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 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 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 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. 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 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 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 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 tropospheric 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), 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 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 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 ZTD - like most of the observations - include systematic errors which must be taken into account in the assimilation procedure. Better characterization and 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 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 preprocessing 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 conclusions are drawn with a brief future outlook.

2 Description of operational model and observations

At the Hungarian Meteorological Service (OMSZ) limited-area (LAM) NWP activities were started in the 1990s by joining the ALADIN (Aire Limitée Adaptation Dynamique Développement International) 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 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) (Masson et al., 2013) before every model integration.

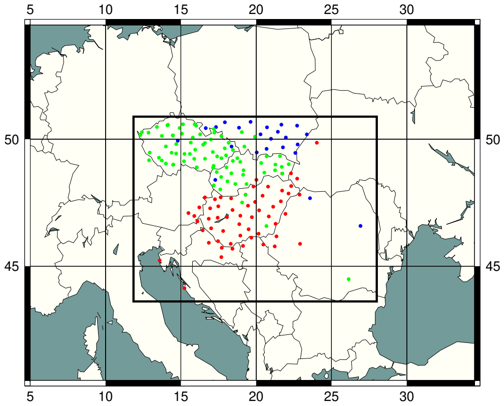
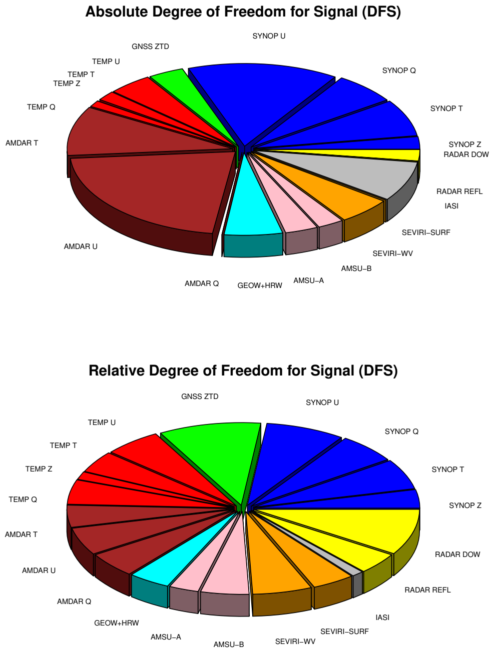


Figure 1. The computational domain of AROME/Hungary (black rectangle) and all available GNSS stations from SGO1 (red), GOP1 (green), and WUEL (blue) E-GVAP networks.

For the time being, upper-air assimilation system of AROME/Hungary 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 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 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):

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

where $\mathbf{HK}$ 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 $\mathbf{y}$ and $\mathbf{y}^{'}$ are the unperturbed and perturbed observation 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 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.


Absolute Degree of Freedom for Signal (DFS)

Relative Degree of Freedom for Signal (DFS)

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.

3 GNSS ZTD observations

The first tests of ZTD retrievals using permanent GNSS stations in Hungary started in 2009 (Rózsa et al., 2009). Due to the positive results of this study, a near-real time GNSS processing facility was set up by the collaboration 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 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 most of the ZTD estimates in the AROME/Hungary's NWP domain. To extend the coverage of GNSS 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 (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 very large observation errors has been conducted in an experimental AROME/Hungary system for a training period. This "passive" assimilation allows monitoring of ZTD observations inside the variational assimilation scheme without influencing the analysis. 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). 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 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 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. 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 part of the procedure to avoid observation error correlations. More details about the pre-selection design are given in Yan et al. (2009b) and Poli et al. (2007).

4.2 Results of the pre-selection procedure

The actual training period led to the availability of 197 GNSS stations inside the NWP domain (from three different networks). The pre-selection procedure excluded more than 30 percent of them, resulting in 122 trusted GNSS stations for active assimilation experiments. Due to time coverage (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 pre-defined limits. The thresholds of bias, standard deviation and altitude difference limits were set according to Yan et al. (2009b). Due to 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.

