Author's Response

"The use of GNSS zenith total delays in operational AROME/Hungary 3D-Var over a Central European domain" by Máté Mile et al.

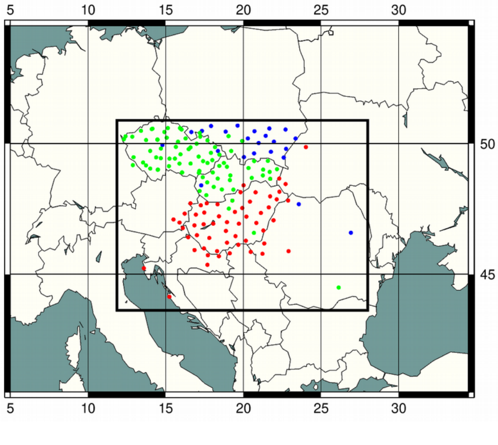
We would like to thank all referees for his/her valuable suggestions. In the following, you will find our responses, separately for each comment/concern.

In black: referee observations
In blue: our response

Anonymous Referee #1
Received and published: 14 January 2019
This paper presents results on the impact in terms of forecast scores of assimilating GNSS ZTD in a convective scale numerical weather prediction model within an experimental framework compatible with operational applications. Many papers have already been published on this subject during the last 15 years. An original aspect of the present study is the application over Central Europe with a specific network of surface stations. This study also examine the interest of using a variational bias correction scheme on the observations which has only been recently assessed by Sanchez-Ariola et al. (2016) and Lindskog et al. (2017). The presentation is clear and the forecast impacts on low level parameters and surface precipitation are consistent with previous published studies. My recommendation is to accept the publication once minor modifications suggested below are taken into account.

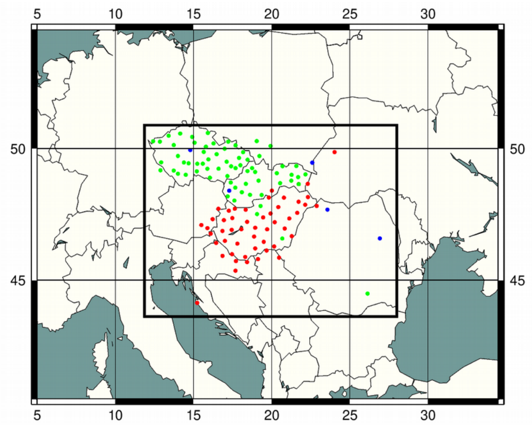
P1L12-13: replace "At the end of this article, the conclusion is drawn" by "Finally, conclusion are drawn"
Corrected.
P1L16: replace "System" by "Systems"
Replaced.
P2L2: replace "rely on more the remote" by " rely significantly on remote"
Replaced.
P2L4: replace "taken up" by "included"
Replaced.
P2L15: replace "employing" by "using"
Changed.
P2L17-18: replace "Recently new European" by "Recently a new European"
Replaced.
P2L21: replace "All of these" by "All these"
Replaced.
P2L23: replace "error" by "errors"
Replaced.
P2L24: replace "assay of ZTD bias were examined" by "assessment of ZTD were proposed"
Changed.
P2L25: replace "demonstrated the" by "demonstrated that the"
Replaced.
P2L29: replace "utilized" by " used"
Replaced.
P2L34: replace "the conclusion is drawn" by "conclusions are drawn"
Replaced.
P3L1: replace "Applied" by "Description of"

Replaced.
P3L3: replace "consortia" by "consortium"
Replaced.
P3L6: replace "Meso-NH(?)" by "Meso-NH (Lac et al., 2018)"
Lac, C., Chaboureau, J.-P., Masson, V., Pinty, J.-P., Tulet, P., Escobar, J., Leriche, M., Barthe, C., Aouizerats, B., Augros, C., Aumond, P., Auguste, F., Bechtold, P., Berthet, S., Bielli, S., Bosseur, F., Caumont, O., Cohard, J.-M., Colin, J., Couvreux, F., Cuxart, J., Delautier, G., Dauhut, T., Ducrocq, V., Filippi, J.-B., Gazen, D., Geoffroy, O., Gheusi, F., Honnert, R., Lafore, J.-P., Lebeaupin Brossier, C., Libois, Q., Lunet, T., Mari, C., Maric, T., Mascart, P., Mogé, M., Molinié, G., Nuissier, O., Pantillon, F., Peyrillé, P., Pergaud, J., Perraud, E., Pianezze, J., Redelsperger, J.-L., Ricard, D., Richard, E., Riette, S., Rodier, Q., Schoetter, R., Seyfried, L., Stein, J., Suhre, K., Taufour, M., Thouron, O., Turner, S., Verrelle, A., Vié, B., Visentin, F., Vionnet, V., and Wautelet, P.: Overview of the Meso-NH model version 5.4 and its applications, Geosci. Model Dev., 11, 1929-1969, https://doi.org/10.5194/gmd-11-1929-2018, 2018.
New reference (Lac et al. (2018)) was added. The previous (Lafore et al. (1997)) was also kept and corrected its appearance in the manuscript.
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., Vilà-Guerau de Arellano, J.: The Meso-NH atmospheric simulation system. Part I: Adiabatic formulation and control simulations. Ann. Geophys., 16, 90–109., 1997.
P3L10: replace "Later major upgrades consisting direct" by "Later, major upgrades consisting of a direct"
Replaced.
P3L12: replace "improvement" by "improvements"
Replaced.
P3L15: replace "(Mahfouf, 1991)" by "(Mahfouf, 1991; Masson et al. 2013)"
Masson, V., Le Moigne, P., Martin, E., Faroux, S., Alias, A., Alkama, R., Belamari, S., Barbu, A., Boone, A., Bouyssel, F., Brousseau, P., Brun, E., Calvet, J.-C., Carrer, D., Decharme, B., Delire, C., Donier, S., Essaouini, K., Gibelin, A.-L., Giordani, H., Habets, F., Jidane, M., Kerdraon, G., Kourzeneva, E., Lafaysse, M., Lafont, S., Lebeaupin Brossier, C., Lemonsu, A., Mahfouf, J.-F., Marguinaud, P., Mokhtari, M., Morin, S., Pigeon, G., Salgado, R., Seity, Y., Taillefer, F., Tanguy, G., Tulet, P., Vincendon, B., Vionnet, V., and Voldoire, A.: 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, 2013.
Added.
P3L15-16: remove "called OI_main"
Removed.
P3L17: I suggest to provide the location of the ground based GNSS receivers on this map, instead of the model orography (that is not commented and not necessary)
New figure is added to the manuscript.



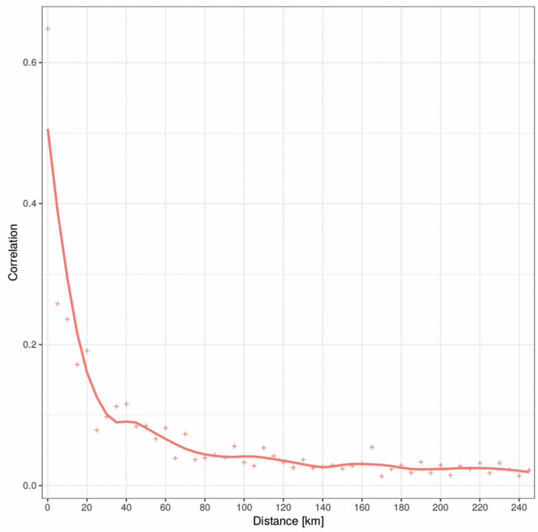
P3L18: replace "employs" by "considers"
Replaced.
P4L1 : replace "appiled" by "applied"
Corrected.
P4L4 : It is not clear what are the instruments that are used from NOAA-19 (AMSU-A only or AMSU-A and MHS ?)
Both AMSU-A and MHS from NOAA-19 were used, the related sentence is corrected.
P4L9: replace "(Girard, 1987)" by "(Girard, 1987; Chapnik et al., 2006)"
Chapnik, B., G. Desroziers, F. Rabier and O. Talagrand, 2006 : Diagnosis and tuning of observational error in a quasi-operational data assimilation setting. Quart. Jour. Roy. Meteor. Soc., n ◦ 615, Part B, volume 132, pp 543-565.
New reference is added.
P4L11-12: replace the sentence by "where HK is the product of the linearized observation operator by the Kalman gain, and the DFS scores can be approximated by its trace as (1). The y and y' are the unperturbed and perturbed observations sets"
Replaced.
P4L13: replace "states at the observation space" by "states in the observation space"
Replaced.
P4L19: replace "dates back" by "started in"
Replaced.
P4L20: replace "experiences" by "results"
Replaced.
P4L27: replace "provides the most of ZTD estimated" by "provides most of the ZTD estimates"
Replaced.
P4L30: remove "estimation for"
Removed.
P5L1-2: Explain what is a relative DFS (division by the number of observations). A 2-D pie chart would be more readable
Explained. "The relative DFS is a normalized value by the amount of observations for each observation subset providing the diagnostic information regardless the actual amount and geographical coverage in the assimilation system."
If it's not a big concern, we would prefer to keep the 3D pie.
P5L3-4: As mentioned above (comment about Figure 1). A map showing the GNSS stations would be very useful
Done.
P5L7: replace "with increased observation error" by "with very large observation errors"
Replaced.
P5L8: put "passive" with quotes
Done.
P5L9: replace "without its influence on the analysis" by "without influencing the analysis"
Replaced.
P5L10-13: I propose to reformulate this sentence that is not clear enough: "background check(which is dedicated to reject observations far from model background state) one also needs to ensure that only observations with Gaussian, zero mean and uncorrelated errors are selected in the assimilation (i.e. reliable stations). For that purpose, a specific pre-selection procedure has to be performed by checking passive observation minus first-guess (OMF) departures on a training period. Due to the increased"
It is accepted and reformulated.
P5L13: "Due to the increased" : one can wonder with respect to what ? It would be

better just to state "Due to the high"
Replaced.
P5L15: remove "examined"
Removed.
P6L1-2: There is a need to clarify what you mean by "station multiplication". My understanding is that one specific station can be processed by several analysis centre and you have to select the best duple (station/analysis centre)
The sentence is changed according to this remark. “Considering that particular stations can be processed by several analysis centre (we can call it station multiplication) that station/processing centre pair is selected which has the smallest standard deviation of OMF.”
P6L2: replace "is also a part" by "is also part"
Replaced.
P6L3: replace "are written in" by "are given in"
Replaced.
P6L6-7: I propose to rewrite as follows: "The actual training period led to the availability of 197 GNSS stations inside the NWP domain (from three different networks). The preselection procedure excluded more than 30 % of them, resulting in 122 trusted GNSS stations for active assimilation experiments"
Rewritten.
P6L6-7: Again a map with the location of the stations (all + selected ones) would be useful
Another new figure is added as well. See the figure of all GNSS stations above and another of the selected ones below. The high quality figures are going to be inserted into the manuscript.



P6L8: replace "coverage issues" by "coverage"
Replaced.
P6L9: replace "than the pre-defined limits" by "than pre-defined limits"
Replaced.
P6L11: replace "station multiplication" by "multiple (station/analysis centre)" See similar comment above
Replaced.
P6L12: "observation error correlations" by "horizontal observation error correlations"
Added.
P6L17: replace "having" by "considering"
Replaced.
P6L19: replace "cheap approach" by " efficient approach"
Replaced.
P6L19: replace "another whitelist is originally" by "a revised whitelist is" You should explain above what you mean by "whitelist" since it has not been defined before.

Replaced and whitelist is explained above. " The selected GNSS stations are written into a specific whitelist which ensures the active assimilation of ZTDs."
P6L22: replace "on Figure 3 20 km" by "in Figure 3, a 20 km" Why not using a curve fitting of the correlation function for an objective estimation of the thinning distance ?
Replaced and the local polynomial regression method (LOESS) was used for fitting a smooth curve. It is now mentioned in the caption of the figure (in the manuscript).



