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SUPERSATURATION PROBLEM IN MODELS WITH SPPT

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1. Acknowledgement

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2. Introduction

Ensembles are used nowadays not only for global models [1], but also for models on limited area domain. Uncertainty of initial state and boundery conditions are solved by ALADIN-LAEF member ensemble system. Stochastically perturbed physics tendencies (SPPT) are used to asses the uncertainty of the model itself.

Deterministic model state $X(t)$ at the time t can be written as:

$$X(t) = \int_0^t \big(A(X,\tau) + P(X,\tau)\big) d\tau, \tag{2.1}$$

where $A(X,\tau)$ represents the dynamics of the model and $P(X,\tau)$ represents physics of the model. SPPT for perturbed member model j can be written as:

$$X_j(t) = \int_0^t \big(A(X_j,\tau) + P'(X_j,\tau)\big) d\tau, \tag{2.2}$$

so this scheme is perturbing only physics tendencies $P'(X_j,\tau)$. Perturbing procedure is restricted for temperature T, specific humidity q and wind components u, v at all model levels L:

$$P'(X_j,h,\tau) = (1 + \alpha(h) r_j) P'(X_j,\tau), \tag{2.3}$$

where r_j is normal distribution with $\mu = 0$ and σ. $\alpha(h)$ is tappering function, which damps perturbations near the surface and close to the top of the atmosphere due to model stability. The value of $\alpha(h)$ lies beetween $0 \leq \alpha(h) \leq 1$, see fig. 2.1.

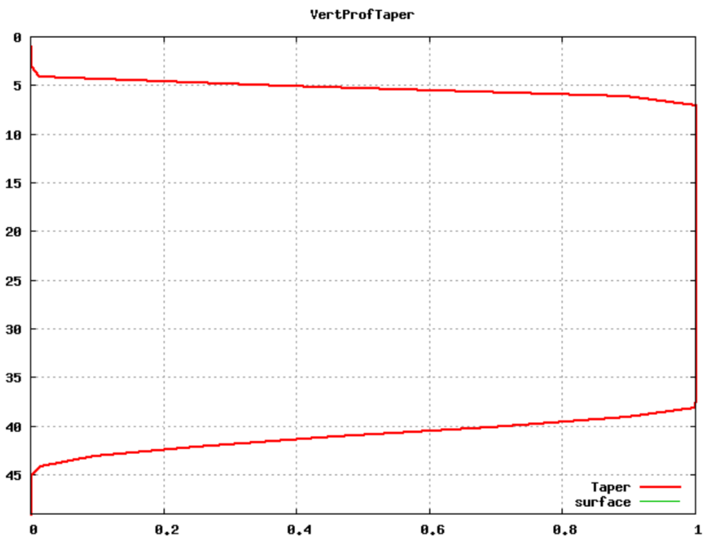

Figure 2.1: Tapering function $\alpha(h)$, [2].

The SPPT scheme systematically reduces humidity in the atmosphere [3]. The reason is that the perturbation of specific humidity or temperature can easily push the model to the "supersaturation" state. It is due to irreversible precipitation processes that lead to the drying of the model atmosphere. Some tests were done by Mihaly [4], see fig. 2.2. The main result is that SPPT also with different supersaturation check methods produces negative bias for humidity and precipitation.

