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Improving wintertime low level cloud forecasts in a high resolution numerical weather prediction model

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Abstract— In this study, the performance of a high resolution numerical weather prediction (NWP) model is investigated in a particular weather situation, namely, in winter anticyclonic cases over land with low level clouds and fog. Most NWP models tend to underestimate low level cloudiness during these events which causes the overestimation of daytime temperature. Several sensitivity tests are performed to trace the cause of the erroneous model performance, and it is shown that model microphysics and, in particular, the autoconversion of cloud ice to snow is responsible for the underestimation of cloud cover. A modification is proposed which significantly reduces ice autoconversion and consequently keeps the low level clouds for situations with temperatures below freezing level. The modification is tested on several case studies and also on longer time intervals and proves to be applicable for operational model runs.

Key-words: numerical weather prediction, low level clouds, physical parameterization, cloud microphysics, ice autoconversion

1. Introduction

Simulating wintertime low level cloud cases is a challenging task for most operational numerical weather prediction (NWP) models. The difficulty of these situations from the modeling point of view is that several processes (radiation, turbulence, microphysics) are interacting to form the low level cloud layer. Recently, several modeling groups started to investigate these cases in more details and proposed modifications to improve model performance. At the European Centre for Medium-Range Weather Forecasts (ECMWF), experiments concentrated on low level cloud cases over sea (*Ahlgrimm* and *Forbes*, 2014) and over high latitudes (*Forbes* and *Ahlgrimm*, 2014) and proposed several modifications in the boundary layer and shallow convection schemes and in the microphysics parameterization. Over the UK, during the 2014 Local and Non-local Fog Experiment (LANFEX, *Price et al*., 2017), observations and LES simulations have been used by the Met Office (*Boutle et al*., 2018) to improve the parameterization of cloud-droplets number in their UKV NWP model. In France, observations from the ParisFog (*Haeffelin et al*., 2010) campaign have been used to study the impact of surface heterogeneities (*Mazoyer et al*., 2017) at very high resolution with the Meso-NH model. A deposition term was added to the droplet sedimentation (representing the interception of droplets by the plant canopies), in order to have more realistic cloud water contents. At Météo-France, dedicated studies on fog have been performed with the AROME (*Seity et al*., 2011) model, such as *Philip et al.* (2016) who showed the impact of the model vertical resolution, and exhibited model deficiencies in cloud-base-lowering fog cases.

In this paper, the performance of the AROME model is investigated in winter anticyclonic cases over land. During strong winter anticyclones, cold air resides near the surface and no significant fronts occur which could sweep out the cold air from the Pannonian Basin. As solar irradiation is quite low in this season, the morning fog is not dissolved, it is only elevated to about 300-500 m above ground level, and a stratus layer is formed which stays constant during daytime. The elevation of the fog layer is basically caused by the high albedo of the cloud top, which causes the cloud top to cool even after sunrise. Consequently, condensation occurs at the cloud top and the fog starts to elevate. This kind of situation can typically last for 7–10 days over Hungary. Due to low wind speeds and constant cloudiness, the mixing height of pollutants is relatively low and the concentration of air pollutants can rise significantly. Generally, the AROME model – similarly to other NWP models applied at the Hungarian Meteorological Service (HMS) – is not very successful in simulating this weather phenomenon. The stratus layer tends to be dissolved by the model by early afternoon, and consequently, afternoon temperatures are overestimated and night temperatures are underestimated by the model.

2. Experimental setup and case study

For this study, the AROME non-hydrostatic high resolution model was used (*Termonia et al*., 2018). The development of AROME (Application of Research to Operations at Mesoscale) was initiated at Météo-France (*Seity et al*., 2011) at the beginning of the 2000’s and is currently further developed in the ALADIN and HIRLAM NWP modeling consortia. The AROME model has three main components: the non-hydrostatic ALADIN dynamical core (*Bubnová et al.*, 1995; *Benard et al.*, 2010), the atmospheric physical parameterizations, which are taken from the French Meso-NH research model (*Lafore et al.*, 1998), and the SURFEX surface model (*Masson et al.,* 2013). A mesoscale data assimilation system with a three-dimensional variational (3D-VAR; *Fischer et al.*, 2005) scheme for the upper-air and an optimum interpolation technique for the surface analyses provides reliable initial conditions for the AROME model.

At the Hungarian Meteorological Service, the AROME model is run operationally since 2010 (*Szintai et al.*, 2015; and model references therein). The model is integrated at 2.5 km horizontal resolution with 60 vertical levels and uses lateral boundary conditions from the IFS (Integrated Forecast System) model of ECMWF. The AROME assimilation system, using conventional observations (synop, radiosoundings, AMDAR), was operationally implemented in 2013 (*Mile et al.,* 2015).

The selected case study (November 30, 2011) was a late autumn day with stratus cover of nearly the whole Pannonian Basin. The simulation started at 00 UTC on November 30, 2011 and lasted 14 hours. In the reference simulation, initial and lateral boundary conditions for AROME were interpolated from the ARPEGE model, which is a global model run operationally at Météo-France (*Courtier et al.*, 1991).

Fig. 1 shows the ARPEGE and AROME forecasts and the satellite observations of low level cloud cover. At the start of the simulations both models diagnose the spatial extension of the fog well. As the simulation proceeds, both models erroneously dissolve the fog over the western part of Hungary. Over the eastern part of the country, ARPEGE keeps most of the low level clouds, while AROME dissolves a considerable part of the fog.

First, the performance of ARPEGE and AROME over the western part of Hungary was investigated. Over this area both models dissipate the fog and give wrong low level cloud forecasts. Vertical profiles of wind speed (*Fig. 2*) in AROME show that there is a substantial difference between the western and eastern parts of Hungary. Over the eastern part, wind at higher levels (i.e., at and above the height of the stratus layer) is constant or even decreasing during the simulation, while over the western part wind speed is increasing to about 14 m/s above the boundary layer. It is assumed that over the western part this strong wind increases the mixing in the model in the boundary layer and dissolves the fog/stratus. As this effect is considered to be a large scale phenomenon, in the following the investigation is focused on the eastern part of Hungary.