P7L1 : The figure should be improved (horizontal axis unreadable) and the legend should be completed (provide information on the period and on the domain)
The quality of figure is improved (see above).
P7L5: replace "it presumes the" by "it assumes that the"
Replaced.
P7L7: replace "are plotted on Figure 4" by "is plotted in Figure 4"
Corrected.
P7L8: replace "on Figure 5 and 6 that observed" by "in Figure 5 and 6 that the observed"
Replaced.
P7L9: replace "Therefore bias correction" by "Therefore the bias correction"
Replaced.
P7L14: replace "experiments in the Section 5" by "experiments presented in Section 5"
Replaced.
P8L1: Enhance the legend (specify that it is ZTD, provide the period and the domain)
Done.
P8L2: Enhance the legend (specify that it is ZTD). The information given on the horizontal axis is totally unreadable.
Enhanced, the names of GNSS stations are enlarged, and the size of the figure is increased as well.
P8L5: Provide a reference defining the stiffness parameter in terms of VARBC formulation (e.g. a paper by Dick Dee or the ECMWF documentation on data assimilation)
The following reference was added.
"Dee, D. P., 2004: Variational bias correction of radiance data in the ECMWF system. Proceedings of the ECMWF workshop on assimilation of high spectral resolution sounders in NWP, Reading, UK, Vol. 28, 97–112."
P8L7: replace "information in every new analysis" by "information at every analysis"
Replaced.
P9L1: The horizontal axis of the Figure is not readable. Specify that the quantity is

ZTD. replace "purpule" by "purple"
Replaced, the names of GNSS stations are enlarged, and the size of the figure is increased as well.
P9L2: replace "prepare warmstart" by "prepare a warm start"
Replaced.
P9L9: replace "operational setup" by "operational setup (without ZTD observations". It is not clear to me if satellite observations are included in this "operational setup". The confusion comes from P3L18-19 defining the operational configuration. Have the satellite observations only been introduced for the DFS or also for this reference experiment ?
Replaced. Configurations are explained with more details in the manuscript.
“The non-conventional satellite and RADAR observations were added to AROME experimental analyses solely for diagnostic study and they were not considered in the GNSS ZTD observing system experiments.”
P9L10: replace "of operational observation set an static bias correction is compared with the reference" by "of the operational observation set an a static bias correction is compared to the reference".
Replaced.
P9L11: replace "employs variational" by "employs a variational"
Replaced.
P9L14: replace "traning" by "training"
Corrected.
P9L15: replace "till" by "until"
Replaced.
P9L18: replace "expected to seen in" by "expected to reflect more on"
Replaced.
P10L1: replace "Outline" by "Summary"
Replaced.
P10L1: specify in the text is EEGPS2 includes or not satellite data
Explained.
P10L2: replace "on Figure 8" by "in Figure 8"
Replaced.
P10L5: replace "error reduction" by "error reduction with respect to the reference"
Replaced.
P10L5-6: "Furthermore, similar results are obtained with the static bias correction, but they are not statistically significant (not shown)"
Corrected.
P10L7: replace "on Figure 9" by "in Figure 9"
Replaced.
P10L7: replace "where the Equitable Threat Score (ETS) and the Symmetric" by "in terms of Equitable Threat Score (ETS) and Symmetric". Please provide a suitable reference for the definition of the SEDI.
Replaced and a reference is added.
“Ferro, C., A., T., and Stephenson, D., B.: Extremal Dependence Indices: Improved Verification Measures for Deterministic Forecasts of Rare Binary Events. Weather and Forecasting, pp 699-713, https://doi.org/10.1175/WAF-D-10-05030.1, 2011.”
P10L8: replace "+12 hours precipitation forecasts can be seen" by "+12 hour forecast range"
Replaced.
P10L10: replace "has clear added value" by "has a clear added value". Given the smaller size of the sample for large precipitation amounts this result is maybe not significant. Could you perform a statistical test of significance ?
Replaced.

We agree with this comment. The verification of larger precipitation thresholds might consist very few data which makes the corresponding results less reliable. The applied verification software (Harmonie monitor verification package) doesn't have a tool for test of statistical significance for skill scores and the raw data are also not easily accessible. Therefore, it would be difficult to perform such examination, however, when more thresholds are added to the SEDI verification, the scores are fluctuating for larger precipitation thresholds which is a clear signal of limited data amount (around 1-3 observation-forecast pairs). Therefore, we would like to propose to exclude larger precipitation thresholds (i.e. keep thresholds smaller than 10mm) from the verification of precipitation skill scores and mention this in the manuscript accordingly.

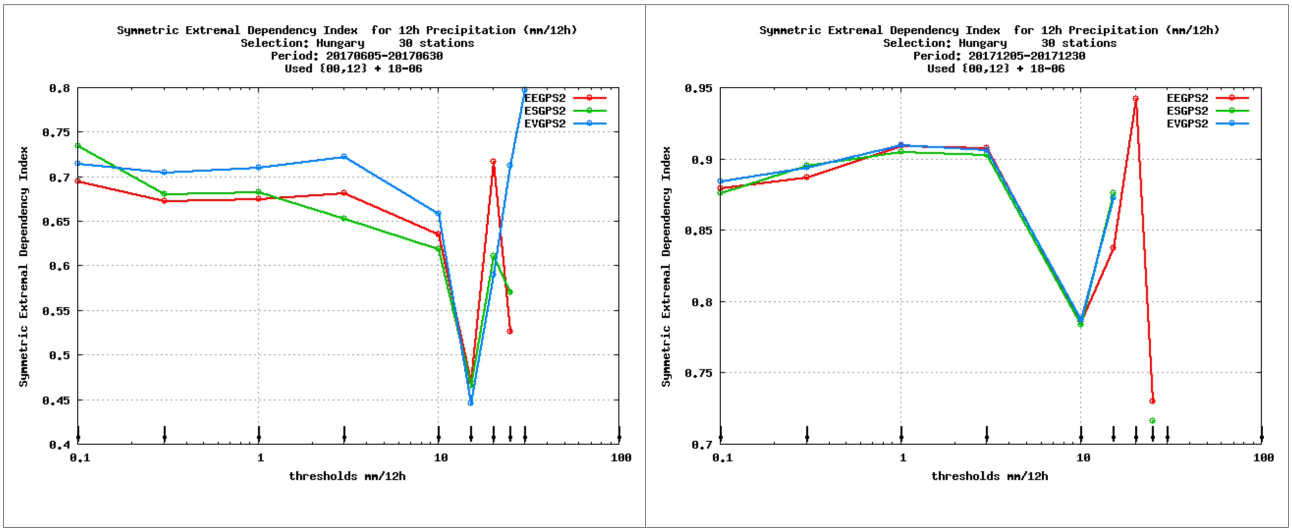


Figure: SEDI with additional 15, 20, 25mm thresholds for summer (left) and winter (right) impact studies.

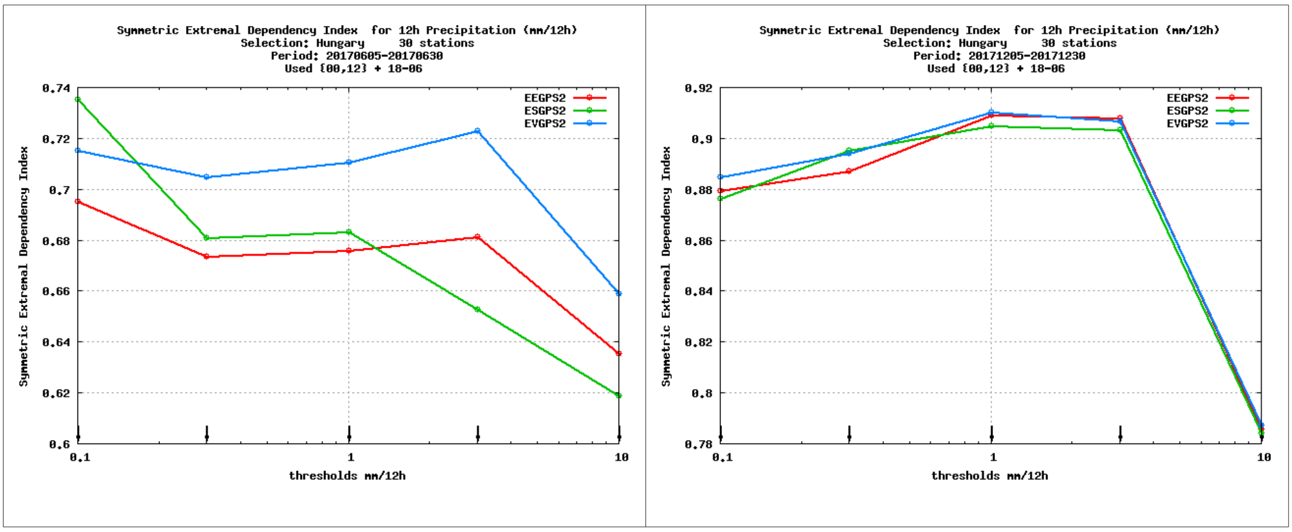


Figure (proposal): SEDI with restricted (below 10mm) thresholds for summer (left) and winter (right) impact studies.

Proposal for modification in manuscript's text.
Original:
"The AROME's precipitation forecasts are verified on Figure 9, where the Equitable Threat Score (ETS) and the Symmetric External Dependency Index (SEDI) (Ferro and Stephenson, 2011) for +12 hours precipitation forecasts can be seen. Overall, for the small precipitation thresholds both ESGPS2 and EVGPS2 can improve the precipitation forecasts, but for higher thresholds only the experiment EVGPS2 with ZTDs and VARBC has a clear added value."

Proposal:
"The AROME's precipitation forecasts are verified on Figure 9, where the Equitable Threat Score (ETS) and the Symmetric External Dependency Index (SEDI) (Ferro and Stephenson, 2011) for +12 hours precipitation forecasts can be seen. Overall, for small (less or equal than 1 mm) precipitation thresholds both ESGPS2 and EVGPS2 can improve the precipitation forecasts, but for 3 or 10 mm thresholds only the experiment with ZTD and VARBC (EVGPS2) has positive impact compared to the reference. Due to the limited number of high precipitation cases, the verification of larger precipitation thresholds (above 10 mm) is not taken into account."

P10L14: The information on the use of 30 stations has to be put in the legend of Figure 7.
The information is added.
P10L14: replace "This is due to taking into" by "Taking into"
Replaced.
P10L15: replace "smaller impact of the relatively" by " a smaller impact given the relatively"
Replaced.
P10L15: replace "employed" by "assimilated"
Replaced.
P10L16: replace "the cause" by "another reason"
Replaced.
P10L16-17: The sentence needs to be clarified since the writing is awkward.
Rewritten. "Furthermore, another reason might be that AROME/Hungary's background errors are derived from an AROME EDA (Ensemble Data Assimilation) which statistics provide more localized increments and sharp background error correlations."
P10L19: replace "chosen to run the second" by "selected to perform a second"
Replaced.
P10L20: replace "as the summer trial" by "as for the summer trial"
Replaced.
P10L21: replace "applied for the" by "applied to the"
Replaced.
P10L22: replace "but has the possibility to" by "but allows to"
Replaced.
P11L1-2: indicate the statistics are performed using 30 SYNOP stations.
Done.
P11L4: replace "to static bias correction. Examining" by "to the static bias correction. By examining"
Replaced.
P11L4: replace "on Figure 10" by "in Figure 10"
Replaced.
P11L5-6: replace "obtained in summer period is slightly remained for short-ranges" by "obtained for the summer period slightly remains at short-ranges"
Replaced.
P11L6: replace "slightly" by "slight"
Corrected.
P11L7: what do you mean by "for one or two forecast ranges" ?
Explicitly written. "...statistically significant for +3 hour T2m forecast and for +1, +2 hour Rh2m forecast ranges."
P11L8: what do you mean by "overfitting issues" ?
Overfitting of the observations in the assimilation by the inaccurate and most probably too small observation errors. Sentence was corrected to "observation overfitting".
P11L9: replace "were overestimated by the" by "are overestimated using the". If observation errors are too large, it should not lead to an "overfitting". Please clarify