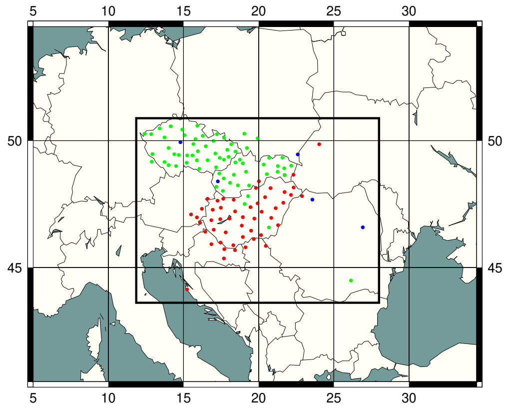


Figure 3. The computational domain (black rectangle) and pre-selected GNSS stations from SGO1 (red), GOP1 (green), and WUEL (blue) E-GVAP networks.

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 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 efficient approach. For this diagnostic purpose, 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 in Figure 4, a 20km thinning distance is chosen for the final GNSS pre-selection procedure.

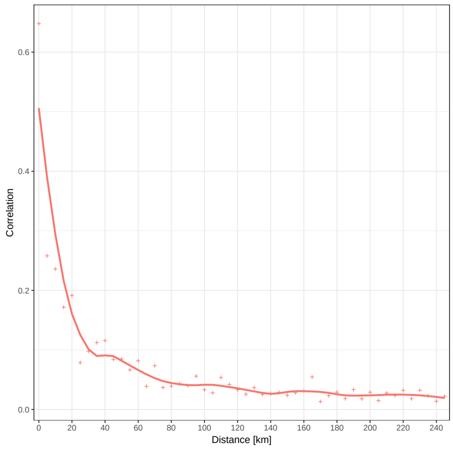


Figure 4. Observation error correlations estimated by Desroziers method as a function of separating distances for GNSS ZTDs inside AROME/Hungary's domain. Local polynomial regression method was used for fitting a smooth curve and the diagnostic was computed for the period of 15-31st of May, 2017.

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 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 time-average of observation (o_i) minus model-background (b_i) differences considering the number of analyses (n) during the time period (3).

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

Although, it 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 is plotted in Figure 5. Concerning the detected bias of each GNSS station separately, one can see 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.

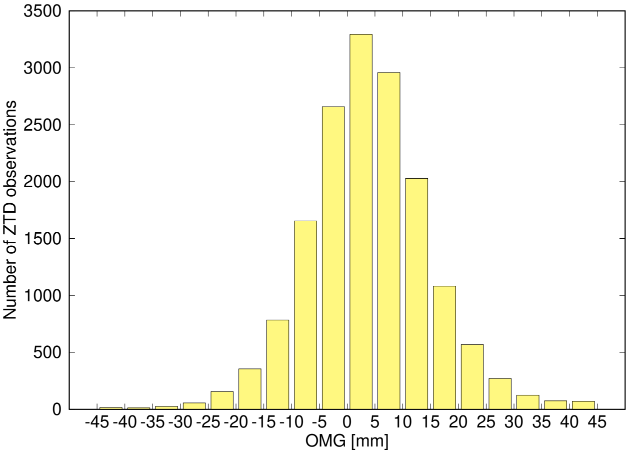


Figure 5. Distribution of OMF values for all GNSS stations inside AROME/Hungary's domain. The period of 15-31st of May, 2017 was used for the calculation of OMF statistics.

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 presented in Section 5.

