Application of Mode-S data in numerical weather prediction at SHMU

(Aplikácia Mode-S dát v numerickej predpovedi počasia na SHMÚ)

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Abstrakt

Letecké merania sú významným príspevkom do siete meteorologických meraní vo vyšších vrstvách atmosféry. Novým druhom meraní sú údaje typu Mode-S, ktoré nachádzajú využitie najmä v navigácii v letectve. Z údajov typu Mode-S je možné priamo alebo odvodením získať aj meteorologickú informáciu a následne ju využiť do asimilácie do numerického predpovedného modelu.

Na začiatku bolo potrebné urobiť kontrolu kvality využitím experimentálneho numerického predpovedného modelu AROME/SHMU metódou výpočtu odchýlok pozorovaní od pozaďového poľa. Výsledky boli štatisticky vyhodnotené. Pristúpilo sa k dvojkrokovému orezaniu vzorky dát a vytvoreniu zoznamu lietadiel so spoľahlivými meraniami na základe ich unikátneho identifikátora.

V ďalšom spracovaní boli využité v asimilácii iba spoľahlivé merania. Ukázalo sa, že Mode-S merania významne ovplyvnili analýzu aj predpoveď ako výstupy z asimilácie. Výsledky boli prezentované na prípadovej štúdii výskytu inverzie v Prostějove v januári 2018.

Anotácia

Modelovanie počasia vo vysokom rozlíšení ťaží z hustej siete pozorovaní. Letecké merania typu Mode-S sú veľkým novým zdrojom meraní vo vyšších vrstvách troposféry. Najprv bola kontrolovaná kvalita Mode-S údajov a následne bol vytvorený zoznam spoľahlivých meraní. Iba spoľahlivé údaje boli použité na asimiláciu v experimentálnom predpovednom modeli počasia AROME/SHMU vo vysokom rozlíšení. Prípadová štúdia zo zimného obdobia ukázala vplyv Mode-S meraní na predpoveď.

Kľúčové slová : numerická predpoveď počasia, analýza a asimilácia dát, Mode-S dáta

Annotation

High resolution weather modelling benefits from dense observation network. Aircraft Mode-S measurements are a big but new source of data in upper layers of the troposhere. The new observation type was first quality checked and a whitelist of reliable data was created. Only whitelisted data was exploited for assimilation in experimental high resolution model AROME/SHMU. The case study from winter period shows the impact of Mode-S data on the forecast.

Key words : numerical weather prediction, data analysis and assimilation, Mode-S data

1 Introduction

Recent years are marked by a tendency of thickening the network of available meteorological observations that can be further used for assimilation into numerical weather prediction (NWP) systems. The increasing number of observation sources improves the precision of the forecast. This can be beneficial for forecasters as well as for public.

Apart from conventional observation types as SYNOP (synoptic stations), TEMP (radiosondes), AMDAR (aircraft dedicated system), SHIP and BUOY (station on board of a ship or on buoys in the ocean), there are also radar and sattelite measurements which provide meteorological information from a larger area. A majority of these observations proceed from the boundary layer. The lack of data from upper levels can be supplemented by aircraft measurements.

During the past ten years a research on availability and use of Mode-S (mode selective) aircraft data in NWP has been developed. A feasibility study [3] was performed by EUMETNET (European Meteorological Services Network) expert team.

Mode-S data are measurements taken by airborne equipment. These measurements were originally thought for navigation in air traffic. Only a minority of the collected Mode-S data contains direct measurements of meteorological parameters, this data type is called Mode-S MRAR (Meteorological routine air report). A big part of the reports contain measured quantities that are generally used for aviation purposes and meteorological information can only be derived, these are known as Mode-S EHS (Enhanced surveillance). The derivation method was described by de Haan in the scientific report [2].

Direct measurements of temperature and wind speed and wind direction are available in Mode-S MRAR data. These quantities are taken by the same equipment as the information encoded in AMDAR data, if AMDAR is available on board of the particular aircraft. Further details on AMDAR measurements can be found in [4]

The same meteorological elements are derived from measurements of pressure, Mach number, magnetic heading, etc. and saved into Mode-S EHS data. Here, no need for special airborne instruments is required. A big convenience of Mode-S EHS data is its coverage. As the EHS data are derived from parameters generally registered by standard airborne equipment, no additional costs for accessories are needed.