The observation error is estimated (not overestimated) which means we computed ZTD observation errors (and the whitelist) on the spring training period and that might not be accurate for the winter period. We assume that observation error is probably smaller (than it should be), according to the verification results.
P11L9: replace "the impact of other forecast parameters was" by "the impact on other forecast parameters is"
Replaced.
P11L10: replace "to summer" by "to the summer"
Replaced.
P11L11: replace "include" bu "show". replace "This is positive" by "The impact is positive"
Replaced.
P11L12: replace "3mm" by "3 mm"
Replaced.
P11L12-13: "Similarly to the summer OSE, the value of an adaptive bias correction is confirmed by the results of the winter trial as well"
Corrected.
P11L14: replace "SYNOP stations, therefore overall results show neutral" by "SYNOP stations. Indeed, overall results show a neutral"
Replaced.
P12L5-6: reformulation of the sentence: "The potential and importance of this observation type was shown through DFS diagnostics. This is particularly relevant in data assimilation systems with a high frequency analysis cycle"
Replaced.
P12L7: replace "having potential" by "have the potential"
Replaced.
P12L8: remove "As ZTD observations are by default blacklisted"
Removed.
P12L8: replace "the pre-selection procedure of the trusted GNSS" by "A pre-selection of reliable GNSS"
Replaced.
P12L8-9: replace "has to be done" by "has been done"
Replaced.
P12L9: replace "sufficiently cover the wider area" by "cover sufficiently a wide area" (this has to be presented in a Figure plotting the stations)
Replaced. Figure is added (see above).
P12L12: replace "without risking" by "and to avoid"
Replaced.
P12L13: what do you mean by "separate correction" ? a specific correction for each (station/analysis centre) ?
Corrected.
P12L14: replace "debiasing" by "removing the bias of"
Replaced.
P12L15: replace "GNSS data has positive" by "GNSS data have a positive"
Replaced.
P12L16: please clarify what you mean by "if bias information is also up-to-date" ? This was not the case in winter
This part of the sentence was not appropriate and does not necessary. Removed.
P12L16: replace "The observation impact in the verification of" by "This positive impact on forecast scores during the"
Replaced.
P12L17: replace "using only" by "given the"

Replaced.
P13L1: replace "12 hours" by "12 hour". Replace "cummulation" by "accumulation"
Replaced.
P13L4: replace "when" by "using the". Remove "was employed"
Replaced and removed.
P13L4: replace "but with" by "whereas with the"
Replaced.
P13L8: replace "concluded that" by "concluded that the"
Replaced.
P13L11: replace "smaller" by "small"
Replaced.
P13L13: "an improved stiffness parameter might be investigated in order to allow more flexibility to the system"
Replaced.
P16L1: replace "12 hours" by "12 hour". Replace "cummulation" by "accumulation"
Replaced.

Anonymous Referee #2
Received and published: 23 January 2019
This paper presents the results on the impact studies of assimilating GNSS ZTD observations together with conventional observations, radar reflectivities and Doppler winds, and radiances from satellites with an experimental AROME/Hungary system over a domain in central Europe for two periods. The pre-processing, the description of the experiments , and the results are explained in detail. And the impact shown seems to be consistent with previous published studies. My recommendation is to accept the publication once minor modifications suggested below are taken into account:
- A map of the GNSS stations coverage before and after the 20km thinning could be recommended to include.
The figure of NWP domain and orography is replaced by figure 1 below which includes all GNSS stations inside the NWP domain as well.

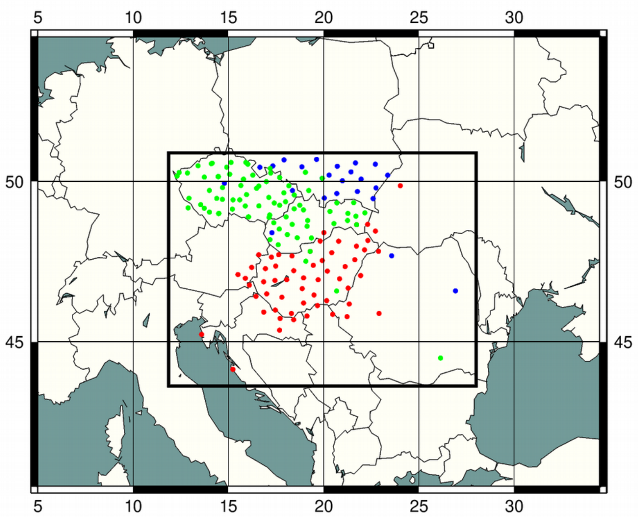


Figure 1. All GNSS stations inside the AROME/Hungary's NWP model

Another figure is added to the manuscript which shows the selected stations with 20km thinning distance (see figure 2 below). Furthermore a third figure (figure 3 below) is prepared (but not inserted to the manuscript for the time being) which shows reliable stations without 20km thinning.

The biggest differences between figure 2 and 3 can be observed over Czech Republic (e.g. around Prague). If the reviewer can agree, we would like to propose putting only the first and the second figures which show the stations before and after the pre-selection procedure. The third figure – we believe – can be less illustrative for a reader.

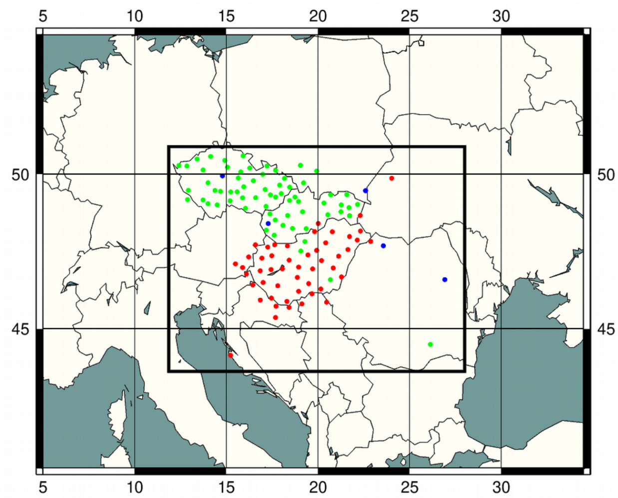


Figure 2. Selected GNSS stations with 20km thinning distance

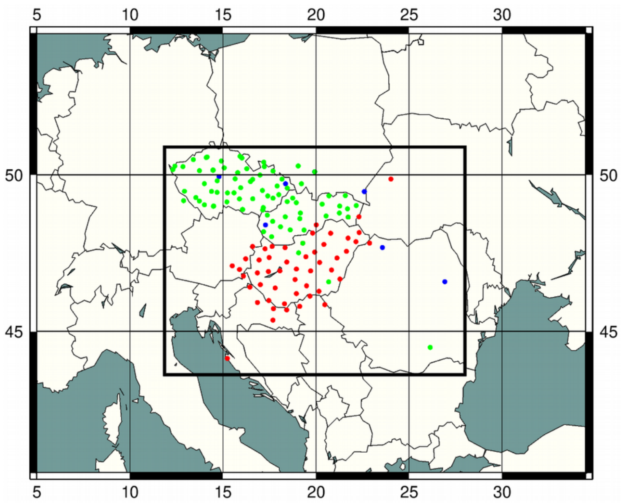


Figure 3. Selected GNSS stations without thinning distance removal

- As it is well explained in this study, the winter period has been carried out without the previous adaptation of the bias coefficients and then the impact is more neutral. It could be reconsidered here the possibility to include a study of these bias values in the period itself to check if they have already stabilized, as it is suggested in the text, or even if it is necessary to include this period in this work due to showing the impact of assimilating GNSS ZTD observations and also the impact of using variational or static bias corrections (as Sanchez-Arriola et al. 2017) with the domain and nwp system selected might be enough.

Due to the observation error and bias were not updated for winter assimilation runs, it is difficult to make clear conclusion from the winter OSE’s verification scores. Therefore, we agree to remove this winter impact study from the manuscript (in accordance with the reviewer’s comment). The related results were criticized by other reviewers as well. Additionally, we would like to propose to add one more verification result (dew point temperature forecast) to the summer trial which also indicates the significant improvement of the GNSS ZTD assimilation.

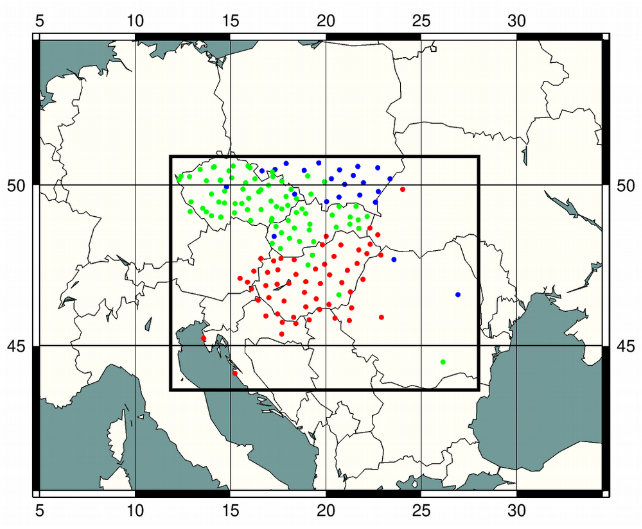
Other suggestions are:
P1L2: replace "numerial" by "numerical”
Replaced.
P1L4: replace "ZTDs" by "ZTD"
Replaced.
P1L8: replace "ZTDs" by "ZTD"
Replaced.
P2L33: You may probably have forgotten to add the TOUGH (Targeting Optimal Use of GPS Humidity Measurements in Meteorology) Project in the list that took place just after COST 716 and before EGVAP (http://tough.dmi.dk/)
Added.
P3L10: replace "ZTDs" by "ZTD"

Replaced.
P3L16: replace "ES1206" by "COST ES1206"
Replaced.
P3L22: replace "Applied" by "Description of the"
Replaced.
P3L27: replace "Meso-NH(?)" by "Meso-NH (Lac et al., 2018)"
Replaced. Another reference was also added.
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., Vilà-Guerau de Arellano, J.: The Meso-NH atmospheric simulation system. Part I: Adiabatic formulation and control simulations. Ann. Geophys., 16, 90–109., 1997.
P3L50: Assimilated satellite observations could be more explained
The satellite and RADAR observations were assimilated only for DFS diagnostic purposes and those non-conventional observations were not taken into account in GNSS ZTD OSEs. It is now explained in the manuscript more clearly. The use of satellite observations in DFS diagnostic is also explained with more details in the text.
"The non-conventional satellite and RADAR observations were added to AROME experimental analyses solely for diagnostic study and they were not considered in the GNSS ZTD observing system experiments."
P4L18: replace "COST Action ES-1206" by " COST ES1206"
Replaced.
P4L35: replace "ZTDs" by "ZTD"
Replaced.
P5L5: replace "station multiplication " by "stations that are processed by more than one Analysis Centre"
Replaced. "Considering that particular stations can be processed by several analysis centre (we can call it station multiplication) that station/processing centre pair is selected which has the smallest standard deviation of OMF."
P5L10: replace "consist 197" by "consist of 197"
Replaced.
P7L25: Figure 7 could be a little bit more explained.
One more sentence is added about bias results and the result of dew point temperature is also mentioned here.
"For these surface parameters the error reduction with respect to the reference during the first 6 hours in AROME forecast is apparent by the use of ZTD observations with both static and variational bias correction. Nevertheless, the temperature bias is slightly overestimated, but dew point temperature and relative humidity bias are remained more or less the same for short forecast ranges. The most important is that the error reduction is statistically significant for the short-, very short-range ..."

P7L: replace "consist 197" by "consist of 197" Cannot Figure 9 and Figure 10 be after Figure8 and before the Conclusions?
Replaced. The manuscript was compiled by Latex editor with "amtd" document class. The figure's location is more or less determined by Latex software. The current version is only for review process and for discussion (e.g. one column template), therefore the position of figures can be changed later.