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.,

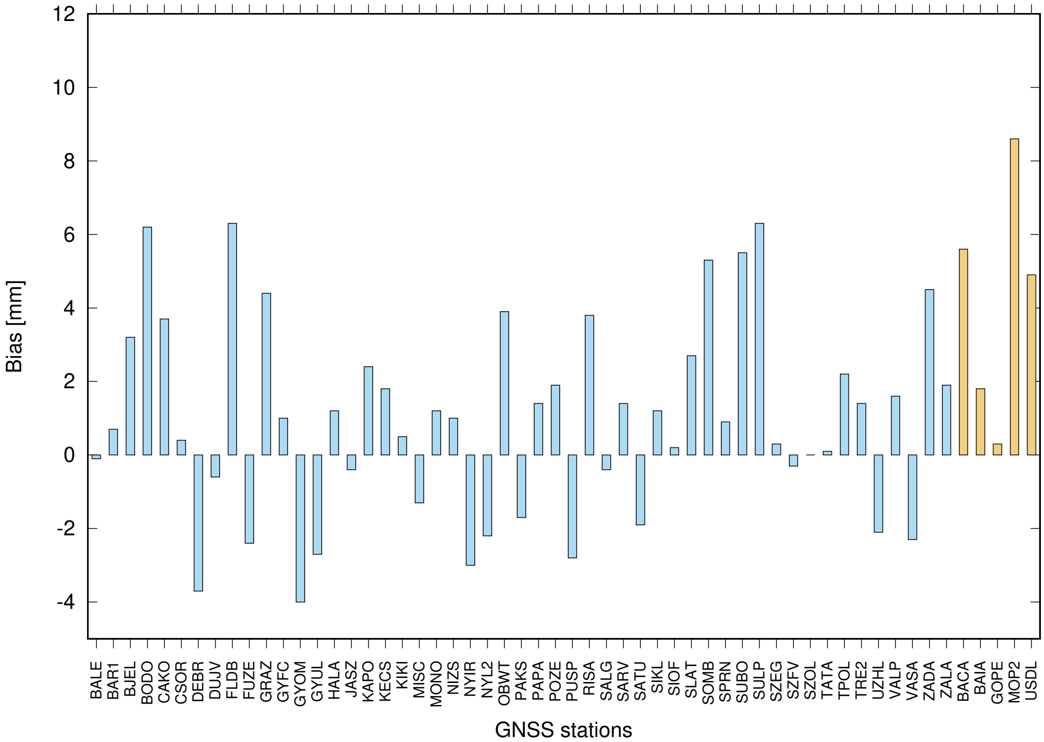


Figure 6. The ZTD BIAS in mm for SGO1 (light blue) and WUEL (light orange) networks calculated for the period of 15-31st of May, 2017

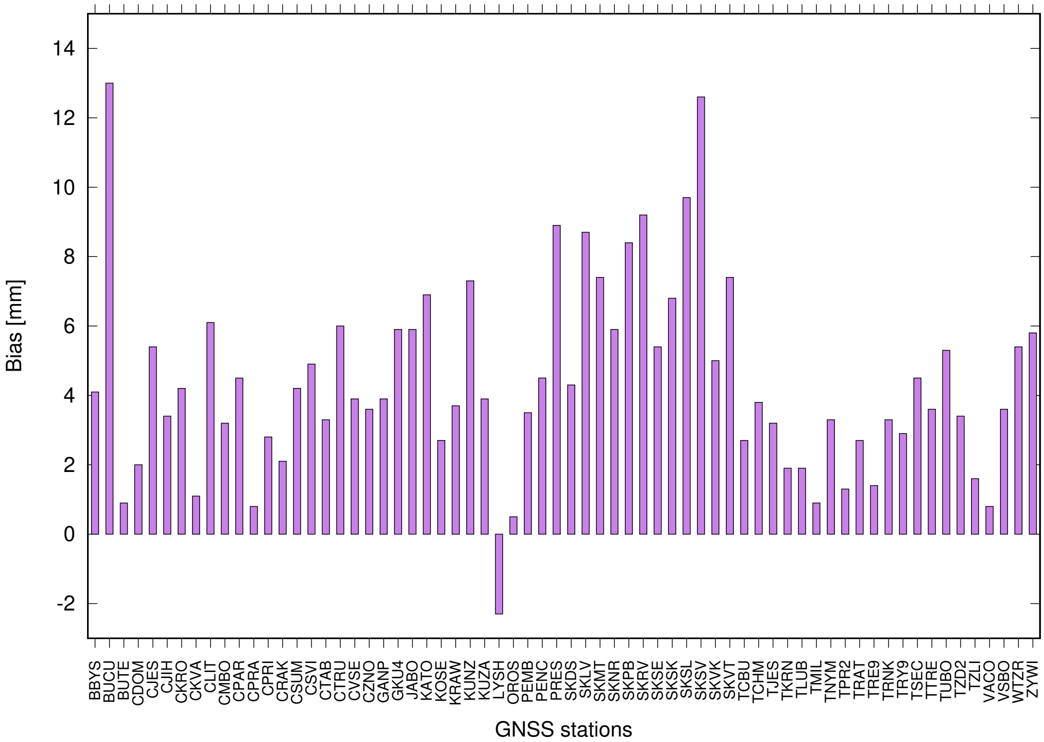


Figure 7. The ZTD BIAS in mm for GOP1 (purple) network calculated for the period of 15-31st of May, 2017