Mode-S data are gathered by TARs (tracking and ranging radars) on the ground. The TARs are usually operated by local ATC (air traffic control). The airborne instruments respond to queries from TARs. The communication is going on specific radio frequencies, different for Mode-S MRAR and for Mode-S EHS data.

From now on, when reffered to Mode-S data, it means Mode-S EHS and Mode-S MRAR together in general. The particular types will be denoted as MRAR or EHS only.

2 Data sample

The studied data sample was provided by Slovak ATC, namely LPS SR (Letové prevádzkové služby Slovenskej republiky). It is a sample of 2 months of measurements of Mode-S MRAR and Mode-S EHS data registered by four TARs (Buchtův kopec - CZ, Vienna - AT, Mošník - SK, Malý Javorník - SK). MRAR data were available only from Czech republic and from Austria due to radar settings. EHS data in this sample were registered by Mošník and Malý Javorník in Slovakia and also by Buchtův kopec in Czech republic. The total number of measurements from each of the listed TARs is listed in the following table 1. The column on the right shows the total number of aircrafts in the range of each TAR disregarding the number of overflights during the studied period.

Table 1: The total amounts of raw MRAR, EHS, AMDAR observations from the entire studied period.

Radar (data type)	Number of all observations	Number of different aircrafts
JAVOR (EHS)	9 898 618	8 428
MOSNIK (EHS)	4 752 200	7 110
BUKOP (EHS)	6 994 443	9 479
BUKOP (MRAR)	1 837 475	530
VIENNA (MRAR)	95 758	401
(AMDAR)	215 577	1 807

The last line in table 1 shows the number of AMDAR measurements. The AMDAR data is reliable and proved aircraft data sample. This data is operationally used at SHMU. AMDAR data was considered a reference for the quality check. Although the quality of AMDAR data is widely known, the system requires considerable expenses for the equipment and software. Thus, only large airline companies are willing to participate in AMDAR system.

The raw Mode-S data sample studied in this work was provided by LPS SR. It was obtained in files of merged measurements from each day and each TAR separately.

The data assimilation procedures are set to be run every 6 hours, in particular at 00, 06, 12 and 18 UTC. Hence, the raw data were parsed and 6 h/3 h long ($\pm$3 h/1.5 h around the assimilation hours) measurements selections were created for MRAR/EHS respectively. Further, the csv data format was converted to obsoul format readable by data assimilation AROME/SHMU model procedures. The statistics presented in section 4.1 were calculated over the timeslots of data described here.

3 Methodology

Mode-S data used for meteorological purposes is a new kind of observation in Slovak environment. Once the data sample was provided by local ATC, the quality control had to be performed. The quality check based on calculation of the differences between the measurements and the values obtained from NWP model first guess was opted for. The observation minus first guess departures (OMG) are calculated in the points of collected measurements, it means, NWP model interpolates its values to the positions defined by measurements coordinates. This method is commonly used for quality control of new observation kinds.

The experimental AROME/SHMU NWP model was exploited for the calculation of OMG and also in the consequent case study experiments presented in this contribution. The parameters of the AROME/SHMU model are described in the following table 2.

Table 2: Parameters of AROME/SHMU NWP model.

	AROME/SHMU
status	experimental
code version	CY40T1bf07_export
coupling model	ALADIN/SHMU
horizontal resolution	2.0 km
vertical levels	73
time step	144 s

The quality was tested by the OMG calculation. The OMG were further statistically analysed.

The OMG departures are calculated in the screening routine which belongs to the quality control step of the assimilation procedure. The data assimilation is a process of analysis of observations with the objective to model the true state of the atmosphere, called analysis.

The data assimilation consist of quality testing of measurements, further interpolation of model variables into the observations geografical poisitions and computation of values of meteorological variables in a regular grid. Then the initialization of the processes has to be executed to balance the model. The final product is called analysis and it can be later used as an initial state for a forecast.