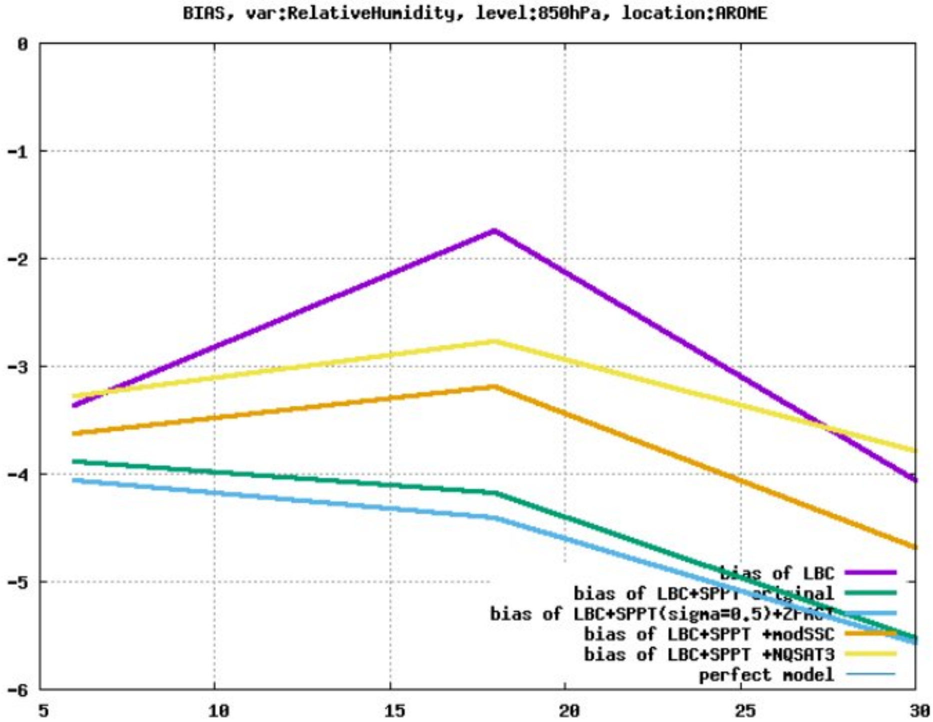

Figure 2.2: Relative humidity bias. 10 ensemble runs in Hungarian AROME domain. Collected convective cases (spring and summer 2015). Runs started at 18UTC and are coupled to PEARP members. Purple line: without SPPT. Green line: SPPT with NQSAT_SDT=0. Blue line: SPPT with NQSAT_SDT=0 and Mihaly's modification. Orange line: SPPT with Mihaly's supersaturation check. Yellow line: SPPT with NQSAT_SDT=3 [4].

3. Results

The aim of my work during the RC LACE stay at ZAMG Vienna was an investigation of the negative bias of specific humidity in SPPT in ALARO-1 cy40t1.

3.1 SPPT ISBA

First task of my stay was to test the SPPT ISBA (surface) without SPPT upper-air. A small domain with horizontal resolution 4.8 km and 360 x 288 gridpoints over Central Europe was used. ALARO-1 cy40t1 pack on ECMWF supercomputer was utilized. According to the report [5] in SPPT ISBA only the following tendencies are perturbed: surface temperature, liquid soil water content, frozen soil water content, snow albedo, snow reservoir water content, snow density and water intercepted by vegetation. SPPT surface is working when LSPSDT = .T., with pack including SPPT surface.

Following namelist settings were used:

```
&NAMSPSDT
LRDPATINIT_SDT = .F.,
LSPSDT = .T.,
LWRITE_ARP = .F.,
NSEED_SDT = MEMB,
SDEV_SDT(1) = 0.50,
TAU_SDT(1) = 7200.,
XLCOR_SDT(1) = 500000.,
/
```

Temperature scores of various model runs from 15th May 2011 for forecast length of 48 hours are plotted on the fig. 3.1. Reference was calculated as deterministic model run coupled with LAEF LBC for member 0. SPPT ISBA mean was calculated from 8-member ensemble, with the same LAEF LBCs as were used for member 0, in order to catch the effect of pure SPPT. Only stations with altitudes below 600 m a.s.l. were used for verification to limit large differences between model and real altitudes at the verification points. RMSE of ensemble mean for temperature (orange line) is during whole forecast similar to the reference run (blue line) without any significant deviations. The same results are observed for BIAS (red and green lines). Spread of the mean (black line) is less than 0.3°C. Similar results are achieved for the relative humidity at 2m, fig. 3.2. Labeling of the lines is the same as for previous figure. Spread of the ensemble mean is less than 2%.