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 stiffness parameter (N_{bg}) (Dee, 2004) (4).

$$\sigma^2_{\beta_\mathbf{b}} = \frac{\sigma^2_\mathbf{o}}{\mathbf{N_{bg}}} \tag{4}$$

In contrast to the static scheme, the VARBC adjusts bias information 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 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 prepare 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 experiment

An observing system experiment (OSE) has been carried out for a summer 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 to the reference. Furthermore, the second experiment is similar to ESGPS2 but employs a variational bias correction (EVGPS2) which is analyzed together with ESGPS2. The experiment and the basic setup are summarized in Table 1.

Table 1. Summary of the 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	+	-	-
ESGPS2	05/06-30/06/17	+	static	active
EVGPS2	05/06-30/06/17	+	VARBC	active

5.1 Verification of AROME/Hungary forecasts

The examined summer period is basically the continuation of the training period excluding 5 days from the verification and covering 25 days 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 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, relative humidity, and dew point temperature forecasts, while 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. 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 the short-, very short-ranges (see Figure 9) when variational bias correction is used. Furthermore, similar results are obtained with the static bias correction, but they are not statistically significant (not shown).

The AROME's precipitation forecasts are verified in Figure 10, in terms of Equitable Threat Score (ETS) and Symmetric External Dependency Index (SEDI) (Ferro and Stephenson, 2011) for +12 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 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. These results suggest that the update of bias information

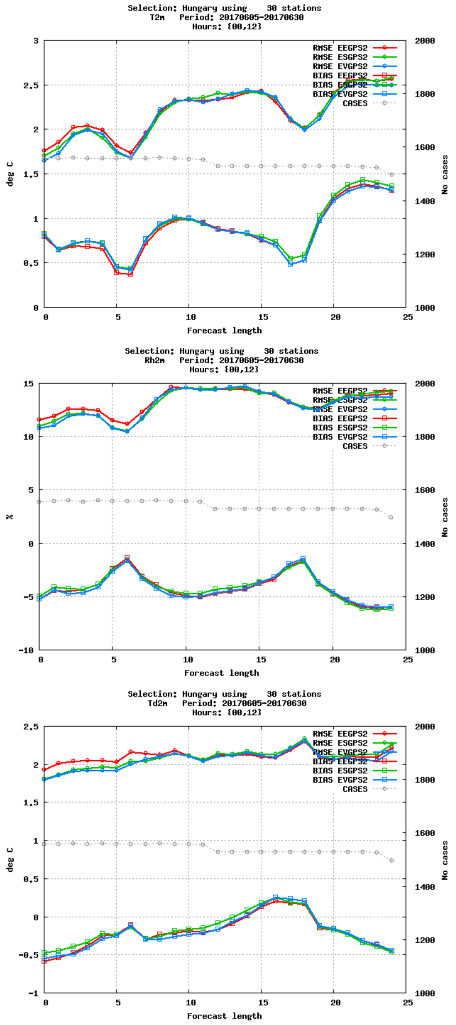


Figure 8. The RMSE and BIAS of screen-level temperature (°C), relative humidity (%), and dew point temperature (°C) as a function of forecast range. Scores are plotted for EEGPS2 (red), ESGPS2 (green) and EVGPS2 (blue). Verification period between 5th and 30th of June 2017, Data selection: Hungary, 30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