4 Results

4.1 Quality control and whitelist

For the statistical analysis of OMG departures nine data sets were selected. Each for one data type (EHS, MRAR and reference AMDAR) and at the same time separately for three studied meteorological quantities - temperature, wind speed and wind direction. These nine datasets were first gross error checked and OMG values over tresholds from table 3 were eliminated. The results are not shown here and can be found in the diploma thesis [1].

Table 3: Tresholds for gross error check

temperature	$\pm$4 K
wind speed	$\pm$20 m/s
wind direction	$\pm$45 deg

The second truncation was performed by diminishing the data sample for each data type and analysed parameter to 2σ from the whole gross error checked data set. The objective of the two step truncation was to eliminate outliers and improve the sample statistics.

Then the mean value and standard deviation were calculated for the rest of the data in each data set. The results for Mode-S data were compared to AMDAR data. As it was expected, the results for MRAR data were closer to the results of AMDAR data. This behaviour was also observed in cited literature [5] and can be explained by the effect of direct measurements instead of derivated meteorological parameters in EHS data.

Generally, the statistical characteristics - mean value and standard deviation are lower for temperature measurements than wind speed or wind direction. That pattern was present in case of all the three data types. An explanation is that the temperature is a large scale parameter while the wind speed or wind direction changes are greater and more frequent. These results are not shown in this work.

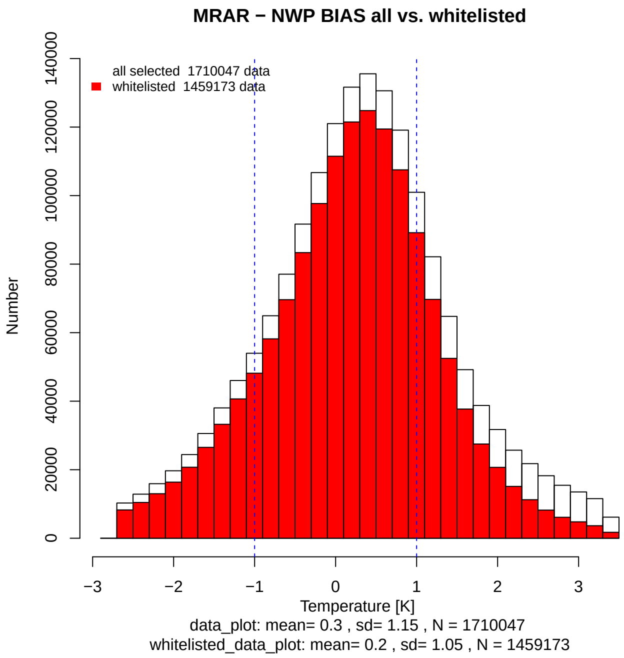
Once the general statistical analyses was completed, the whitelisting method was adopted. The whitelist is a method based on selection of reliables measurements proceeding from reliable aircrafts. The selection of aircrafts is executed according to the whitelisting criteria listed in table 4. The aircrafts are distinguished by the ICAO address included in every measurement. ICAO address is a unique identifier of the aircraft which usually remains the same for years of aircraft operation.

Table 4: Whitelist criteria

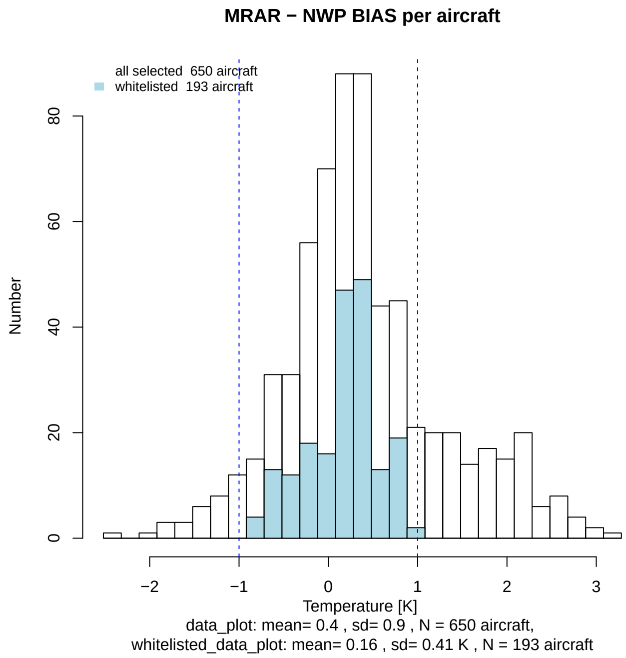
	Mean	σ	Number of data
Temperature	1 K	2 K	1000
Wind speed	1 m/s	5 m/s	1000
Wind direction	10 deg	100 deg	1000