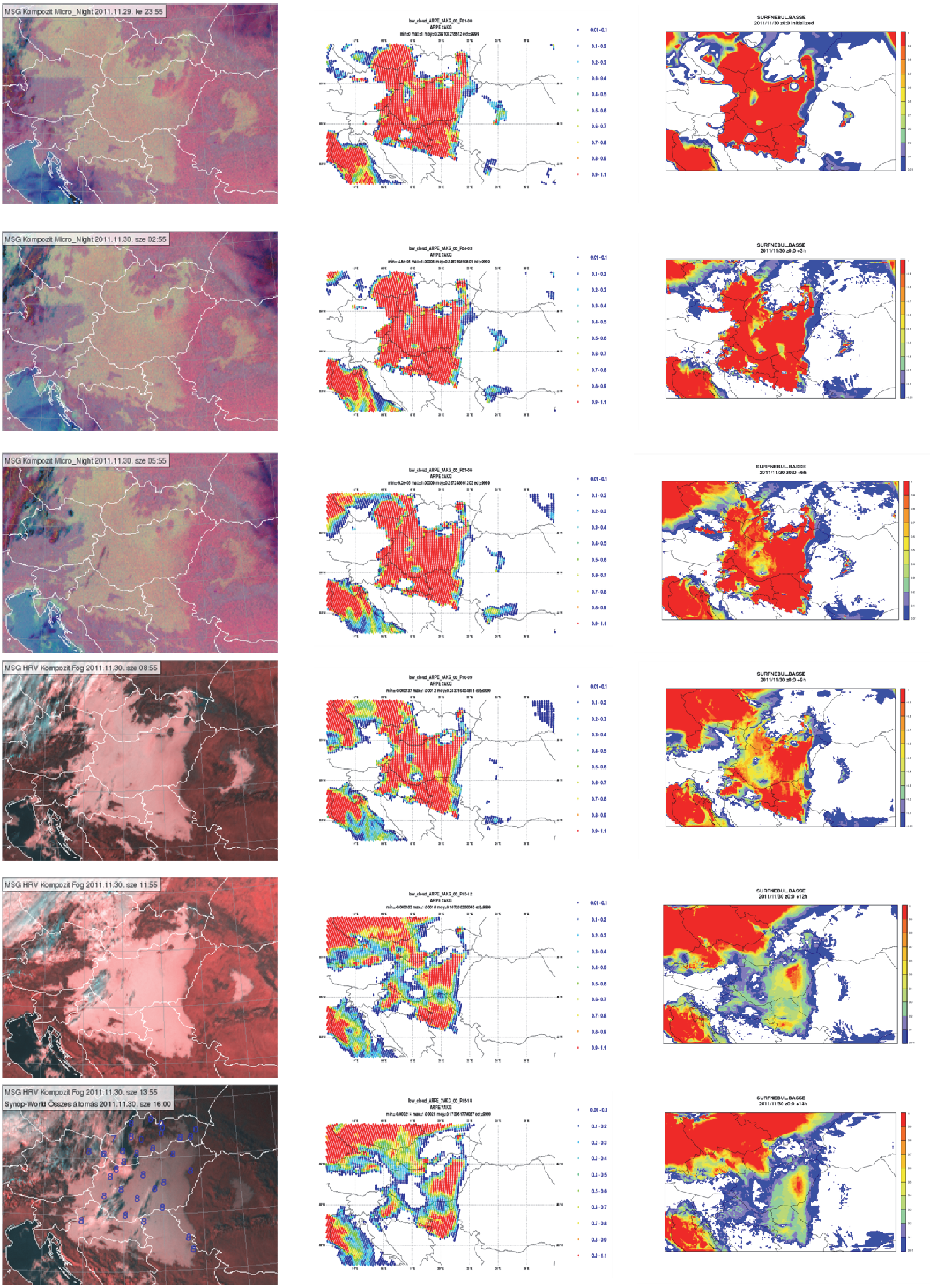

Fig. 1. Reference runs of the selected case study (November 30, 2011). Satellite observations (first column), ARPEGE (second column) and AROME (third column) forecasts of low level cloud cover. Each row refers to a single forecast time: 00 UTC (initial time), 03 UTC, 06 UTC, 09 UTC, 12 UTC, and 14 UTC. On the lower left picture, numbers indicate synop observations of low level cloudiness. For the model fields, white indicates no clouds, red indicates full cloud cover.

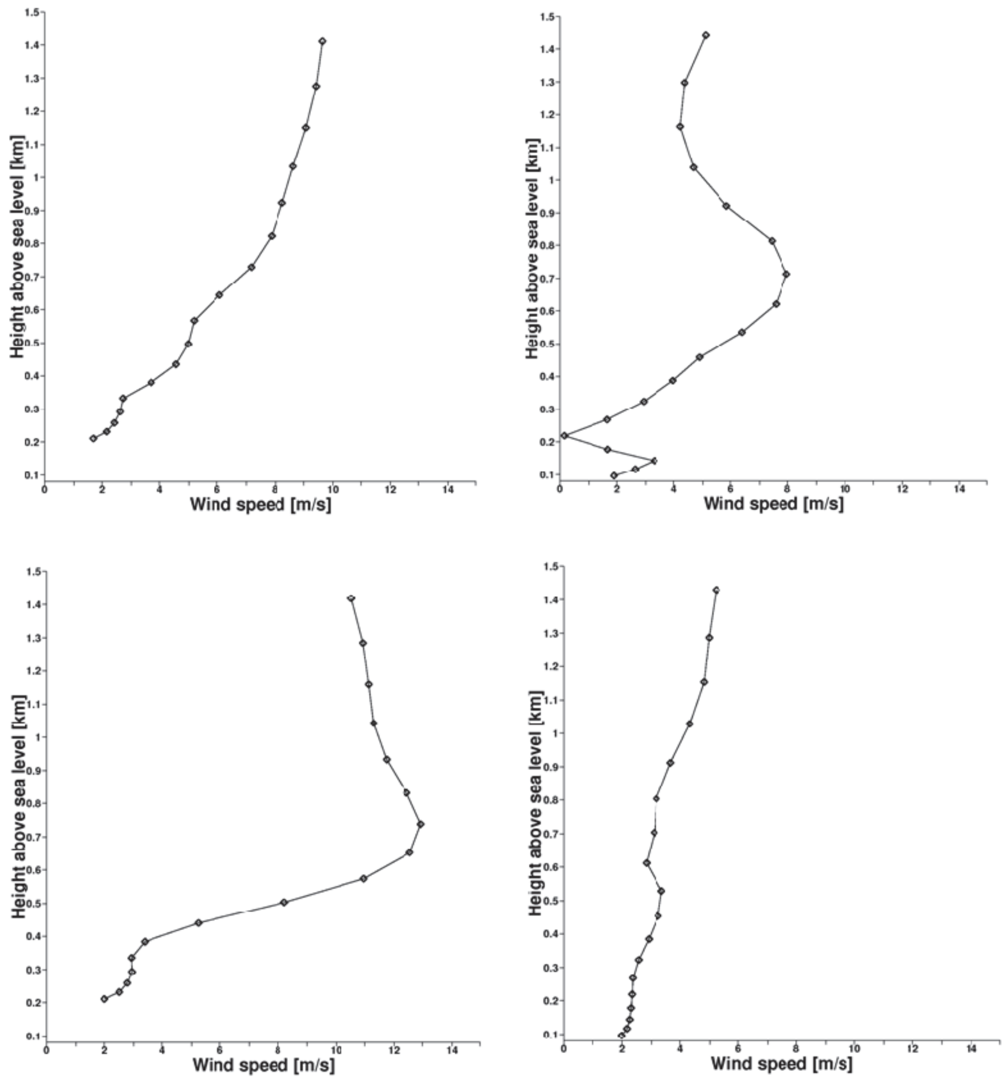

Fig. 2. Profiles of wind speed in AROME for a grid point in the western (left column) and eastern (right) parts of Hungary for November 30, 2011. Forecast range is +1h (01 UTC, upper row) and +14h (14 UTC, lower row).

3. Sensitivity tests

As a priori it was not known which of the processes involved (radiation, turbulence, microphysics) are responsible for the wrong forecast in the AROME model, several sensitivity tests were completed to diagnose the problem. These experiments are described in detail in the following.

The reference run was not using data assimilation, AROME was run in dynamical adaptation mode, i.e., the initial state was produced by interpolating the ARPEGE analysis to the AROME grid. In the first sensitivity test, the impact of data assimilation was tested. An assimilation cycle with 5-day spin-up was run for the selected case. In the atmosphere, the 3DVAR method was applied using conventional (synop and radiosounding) observations, while on the surface, the optimal interpolation method (OI_MAIN) was applied. The application of data assimilation has an overall neutral but spatially variable impact on the low level cloud forecast in AROME (*Fig. 3a*).

The second sensitivity test aimed at quantifying the impact of lateral boundary conditions. In this experiment, boundary conditions from the ECMWF/IFS global model were used instead of the ARPEGE global model. Impact on the stratus cloud cover over Hungary was rather small (*Fig. 3b*).

The choice of the subgrid statistical cloud scheme has also been investigated. At the Hungarian Meteorological Service, a diagnostic formulation (*Sommeria* and *Deardorff,* 1977) is used operationally (used also in the reference run), while at Météo-France a prognostic one (*Chaboureau* and *Bechtold,* 2002). As experienced for several other case studies, the prognostic formulation gives much less low level clouds and tends to produce a low level cloud cover value of "zero or one". For the given stratus case, the prognostic formulation gives much worse results than the reference (*Fig. 3c*).

The impact of turbulence parameterization has also been tested. It was supposed that Turbulent Kinetic Energy (TKE) is too high in the boundary layer and too strong mixing dissipates the fog in AROME. To test this assumption, the dissipation rate for TKE was increased. Surprisingly, this resulted in even less stratus (not shown). In a second experiment, the dissipation rate was decreased (from 0.85 to 0.2) which resulted in slightly more low level clouds in AROME (*Fig. 3d*). This model behavior is still under investigation.

It was assumed that one reason for the dissipation of stratus in AROME could be that after sunrise, more short wave radiation is transmitted through the fog layer in the model than in reality. Consequently, surface downward short wave radiation simulations were verified with the radiation measurement network of the Hungarian Meteorological Service, which consists of 39 stations. For the present case study, only four stations were selected in the eastern part of Hungary, where stratus was present the whole day both in reality and in ARPEGE, but not in AROME. Time series show that ARPEGE slightly overestimates the short wave radiation after sunrise, and the reference version of AROME simulates even higher values than ARPEGE. One of the main differences in the radiation settings of the two models is the value of the long wave inhomogeneity factor (*Nielsen et al.*, 2014), which accounts for an increased radiation transfer in clouds. This parameter is set to 0.9 in ARPEGE and 0.7 in AROME. To test the impact of this parameter, both the short wave and long wave inhomogeneity factors were set to 1.0 in AROME. These settings result in a lower downward short wave radiation flux at the surface in AROME (*Fig. 4*). The increased optical thickness of clouds and the consequently slower heating of the boundary layer slightly increase the low level cloud cover over the eastern part of Hungary (*Fig. 3e*). In areas with frontal activity (north of Hungary), the modification has no impact on cloud cover.