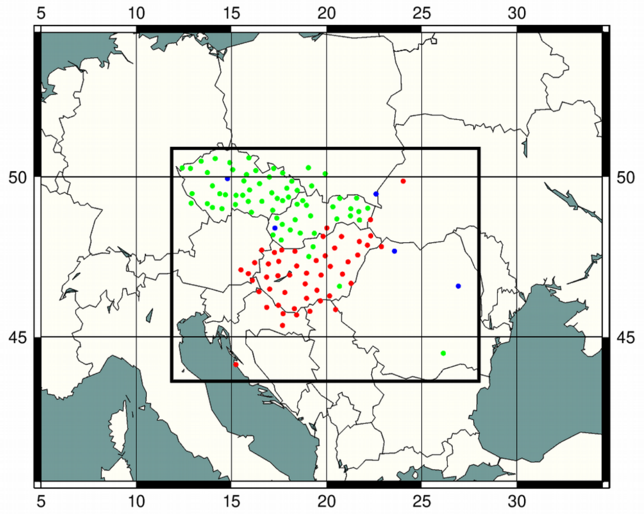
Anonymous Referee #3
Received and published: 7 February 2019
This paper describes experiments made with ground based GNSS observations as an additional observation type in the Hungarian NWP setup. There is nothing novel presented but it is an interesting contribution to the field in the sense that it confirms previous results also in a model domaine over central Europe. The paper describes the setup and assimilation procedure well and can be published. There are however a few things that need to be clarified first. One thing that is valid through the entire manuscript is that the figures are unreadable and not well explained. For example are the labels on the x-axis on figures 3, 5 and 6 impossible to read.
The quality of above mentioned figures is now improved in the manuscript.

Specific comments:
Page 2, line 33: The authors should also mention the project TOUGH, Targeting Optimal Use of Gps Humidity measurements in meteorology which was the predecessor to E-GVAP. Perhaps also a reference to the projects mentioned here, final report or a publication (e.g. http://tough.dmi.dk/deliverables/d14-final-rep.pdf)
This is now mentioned in the manuscript.
Page 3, line 23, Remove “to” in “...started in the 1990s joining to...”
Corrected.
Page 3, line 27, Missing reference right after Meso-NH?
Fixed (Lafore et al. (1997)). Lac et al. (2018) is also added.
Page 3, line 36-37: Remove “called OI_main”
Removed.
Page 3, figure 1: I would like to see a map over a slightly larger area with the model domain indicated by lines. It will make it easier to orient oneself and get a better feeling of where we are in the world.
New figure is added which shows GNSS stations as well.



Page 4, lines 7-10: Please explain figure 2 in more detail. What does absolute and relative mean?
Explained and more details are added. Figure’s caption is also improved.
“The relative DFS is a normalized value by the amount of observations for each observation subset providing the diagnostic information regardless the actual amount and geographical coverage in the assimilation system.”
Page 4, section 3: It would be helpful with a figure indicating the position of the GNSS stations. Perhaps include it in figure 1? It would also be nice to see which of all stations

that are active in the assimilation, i.e. highlighted in some way.
We agree and new figures are added. Figure 1 shows now all available GNSS stations inside NWP domain (see above), and another figure highlights only selected GNSS stations (see below).



Page 5, lines 31-33: Very strange sentence. I do not really understand. Please re-formulate and clarify.
The sentence is reformulated.
“Although quality control procedure of the variational scheme contains the so-called background check (which is dedicated to reject observations far from model background state), one also needs to ensure that only observations with Gaussian, zero mean and uncorrelated errors are selected in the assimilation (i.e. reliable stations).”
Page 5, line 35: “...GNSS ZTDs by default are blacklisted in the system.” Why is this the case and what does it mean?
This sentences was reformulated and the above mentioned (unnecessary) part was removed as well.
“For that purpose, a specific pre-selection procedure has to be performed by checking passive observation minus first-guess (OMF) departures on a training period.”
This half-sentence about blacklisting is basically a technical remark which is trying to highlight that GNSS ZTD is a special observation type in the AROME’s assimilation system. Due to historical reasons, the use of E-GVAP ZTD data required this special whitelisting approach, because processing upgrades, network expansion, and new analysis centers do not support to apply regular blacklisting solution (i.e. all data are active). It might explain why the pre-selection and a whitelist generation are necessary, but not really important to mention such technical detail in the manuscript if the reviewer can agree.
Page 5, line 37: It is assumed that the training period is sufficient. Can this be verified in some way.
Due to AROME/Hungary has 8 analyses in a day, the 15 days (or actually 16 days from 15th to 31st of May) together gives 128 observation minus background departures per GNSS station to compute statistics (static bias, observation error, etc). It was not verified, but similar approach and data amount were applied in other studies (e.g. Yan et al. (2009) with AROME/France).
Page 6, line 13: Since the study includes a bias correction the predefined limits of OMF can be set more tolerant during the training period. This may include stations with a large bias that after bias correction can give a useful contribution.
We agree with this comment. There is still room for better pre-selection and bias correction in the future. We accepted the limits proposed by Yan et al. (2009), hence only 9 stations out of the total 197 (less than 5%) were excluded due to bias and stdv maximum thresholds.
Page 7, line 8: “...a space/time -average...” How does the space-part come into this?

This is done fore each observation station individually is it not?
This is a mistake and the manuscript was corrected accordingly (i.e. “space” is now removed).
Page 7, equation 3: What is n here? All observations in total or all observations from one station during the training period? I hope for the latter and that BIAS really is BIAS(i).
We agree that equation 3 was not fully correct and as the reviewer remarked the latter is correct. The sentence and the equation are modified as the following.
“The observation bias of a GNSS station (station) is detected as a time-average of observation (oi) minus model-background (bi) differences considering the number of analyses (n) during the time period (3).”

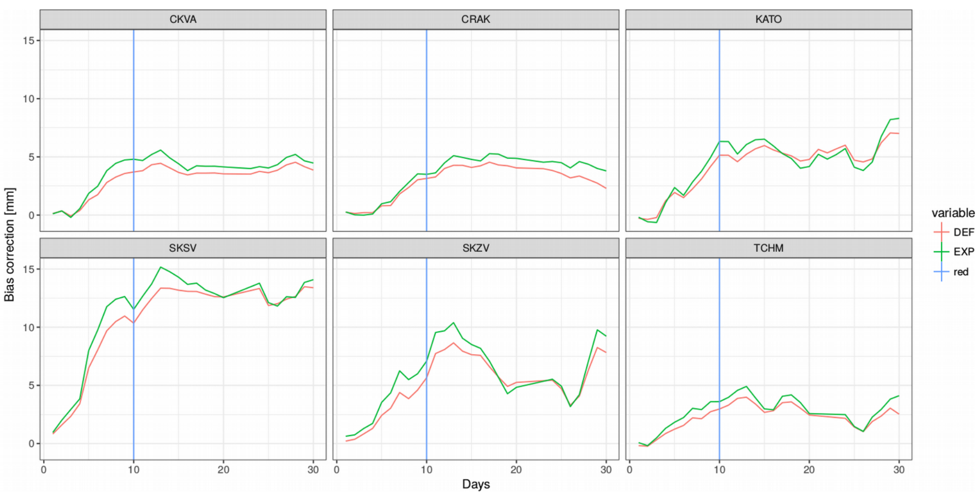
(3) $$BIAS_{station} = \frac{1}{n}\sum_{i=1}^{n} o_i - b_i$$

Page 7, line 14: OK, so the bias is calculated for each station separately. It is not really clear from the above.
The previous sentence was changed to make it more understandable. See the new sentence above.
Page 8, figures 4 and 5: Is the time period the same for both figures?
Yes, the figure’s caption is now improved.
Page 8 line 24: “...default set to 60...” 60 what?
The stiffness parameter is a positive scalar parameter without physical dimension which determines the adaptivity of bias correction.
Page 8 line 25: Is 15 days enough for all stations, even those with a very large bias? Has this been checked?
According to variational bias correction scheme, the bias halving time is 5 days with default adaptivity parameter (Nbg = 60) and 8 AROME analyses per a day. There is a paper from Cameron and Bell (2016) (now cited in the manuscript) which explains it in details. The total bias elimination time is replaced by bias halving time which is more appropriate.

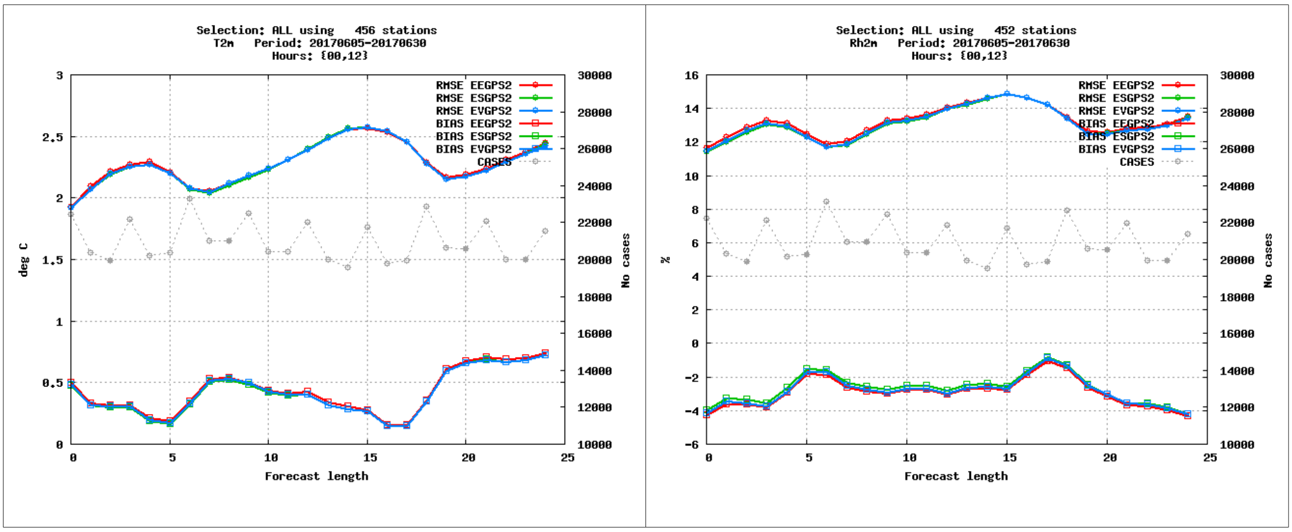
“The magnitude of the adaptivity is decided by the stiffness parameter which is by default set to 60 and taking into consideration that AROME/Hungary has 8 analyses in a day, the bias halving time corresponds to about 5 days (Cameron and Bell, 2016)”

“Cameron, J., and Bell, W.: The testing and planned implementation of variational bias correction (VarBC) at the Met Office. https://cimss.ssec.wisc.edu/itwg/itsc/itsc20/papers/11_01_cameron_paper.pdf, 2016.”

For 30 days of the summer period, the time evolution of bias correction was checked for various GNSS stations with the default and an experimental (Nbg = 40) setup. It can be seen on figure below that bias was eliminated with default (DEF - red curves) setup within 15 days. It is true for SKSV station which has generally larger bias than other stations.



Additionally, the first 5 days from summer impact study was excluded, but the variational bias correction was performed continuously resulting 21 days (i.e. 3 weeks between 15^{th} of May and 5^{th} of June, 2017) “bias spin-up” before first long AROME forecast in OSE.
Page 10, lines 5-7: Why only 30 synop stations? How are these selected? Are the ZTD observations distributed over the entire model domain?
These are the most reliable SYNOP stations from the Hungarian Met Service (called main synoptic stations) exchanged internationally in Global Telecommunication System (GTS) as well. These SYNOP stations are not covering the entire NWP domain, but Hungary.
Page 11, figure 7: Perhaps outside the scope of this study but there is a very strange diurnal (?) cycle in the verification. Just a few words to explain would be good.
We agree and that can be explained by the characteristics of the surface model (SURFEX) and surface assimilation scheme which is mentioned in the Section 2. There are ongoing surface modelling activities at OMSZ which is aiming to improve surface fields of AROME model. However, the GNSS ZTD is assimilated in upper-air 3D-Var assimilation. A short sentence is now added to Section 5 reflecting to this behavior as the following.
“The AROME/Hungary forecasts have usually warm and dry bias during night-time, however, the assimilation of GNSS ZTD cannot mitigate this issue.”
Page 11, line 20: Overfitting is not likely the explanation here. That would show up in the 1-3 hour forecast range and would be clearly visible in figure 10.
The winter OSE is proposed to be removed from the manuscript according to the remarks of other reviewer.
Page 11, lines 26-27: I do not understand the conclusion that the results are neutral since it was verified against Hungarian synop stations. Would the conclusion be different if it was verified against more stations?
Verification against all available SYNOP stations shows limited impact (closer to neutral), because we are not assimilating GNSS ZTDs from many neighboring countries like Romania, Austria, Slovenia, Croatia, and/or Serbia. Please see below RMSE and BIAS verification scores against all available SYNOP stations for T2m and RH2m.