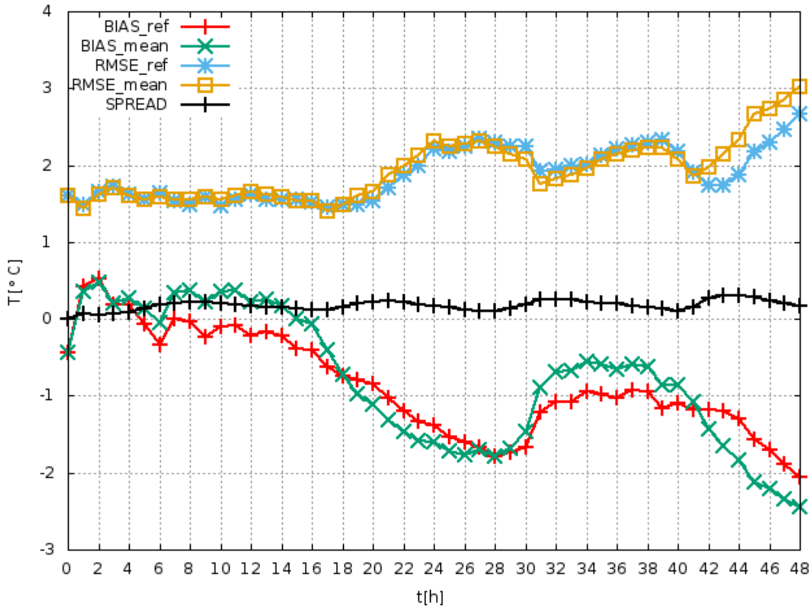

Figure 3.1: 2m temperature verification statistics for the model run from 15th May 2011. Hourly measurements from stations in the domain which elevation is less than 600 m a.s.l. were used. Red line: Bias of deterministic model run. Green line: Bias of 8-member ensemble mean. Blue line: RMSE of deterministic model run. Orange line: RMSE of 8-member ensemble mean. Black line: Spread of 8-member ensemble mean.

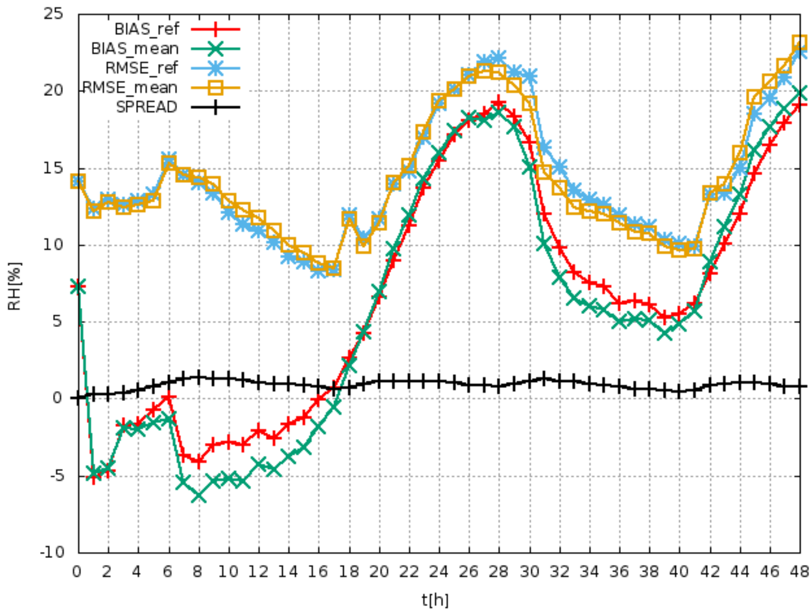

Figure 3.2: 2m relative humidity verification statistics for the model run from 15th May 2011. Hourly measurements from stations in the domain which elevation is less than 600 m a.s.l. were used. Red line: Bias of deterministic model run. Green line: Bias of 8-member ensemble mean. Blue line: RMSE of deterministic model run. Orange line: RMSE of 8-member ensemble mean. Black line: Spread of 8-member ensemble mean.

Both figures (fig. 3.1 and fig. 3.2) suggest that the effect of SPPT ISBA with the same LBCs is insignificant. Supersaturation effect is not clearly visible in this case. However, comparing these conclusions with work [5], where both perturbation methods (different LBC and SPPT ISBA) were used, the spread of the ensemble mean was singnificantly better in [5].