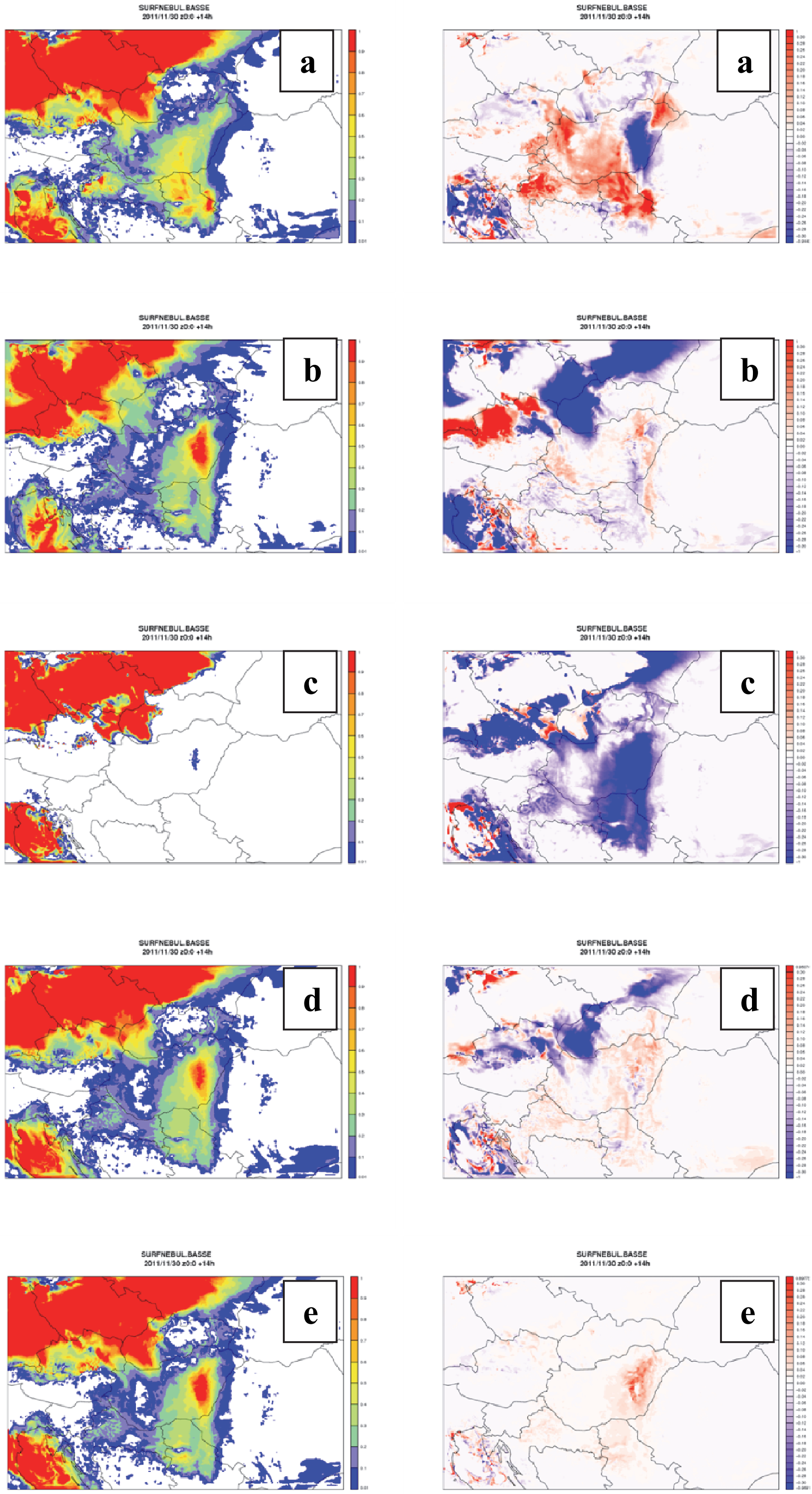

Fig. 3. Sensitivity experiments for AROME on November 30, 2011, at 14 UTC: (a) data assimilation, (b) lateral boundary conditions, (c) statistical cloud scheme, (d) turbulence parameterization, (e) cloud inhomogeneity factor in the radiation parameterization. Left column: low level cloud cover (white indicates no clouds, red indicates full cloud cover); right column: low level cloud cover difference (experiment-reference; red colors indicate more low level clouds in the experiment).

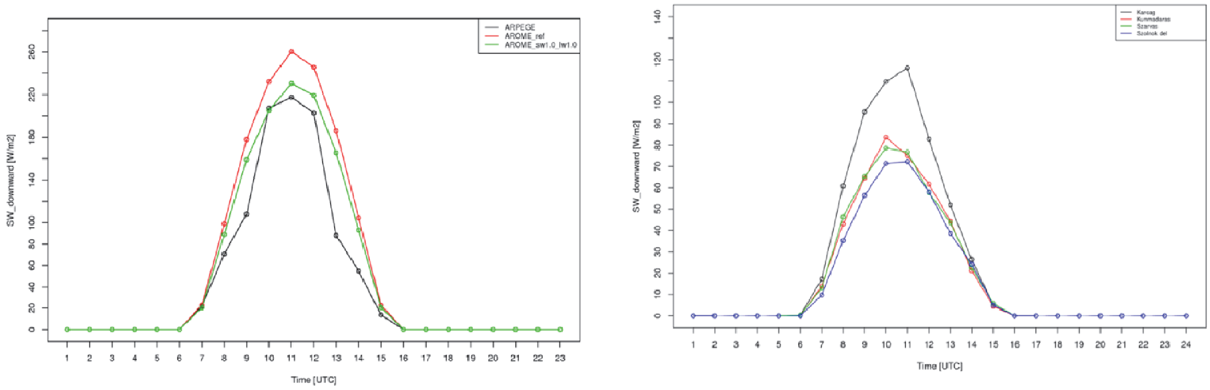

Fig. 4. Simulated (left) and observed (right) time series of downward short wave radiation on the surface on November 30, 2011. Model values are horizontally averaged on a 1º×1º box, which includes the ground measurements plotted on the right panel. Note the scale difference of the vertical axes between the two plots.

As shown in *Fig. 4*, even with the modification of the inhomogeneity factor, the simulated shortwave downward radiation of AROME is about three times as large as the measurements around noon (220 W/m^2 in AROME as compared to 70 W/m^2 in the measurements). To validate whether this overestimation is caused by the error in the radiation or in the microphysics scheme, the one-dimensional version of the AROME model (MUSC) was used. In this experiment, MUSC was initialized with the profiles and surface properties of the 3D AROME model and was also forced with tendencies obtained from the 3D AROME model. It was found that at 12 UTC, if the thickness of the cloud is enlarged by a factor of two (a value assumed to be close to reality) and the cloud liquid water content is increased from 0.1 g/kg to 0.3 g/kg (the latter is a typical value for continental stratus according to *Hoffmann* and *Roth*, 1989), then the simulated downward shortwave radiation is close to observations. Consequently, the radiation parameterization is most likely not responsible for the wrong low level cloud simulation of AROME.

Sensitivity tests on surface parameters were performed with MUSC in one dimension. AROME and ARPEGE 1D use the same initial vertical profiles. Only a few variables are changed in the initial surface file. *Fig. 5* shows that this case is very sensitive to the vegetation fraction (VEG) and soil wetness index (SWI). With a bare (VEG=0) and moist (SWI=0.8) ground, AROME is not able to dissipate the cloud even if the cloud base and top are higher than in ARPEGE. In that case, moisture is easily taken from the first ground layer. With VEG=100% (a and c), it is more difficult to feed the atmosphere with moisture coming from the ground. Indeed, water has to be taken by the roots and is then provided to the atmosphere via plant evapotranspiration. Moreover, a too dry soil (SWI = 0) dissolves the fog during the afternoon, both in ARPEGE and AROME (c and d). Consequently, differences in soil moisture and/or vegetation fraction may partly explain differences observed between ARPEGE and AROME 3D runs.

