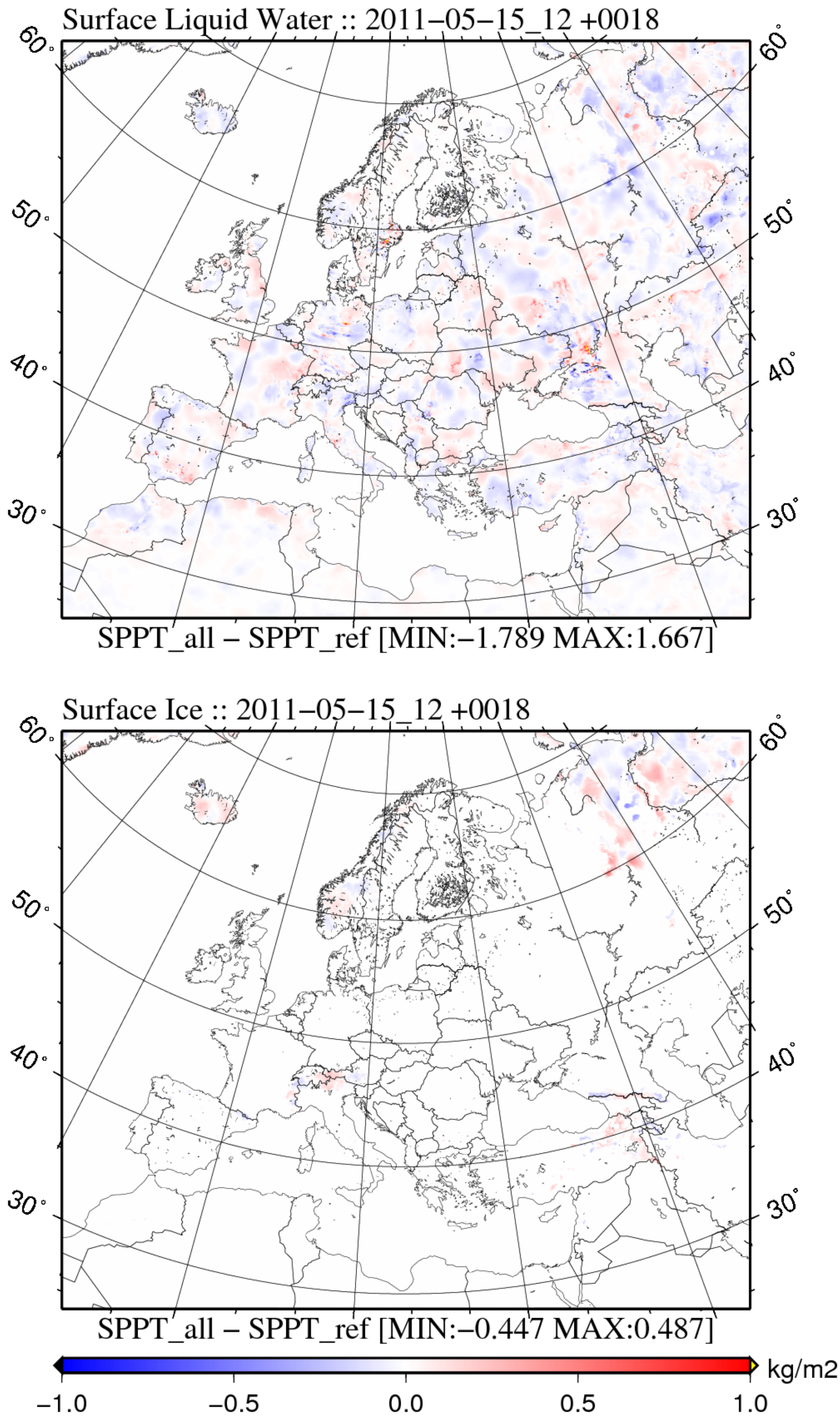

Fig 7: Departure from the unperturbed reference for the Surface Liquid Water (up) and Surface Ice (down) after 18 hours of integration with new SPPT scheme for one selected EPS member.