The improvement of statistics was obvious on the majority of the studied data sets. Here an example of the MRAR temperature statistics is presented. The left figure 1a shows the distribution of all measurements before whitelist (white) and after whitelist (red). The right figure 1b depicts the distribution of measurements computed per aircraft before whitelist (white) and after whitelist (blue). The blue lines in the plots designate the whitelisting criteria. A brief summary of the obtained statistical characteristics is shown below each plot.

The mean value and standard deviation decreased after whitelisting 1a and approximately 85% of measurements remained in the dataset after whitelisting. A smaller rate of aircrafts remained in the computation per aircraft 1b but the improvement of the statistics is even more significant.



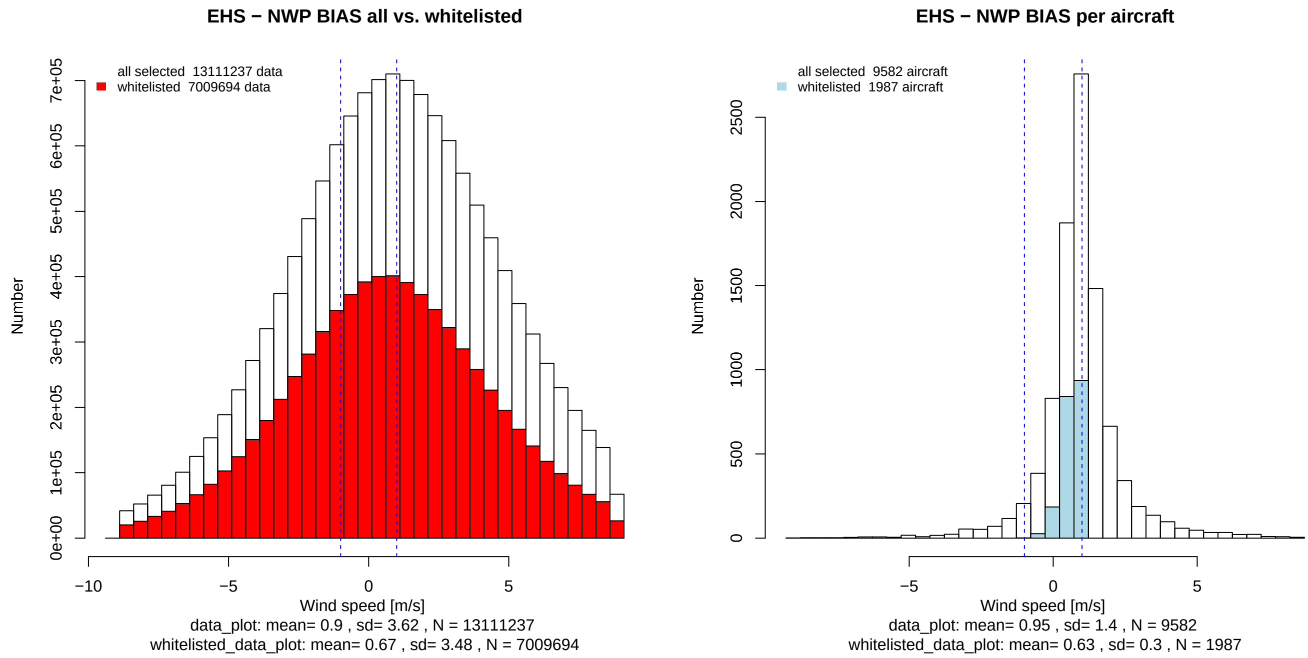
(a) MRAR all whitelisted temperature data



(b) MRAR whitelisted temperature data per aircraft

Figure 1: Distribution of (a) all vs. whitelisted MRAR OMG departures and (b) all vs. whitelisted MRAR OMG departures calculated per aircraft for temperature after the gross error check and truncation to $\pm$ 4K.