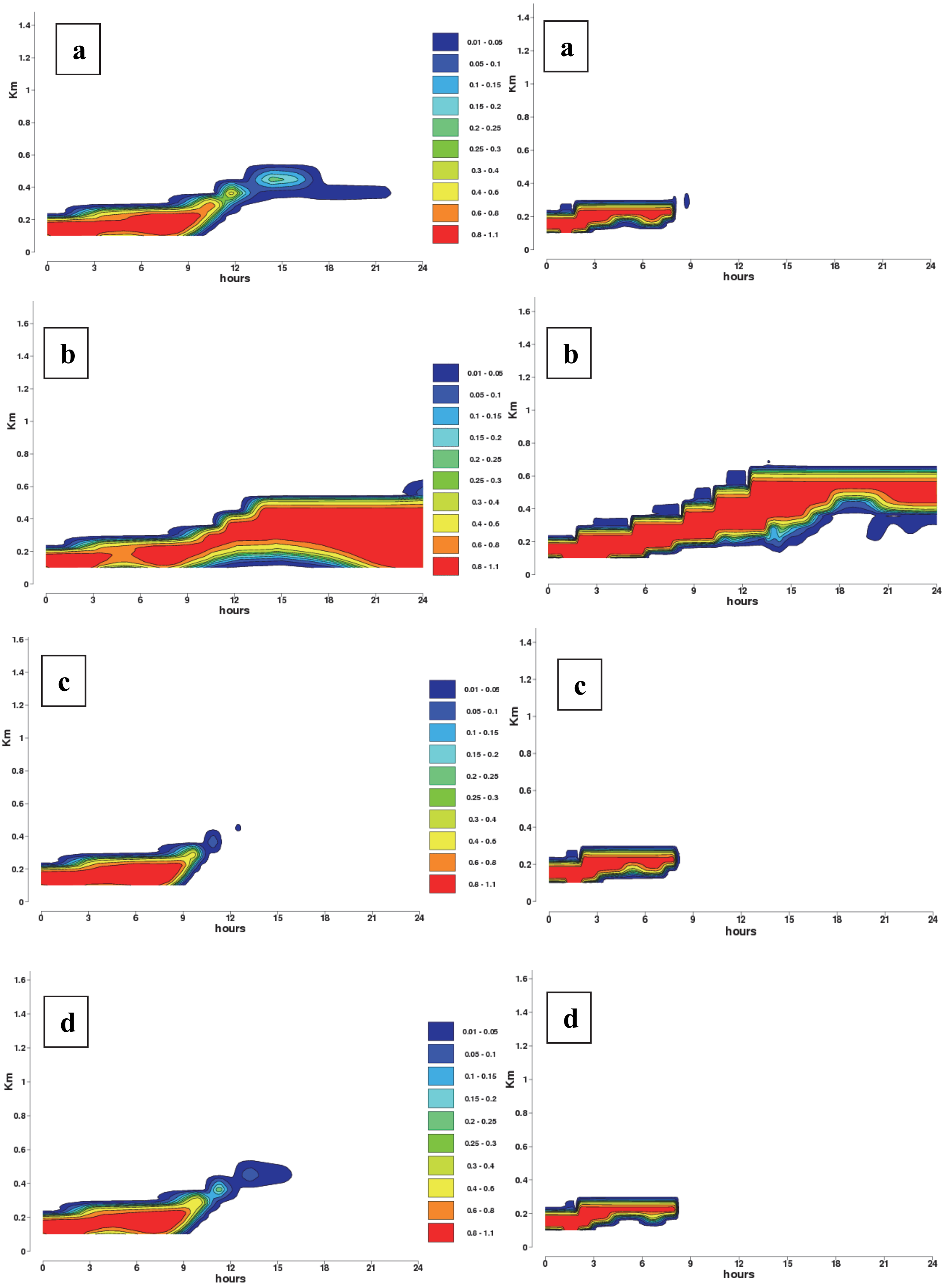

Fig. 5. One dimensional experiments: sensitivity tests on surface. Simulated cloudiness (white indicates no clouds, red indicates full cloud cover) time evolution in ARPEGE (left) and in AROME (right). (a) VEG=100% SWI=0.8, (b) VEG=0, SWI=0.8, (c) VEG=100% SWI=0, (d) VEG=0 SWI=0.

4. *Tuning of microphysics*

4.1. *Case study*

After the sensitivity experiments described above, the microphysics parameterization of AROME has also been investigated. After the subjective investigation of several other case studies (not shown), it was found that for wintertime stratus cases the AROME model often produces light precipitation. In the model, if temperature close to the surface is above 0 ºC, the precipitation phase is liquid and the amount (typically around 0.3—0.5 mm/12h) is close to observations and other operational models (e.g., ECMWF/IFS, ARPEGE, WRF). Otherwise, for negative temperature the precipitation phase is solid and AROME gives higher values than the observations or other models (*Fig. 6a*).

This behavior is not due to dynamics or horizontal/vertical resolution differences, as it is not present in a forecast using ARPEGE physics but AROME dynamics on the AROME grid (*Fig. 6b*). It may come from differences in microphysics processes (Lopez scheme in ARPEGE (*Lopez*, 2002) with modifications of *Bouteloup et al.* (2005)), ICE3 in AROME (*Pinty* and *Jabouille*, 1998)).

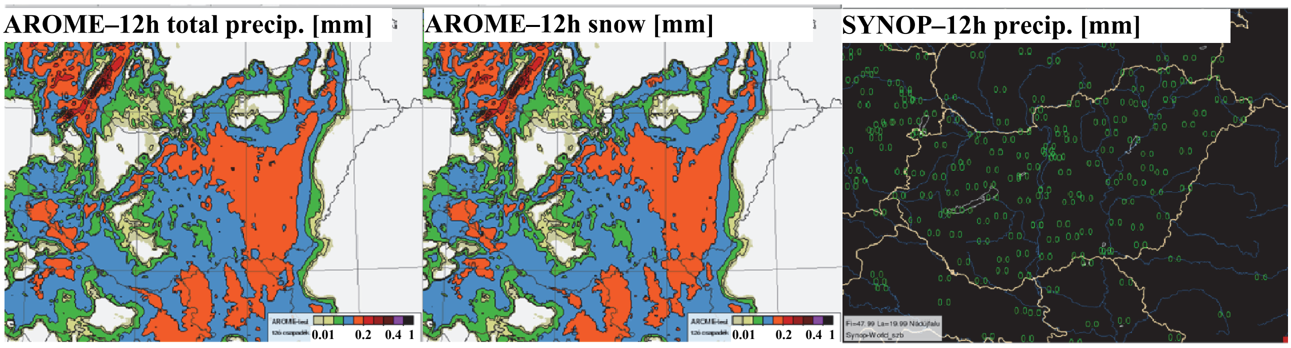

Fig. 6a. Accumulated 12h precipitation (in mm/12h) from AROME on November 30, 2011, at 12 UTC (+12h forecast) compared to synop observations. Left: total precipitation from AROME, middle: snow from AROME, right: synop observations.

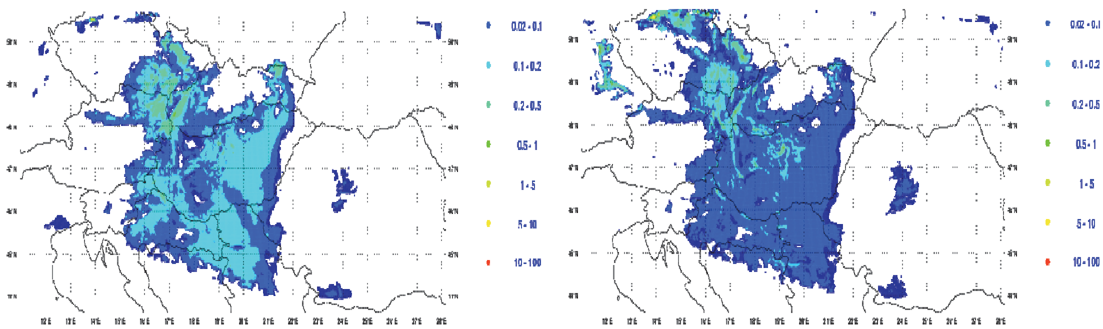

Fig. 6b. Accumulated 12h snowfalls on November 30, 2011, at 12 UTC (+12h forecast): left: ARPEGE physics at 2.5 km, right: AROME.

To understand the problem, budget profiles of microphysics were investigated from AROME (*Fig. 7*).

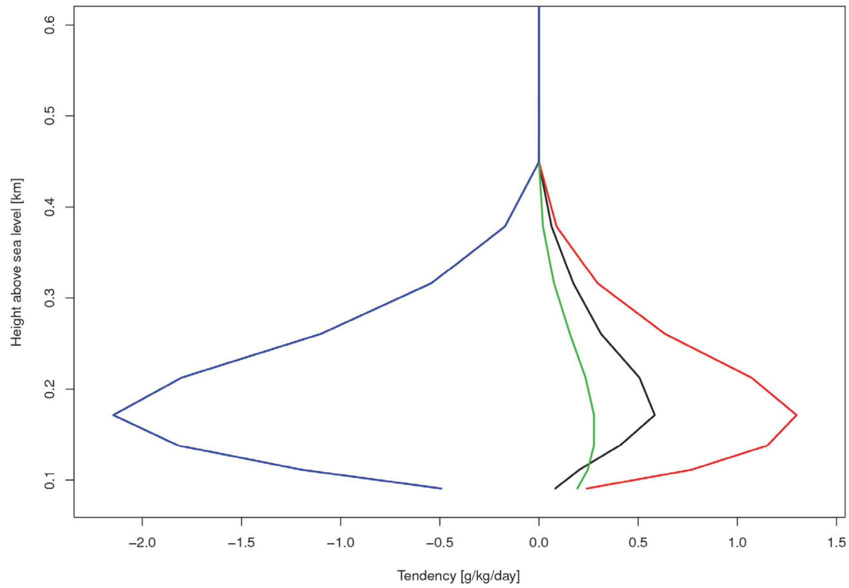

Fig. 7. Budget profiles for snow mixing ratio (in g/kg/day) from the AROME reference run between 00 and 06 UTC on November 30, 2011. The horizontal averaging was made on a 1 degree x 1 degree domain over the eastern part of Hungary. Main budget terms: sedimentation (blue), deposition on snow (red), autoconversion of ice to snow (black), riming by cloud droplets (green).