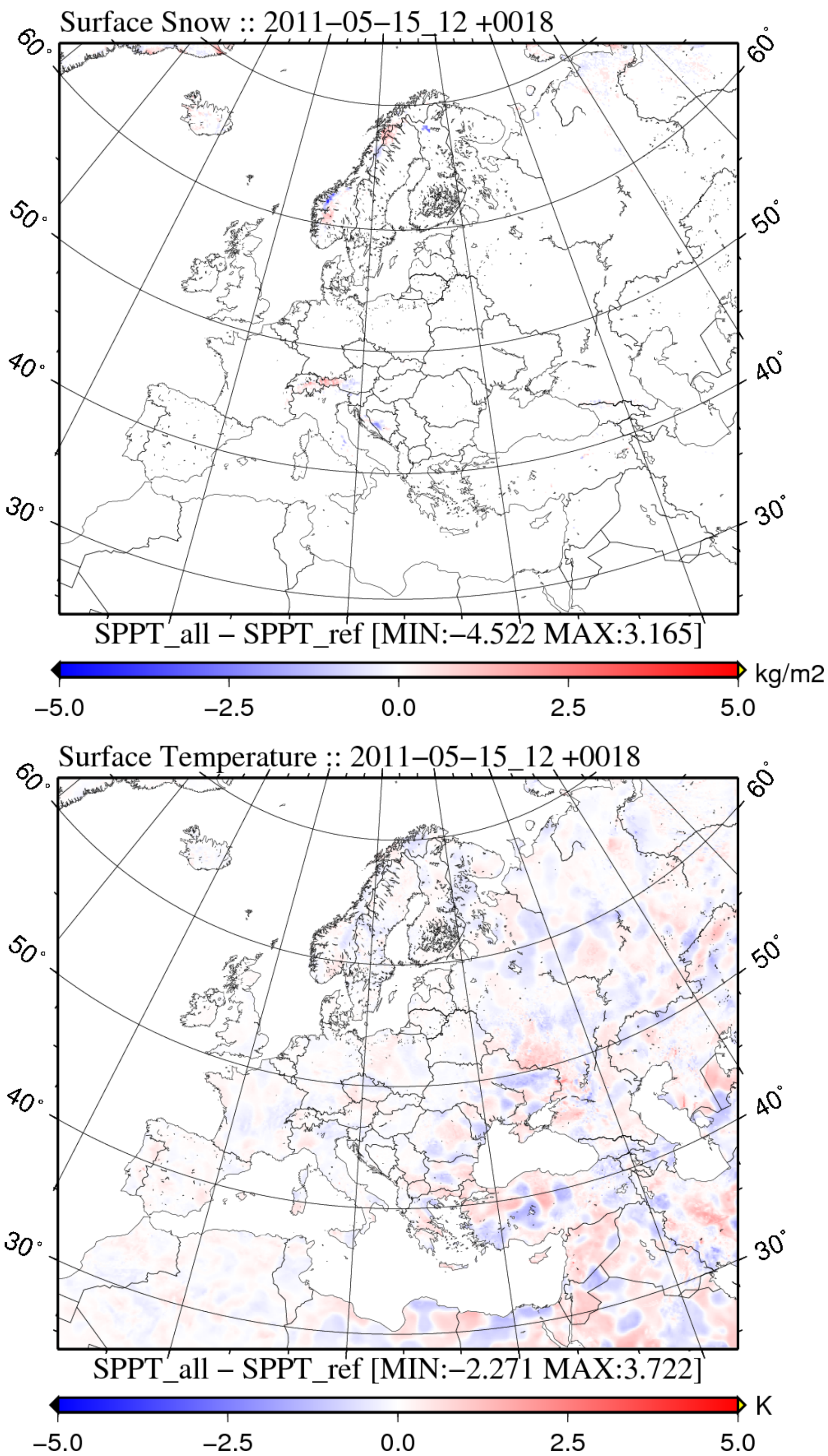

Fig 8: Departure from the unperturbed reference for the Surface Snow (up) and Surface Temperature (down) after 18 hours of integration with new SPPT scheme for one selected EPS member.