In case of EHS wind speed data an improvement was also observed. Compared all the gross error checked measurements to the whitelisted, the mean value and standard deviation decreased after whitelisting 2a. Approximately 47% of data were excluded from the statistics due to whitelisting. The positive bias of the distribution remained. Similarly to MRAR whitelisting statistics, the proportional number of eliminated aircrafts is higher when the statistics are computed per aircraft 2b. Here the correction of the bias and standard deviation is more significant than in case of all measurements distribution 2a.



(a) EHS OMG departures

(b) MRAR OMG departures

Figure 2: Distribution of (a) EHS OMG departures and (b) MRAR OMG departures for wind speed after the gross error check and truncation to $\pm$ 20m/s.

The figures above constitute the examples of positive impact of whitelisting on the distribution characteristics of MRAR temperature and wind speed EHS dataset. The rest of the nine datasets described at the beginning of the section 4.1 were also analysed and similar results were obtained. The plots are not shown here.

According to the whitelisting criteria a list of whitelisted aircrafts was created and it was further exploited in the case study described in the section 4.2.

4.2 Case study

The whitelisting showed an improvement on the statistics, hence the case study was performed to show the impact of whitelisted data on the assimilation process.

The situation of an inversion incidence was selected for the case study. The inversion occured in Prostějov (Czech republic) the 25th of January of 2018 at 12UTC. The evidence is shown in figure 3, where a sounding profile[1] is presented. The inversion layer was present approximately between 700-1300 m of height as it is obvious from figure 3.

From a synoptic point of view, the region of Czech republic on the 25th of January of 2018 was located in the warm sector of a cyclone with the centre approaching the west coast of southern Scandinavia. The warm front passed through Prostějov during the night from 24th to 25th of January.

[1]The sounding profile was retrieved 10 October 2019 from http://weather.uwyo.edu/cgi-bin/sounding?region=europe&TYPE=GIF%3ASTUVE&YEAR=2018&MONTH=01&FROM=0100&TO=3112&STNM=11747

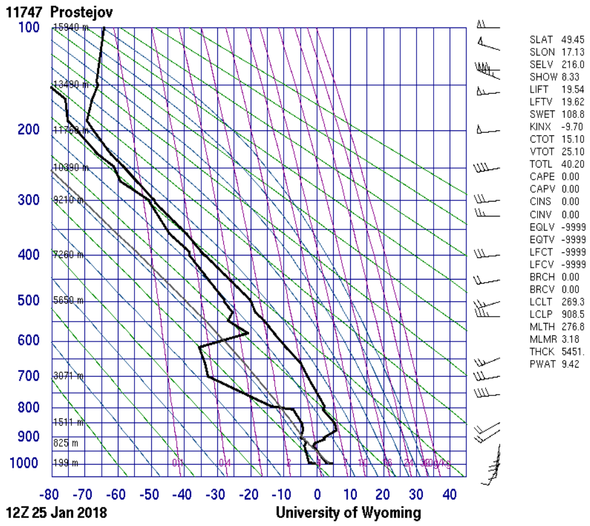


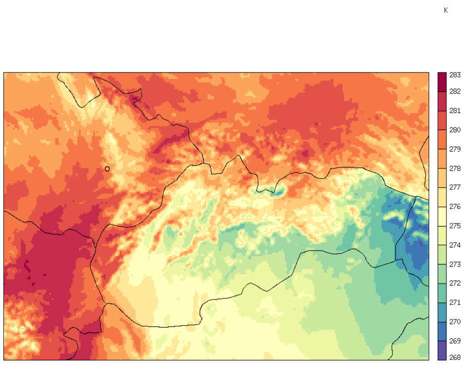
Figure 3: Sounding profile from Prostějov on 25th of January 2018 at 12UTC.