3.2 SPPT upper-air

These preliminary reference experiments were extended with SPPT upper-air at SHMU Bratislava. SPPT upper-air on ALARO-1 cy40t1 in our SHMU HPC (OS red hat linux) was implemented. At first, comparison beetween NQSAT_SDT=0, NQSAT_SDT=3 and deterministic model was done in order to cross-check with Mihaly results. Detailed description of these options is specified in the document [4].

As the next step the perturbation of tendencies for specific humidity and temperature was switched off, directly by modification of the routine: "src/local/arpifs/phys_ec/sppten.F90". It means only the perturbations of the wind components were used.

To optimize usage of CPU time, the small domain with 180x144 gridpoints and horizontal resolution 9.6km, see fig. 3.3 was created. The area of domain is the same as was used at ZAMG experiments (SPPT ISBA), but contains 4 times less gridpoints, each gridbox having 4 times larger area.

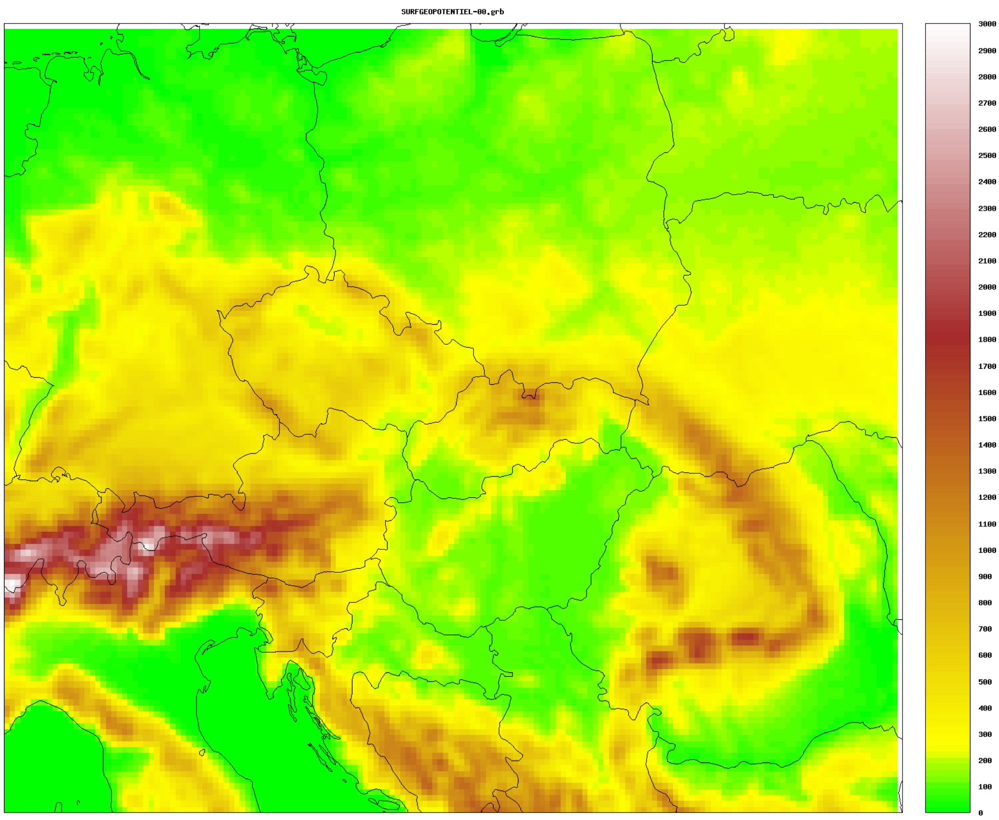

Figure 3.3: Orography of ALARO mini testing domain. 180x144 gridpoints, 9.6km horizontal resolution.

For cross-check with Mihaly's results temperature and relative humidity at the 850 hPa level were examined. On the figures 3.4 and 3.5 domain average differences of relative humidity between SPPT upper-air and reference deterministic model runs are plotted. Same LBCs for each ensemble member were used. Four independent 48h forecast runs that are plotted on small figures 3.4. Their average is shown on the big figure 3.5. Green line corresponds to the difference between ensemble mean for option NQSAT_SDT= 0 and reference. This case is on average 3% dryer compared to reference. It is in agreement with Mihaly's experiment, see fig. 2.2. NQSAT_SDT= 3 (blue line) is $\sim 0.5\%$ dryer than the reference.