::IV. Experiments and verifications

Two main experiments have been run to test the influence of the stochastically perturbed physics tendencies of the surface prognostic fields on the overall LAM EPS scores. The results have been verified using new LAEF Verification Package. The first experiment was performed for full 3 months period of 2011 data set (mid-May to mid-August) with σ equal to 0.10. Since its sensitivity to LAM EPS performance was rather small but positive, or neutral (see Fig.10), additional experiment with σ equal to 0.25 was run for 1 month. The latter perturbation is stronger by 30% on both sides (σ=0.1 corresponds to +/-20% of the original physics tendency, while σ=0.25 means fluctuation by 50% around the unperturbed values). The impact of σ=0.25 on the general verification scores is already significant (see Fig.11, where the comparison is done for all three experiments: σ=0.1, σ=0.25 and the unperturbed reference for 1 month of ALADIN-LAEF integration).

The verification scores shown in the pictures (Fig.10 and 11) are organized by the forecast ranges averaged over the verification period and the verification domain (upper foursome) and by experiment days (bottom foursome). Daily scores of Temperature BIAS and RMSE (third row), and Outliers with Spread (last row) confirm mostly consistent improvement of ALADIN-LAEF performance over the whole experiment duration. Obviously, this effect is even more pronounced for the stronger perturbation with σ=0.25.

For the 2 meters Temperature and Humidity the scores are improved over the night hours (experiments were done for 12 UTC network, which must be taken into account looking at the plots) while for daily hours the impact is rather neutral. Likewise neutral are the scores for MSLP and Wind parameters (not shown). More importantly, there is no visible score deterioration at all. We just want to stress, that the verification domain is from technical reasons much smaller than the whole integration domain and that's why the scores are representing only the model skills in the middle Europe (see Fig.9).

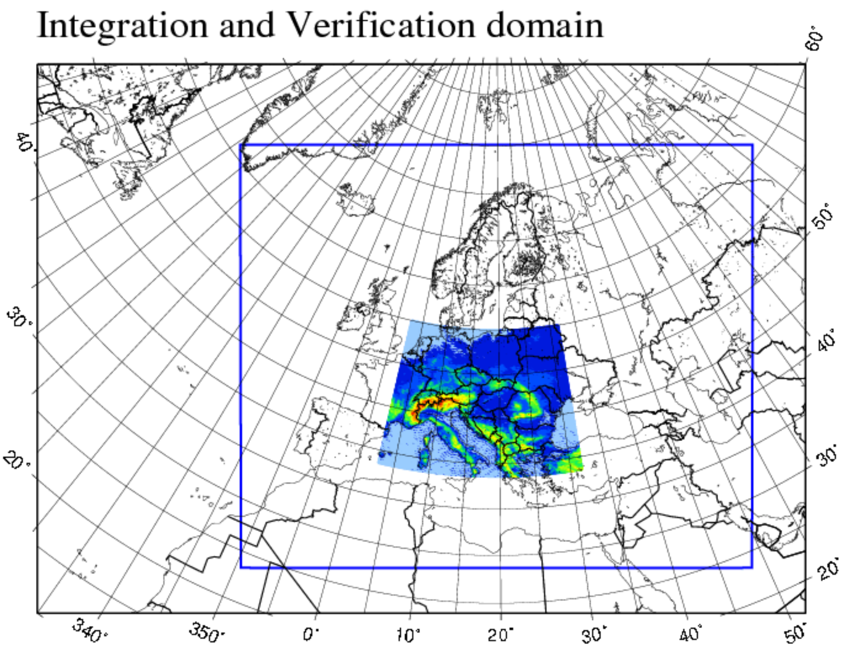

Fig 9: ALADIN-LAEF integration domain (blue rectangle) defined in Lambert projection and the verification domain with drawn model orography (regular in lat/lon projection).