Here is the description of the data selection chosen for the case study. The raw data was first filtered according to the whitelist created thanks to the statistical analysis. Then the timeslots were shortened to 3 h long sets of measurements for both EHS and MRAR data in contrast with the quality control analysis described at the end of section 2. These data samples were assimilated and forecasts were computed.

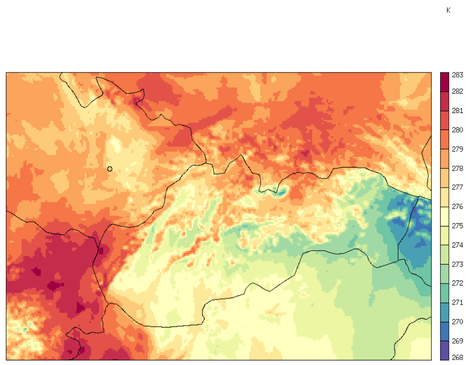
The purpose of the experiment is to demonstrate the impact of Mode-S data on the analysis and consequently on the forecast. Two forecast with different setups were computed to be compared. The reference forecast was calculated after assimilation of SYNOP, TEMP and AMDAR measurements into AROME/SHMU model. The experimental forecast includes Mode-S MRAR and Mode-S EHS measurements from whitelisted aircrafts on top of SYNOP, TEMP and AMDAR. The comparison described further focuses on forecasting temperature in boundary layer.

In the following figures, the temperature fields are shown in different AROME/SHMU model layers. The height of the corresponding model layer is attributed according to international standard atmosphere (ISA). ISA is a standard static model defined to represent the reference of pressure and temperature profiles in the atmosphere.

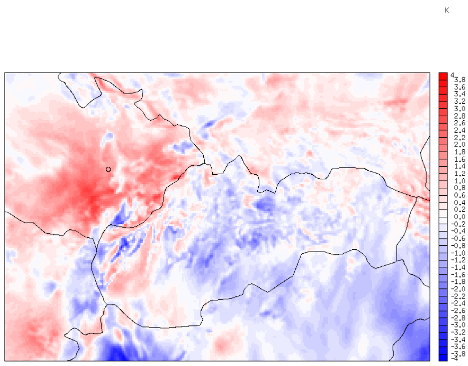
The first figures 4a,4b depict the temperature field inside the inversion layer at 923 m of height according to ISA. The figures represent the forecast starting from 25th of January, 2018 at 12 UTC valid for +00 forecasted hours. The left picture 4a displays the reference forecast when only SYNOP, TEMP and AMDAR were exploited. The differences between the reference forecast and the experimental one shown in figure 4b is plotted in picture 4c. The difference in temperature near Prostějov is significant. The reference is warmer approximately by 2 K and both forecasts predicted lower values than those measured by radiosonde.



(a) reference forecast



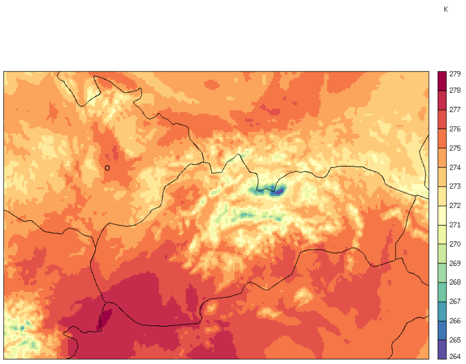
(b) forecast with Mode-S



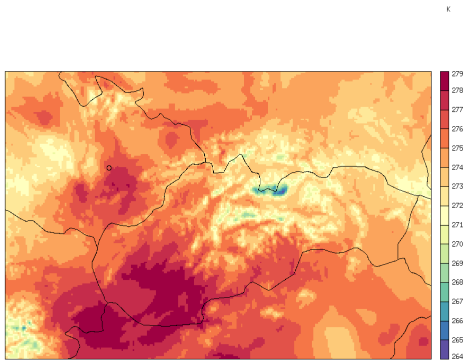
(c) difference of forecasts

Figure 4: Forecasted temperature at model level 46 (height of 923 m according to ISA). The forecast is from January 25, 2018 at 12 UTC valid for +00h. Prostejov station is depicted by the circle in eastern part of Czech republic.