Perturbation of only wind and temperature without specific humidity and without supersaturation check was aslo tried (orange line, figs. 3.4, 3.5). It is interesting that such option also causes drying of the atmosphere. Finally, perturbation of only wind components doesn't cause atmosphere drying (black line, 3.4, 3.5).

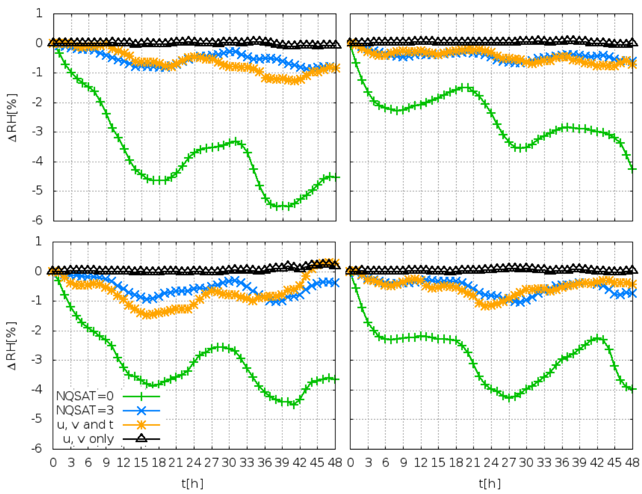

Figure 3.4: Average relative humidity difference between SPPT (8 members) and reference deterministic model run (LSPSDT=.F.) over the whole domain at the 850 hPa level. Four independent model runs averages for forecast length 48 hours were used: 29th April 2017 00 UTC (top left), 1st May 12 UTC (top right), 4th May 00 UTC (bottom left), 6th May 12 UTC (bottom right). Green line: 8-member ensemble mean with NQSAT_SDT= 0 option. Blue line: 8-member ensemble mean with NQSAT_SDT= 3 option. Orange line: 8-member ensemble mean, perturbation of only wind components and temperature without specific humidity. Black line: 8-member ensemble mean, perturbation of wind components only.

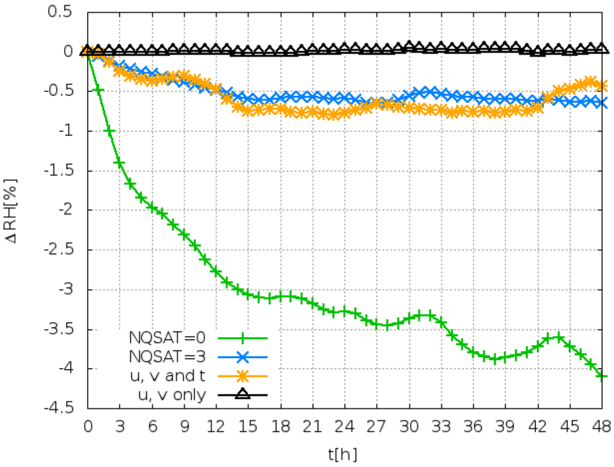

Figure 3.5: Average from dates used in fig. 3.4 of relative humidity difference between SPPT (8 members) and reference deterministic model run (LSPSDT=.F.) over the whole domain at the 850 hPa level. Green line: 8-member ensemble mean with NQSAT_SDT= 0 option. Blue line: 8-member ensemble mean with NQSAT_SDT= 3 option. Orange line: 8-member ensemble mean, perturbation of only wind components and temperature without specific humidity. Black line: 8-member ensemble mean, perturbation of wind components only.

On the figures 3.6 and 3.7 the temperature average differences at the 850 hPa level are plotted. The labeling of the lines is the same as on the previous figures. Both NQSAT_SDT= 0 and NQSAT_SDT= 3 runs are overheated. On the other hand perturbation of only temperature and wind components has negative bias. If also perturbation of temperature is switched off, the temperature at the 850 hPa is unbiased.