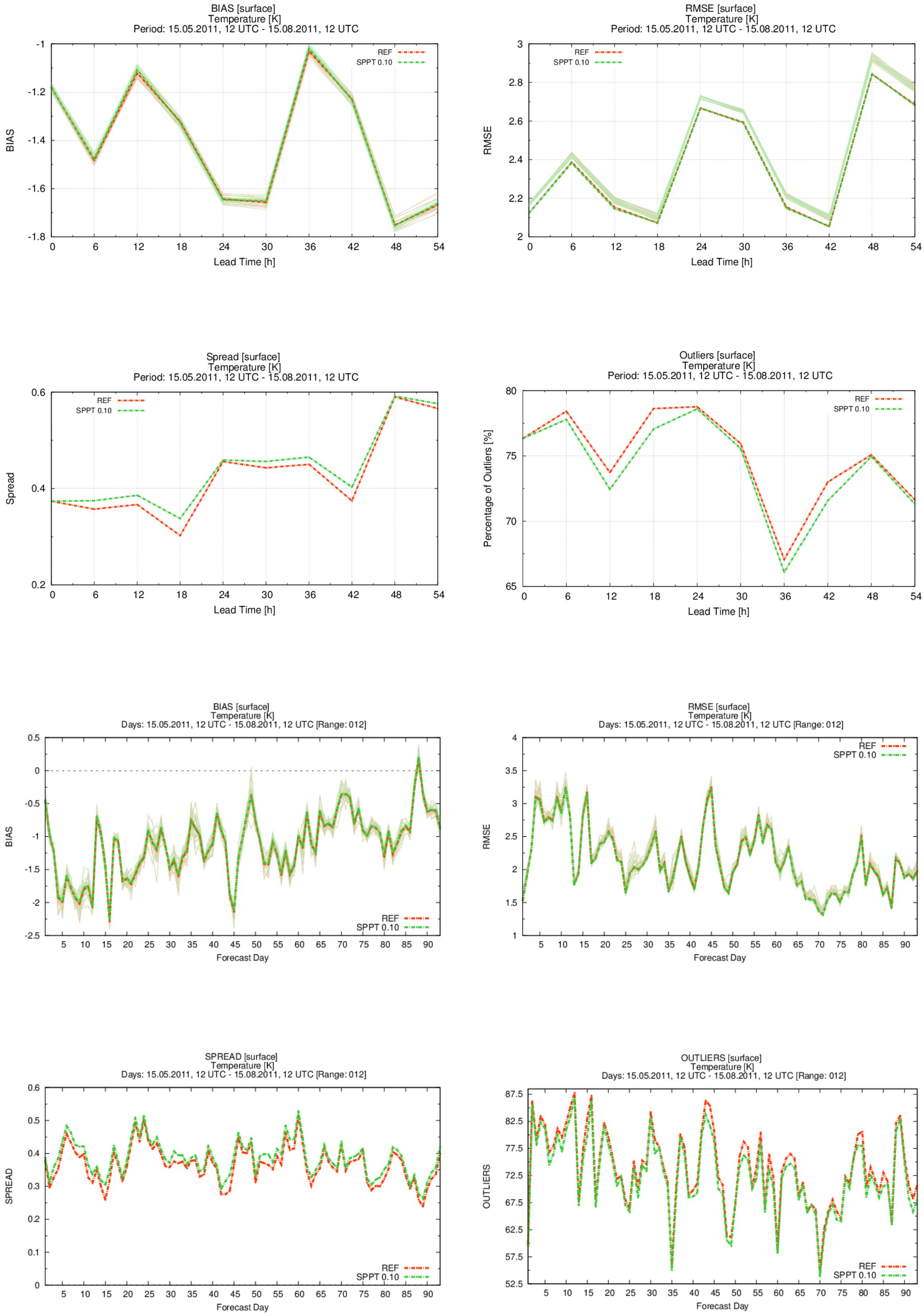

Fig 10: T2m BIAS and RMSE (first and third row), Spread and Outliers (second and last row) for the reference and perturbed experiment (SPPT, σ=0.10). [93 days verified]