Page 14, figure 10: Again a strange cycle in the verification that could be explained with a few words (if possible).
Yes, please see above.

The use of GNSS zenith total delays in operational AROME/Hungary 3D-Var over a Central European domain

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Abstract. The delay of satellite signals broadcasted by Global Navigation Satellite System (GNSS) provides unique atmospheric observation which endorses ~~numerial~~ numerical weather prediction from global to limited-area models. Due to the possibility of its frequent and near real-time estimation, the zenith total delays (ZTD) are valuable information for any state-of-the-art data assimilation systems. This article introduces the data assimilation of ~~ZTDs~~ ZTD in a Hungarian numerical weather prediction system which was carried out taking into account observations from Central-European GNSS analysis and processing centres. The importance of ZTD observations is described and showed by a diagnostic tool in the three hourly updated 3D-Var variational assimilation scheme. Furthermore, observing system experiments are done to evaluate the impact of GNSS ~~ZTDs~~ ZTD on mesoscale limited-area forecasts. The results of the use of GNSS ZTDs showed a clear added value to improve screen-level temperature and humidity forecasts when bias is accurately estimated and corrected in the data assimilation scheme. The importance of variational i.e. adaptive bias correction is highlighted by verification scores compared to static bias correction. Moreover, this paper reviews the quality control of GNSS ground-based stations inside the Central-European domain, the calculation of optimal thinning distance and the preparation of two above mentioned bias correction methods. ~~At the end of this article, the conclusion is~~ Finally, conclusions are drawn about different settings of the forecast and analysis experiments with a brief future outlook.

1 Introduction

The interaction of satellite signals from Global Navigation Satellite ~~System~~ Systems (GNSS) with atmospheric constituents has been recognised as valuable information for meteorological applications and numerical weather prediction (NWP). The GNSS signals delay along the emitted satellite ray's path which can be formulated as an excess length and most generally determined in zenithal path above the ground-based receiver station providing the zenith total delay (ZTD) (Bevis et al., 1992). The total delay includes a wet delay component which is a function of the water vapour distribution of the troposphere bringing key humidity related observations for meteorological users. The high-resolution NWP and data assimilation are demanding more frequent and denser observations (Benjamin et al., 2004, 2010) in particular by employing non-conventional data sources to a larger extent. Consequently, state-of-the-art data assimilation systems rely ~~on more the~~ significantly on remote sensing measurements like RADAR, satellite products including data from navigation satellites as well. Therefore, the use of GNSS measurements has been widely ~~taken up~~ included in experimental and also operational data assimilation systems since the second half of the 2000s. In a global 4D-Var system, Poli et al. (2007) demonstrated positive forecast impact of the ZTD observations by correcting synoptic scales up to 4 days. Macpherson et al. (2008) and De Pondeca and Zou (2001) published data assimilation impact and case study respectively showing that the use of zenith troposperic delay observations over North America led to forecast improvements and error reductions. At that time the added value of ZTDs in European limited-area DA systems has been also justified by a number of authors such as Cucurull et al. (2004); Faccani et al. (2005); Yan et al. (2009b) and Boniface et al. (2009) focusing on local area and dataset. After various inter European studies and projects e.g. MAGIC (Meteorological Applications of Global Positioning System Integrated Column Water Vapour Measurements in the Western Mediterranean)~~and~~ , COST Action 716, and TOUGH (Targeting Optimal Use of GPS Humidity Measurements in Meteorology) the European Meteorological Services Network (EUMETNET) organized the GNSS Water Vapour programme (E-GVAP). This EUMETNET observation programme shares ZTD estimates in near real-time (NRT) primarily for use in operational meteorology, aims to expand the existing network with inclusion of new regions and helps its members ~~employing~~ using ground-based GNSS data in their operations. The programme was set up in April 2005 establishing timeliness and precision requirements of distributed ZTD data. Given the efforts of E-GVAP programme, and with a view of increasing such observation usage, new actions and explorations of meteorological applications were initiated during the last decade. Recently a new European COST Action (ES1206) aiming advanced GNSS products for severe weather events and climate (Guerova et al., 2016) was also launched. In the meantime, more recent studies have been carried out by for instance, Bennitt and Jupp (2012); De Haan (2013); Mahfouf et al. (2015) pursuing the objective of improved GNSS ZTD assimilation and taking into account one or more E-GVAP networks. All ~~of~~ these studies agreed that more accurate description of humidity and precipitation forecast can be gained by the use of GNSS ZTD although its absolute contribution in terms of observation number is smaller compared to other observation types. However, GNSS ~~ZTDs~~ ZTD - like most of the observations - include systematic ~~error~~ errors which must be taken into account in the assimilation procedure. Better characterization and ~~assay of ZTD bias were examined~~ assessment of ZTD were proposed by e.g. Storto and Randriamampianina (2010)) and recently Sánchez-Arriola et al. (2016) and Lindskog et al. (2017) who demonstrated that the variational bias correction approach is successful to eliminate GNSS ZTD bias and advantageous to control bias correction in an adaptive manner. Main objectives of this paper are to assess the added value of GNSS ZTD observations in a Central-European domain taking into account all available E-GVAP ZTD networks and to summarize the work that has been done in the frame of COST ES1206. In addition, the latest bias correction developments are studied and ~~utilized~~ used in the data assimilation system of AROME/Hungary. The paper is constructed as follows. Section 2 introduces the operational AROME NWP model and data assimilation system used in the current study. Section 3 gives an overview of the applied data, the characteristics of E-GVAP networks and their ZTD observations. In Section 4 the passive assimilation experiment, the pre-processing of ZTD observations and the bias correction are described. In Section 5 the results of active assimilation runs are discussed and in the last Section ~~the conclusion is~~ conclusions are drawn with a brief future outlook.

2 ~~Applied~~ Description of operational model and observations

At the Hungarian Meteorological Service (OMSZ) limited-area (LAM) NWP activities were started in the 1990s by joining ~~to~~ the ALADIN (Aire Limitée Adaptation Dynamique Développement International) ~~consortia~~ consortium which led to the implementation of the ALADIN model (Horányi et al., 1996) and later its data assimilation system (Bölöni, 2006). For the purpose of having a high (kilometric) spatial resolution of LAM, the non-hydrostatic dynamical core of ALADIN (Bubnová et al., 1995) and the physical parametrization package of the French research model called Meso-NH ~~(?)~~ (Lafore et al., 1997) (Lac et al., 2018) have been merged setting up the AROME (Application of Research to Operations at Mesoscale) model. After the successful operation of AROME at Météo-France (Seity et al., 2011), OMSZ also began to implement an AROME system running over a Central-European domain. The first Hungarian AROME configuration (Arome/Hungary) has been performed with dynamical adaptation of ALADIN/Hungary forecasts as initial and boundary conditions. Later, major upgrades consisting of a direct coupling to ECMWF (European Centre for Medium-Range Weather Forecasts) IFS (Integrated Forecasting System) global model together with local 3D-Var data assimilation system brought significant ~~improvement~~ improvements on operational AROME/Hungary forecasts (Mile et al., 2015). The recent operational NWP model domain covers the entire Carpathian-basin (highlighted by the black frame in Figure 1) with a horizontal mesh size of 2.5 km and 60 vertical levels from surface up to 0.6 hPa. The surface characteristics of AROME model are described by the surface scheme of Meso-NH called Externalized Surface (SURFEX) and initialized by optimal interpolation method (Mahfouf, 1991) ~~called OI_main~~ (Masson et al., 2013) before every model integration.

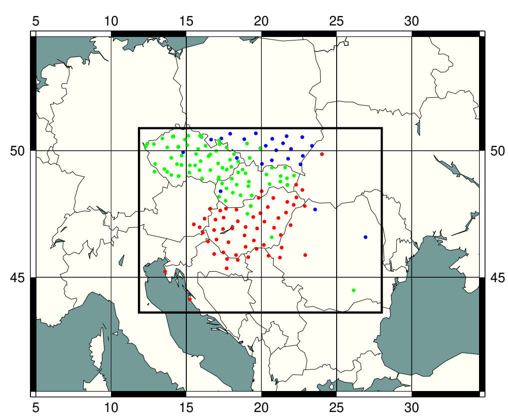

Figure 1. The computational domain of AROME/Hungary (black rectangle) and all available GNSS stations from SGO1 (red), GOP1 (green), and WUEL (blue) E-GVAP networks.

For the time being, upper-air assimilation system of AROME/Hungary ~~employs~~ considers only conventional observations namely surface SYNOP, aircraft (AMDAR, ACARS and Mode-S from Slovenia) and radiosonde reports. To use a larger number of conventional observations, the 3-hour assimilation cycle is set producing 8 analyses per a day which for example enables the utilization of aircraft data measured at asynoptic network times by the +/- 1.5 hour assimilation window in 3D-Var. The timeliness of conventional observations collected from GTS (Global Telecommunication System) plus local sources in a 3 hourly rapid update cycle (RUC) is still met with the time-critical applications of operational AROME/Hungary. For forecaster's needs at OMSZ, the short cut-off AROME analysis and related forecast are scheduled to be performed not later than 2 hours after its actual time which production includes the long cut-off analyses and updated first guesses for the more accurate background information. Regarding future perspectives of AROME/Hungary's upper-air DA, the ~~appiled~~ applied RUC approach favors those observations which have large temporal frequency and small latency. For particular diagnostic purposes the AROME 3D-Var was experimentally run with all available non-conventional observations i.e. satellite radiances from Meteosat-10 SEVIRI (Spinning Enhanced Visible and Infrared Imager), from NOAA-19 ~~and Metop~~ AMSU-A (Advanced Microwave Sounding Unit-A) ~~,~~ and MHS (Microwave Humidity Sounder), from Metop-A and Metop-B AMSU-A, MHS, and IASI (Infrared Atmospheric Sounding Interferometer) sensors, with satellite derived winds MPEF (Meteorological Product Extraction Facility) called Geowind and HRW (High Resolution Winds), furthermore with RADAR reflectivity and radial winds from Hungarian RADAR sites, with AMV (Atmospheric Motion Vectors) satellite wind retrievals and most importantly with GNSS ZTD observations. The non-conventional satellite and RADAR observations were added to AROME experimental analyses solely for diagnostic study and they were not considered in the GNSS ZTD observing system experiments. This experimental DA system performed 3D-Var analyses with perturbed and unperturbed observation sets on a 10-day period (between 5th and 15th of June, 2017) in order to compute Degree of Freedom for Signal (DFS) diagnostic as the following (Girard, 1987) (Chapnik et al., 2006):

$$DFS \approx Tr(\mathbf{HK}) \approx (\mathbf{y}^{'} - \mathbf{y})^{T}\mathbf{R}^{-1}(\mathbf{H}(\mathbf{x}_{\mathbf{a}}^{'}) - \mathbf{H}(\mathbf{x}_{\mathbf{a}})) \qquad (1)$$

where $\mathbf{HK}$ is the product of the linearized observation operator ~~and~~ by the Kalman gain~~respectively~~, and the DFS ~~score~~ scores can be approximated by ~~their~~ its trace as (1). The $\mathbf{y}$ and $\mathbf{y}^{'}$ are the unperturbed and perturbed observation ~~arrays~~sets, $\mathbf{R}$ is the observation-error covariance matrix, $\mathbf{H}(\mathbf{x}_{\mathbf{a}})$ and $\mathbf{H}(\mathbf{x}_{\mathbf{a}}^{'})$ are the unperturbed and perturbed analyses states ~~at~~ in the observation space respectively. DFS provides information on the observation's influence on analyses with respect to the different observation types. Figure 2 shows absolute and relative DFS scores computed on the 10-day period in the AROME/Hungary system. The relative DFS is a normalized value by the amount of observations for each observation subset providing the diagnostic information regardless the actual amount and geographical coverage in the assimilation system. The GNSS ZTD has a limited absolute DFS due to the small number of ZTD observations compared to other observation types. However, it has a considerably high relative contribution which can significantly affect the AROME/Hungary's analysis.