The possible explanation of drying and overheating observed for both options NQSAT_STD = 0 and NQSAT_STD = 3 is that the supersaturation check in both cases produces more perturbations with negative signs of the humidity tendencies. In other words, perturbations with positive tendencies of humidity are cut off, when saturation is reached. On the other hand, for temperature, perturbations with negative temperature tendencies are cut off when the dew point is reached. In case of perturbations of temperature tendencies without supersaturation check only, sometimes vapor condensates to water and precipitates to surface. That is in agreement with orange line in fig. 3.4 and 3.5. Interesting is that it causes cooling, see fig. 3.6 and 3.7 (orange line). My hypothesis is that initiation of an extra precipitation from higher levels cools lower levels including 850 hPa level. In order to check this hypothesis we propose to investigate full vertical profile in future.

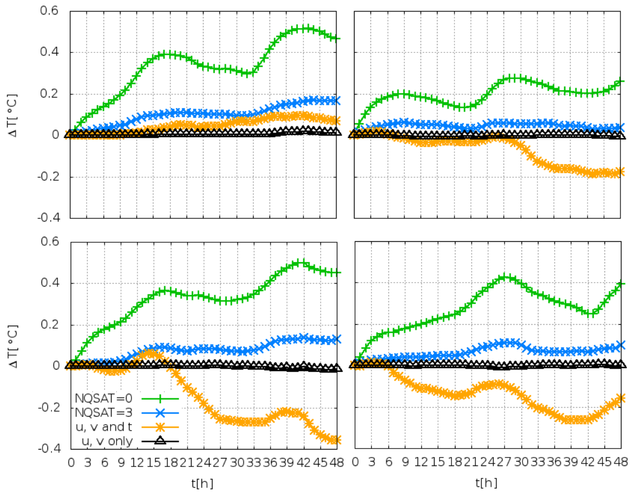

Figure 3.6: Average temperature difference between SPPT (8 members) and reference deterministic model run (LSPSDT=.F.) over the whole domain at the 850 hPa level. Four independent model runs averages for forecast length 48 hours were used: 29th April 2017 00 UTC (top left), 1st May 12 UTC (top right), 4th May 00 UTC (bottom left), 6th May 12 UTC (bottom right). Green line: 8-member ensemble mean with NQSAT_SDT= 0 option. Blue line: 8-member ensemble mean with NQSAT_SDT= 3 option. Orange line: 8-member ensemble mean, perturbation of only wind components and temperature without specific humidity. Black line: 8-member ensemble mean, perturbation of wind components only.

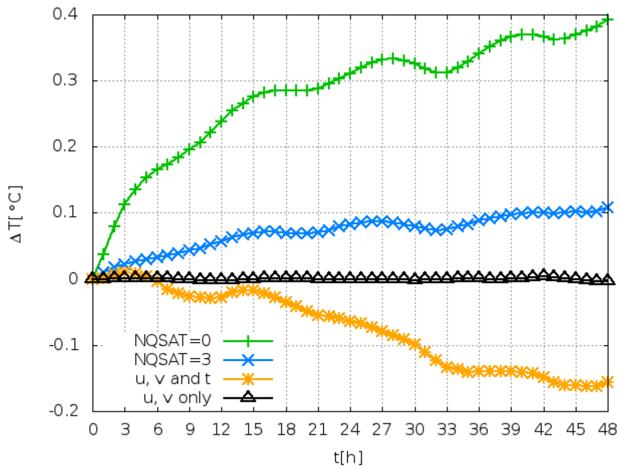

Figure 3.7: Average from dates used in fig. 3.6 of temperature difference between SPPT (8 members) and reference deterministic model run (LSPSDT=.F.) over the whole domain at the 850 hPa level. Green line: 8-member ensemble mean with NQSAT_SDT= 0 option. Blue line: 8-member ensemble mean with NQSAT_SDT= 3 option. Orange line: 8-member ensemble mean, perturbation of only wind components and temperature without specific humidity. Black line: 8-member ensemble mean, perturbation of wind components only.