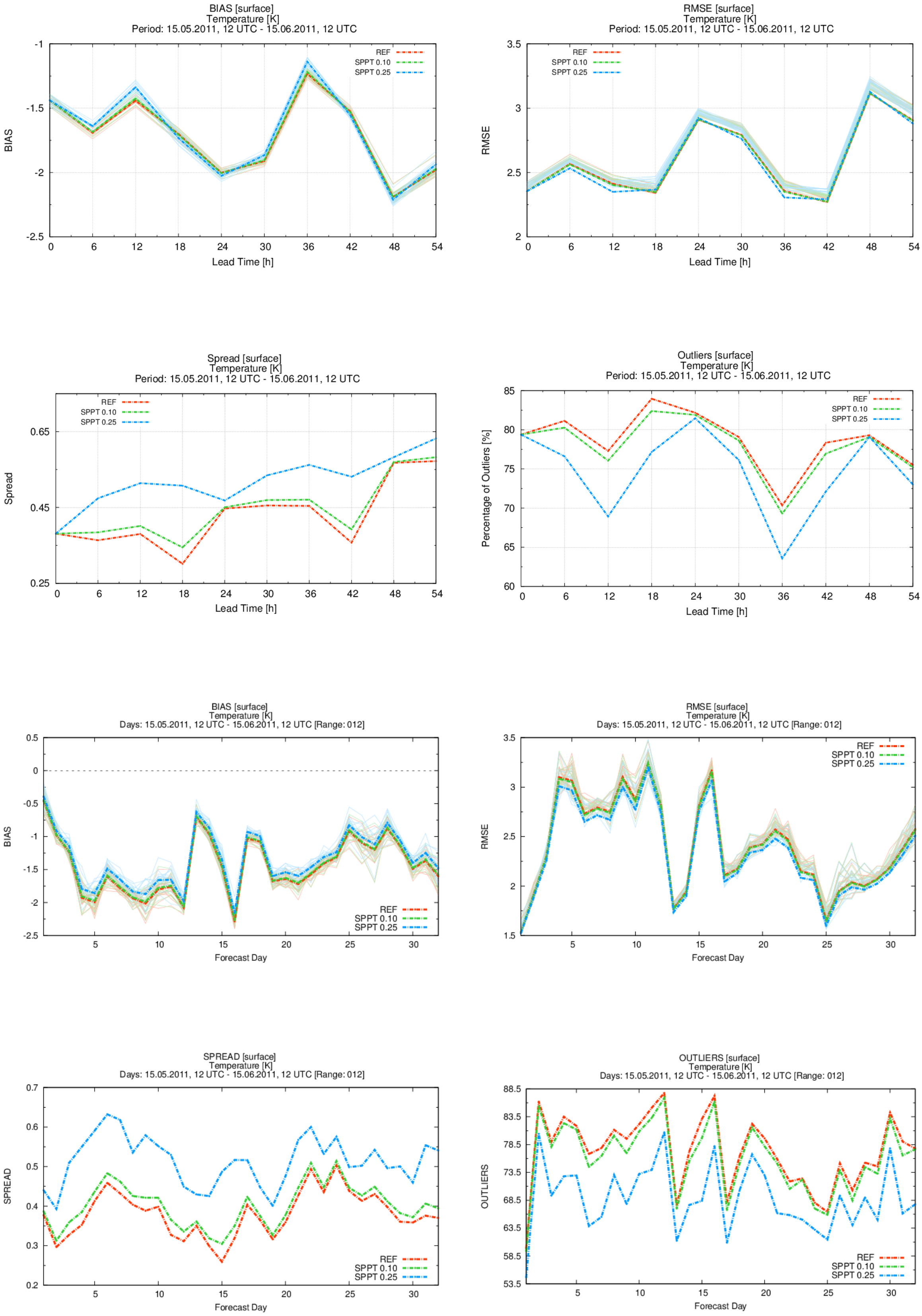

Fig 11: T2m BIAS and RMSE (first and third row), Spread and Outliers (second and last row) for the reference and perturbed experiments (SPPT, σ=0.10 and σ=0.25). [32 days verified]

::Conclusions

New SPPT scheme was implemented into ALADIN-LAEF system in order to add a stochastic perturbation into the surface model fields. This upgrade has to simulate the intrinsic model uncertainty. Technical correctness of the implementation was tested in several experiments and its impact on the whole ALADIN-LAEF system was verified for 3 months period (mid-May to mid-August 2011 data set).

Our ALADIN-LAEF system with SPPT scheme applied on the full set of surface prognostic fields proved to be stable and reliable in spite of the fact, that this approach was intentionally avoided by other centers (because of expected model instability). However, it must be stressed, that we were perturbing only the surface fields and not the upper-air ones.