It was found that for the given case, three processes are responsible for the generation of falling snow: deposition, autoconversion of ice to snow and riming. The deposition process does not exist in ARPEGE Lopez scheme. That may explain differences shown in *Fig. 6b*. It was assumed that the largest uncertainty lies in the parameterization of autoconversion, so this process was selected for a tuning exercise. To reduce the solid precipitation in the model, the critical specific humidity value above which autoconversion could occur was increased from 0.02 g/m^3 (as in (*Chaboureau et al.*, 2002) to 1 g/m^3 (as in *Lin et al.*, 1983), keeping the temperature dependency of the critical value. Due to reduced solid precipitation, the low level cloud cover increases for the selected case (*Fig. 8*).

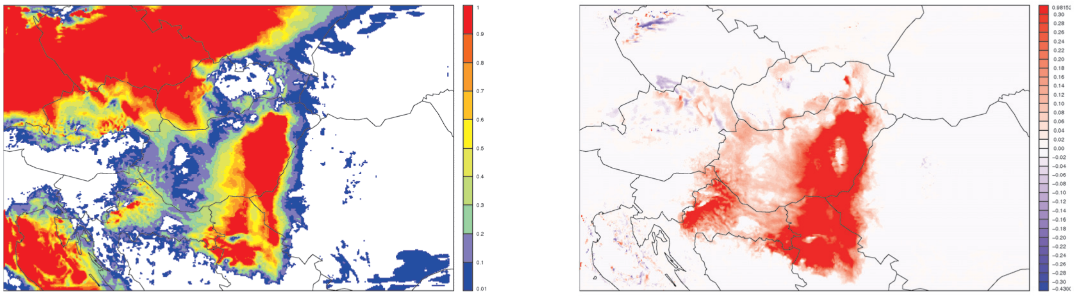

Fig. 8. Forecasted low level cloud cover by AROME with the modified autoconversion for November 30, 2011, at 14 UTC. Left: low level cloud cover, right: difference form the reference run.

4.2. Longer period with stratus

The proposed modification of the microphysics was tested on a two-week period in late autumn, 2011. This period was characterized by a frequent occurrence of daytime stratus due to a persistent anticyclone over Hungary. For every day of the period, a 24-hour forecast was run starting at 00 UTC. The configuration of this experimental chain was similar to the operational AROME-Hungary configuration in 2014, so an atmospheric 3DVAR data assimilation system was used with three hourly assimilation cycle. For the 3DVAR only conventional observations (synop stations, radiosoundings, and AMDAR data) were used. The initial condition of the soil was produced by interpolating the operational soil analysis of the ALADIN model (run at 8 km horizontal resolution). Three model configurations were compared: the reference run ("ref") which has similar settings to the operational AROME-Hungary (diagnostic subgrid cloud scheme and original autoconversion); the first experiment ("exp1") with modified autoconversion as described above (with diagnostic subgrid cloud scheme); and a second experiment ("exp2") with prognostic subgrid cloud scheme and modified autoconversion. Significant differences were only detected in cloud cover and 2-meter temperature (*Fig. 9*). By comparing "ref" and "exp1" it can be noticed, that the modified autoconversion slightly increases cloud cover, thus decreases the model bias, and it also improves the temperature forecast. The comparison of "exp1" and "exp2" shows the impact of the saturation deficit variance parameterization. It is apparent that the prognostic subgrid cloud scheme gives much less clouds and also deteriorates the temperature forecast, especially during night for the selected time period.

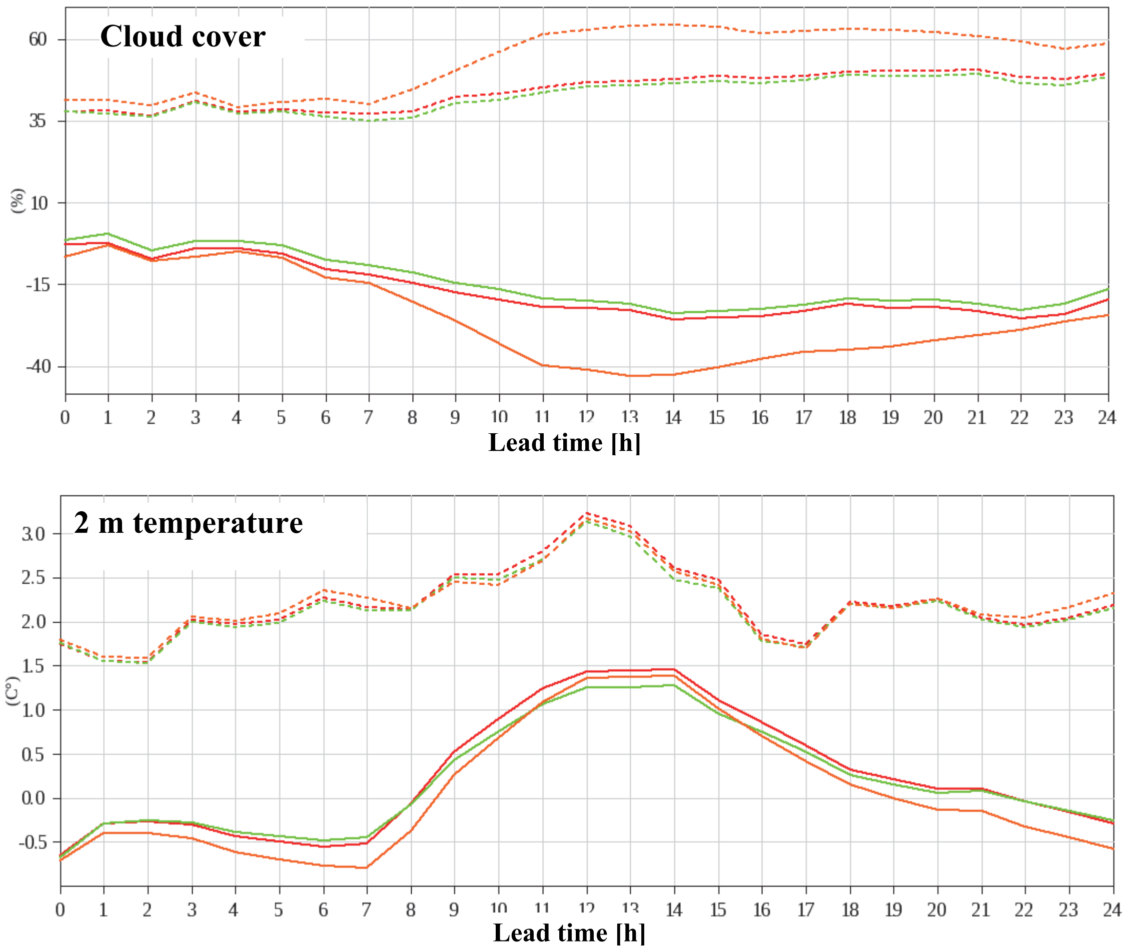

Fig. 9. Verification scores as a function of lead time for different AROME configurations for the period between November 18, 2011 and December 2, 2011. For the verification synop stations below 400 m were used over the AROME-Hungary domain. Upper panel: cloud cover, lower panel: 2-meter temperature. Solid lines: bias, dashed lines: RMSE. Red: reference run; green: first experiment (diagnostic subgrid cloud scheme, modified autoconversion); orange: second experiment (prognostic subgrid cloud scheme, modified autoconversion).

5. *Control cases*

The proposed modification of the microphysics parameterization has also been tested on so-called control cases. These cases should be characterized by different synoptic conditions than the one for which the modification have been developed. As the original case was a winter anticyclonic case, for the first control case a winter cyclonic situation with heavy snowfall was chosen, while for the second control case a summer convective event was selected.

On January 24, 2014, a Mediterranean cyclone was passing over Hungary causing heavy snowfall over the southwestern part of the country. According to synop measurements, the depth of fallen snow exceeded 20 cm in large areas, and in mountainous regions values over 30 cm were also measured. Operational models (both hydrostatic and non-hydrostatic) forecasted the event successfully, however, the high values associated to orography were only present in the non-hydrostatic models (AROME and WRF). The run with the modified microphysics ("exp1") simulated a snowfall pattern similar to the reference AROME run, with slightly lower values of snowfall (*Fig. 10)*. No significant differences were detected for other variables, like temperature, cloud cover, or wind.