Following step was to compare these experiments against analyses, figs. 3.8 and 3.9. Operational initial states (our operational 4.5km model ALARO-1 in Slovakia every 6 hours) were chosen as reference analyses. On the figure 3.8 an average bias for relative humidity over the whole domain is plotted. Reference deterministic model average is more wet than analysis. Their difference is marked with red line. The possible reason is an incorrect amount of the water in the deterministic model. SPPT bias with (green and blue line) and without supersaturation check (orange line) is closer to analysis. But this conclusion might be confusing as two systematic bugs (supersaturation and incorrect amount of the water in the deterministic model) in the model are compensating each another.

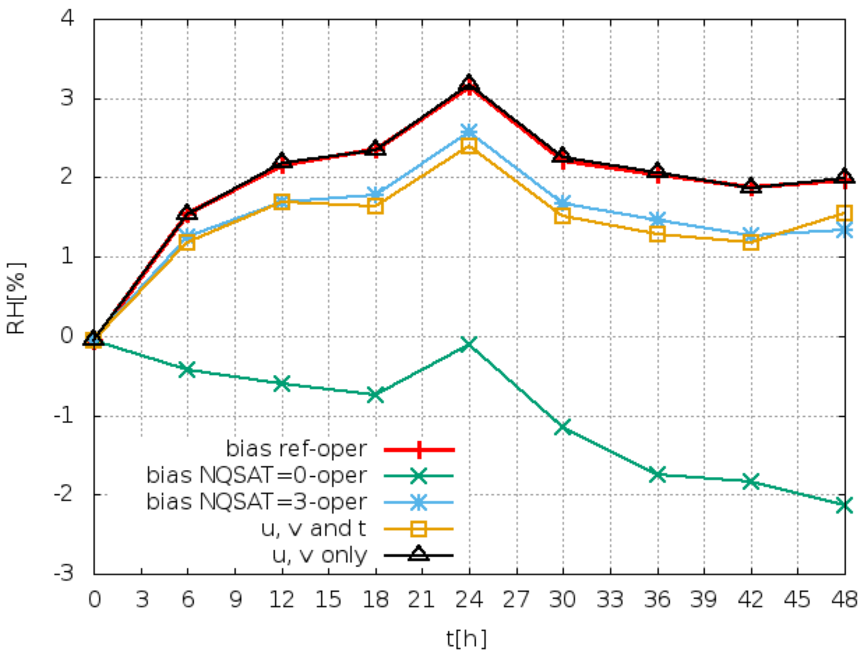

Figure 3.8: Average relative humidity difference over the whole domain at the 850 hPa level. Four independent model runs averages for forecast length 48 hours were used: 29th April 2017 00 UTC, 1st May 12 UTC, 4th May 00 UTC and 6th May 12 UTC. Red line: Reference model run without SPPT (LSPSDT=.F.). Green line: 8-member ensemble mean with NQSAT_SDT= 0 option. Blue line: 8-member ensemble mean with NQSAT_SDT= 3 option. Orange line: 8-member ensemble mean, perturbation of only wind components and temperature without specific humidity. Black line: 8-member ensemble mean, perturbation of wind components only.

Temperature lines, fig. 3.9 are in different order. Reference deterministic average is in first hours of forecast generally cooler and than after 36 hours slightly warmer. Best score is reached for NQSAT_STD = 3, but again it is a consequence of the mutual compensating of two different bugs.