The overall statistical scores have shown expected results. The ensemble system with perturbed surface prognostic fields has bigger spread and less outliers in comparison with the unperturbed reference. Moreover, ensemble mean BIAS and RMSE were improved as well, especially significant response was observed for stronger perturbation with $\sigma=0.25$. For some fields, like MSLP and Wind, this upgrade is rather neutral and there seems to be no scores deterioration at all.

However, statistical verification, as it was done here by LAEF Verification Package, is indeed not very suitable for the verification of discontinuous fields like precipitation. That is more true especially for relatively short verification period (even three months are obviously not enough). But such LAM EPS feature is obviously the one we are interested in. Therefore, a case study quantification of the new SPPT scheme applied on the surface physics tendencies and its impact on the ensemble quality (focused solely on precipitation forecast) would be highly appreciated. That could be perhaps the priority for further continuation of this topic.

::Appendix

Some technical notes - source code and output data location:

(**ECMWF**)
<u>Perl applications for ALADIN-LAEF (source code):</u>
/home/ms/at/kah/bellus/app_SPPT/

```
drwxr-x---   4 kah   at       8192 May 22 12:22 laeff/
drwxr-x---   2 kah   at       8192 Jun 18 08:08 setup/
```

/home/ms/at/kah/bellus/app_SPPT_REF/

```
drwxr-x---   4 kah   at       8192 Jun  4 11:12 laeff/
drwxr-x---   2 kah   at       8192 Jun  4 11:12 setup/
```

Perl and Shell scripts for running the experiments:
/home/ms/at/kah/bellus/exp/SPPT/
-rw-r----- 1 kah at 4669 Jun 11 14:26 cmd.exp-SPPT.sh
-rwxr-x--- 1 kah at 3224 Jun 18 08:06 run_SPPT.pl
-rwxr-x--- 1 kah at 108 Jun 18 08:07 submit_SPPT.sh

/home/ms/at/kah/bellus/exp/SPPT_REF
-rw-r----- 1 kah at 4615 Jun 10 12:22 cmd.exp-SPPT_REF.sh
-rwxr-x--- 1 kah at 3240 Jun 12 12:51 run_SPPT_REF.pl
-rwxr-x--- 1 kah at 107 Jun 12 12:46 submit_SPPT_REF.sh

ICMSH and PF data (the results):
ec:/kah/mbell/SPPT/TCC/lae/
2011051512/ .. 2011081512/ (ICMSHDW<mb>+00<rr>, PFLAEFDW<mb>+00<rr>)

ec:/kah/mbell/SPPT_REF/TCC/lae/
2011051512/ .. 2011081512/ (ICMSHDW<mb>+00<rr>, PFLAEFDW<mb>+00<rr>)

ec:/kah/mbell/SPPT025/TCC/lae/
2011051512/ .. 2011061512/ (ICMSHDW<mb>+00<rr>, PFLAEFDW<mb>+00<rr>)

GMK-packs (aladin source code):
/perm/ms/at/kah/mbell/packs/
drwxr-x--- 6 kah at 8192 Jun 11 14:11 **cy38t1**/
arp/phys_dmn/mf_phys.F90 - CALL SPPTEN_ISBA
arp/phys_dmn/sppten_isba.F90 - new routine to perturb phys.tendencies of ISBA fields
xla/module/spectral_arp_mod.F90 - bugfix

drwxr-x--- 6 kah at 8192 Jun 10 12:04 **cy38t1_ref**/
xla/module/spectral_arp_mod.F90 - bugfix

(**ZAMG**)
GRIB data for the verification domain:
/ment_arch/mproj/bellus
SPPT_REF: reference run without perturbed ISBA fields (TCC, DADA)
SPPT_ALL: run with stochastically perturbed phys.tend. of surface fields: Ts, Ws, Wsi, Wr, Sn, An, Rn (TCC, SPPT sigma=0.1, L=500km, t=2h, DADA)
SPPT_025: run with stochastically perturbed phys.tend. of surface fields: Ts, Ws, Wsi, Wr, Sn, An, Rn (TCC, SPPT sigma=0.25, L=500km, t=2h, DADA)

Verification period:
SPPT_REF, SPPT_ALL - for 3m period (15.05.2011 ~ 15.08.2011, 12 UTC run)
SPPT_025 - for 1m period (15.05.2011 ~ 15.06.2011, 12 UTC run)