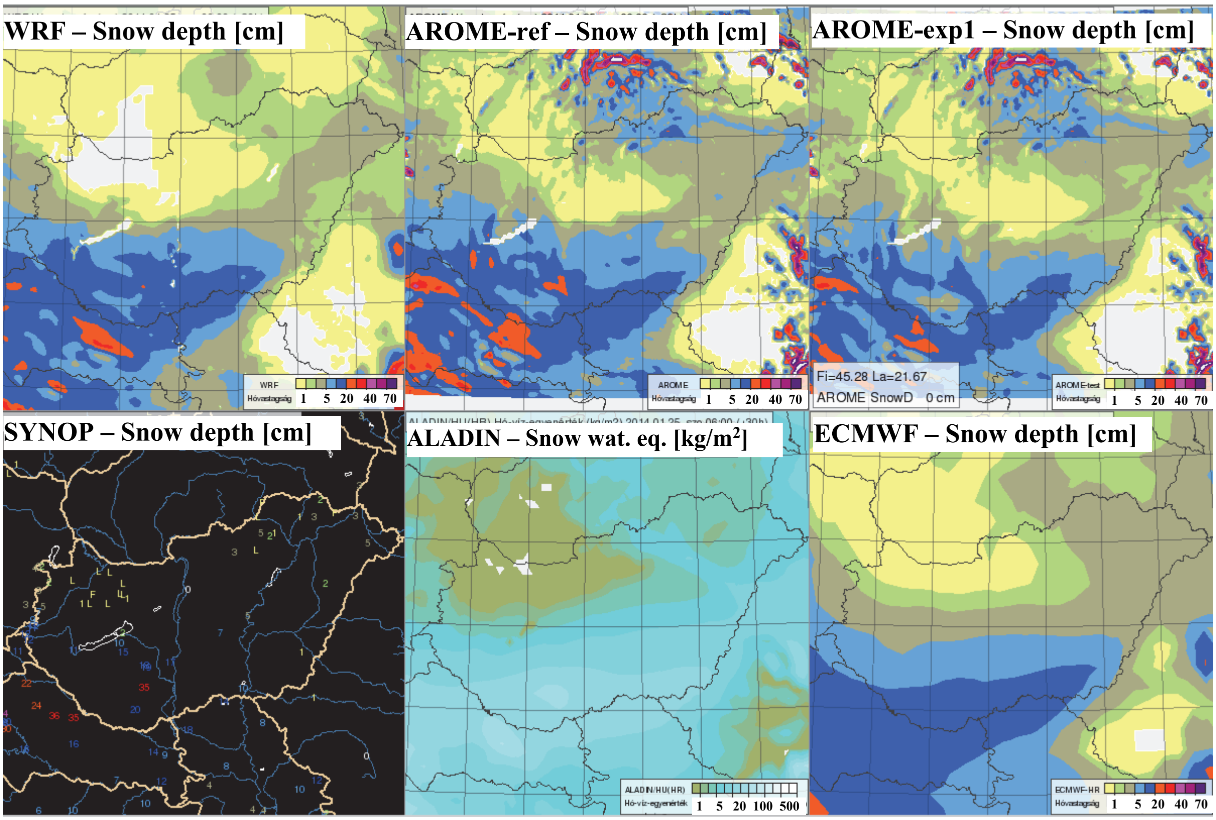

Fig. 10. Model forecasts and synop observations for the first control case. All models were initialized at 00 UTC on January 24, 2014, and +30h forecasts were made. Depicted is the 30h cumulated snowfall (except for the ALADIN model) both for models and synop measurements.

On June 24, 2013, a convective event occurred over Hungary. A cold front was approaching the region from northwest, and before the front in the warm sector thunderstorms developed which caused heavy precipitation (locally over 50 mm/24h). *Fig. 11* compares the precipitation forecasts of the reference AROME version and the one with modified microphysics.

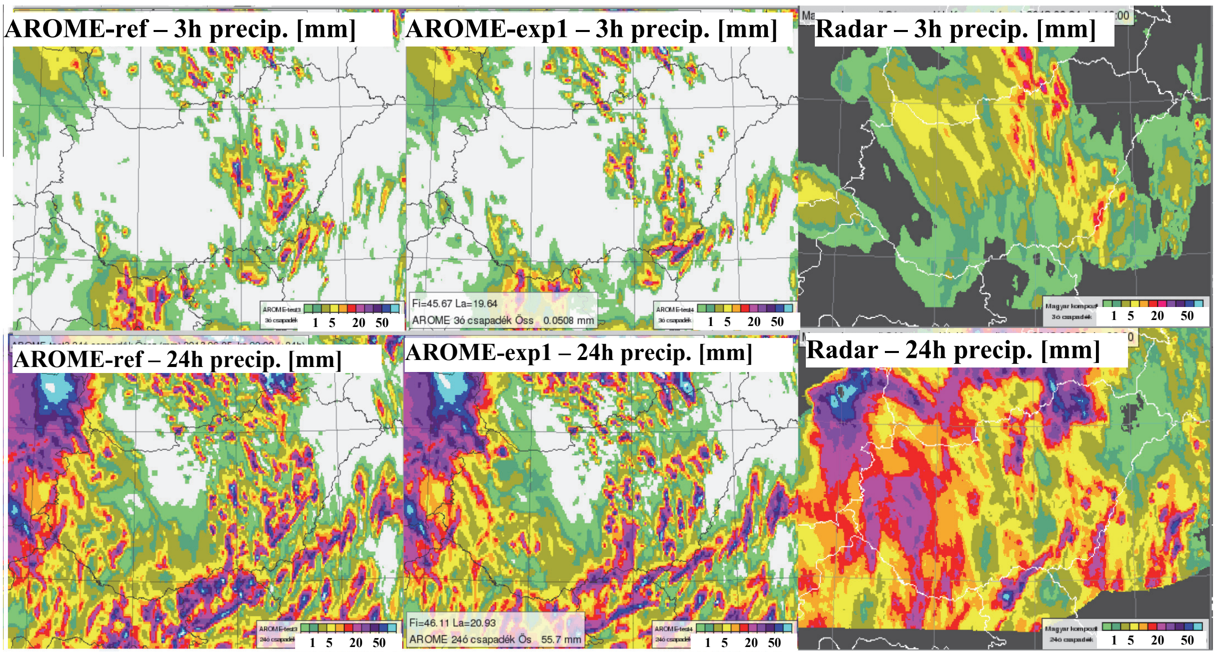

Fig. 11. Model forecasts and radar observations for the second control case. Both models were initialized at 00 UTC on June 24, 2013, and +24h forecasts were made. First row: 3h accumulated precipitation for the +18h lead time; second row: 24h accumulated precipitation for the +24h lead time.

Both versions were fairly successful in forecasting the thunderstorm activity over the eastern part of Hungary, however, over the western part, the precipitation amounts were underestimated by both versions. Regarding the timing of convection and the precipitation amounts, no significant difference was detected between the two versions of AROME.

6. *Verification of longer periods*

The proposed modification was also tested on longer continuous periods, which is a standard procedure to precede the operational implementation of a new model version. For this purpose, a winter (January 6-24, 2014) and a summer period (May 7-20, 2013) was selected. For these days, the AROME version with the proposed modification was run in an operational setting with a separate data assimilation cycle. These forecasts were then verified with observations, and verification scores were compared to the operational AROME model.

Model verification was performed either using standard surface (synop) observations with pointwise model-observation comparison (using the OVISYS system developed at the Hungarian Meteorological Service, *Randrimampianina* *et al.*, 2007), or using a novel spatial verification method (*Rezacova et al.,* 2015) based on the SAL (*Wernli et al.*, 2008) technique. The parameters investigated were temperature, humidity, precipitation, and clouds for the pointwise verification and precipitation for the spatial verification. It has to be noted that the spatial verification was only performed for the summer period. This is due to the fact, that the quantitative radar precipitation measurements used for the spatial scores are less reliable for winter situations with often very small precipitation intensities.

For the winter period, pointwise verification scores of the modified AROME version were very similar to the scores of the operational AROME for all meteorological parameters (not shown). This is mainly due to the fact, that the anticyclonic low level cloud cases were observed only on a small number of days in the period, and for other weather situations the impact of the modification is neutral.

For the summer period, pointwise verification showed no impact for cloudiness, temperature, and humidity. The pointwise precipitation verification showed small improvement for the morning hours of the forecast and neutral impact for the afternoon hours (*Fig. 12*). It has to be noted though, that the investigated period was rather short to be able to draw solid conclusions from pointwise verification in the case of a spatially strongly varying parameter like convective precipitation. Consequently, spatial verification scores were also investigated. *Fig. 13* shows the average intensity of precipitation objects as a function of forecast lead time for the reference and modified AROME versions and for radar observations. The precipitation objects were defined with the SAL method described in *Wernli et al.* (2008) using a dynamic threshold corresponding to 1/15 part of the maximum precipitation value over the domain. The three hourly accumulated radar precipitation measurements were corrected with surface synop measurements to account for the weakening of the Radar signal in the case of heavy precipitation. It can be concluded that the intensity of precipitation objects is overestimated by the AROME model in the late afternoon hours. The proposed microphysical modification improves model performance in this respect, however, a considerable overestimation still remains.