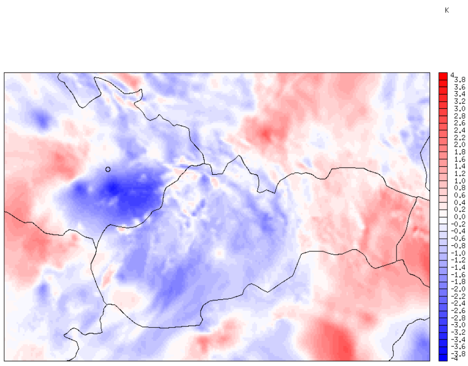
The following figure depicts the temperature field in a close layer above the inversion layer according to the sounding profile 3 shown at the beginning of this section. Here, the reference forecast 5a shows lower value of temperature at the height of 2012 m than the experimental forecast 5b. The temperature difference is close to 1 K plotted in picture 5c.



(a) reference forecast



(b) forecast with Mode-S



(c) difference of forecasts

Figure 5: Forecasted temperature at model level 29 (height of 2012 m according to ISA). The forecast is from January 25, 2018 at 12 UTC valid for +00h. Prostejov station is depicted by the circle in eastern part of Czech republic.

Finally, the impact of Mode-S data assimilation on the analysis is obvious from the following figure 6 of the vertical profile of temperature differences of fist guess from analysis plotted along a north-south oriented line crossing Prostějov situated in the middle. The positive deviation of temperature due to Mode-S data assimilation appeared and the inverison layer is visible from the vertical profile of positive differences in temperature.

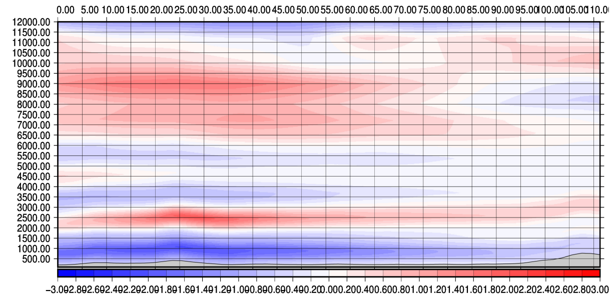


Figure 6: Vertical profile of temperature over a north-south oriented line crossing Prostějov situated in the middle.

5 Discussion and Conclusion

Mode-S data is a new observation type and it was exploited for NWP purposes for the first time in Slovakia. The basic quality control revealed the need to truncate the raw dataset to eliminate unphysical values, so a method of asigning tresholds for acceptable values was created. The quality check was performed by OMG departures calculation and their further statistical analysis. The results for Mode-S data were compared to AMDAR reference dataset. MRAR statictics reached better results than EHS data.

The need for whitelist creation emerged from basic statistical analysis. The whitelisting criteria took into account the mean value, the standard deviation and also the number of observations proceeding from a single aircrafts in the sample. Once the criteria were applied on the data sample, the same statistical analysis was performed and the outcomes were confronted with the previous analysis. The biggest improvement happened in case of EHS wind speed data analysis while MRAR data were of better quality already before whitelisting.

The case study was prepared to demonstrate the impact of Mode-S data on assimilation outcomes. Two forecasts were compared, first only conventional SYNOP, TEMP and AMDAR data were assimilated, second the same data and whitelisted Mode-S were assimilated. The forecasts were compared in the case of inversion layer incidence in Prostějov and confronted with the radiosonde sounding measurement. Significant differences between reference and experimental forecast were observed in different vertical layers in temperature field. The impact of Mode-S data was also confirmed by computation of differences between first guess and analysis field in a vertical profile of temperature plotted along a north-south oriented line crossing Prostějov.

To sum up, although the impact can not be quantitatively evaluated from the experiments described in this contribution, doubtlessly Mode-S data influence the analysis and consequently the forecast. This way Mode-S data became a significant new source of meteorological information in upper troposphere.

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