3 GNSS ZTD observations

The first tests of ZTD retrievals using permanent GNSS stations in Hungary ~~dates back to~~ started in 2009 (Rózsa et al., 2009). Due to the positive ~~experiences~~ results of this study, a near-real time GNSS processing facility was set up by the collaboration

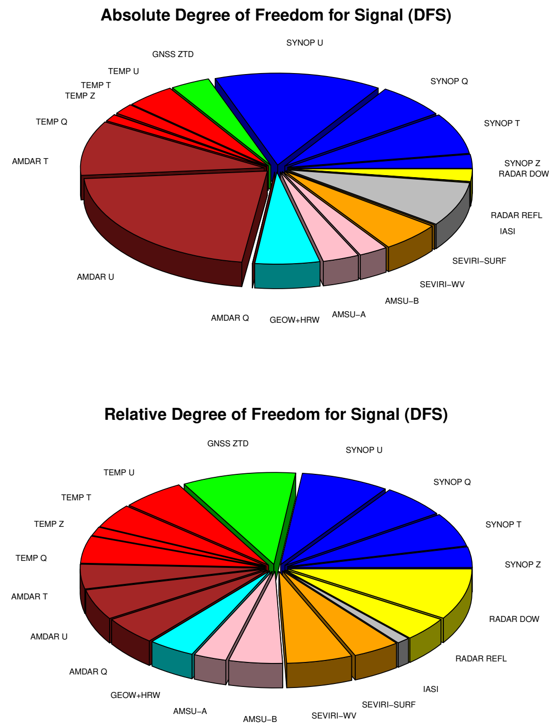

Figure 2. The absolute (top) and relative (bottom) DFS scores computed in AROME/Hungary 3D-Var experimental analyses for the period 5-15th of June, 2017. The considered observations in DFS computation are the following, SYNOP (parameter U, Q, T, Z) with blue, TEMP (parameter U, T, Q, Z) with red, AMDAR (parameter U, T, AMDAR Q) with maroon, GEOW+HRW (parameter U) with cyan, RADAR (parameter reflectivity, radial wind) with yellow, AMSU-A and AMSU-B (parameter Tb) with pink, SEVIRI-WV and SEVIRI-SURF (parameter Tb) with orange, IASI (parameter Tb) with grey, and GNSS (parameter ZTD) with green.

of the Satellite Geodetic Observatory Penc and the Budapest University of Technology and Economics (BME). The applied computational strategy can be found in Rózsa et al. (2014). The processing center (SGOB later renamed to SGO1) joined to the EUMETNET's E-GVAP programme in 2013. Since then, the ZTD estimates at the stations of the Hungarian GNSS Network are available for meteorological applications. Hungary, with its representing institutions BME, OMSZ and SGO, participated in the COST ~~Action ES-1206~~ES1206. The network processed by the SGO1 processing center involves more than 80 ground-based stations and provides accurate ZTD estimates using the Bernese Software v5.2 (Dach et al., 2015). The estimates are computed from the network solution with +90 minutes latency. Due to its coverage, the SGO1 network provides ~~the~~ most of the ZTD ~~estimated~~ estimates in the AROME/Hungary's NWP domain. To extend the coverage of GNSS ~~ZTDs~~ZTD, other Central-European E-GVAP networks were included in this study. The Geodetic Observatory Pecny (GOP) in the Czech Republic has been long time preparing GNSS based measurements for various users and also contributing to E-GVAP with a large network

(~~estimation for~~ more than 120 stations) called GOP1. Moreover, the GNSS network developed by Wroclaw University of Environmental and Life Science (WUELS) serves additional ZTD estimates inside our area of interest. The WUEL analysis center provides ZTD estimates for a network of 130 stations. Both of the latter centres use a network solution provided by the Bernese Software.

4 Evaluation of the quality and use of GNSS ZTDs on a training period

4.1 Passive assimilation and pre-selection procedure setup

The assimilation of ZTDs with ~~increased observation error~~ very large observation errors has been conducted in an experimental AROME/Hungary system for a training period. This ~~passive~~ "passive" assimilation allows monitoring of ZTD observations inside the variational assimilation scheme without ~~its influence on~~ influencing the analysis. Although quality control procedure of the variational scheme contains the ~~so called~~ so-called background check (which is dedicated to reject observations far from model background state), ~~beyond that, one needs to be ensured a priori~~ one also needs to ensure that only observations with Gaussian, zero mean and uncorrelated errors ~~that are employed~~ are selected in the assimilation ~~from reliable GNSS stations. To that a special~~ (i.e. reliable stations). For that purpose, a specific pre-selection procedure has to be ~~executed~~ performed by checking passive observation minus first-guess (OMF) departures on a training period~~, since GNSS ZTDs by default are blacklisted in the system~~. Due to the ~~increased~~ high analysis cycle frequency i.e. 8 AROME/Hungary analyses per a day, the training period of 15th and 31st of May, 2017 is chosen assuming sufficient sample for every ~~examined~~ GNSS station. The pre-selection of GNSS ZTDs means consecutive tests of time availability, normality, maximum standard deviation and bias, metadata consistency check together with domain and altitude difference examination of GNSS stations. ~~The presence of station multiplication has to be prevented by selecting the station with~~ Considering that particular stations can be processed by several analysis centre (we can call it station multiplication) that station/processing centre pair is selected which has the smallest standard deviation of OMF. Furthermore the station thinning is also ~~a~~ part of the procedure to avoid observation error correlations. More details about the pre-selection design are ~~written~~ given in Yan et al. (2009b) and Poli et al. (2007).

4.2 Results of the pre-selection procedure

The actual training period ~~consists~~ led to the availability of 197 GNSS stations ~~situated~~ inside the NWP domain ~~from the three GNSS networksand~~ (from three different networks). The pre-selection ~~filtered~~ procedure excluded more than 30 percent of them~~resulting~~ , resulting in 122 trusted GNSS stations for active assimilation experiments. Due to time coverage ~~issues~~ (e.g. data gaps or outages) and gaussianity issues, 10 percent of the data were rejected. Further 2-3 percent of the stations were denied since the detected bias and standard deviation of OMF were higher than ~~the~~ pre-defined limits. The thresholds of bias, standard deviation and altitude difference limits were set according to Yan et al. (2009b). Due to ~~station multiplication~~multiple station/analysis centre pairs, 12 percent of the stations are excluded from one or two networks during the pre-selection. The selected GNSS stations are written into a specific whitelist which ensures the active assimilation of ZTDs. The location of all available GNSS stations and trusted stations inside the NWP domain can be seen on Figure 1 and on Figure 3 respectively.

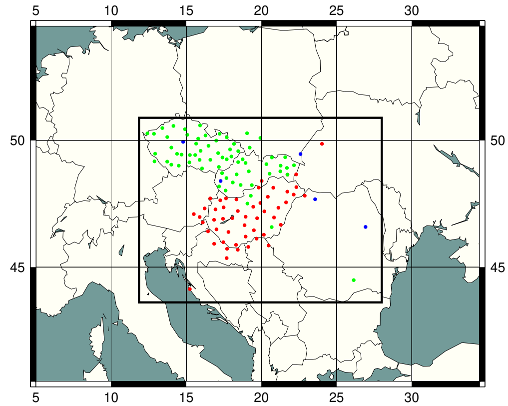

Figure 3. The computational domain (black rectangle) and pre-selected GNSS stations from SGO1 (red), GOP1 (green), and WUEL (blue) E-GVAP networks.

In order to determine the optimal thinning distance which is employed for pre-selection, horizontal observation error correlations as a function of various separation distances have been computed. The computation of error correlations are based on the method proposed by Desroziers et al. (2005):

$$E\left[d_b^o\,(d_a^o)^T\right] = \mathbf{R} \tag{2}$$

where observation error covariances are estimated based on the expected value of background (d_b^o) and analysis (d_a^o) departures ~~having~~ considering various departure pairs for horizontal distances. The Desroziers method has the advantage to provide error correlation structures in observation space i.e. at observation locations from the collected pairs of background and analysis departures in a computationally ~~cheap~~ efficient approach. For this diagnostic purpose, ~~another whitelist is originally~~ a revised whitelist is generated with zero thinning in order to execute very first active assimilation and to collect its OMF departures. Liu and Rabier (2003) showed that horizontal thinning distance is optimal, where the observation error correlations are less than 0.2 - 0.3. By the visualization of these error correlations which can be seen ~~on~~ in Figure 4, a 20km thinning distance is chosen for the final GNSS pre-selection procedure.

4.3 Detected bias and static bias correction

During the pre-selection procedure, OMF departures are used to evaluate the quality of ZTDs and also to identify systematic errors in measurements. The bias might originate from the mapping function of ZTD processing, the conversion of time-delay

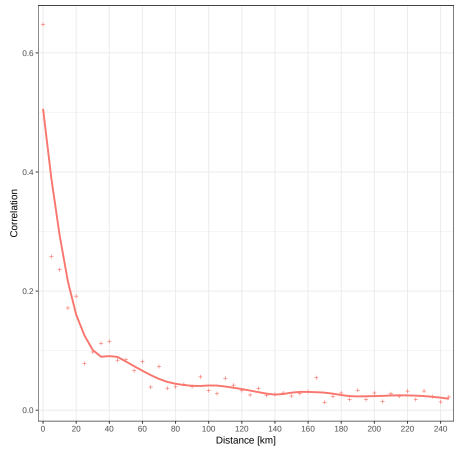

Figure 4. Observation error correlations estimated by Desroziers method as a function of separating distances for GNSS ZTDs inside AROME/Hungary's domain. Local polynomial regression method was used for fitting a smooth curve and the diagnostic was computed for the period of 15-31st of May, 2017.

to excess length, the contribution of the atmosphere above the model top or for instance the altitude differences between the model orography and the GNSS station elevation. The observation bias of a GNSS station ($station$) is detected as a ~~space/~~time-average of observation (o_i) minus model-background (b_i) differences considering the number of analyses (n) during the time period (3).

$$BIAS_{station} = \frac{1}{n}\sum_{i=1}^{n} o_i - b_i \qquad (3)$$

Although, it ~~presumes~~ assumes that the first-guess is an unbiased reference which is not necessarily true, Poli et al. (2007) showed this approach can be efficiently applied for the initial bias estimation of GNSS ZTDs. The distribution of OMF values taking into account all GNSS stations ~~are plotted on~~ is plotted in Figure 5. Concerning the detected bias of each GNSS station separately, one can see ~~on~~ in Figure 6 and 7 that the observed bias is strongly varying station by station in SGO1, WUEL and GOP1 networks respectively. Therefore the bias correction should be done individually for different GNSS stations.

After the pre-selection procedure, the bias and the standard deviation of background departures are added into the whitelist for each station independently. The standard deviation of OMF is assigned as the observation error of trusted GNSS stations ranging between 6 and 14 mm. The static bias information of the whitelist can be applied before active assimilation by removing the bias during the observation pre-processing. The impact of GNSS ZTDs with the use of static bias correction (called ESGPS2 hereafter) is investigated in observing system experiments ~~in the~~ presented in Section 5.