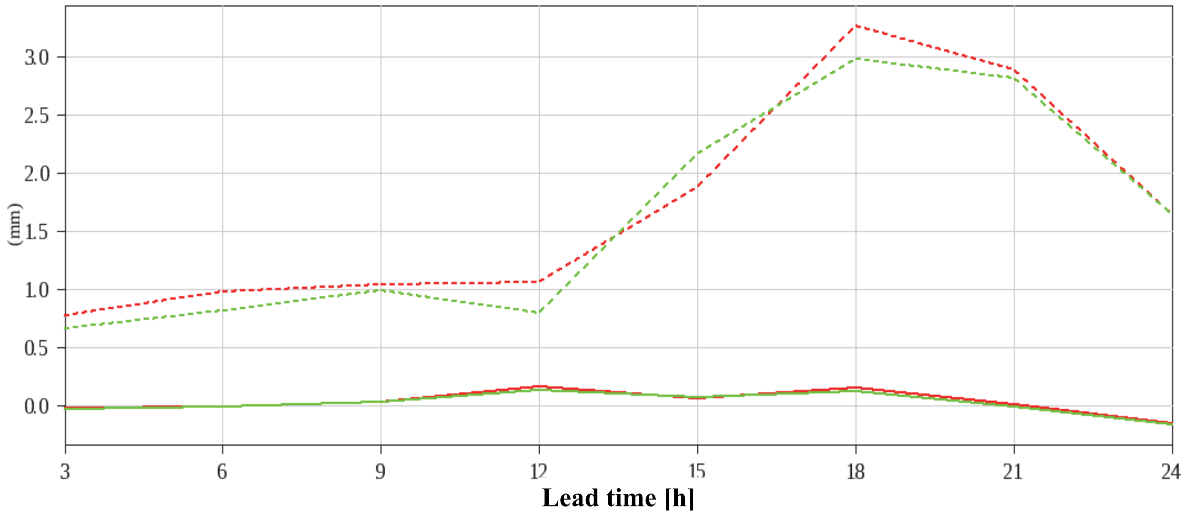

Fig. 12. Verification scores for 3h accumulated precipitation as a function of lead time for the period between May 5, 2013 and May 20, 2013. For the verification synop stations below 400 m were used over the AROME-Hungary domain. Solid lines: bias, dashed lines: RMSE. Red: reference run (original autoconversion); green: experiment (modified autoconversion).

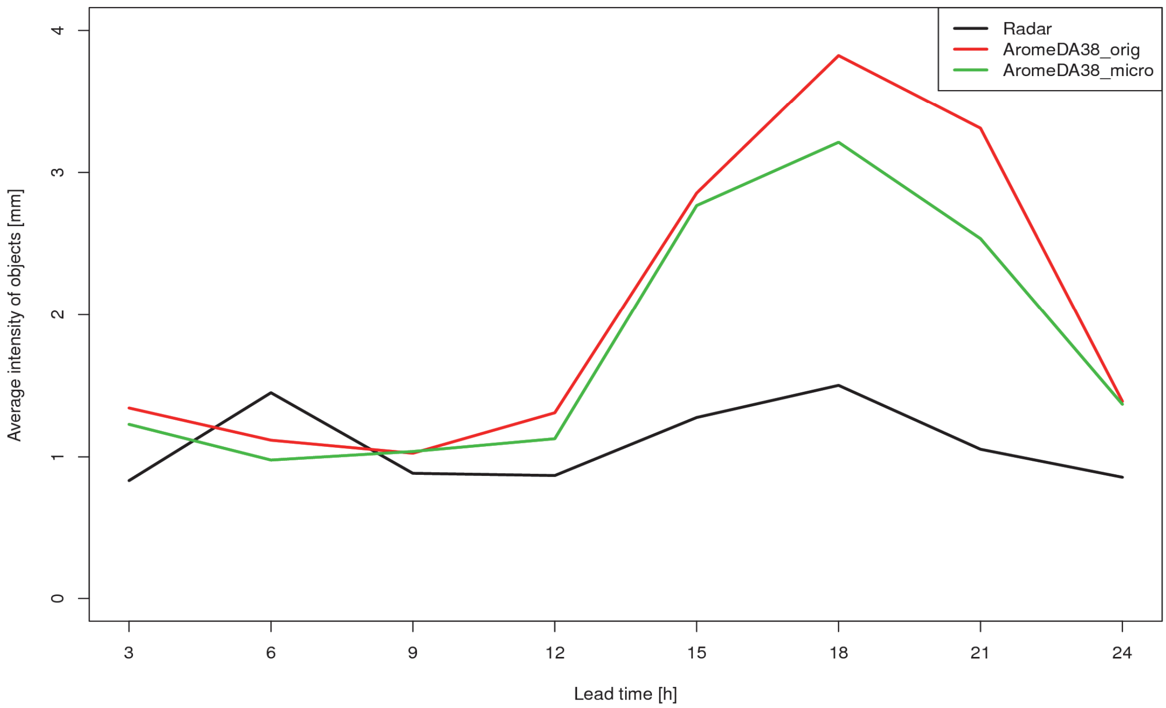

Fig. 13. Average intensity of precipitation objects as a function of lead time for different AROME configurations and radar observations for the period between May 5 and May 20, 2013. Black: radar; red: reference run (original autoconversion); green: experiment (modified autoconversion).

7. *Summary and conclusions*

In the present paper, wintertime low level cloud cases were investigated which are associated with anticyclonic conditions over Central Europe. Based on the experience of the forecasters at HMS, most operational numerical weather prediction models face difficulties when simulating these situations. The most common problem is the underestimation of low level cloud cover. Several sensitivity experiments were performed with the AROME model over Hungary, which investigated model performance in relation to initial and lateral boundary conditions, turbulence and radiation parameterization, surface properties, cloud and precipitation processes. Results indicated that the cause of the inadequate low level cloud forecast can be traced back to the microphysics parameterization. By increasing the critical threshold of cloud ice to snow autoconversion, the overestimation of light snow could be decreased, and consequently the low level cloud cover forecast improves.

After the detailed investigation of the selected wintertime anticyclonic case study, a longer period which mainly consisted of such situations was studied. Verification results proved that the proposed modification improves the simulation of clouds and consequently 2-meter temperature as well. As the next step, so-called "control cases" were investigated, with different weather situations (heavy snowfall and summer convection), showing neutral impact of the modification. Finally, two longer continuous periods in summer and winter were run with a separate data assimilation cycle. Pointwise and spatial verification results showed that the modification has a positive impact on the forecast of cloud cover and summertime convective precipitation. Impact on other meteorological parameters is neutral.

The investigations described above showed that the proposed microphysics modification could improve model performance, and it is worth to consider its implementation in the operational AROME version. Consequently, the modification was introduced as an option in the official code of AROME, and in April 2015, both the Hungarian Meteorological Service and Météo-France started to use it in its operational AROME configurations.

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References

Ahlgrimm, M., and *R. Forbes,* 2014: Improving the representation of low clouds and drizzle in the ECMWF model based on ARM observations from the Azores. *Mon. Weather Rev. 142*, 668–685. https://doi.org/10.1175/MWR-D-13-00153.1

Benard, P., *Vivoda, J.,, Masek, J., Smolikova P.,, Yessad, K., Smith, C., Brozkova,* R., and *Geleyn*, *J-F.,* 2010: Dynamical kernel of the Aladin-NH spectral limited-area model: Revised formulation and sensitivity experiments. *Quart. J. Roy. Meteor. Soc. 136,* 155–169. https://doi.org/10.1002/qj.522

Bouteloup, Y., Bouyssel, F., and *Marquet, P.*, 2005: Improvments of Lopez prognostic large scale cloud and precipitation scheme. ALADIN Newsletter, 28:66,73. 8

Boutle, I., Price, J., Kudzotsa, I., Kokkola, H., and *Romakkaniemi, S.,* 2018: Aerosol-fog interaction and the transition to well-mixed radiation fog, *Atmos. Chem. Phys*., 7827-7840. https://doi.org/10.5194/acp-18-7827-2018

Bubnová, R., Hello, G., Bénard, P., and *Geleyn, J.-F.,*1995: Integration of the fully elastic equations cast in the hydrostatic pressure terrain-following in the framework of the ARPEGE/ALADIN NWP system. *Mon. Weather Rev. 123*, 515–535. https://doi.org/10.1175/1520-0493(1995)123<0515:IOTFEE>2.0.CO;2

Chaboureau, J.-P. and *Bechtold*, *P.,* 2002: A simple cloud parameterization derived from cloud resolving model data: Diagnostic and prognostic applications. *,J. Atmos. Sci. 59*, 2362–2372. https://doi.org/10.1175/1520-0469(2002)059<2362:ASCPDF>2.0.CO;2

Chaboureau, J.-P., Cammas, J.-P., Mascart, P. J., Pinty, J.-P., and *Lafore J.-P.*, 2002: Mesoscale model cloud scheme assessment using satellite observations. *J. Geophys. Res. 107*(D16), 4301. https://doi.org/10.1029/2001JD000714

Courtier, P., Freydier C, Geleyn JF, Rabier F, and *Rochas M.,* 1991: The ARPEGE project at Météo-France. In: Proc. ECMWF Seminar on Numerical Methods on Atmospheric Models. Vol. 2, Shinfield Park, Reading, UK, ECMWF, 193–231.