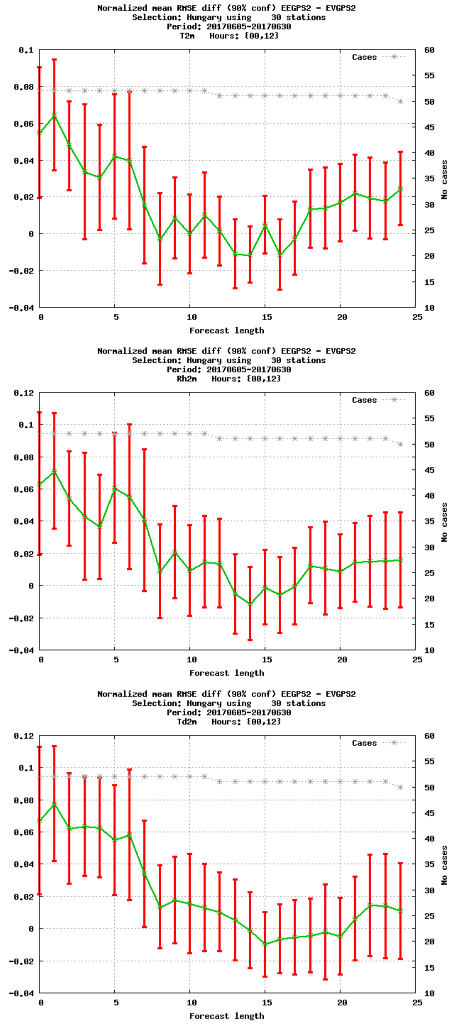


Figure 9. The Normalized RMSE difference of screen-level temperature (°C), relative humidity (%), and dew point temperature (°C) as a function of forecast range. Scores are comparing EEGPS2 and EVGPS2 experiment. Verification period between 5th and 30th of June 2017, Data selection: Hungary, 30 stations

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). Taking into account all available SYNOP stations inside the NWP domain would indicate a smaller impact given the relatively small amount of assimilated ZTD observations. 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.

6 Conclusions

The use of GNSS ZTDs from three Central-European E-GVAP networks in AROME/Hungary was presented and discussed in detail. The potential and the importance of 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 have the potential to improve precipitation forecasts. A preselection of reliable GNSS ground based stations has been done carefully, this was described in Section 4. The studied E-GVAP networks cover sufficiently a wide area of Hungary, although there is still room for further extension and the

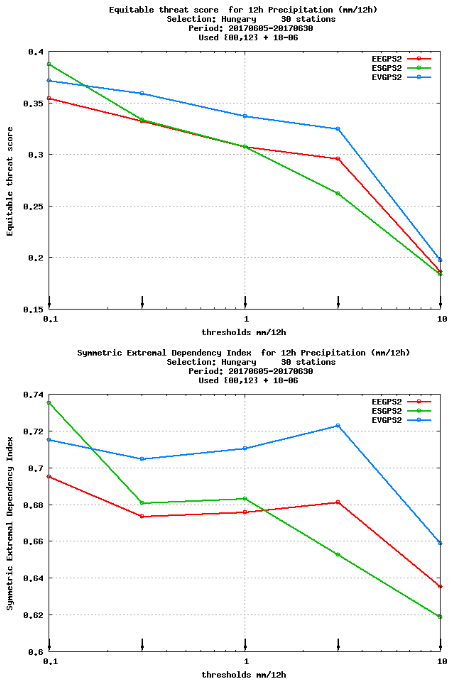


Figure 10. The ETS and SEDI scores of +12 hour precipitation (12-hour accummulation) as a function of precipitation thresholds. Scores are visualized for experiments EEGPS2 (red), ESGPS2 (green) and EVGPS2 (blue). Verification period between 5th and 30th of June 2017, Data selection: Hungary, 30 stations

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 and to avoid observation error correlations. It was also shown that the detected bias is varying station by station, therefore, 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 removing the bias of GNSS ZTD observations in the variational analysis. During the active assimilation experiment, it was demonstrated that GNSS data have a positive impact on short-range screen-level temperature and humidity forecasts. This positive impact on forecast scores during the summer period was held for 6 hours which is considerable given the small number of GNSS observations. Additionally, the precipitation forecasts became clearly better in AROME forecasts using the variational bias correction, whereas with the static bias correction the impact of ZTDs was rather mixed. 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 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, an improved stiffness parameter might be investigated in order to 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.

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