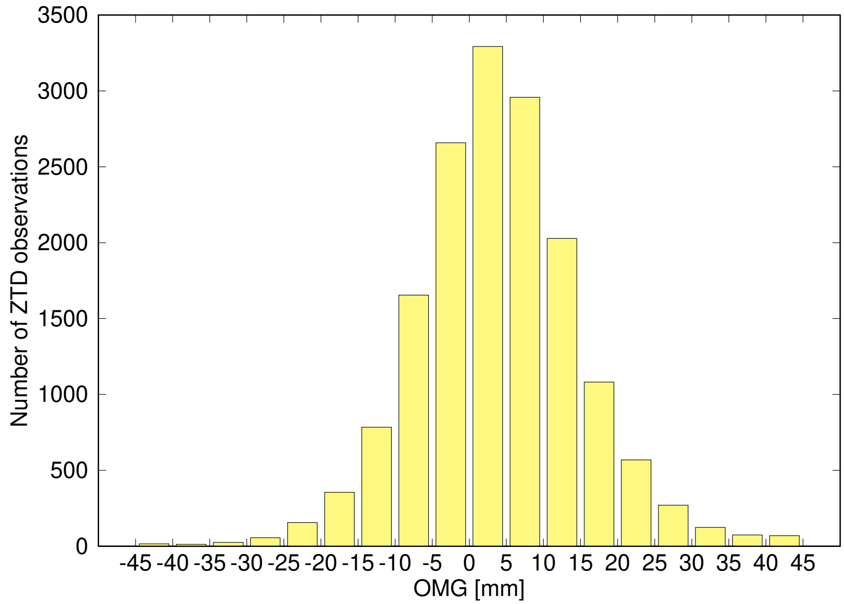

Figure 5. Distribution of OMF values for all GNSS stations inside AROME/Hungary's domain. The period of 15-31st of May, 2017 was used for the calculation of OMF statistics.

4.4 Variational bias correction

Beside the choice of static bias correction, the AROME's variational assimilation system offers the possibility of variational bias correction (VARBC) as well. In this scheme, the bias parameters are parts of the minimization via the extension of control vectors and the cost function (Auligné et al., 2007)(Sánchez-Arriola et al., 2016). The GNSS ZTD is considered as a type of surface observation in the data assimilation, therefore, VARBC similarly to static correction controls the bias separately for each station using a bias offset predictor. This predictor in the current implementation of the linear regression scheme is assumed to remove the major part of the bias. Moreover, the introduction of additional predictors showed by Lindskog et al. (2017) has limited impact on the forecasting system. The simplified background bias parameter error covariance matrix contains only diagonal elements which are characterized by the proportion of observation error variance (σ_o^2) and the ~~so called~~ so-called stiffness parameter (N_{bg}) (Dee, 2004) (4).

$$\boldsymbol{\sigma^2_{\beta_b}} = \frac{\boldsymbol{\sigma_o^2}}{\mathbf{N_{bg}}} \qquad (4)$$

In contrast to the static scheme, the VARBC adjusts bias information ~~in every new~~ at every analysis making bias correction updates in an adaptive manner. The magnitude of the adaptivity is decided by the stiffness parameter which is by default set to 60 and taking into consideration that AROME/Hungary has 8 analyses in a day, the ~~total bias is eliminated in about 15 days period~~bias halving time corresponds to about 5 days (Cameron and Bell, 2016). For the active assimilation trial, instead of coldstart initialization of the bias, VARBC coefficients were spinned up on the pre-selection training period and stored to

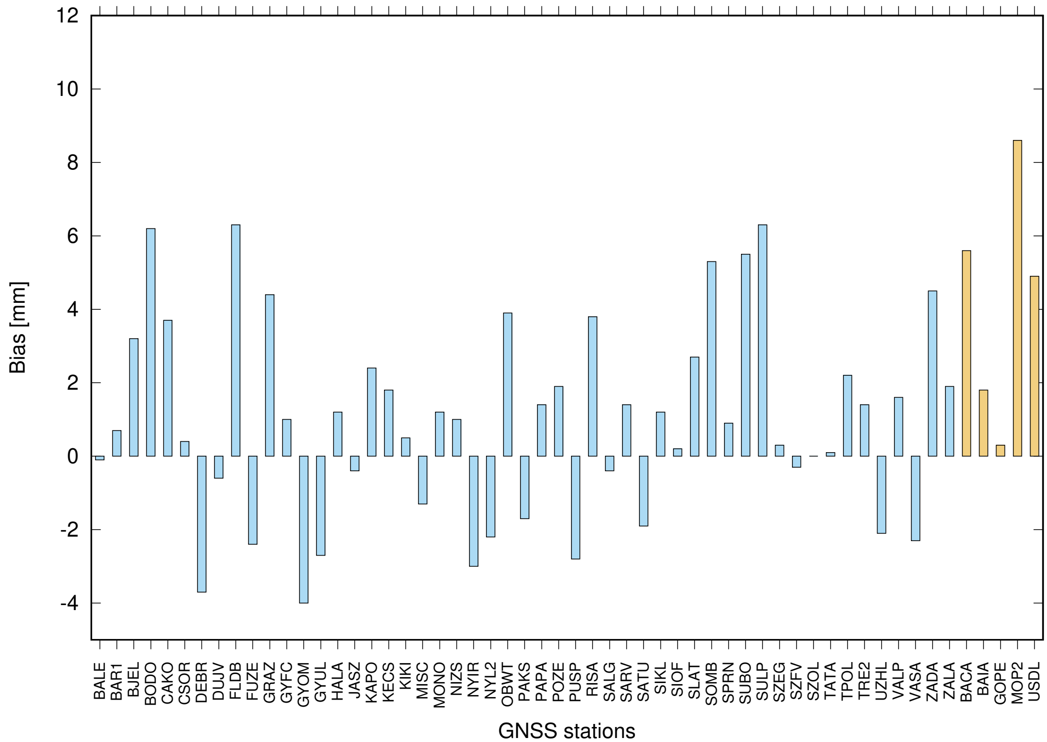

Figure 6. The ZTD BIAS in mm for SGO1 (light blue) and WUEL (light orange) networks calculated for the period of 15-31st of May, 2017

prepare ~~warmstart~~ a warm start initialization. As the observation bias is not significantly varying during a day (not shown), the 3 hourly cycled VARBC strategy was chosen which supports faster adaptivity compared to a daily cycled bias correction. During the impact study, the use of GNSS ZTDs and variational bias correction are called EVGPS2 hereafter.

5 Active assimilation and the observing system ~~experiments~~experiment

~~Two observing system experiments~~ An observing system experiment (OSE) ~~have~~ has been carried out for a summer ~~and a winter~~ period estimating the impact of GNSS ZTDs and the performance of static and variational bias corrections. The first AROME/Hungary configuration using the operational setup (without ZTD observations) is considered as reference (EEGPS2 in verification). The one (ESGPS2) with ZTD observations on the top of the operational observation set and a static bias correction is compared ~~with~~ to the reference. Furthermore, the second experiment is similar to ESGPS2 but employs a variational bias correction (EVGPS2) which is analyzed together with ESGPS2. ~~These experiments~~ The experiment and the basic setup are summarized in Table 1.

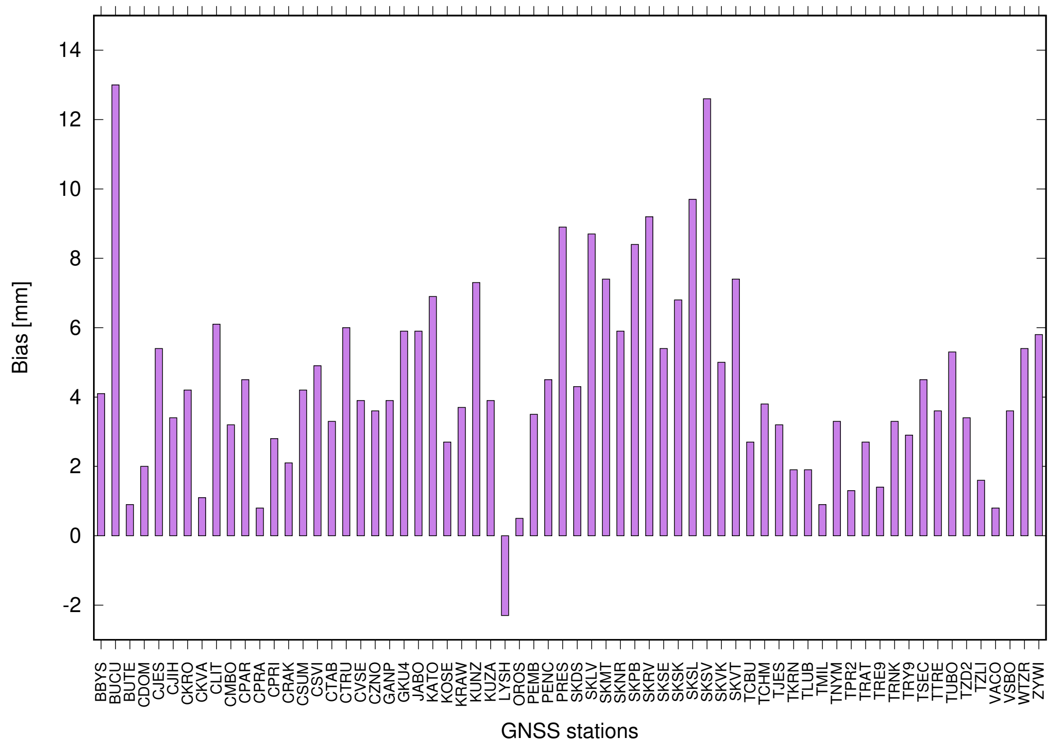

Figure 7. The ZTD BIAS in mm for GOP1 (~~purpule~~purple) network calculated for the period of 15-31st of May, 2017

Table 1. ~~Outline~~ Summary of ~~different experiments~~ observing system experiment with the data assimilation system of AROME/Hungary and the use of GNSS ZTDs.

Exp	*Period*	*Verif*	*BC*	*Status*
(pre-selection)	15/05-31/05/17	-	-	passive
(spin-up)	15/05-31/05/17	-	-	passive
EEGPS2	05/06-30/06/17	+	-	-
~~05/12-30/12/17 + - -~~ESGPS2	05/06-30/06/17	+	static	active
~~05/12-30/12/17 + static active~~EVGPS2	05/06-30/06/17	+	VARBC	active
~~05/12-30/12/17 + VARBC active~~height				

5.1 Verification of ~~summer~~ AROME/Hungary forecasts

The examined summer period is basically the continuation of the ~~traning~~ training period excluding 5 days from the verification and covering 25 days ~~till~~ until the end of June, 2017. This means that statistical verification was computed for 00 and 12UTC AROME +24 hours forecasts between 5th and 30th of June, 2017. The verification was performed against quality controlled conventional observations for the measure of all scores. For the reason that GNSS ZTDs are used as surface observations in the variational assimilation method, the added value of ZTD observations is expected to ~~see in~~ reflect more on near-surface verification scores. More importantly, temperature and humidity parameters are the most influenced because the model equivalent of wet delay is closely related to model's temperature and humidity fields via the observation operator. Figure 8 shows RMSE and BIAS scores for screen-level temperature~~and relative humidity~~, relative humidity, and dew point temperature forecasts, while ~~on~~ in Figure 9, the related normalized RMSE differences of EEGPS2 and EVGPS2 can be seen. For these surface parameters the error reduction with respect to the reference during the first 6 hours in AROME forecast is apparent by the use of ZTD observations with both static and variational bias correction. ~~With variational bias correction,~~ Nevertheless, the temperature bias is slightly overestimated, but dew point temperature and relative humidity bias are remained more or less the same for short forecast ranges. The AROME/Hungary forecasts have usually warm and dry bias during night-time, however, the assimilation of GNSS ZTD cannot mitigate this issue. The most important is that the error reduction is statistically significant for ~~most of~~ the short-, very short-ranges (see Figure 9) when variational bias correction is used. Furthermore, ~~it gives similar results with~~ similar results are obtained with the static bias correction, ~~though this is~~ but they are not statistically significant (not shown).