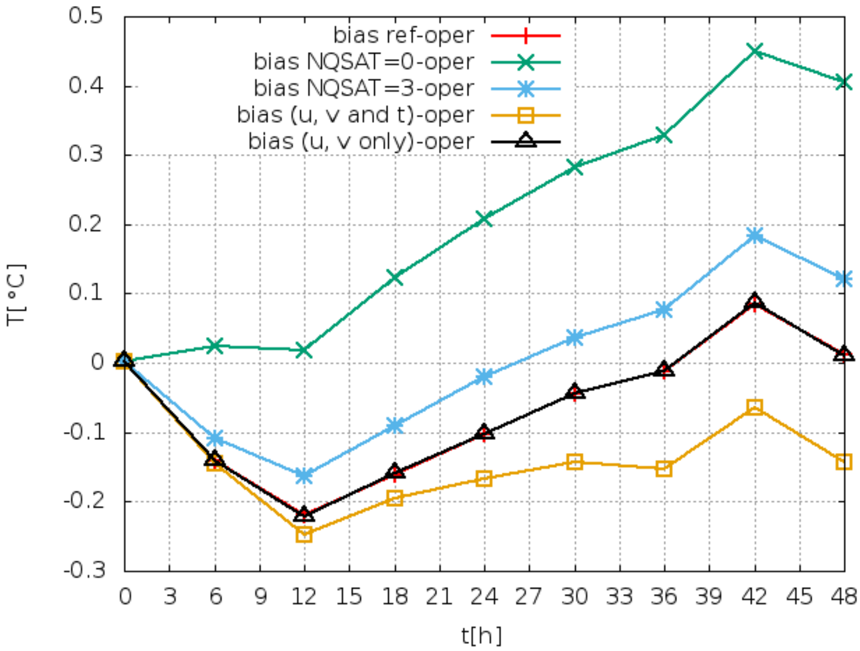

Figure 3.9: Average temperature difference over the whole domain at the 850 hPa level. Four independent model runs averages for forecast length 48 hours were used: 29th April 2017 00 UTC, 1st May 12 UTC, 4th May 00 UTC and 6th May 12 UTC. Red line: Reference model run without SPPT (LSPSDT=.F.). Green line: 8-member ensemble mean with NQSAT_SDT= 0 option. Blue line: 8-member ensemble mean with NQSAT_SDT= 3 option. Orange line: 8-member ensemble mean, perturbation of only wind components and temperature without specific humidity. Black line: 8-member ensemble mean, perturbation of wind components only.

4. Conclusion

During my stay at ZAMG several experiments with SPPT were examined. Tests with perturbations of surface fields (SPPT ISBA) without SPPT upper-air and using deterministic LBCs showed insignificant spread, comparing to work of Martin Bellus[5], where different LBCs for each LAEF member were used. On the other hand, temperature and relative humidity are unbiased, so SPPT ISBA can be used operationally.

Summary of the our results of SPPT upper-air can be formulated as follows:

1. When only the wind components are perturbed, there is no bias for humidity, nor for temperature generated in the model.

2. When also temperature and/or specific humidity are perturbed, negative bias is observed for both humidity and temperature.

The above is obvious due to irreversibility of condensation/precipitation processes. The imbalance exaggerated by SPPT scheme between the global precipitation and evaporation is known problem and ECMWF is trying to solve this by[3]:

1. A correction added to the perturbed tendency in order to have the global integral of the perturbed tendency equal to that of the unperturbed tendency (so called global fix).

2. Revising the supersaturation limiter (and also eliminating the tapering function).

However, it seems that it is difficult to obtain unbiased perturbations with SPPT upper-air. Dumping the perturbation in case of over-saturation in an iterative process still creates anti-symmetric response and decreasing the amplitude of the perturbation by significantly smaller standard deviation must logically result in decreased ensemble spread too. Obviously there is no easy solution to the drying effect caused by stochastic physics and it must be somehow addressed before its implementation in the operational LAEF system. On the other hand, specific humidity in SPPT ISBA is unbiased and so can be used operationally. The other question is how this issue is pronounced using new SPG (with 3D perturbations?) implemented by Mihaly.

Upon reviewing of preliminary results I propose to perturb only temperature tendencies without perturbation of specific humidity. It would be a two steps alghorithm :

1. Firstly the relative humidity is calculated in the next iterative step ϕ_{n+1} using unperturbed tendencies ΔT_n and Δq_n.

2. Than only temperature tendency $\Delta\tilde{T}_n$ is perturbed so that the value of the temperature in the next step is: $\tilde{T}_{n+1} = \tilde{T}_n + \Delta\tilde{T}_n$. The tendency of specific humidity $\Delta\tilde{q}_n$ is calculated from following condition: the value of relative humidity $\tilde{\phi}_{n+1}$ with perturbation of temperature tendency is chosen the same as the value of relative humidity ϕ_{n+1} without perturbation of temperature. So $\tilde{\phi}_{n+1} \equiv \phi_{n+1}$

Thus by symmetric temperature perturbations the ensemble humidity can be unbiased, if the response of the model is linear. This method was never used and can be verified in the future.

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