Fischer, C., Montmerle, T. , Berre, L. , Auger, *L.,* and *Stefanescu, S. E.,* 2005: An overview of the variational assimilation in the Aladin/FranceNWP system. *Quart. J. Roy. Meteor. Soc. 131,* 3477–3492. https://doi.org/10.1256/qj.05.115

Forbes, R.M. and *M. Ahlgrimm*, 2014: On the representation of high-latitude boundary layer mixed-phase cloud in the ECMWF global model. *Mon. Weather Rev. 142*, 3425–3445. https://doi.org/10.1175/MWR-D-13-00325.1

Haeffelin, M., Bergot, T., Elias, T., Tardif, R., Carrer, D., Chazette P., Colomb, M., Drobinski, P., Dupont, E., Dupont, J., Gomes, L.,Musson-Genon, L., Pietras, C., Plana-Fattori, A., Protat, A., Rangognio, J., Raut, J., Rémy, S., Richard, D., Sciare, J., and *Zhang, X*., 2010: PARISFOG: shedding new light on fog physical processes. *Bull. Amer. Meteorol. Soc. 91*, 767–783. https://doi.org/10.1175/2009BAMS2671.1

Hoffmann, H.-E. and *Roth, R.*, 1989: Cloudphysical Parameters in Dependence on Height Above Cloud Base in Different Clouds. *Meteorol. Atmos. Phys. 41*, 247–254. https://doi.org/10.1007/BF01026113

Lafore, J.-P.Lafore, J. P., Stein, J., Asencio, N., Bougeault, P. , Ducrocq, V., Duron, J., Fischer, C., Héreil, P., Mascart, P., Masson, V., Pinty, J. P., Redelsperger, J. L., Richard, E., and *Vilà-Guerau de Arellano J*., 1998: The Meso-NH atmospheric simulation system. Part I: Adiabatic formulation and control simulations. *Ann. Geophys. 16*, 90–109. https://doi.org/10.1007/s00585-997-0090-6

Lin, Y.-L., Farley, R.D., and *Orville*, *H.D.,* 1983: Bulk parameterization of snow field in a cloud model. *J. Climate Appl. Meteor*. *22*, 1065–1092.

Lopez, Ph., 2002: Implementation and validation of a new prognostic large-scale cloud and precipitation scheme for climate and data-assimilation purposes. *Quart. J. Roy. Meteor. Soc., 128*,.229-257. https://doi.org/10.1256/00359000260498879

Masson, V., P. Le Moigne, E. Martin, S. Faroux, A. Alias, R. Alkama, S. Belamari, A. Barbu, A. Boone, F. Bouyssel, P. Brousseau, E. Brun, J.-C. Calvet, D. Carrer, B. Decharme, C. Delire, S. Donier, K. Essaouini, A.-L. Gibelin, H. Giordani, F. Habets, M. Jidane, G. Kerdraon, E. Kourzeneva, M. Lafaysse, S. Lafont, C. Lebeaupin Brossier, A. Lemonsu, J.-F. Mahfouf, P. Marguinaud, M. Mokhtari, S. Morin, G. Pigeon, R. Salgado, Y. Seity, F. Taillefer, G. Tanguy, P. Tulet, B. Vincendon, V. Vionnet, and *A. Voldoire,* 2013: The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes. Geosci. Model Dev. 6, 929-960. https://doi.org/10.5194/gmd-6-929-2013

Mazoyer, M., Lac, C., Thouron, O., Bergot, T., Masson, V., and *Musson-Genon, L*., 2017: Large eddy simulation of radiation fog: impact of dynamics on the fog life cycle, A*tmos. Chem. Phys., 17*, 13017–13035. https://doi.org/10.5194/acp-17-13017-2017

Mile M., Bölöni, G., Randriamampianina, R., Steib, R., and *Kucukkaraca, E.,* 2015: Overview of mesoscale data assimilation developments at the Hungarian Meteorological Service. *Időjárás 119,* 215–241.

Nielsen K.P., Gleeson E., and Rontu, L., 2014: Radiation sensitivity tests of the HARMONIE 37h1 NWP model. *Geosci. Model Dev. 7*, 1433–1449. https://doi.org/10.5194/gmd-7-1433-2014

Philip A., Bergot, T., Bouteloup, Y. and *Bouyssel*, *F.,* 2016: The Impact of Vertical Resolution on Fog Forecasting in the Kilometric Scale Model Arome: A case Study and Statistics. *Weather Forecast. 31*,1655–1671. https://doi.org/10.1175/WAF-D-16-0074.1

Pinty, J.-P. and *P. Jabouille,* 1998: A mixed-phased cloud parameterization for use in a mesoscale non-hydrostatic model: simulations of a squall line and of orographic precipitation. Conf. on Cloud Physics, Everett, WA, Amer. Meteor. Soc., Preprints, 217–220.

Price, J., Lane, S., Boutle, I., Smith, D., Bergot, T., Lac, Duconge, L., C., McGregor, J., Kerr-Munslow, A., Pickering, M., and *Clark, R*.., 2018: LANFEX: a field and modelling study to improve our understanding and forecasting of fog, Bull. Amer. Meteor. Soc., . https://doi.org/10.1175/BAMS-D-16-0299.1

Randrimampianina, R., Balogh, M., Bölöni, G., Csima, G., Hágel, E., Horányi, A., Ihász, I., Kertész, S., Kullmann, L., Lőrincz, A., Radnóti, G., Szabó, L., Szépszó, G., Szintai, B., Tóth, H., and *Vörös, M.*, 2007: Recent development and changes in the operational ALADIN/HU 3D-Var system Poster presented at SRNWP Workshop on Data Assimilation, Emphasis: Use of moisture-related observations, Norrköping, Sweden, 21-23 March, 2007.

Řezáčová, D, Szintai, B , Jakubiak, B., Yano, J-I, and *Turner, S*, 2015: Verification of high-resolution precipitation forecast with radar-based data. In: Robert, S Plant; Jun-Ichi, Yano (ed.) Moist Atmospheric Convection: An Introduction and Overview : Parameterization of Atmospheric Convection. Volume 1: Theoretical Background and Formulation. Imperial College Press, 173–214.

Seity, Y., Brousseau, P., Malardel, S., Hello, G., Bénard, P., Bouttier, F., Lac, C., and *Masson, V*., 2011: The AROME-France Convective-Scale Operational Model. *Mon. Weather Rev. 139*, 976–991. https://doi.org/10.1175/2010MWR3425.1

Sommeria, G. and *J.W. Deardorff,* 1977, Subgrid scale condensation in models for non precipitating clouds. *J. Atmos., Sci. 34*, 344–355. https://doi.org/10.1175/1520-0469(1977)034<0344:SSCIMO>2.0.CO;2

Szintai B., Szűcs, M., Randriamampianina, R., and *Kullmann, L.,* 2015: Application of the AROME non-hydrostatic model at the Hungarian Meteorological Service: physical parametrizations and ensemble forecasting. *Időjárás 119*, 241–265.

Termonia P., C. Fischer, E. Bazile, F. Bouyssel, R. Brožková, P. Bénard, B. Bochenek, D. Degrauwe, M. Derková, R. El Khatib, R. Hamdi, J. Mašek, P. Pottier, N. Pristov, Y. Seity, P. Smolíková, O. Španiel, M. Tudor, Y. Wang, C. Wittmann, and *A. Joly,* 2018: The ALADIN System and its canonical model configurations AROME CY41T1 and ALARO CY40T1. *Geosci. Model Dev. 11*, 257–281. https://doi.org/10.5194/gmd-11-257-2018

Wernli, H., Paulat, M., Hagen, M. and *Frei, Ch*., 2008: SAL - A novel quality measure for the verification of Quantitative Precipitation Forecast. Mon. *Weather Rev. 136*, 4470-4487. https://doi.org/10.1175/2008MWR2415.1