The AROME's precipitation forecasts are verified ~~on~~ in Figure 10, ~~where the~~ in terms of Equitable Threat Score (ETS) and ~~the~~ Symmetric External Dependency Index (SEDI) (Ferro and Stephenson, 2011) for +12 ~~hours precipitation forecasts can be seen~~hour forecast range. Overall, for the small (less or equal than 1 mm) precipitation thresholds both ESGPS2 and EVGPS2 can improve the precipitation forecasts, but for ~~higher~~ 3 or 10 mm thresholds only the experiment ~~EVGPS2 with ZTDs and VARBC has clear added value~~with ZTD and VARBC (EVGPS2) has positive impact compared to the reference. Due to the limited number of high precipitation cases, the verification of larger precipitation thresholds (above 10 mm) is not taken into account. These results suggest that the update of bias information during the (active) assimilation cycles is important for better precipitation forecasts. Other surface variables and also upper-air scores show mostly neutral impact i.e. slightly better or worse scores at various levels without statistically significant differences (not shown). It is also important to note that significant differences can only be seen in surface verification scores against 30 Hungarian SYNOP stations (see the header of verification Figures). ~~This is due to taking~~ Taking into account all available SYNOP stations inside the NWP domain would indicate ~~smaller impact of~~ a smaller impact given the relatively small amount of ~~employed~~ assimilated ZTD observations. Furthermore~~the cause~~, another reason might be that AROME/Hungary's background errors are derived from an AROME EDA (Ensemble Data Assimilation) which ~~results sharp mesoscale variance and increments effecting local impact especially in the vertical.~~

5.2 ~~Verification of winter forecasts~~

~~In order to analyze the impact on another season's forecasts, 25 days of December, 2017 have been chosen to run the second OSE with the same configurations as the summer trial (see Table 1). The pre-selection procedure has not been recalculated, therefore, the same whitelist and bias initialization were applied for the winter period as well. This limits the capabilities of GNSS ZTD assimilation, but has the possibility to simulate a quasi-operational usage when the bias information might not be up to date. In this case, VARBC coefficients due to the adaptive scheme have still the opportunity to adjust the bias during the active~~

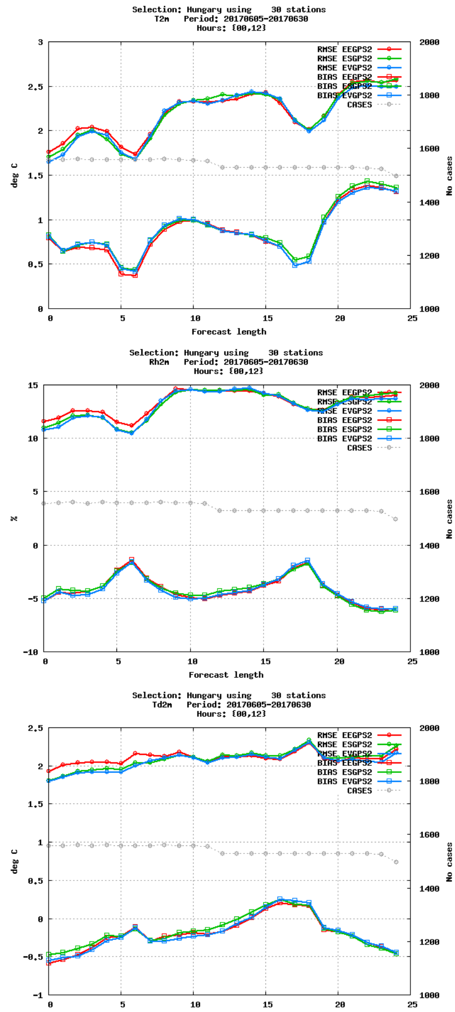

Figure 8. The RMSE and BIAS of screen-level temperature (K°C)and , relative humidity (%), and dew point temperature (°C) as a function of forecast range. Scores are plotted for EEGPS2 (red), ESGPS2 (green) and EVGPS2 (blue). Verification period between 5th and 30th of June 2017, Data selection: Hungary, 30 stations

assimilation study compared to static bias correction. Examining the same screen-level parameters, it can be seen on Figure **??** that for winter forecasts the impact is more or less neutral, however, the positive signal obtained in summer period is slightly remained for short-ranges. Furthermore, Figure **??** shows that the slightly positive impact for normalized RMSE differences is even statistically significant for one or two forecast ranges. Although, it is apparent that for +5 or +6 forecast hours the differences turned to be slightly negative which might be caused by overfitting issues and by the fact that applied observation errors of winter OSE were estimated on the training period of spring 2017. The impact of other forecast parameters was similar to summer period i.e. mostly neutral (not shown). Regarding precipitation forecasts of AROME/Hungary, verification scores

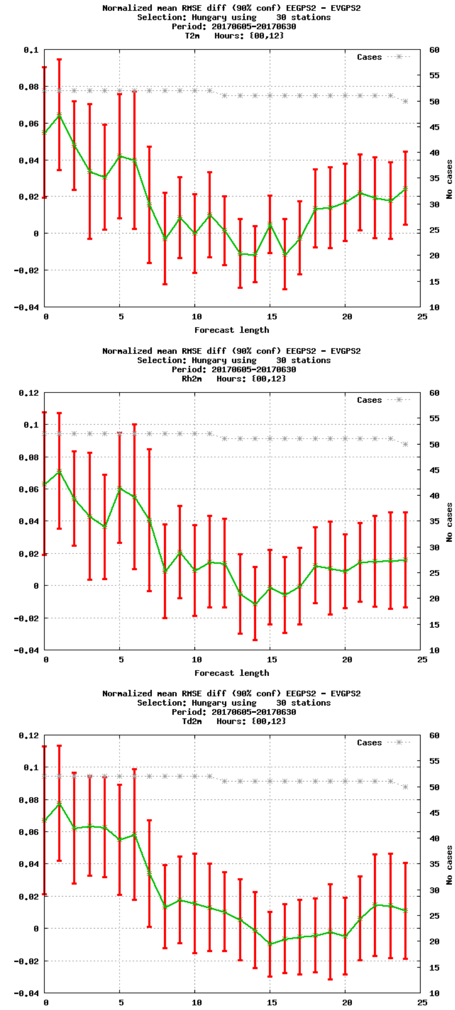

Figure 9. The Normalized RMSE difference of screen-level temperature (~~K~~°C)~~and~~ , relative humidity (%), and dew point temperature (°C) as a function of forecast range. Scores are comparing EEGPS2 and EVGPS2 experiment. Verification period between 5th and 30th of June 2017, Data selection: Hungary, 30 stations

~~for the winter OSE include less differences. This is positive for small precipitation thresholds considering the use of VARBC, but it is slightly worse for one threshold (3mm) in ETS and SEDI scores. Similarly to the summer OSE, the importance of accurate bias correction can be concluded from the results of winter trial as well. Finally, it is important to mention again that demonstrated forecast scores were verified against Hungarian SYNOP stations, therefore, overall results show neutral picture of the use of GNSS ZTDs~~statistics provide more localized increments and sharp background error correlations.

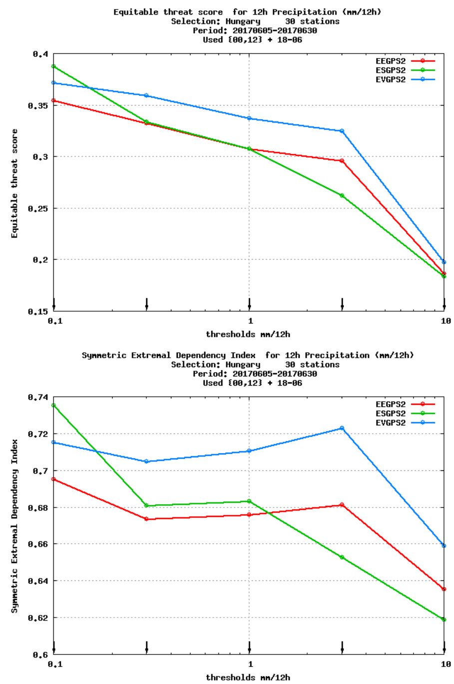

Figure 10. The ETS and SEDI scores of +12 hours hour precipitation (12-hour cummulationaccummulation) as a function of precipitation thresholds. Scores are visualized for experiments EEGPS2 (red), ESGPS2 (green) and EVGPS2 (blue). Verification period between 5th and 30th of June 2017, Data selection: Hungary, 30 stations

The RMSE and BIASS of screen-level temperature (K) and relative humidity (%) as a function of forecast range. Scores are plotted for EEGPS2 (red), ESGPS2 (green) and EVGPS2 (blue). Verification period between 5th and 30th of December 2017, Data selection: Hungary

The Normalized RMSE difference of screen-level temperature (K) and relative humidity (%) as a function of forecast range. Scores are comparing EEGPS2 and EVGPS2 experiment. Verification period between 5th and 30th of December 2017, Data selection: Hungary

The ETS and SEDI scores of +12 hours precipitation (12-hour cummulation) as a function of precipitation thresholds. Scores are visualized for experiments EEGPS2 (red), ESGPS2 (green) and EVGPS2 (blue). Verification period between 5th and 30th of December 2017, Data selection: Hungary

6 Conclusions

The use of GNSS ZTDs from three Central-European E-GVAP networks in AROME/Hungary was presented and discussed in detail. This observation type showed the The potential and the importance concerning DFS diagnostics, especially in a system that uses an increased analysis cyclefrequencyof this observation type was shown through DFS diagnostics. This is particularly relevant in data assimilation system with a high frequency analysis cycle. It was also discussed that GNSS products including ZTD can bring extra humidity related observations for the initial conditions of NWP models and ~~having~~ have the potential to improve precipitation forecasts. ~~As ZTD observations are by default blacklisted, the~~ A pre-selection ~~procedure of the trusted~~ of reliable GNSS ground based stations has ~~to be~~ been done carefully, this was described in Section 4. The studied E-GVAP networks ~~sufficiently cover the wider~~ cover sufficiently a wide area of Hungary, although there is still room for further extension and the system is still lacking such observations from the south and eastern part of the NWP domain. Furthermore, the optimal thinning distance was determined to maximize the number of ZTDs from neighbouring networks ~~without risking~~ and to avoid observation error correlations. It was also shown that the detected bias is varying station by station, therefore, ~~separate correction~~ a specific correction for each station makes sense during the assimilation of GNSS ZTDs. In addition, using only the bias-offset predictor in VARBC scheme satisfies its functionality for ~~debiasing~~ removing the bias of GNSS ZTD observations in the variational analysis. During the active assimilation ~~experiments~~ experiment, it was demonstrated that ~~the GNSS data has~~ GNSS data have a positive impact on short-range screen-level temperature and humidity forecasts~~if bias information is also up-to-date. The observation impact in the verification of~~. This positive impact on forecast scores during the summer period was held for 6 hours which is considerable ~~using only~~ given the small number of GNSS observations. ~~However~~Additionally, the precipitation forecasts became clearly better in ~~summer forecasts when~~ AROME forecasts using the variational bias correction~~was employed, but with~~, whereas with the static bias correction the impact of ZTDs was rather mixed. ~~Besides the summer OSE, a winter trial was demonstrated as well, where pre-selection and bias correction results obtained for the summer period were utilized again. It showed the weight of bias correction with a greater emphasis and the effect of reduced impact of GNSS ZTDs. Despite that the slighlty positive impact was still visible on the results of normalized RMSE differences for screen-level parameters, it can be concluded that overall impact is generally neutral with this configuration~~It can be concluded that the use of GNSS ZTD together with VARBC has positive impact on AROME/Hungary forecasts which results correspond to other impact studies. In this paper the use of Central-European E-GVAP networks and their ZTD estimations were highlighted in an operational AROME mesoscale data assimilation system. It became evident that a ~~smaller~~ small amount of GNSS ZTD observations can still provide valuable atmospheric information for a well characterized and parameterized NWP system and its data assimilation. For future perspectives and knowing the importance of bias correction, ~~a more flexible~~ an improved stiffness parameter might be investigated in order to ~~perform more appropriate adaptivity in~~ allow more flexibility to the system. Moreover, better description and use of observation errors should be studied as well.

Author contributions. Szabolcs Rózsa prepared the GNSS data in appropriate format and helped to establish data dissemination between SGO and OMSZ. Patrik Benáček provided the diagnostic tool to determine optimal thinning distance and contributed to the evaluation of bias correction for GNSS ZTDs. Máté Mile carried out the observation pre-processing, the passive assimilation, and observing system experiments. Máté Mile prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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