Slovak Mode-S data assimilation into AROME/SHMU

report from RC LACE stay in Prague, CHMI, 28 January - 08 February 2019

(parts of this report are directly copied from the master's thesis *High resolution data analysis in the ALADIN/SHMU numerical weather prediction system*)

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Introduction

High resolution data assimilation in a high resolution numerical weather prediction (NWP) model is necessary for precise analysis of mesoscale atmospheric phenomena. Mesoscale meteorological patterns are strongly influenced by local topography. To be able to model such phenomena proper physical parametrizations must be applied in the NWP model. Besides, the high quality observations of sufficient density are important to appropriately mirror the current state of the atmosphere.

Recently, a utilization of measurements recorded by aircraft equipment, namely the SSR Mode-Selective (Mode-S) data, was tested in meteorology [2]. This data was originally created for the purposes of the navigation of aircrafts during the flight. The Mode-S data are basically of two types: the Meteorological routine air report (MRAR) contains real observations of temperature and wind vector and Enhanced surveillance (EHS) from which the meteorological parameters can be derived.

Although the affordability of the Mode-S data is good in Europe [5], as the data is widely used by Air Traffic Control (ATC) that administrate the air traffic, their potential for meteorological purposes is still unfulfilled. Some studies on the quality assessment and achievable impact of Mode-S data on meteorological forecasting were performed. E.g., in the Netherlands [3], Slovenia [10] and Czech Republic [14], the Mode-S data is assimilated operationally into numerical weather prediction (NWP) model and used in everyday forecasts.

Until now, no use of Mode-S data in meteorology was tested in Slovakia. The purpose of this RC LACE stay was to become aquainted with the quality control methods of aircraft data. Followingly, to be able to process the methods in local data analysis. The results from this report are the first step in the process of testing Slovak Mode-S data and their possible implementing into daily forecasting.

The Mode-S data studied here was provided by Air Traffic Services of Slovak republic (Letové prevádzkové služby Slovenskej republiky) (LPS SR) and the Aircraft meteorological data relay (AMDAR) dataset from Global Telecommunication System (GTS) was provided by Czech Hydrometeorological Institute (CHMI).

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1 Aircraft observations: Mode-S and AMDAR

The convenience of aircraft data is the opportunity to have observations above oceans, where conventional types of observations are hardly accessible and also to obtain the vertical profiles. The promising results in exploiting Mode-S data for meterorological modeling and forecasting are noticeable from literature [3] or [10]. In this report the emphasis focuses on the Mode-S EHS, Mode-S MRAR and AMDAR data.

Among Mode-S basically Mode-S EHS and Mode-S MRAR can be distinguished. The shortcut "S" in Mode-S stands for selective mode, it means the aircraft transponder does not send the data automatically but it responds only to interrogations of tracking and ranging radar (TAR) located on the ground. To be able to read Mode-S reports, the TAR must be adapted to the emiting frequency. The frequency of collecting Mode-S data reflects the quering frequency of the radar, it means the velocity of one turn of the antenna to obtain the full scan. The reports are distributed from TAR to local ATC in ASTERIX (All Purpose Structured Eurocontrol Surveillance Information Exchange) format and except of the information listed in tables 1, 2, they contain also the current position of the aircraft.

1.1 Mode-S EHS

The parameters that can be obtained from Mode-S EHS messages are listed in the table 1 below. All of them are directly measured or precalculated on board. Depending on the traffic, the frequency of emitting the messages from the aircraft to the ground TAR is from 4 to 20 seconds. The broadcast lasts during the whole flight, take-off and landing included and it can extend to some minutes even after the touch down.

Table 1: Parameters contained in Mode-S EHS messages.

parameter	range	unit
altitude	0;65 520	ft
barometric pressure setting (minus 800 mb)	0;410	mb
roll angle	-90;90	deg
true track angle	-180;180	deg
ground speed	0;2046	kt
track angle rate	-16;16	deg/sec
true air speed	0;2046	kt
magnetic heading	-180;180	deg
indicated airspeed	0;1023	kt
Mach number	0;4,092	-
barometric altitude rate	-16 384;16 352	ft/min
inertial vertical velocity	-16 384;16 352	ft/min

The raw data is collected by TARs, usually owned by local ATC. In case of this study, the preprocessing was done before the provision of the dataset by LPS SR. The method exploited by LPS SR was inspired from [8]. The temperature can only be determined from true air speed (v_t), Mach number (M) and taking into account the dependence of speed of sound on the temperature of the matter. The dataset of Mode-S EHS studied in this work was prepared according to the formula (1) for temperature (in Kelvin) calculation. The coefficient 38.975 $\mathrm{ktK}^{-1/2}$ is the conversion factor.

$$T = (\frac{v_t}{38.975M})^2 \tag{1}$$

Wind speed and wind direction are calculated by vector difference of heading vector and ground track vector. Heading vector is defined by true air speed (v_t) and heading angle (α_t) while ground track vector is defined by groundspeed (v_g) and track angle (α_g). The magnetic declination (α_{mag}) is included to correct the measurements as the magnetic field is time and space dependent. These values were taken from the World Magnetic Model valid for the period of 2015-2020 years. The date and the position were the input for the magnetic model field. The formula (2) was presented in [8].

$$
\begin{aligned}
u &= v_g sin(\alpha_g) - v_t sin(\alpha_t + \alpha_{mag}) \\
v &= v_g cos(\alpha_g) - v_t cos(\alpha_t + \alpha_{mag})
\end{aligned} \tag{2}
$$

In this work, the wind speed (ff) and wind direction (dd) calculated by the following formulas (3) will be treated.

$$
\begin{aligned}
ff &= \sqrt{(u^2 + v^2)} \\
dd &= (270 - arctg(\frac{v}{u}))mod(360)
\end{aligned} \tag{3}
$$

The great convenience of Mode-S EHS data is its extensive availability, the opportunity to profit from derived measurements of wind speed, wind direction and temperature. The use of Mode-S EHS data does not bring any additional costs, because the information is already transmitted from aircraft to local ATCs, it is only not fully exploited. However, the quality of these data compared to other types listed here is lower and the proper preprocessing is inevitable.

1.2 Mode-S MRAR

Mode-S MRAR data is less frequent than its EHS counterpart, beacause of the TAR setting to enable the MRAR data gathering. The transponder on board of the aircraft also has to be adjusted to emit the observed information in BDS register 4.4. Even, there are less and less airplane transponders adapted to the register 4.4, because it is not required by any regulations in aviation. As reported by EUMETNET [5], there were only few radars adapted to MRAR in 2015, particulary there is one in Austria, two in Slovenia, three in Czech Republic and one more in Denmark. However, there are about 200 EHS radars in Europe, as found in [6]. The broadcasting frequency is one message every 4 seconds, but it may vary. The frequency is limited by the amount of information that can be transmitted by one turn of the radar reciever.

The parameters contained in MRAR messages are listed in the table 2.

Table 2: Parameters contained in Mode-S MRAR messages.

parameter	range	unit
wind speed	0;511	kt
wind direction	0;360	deg
static air temperature	-128;128	°C
average static pressure	0;2048	hPa
turbulence	-	-
humidity	0;100	%

The biggest advantage of Mode-S MRAR is that MRAR data is direct measurement whilst the EHS is only derived data. It was already proved by various studies [5] or [9], that the quality of MRAR is much better than of EHS.

Further in the text, when we refer to Mode-S data, we mean the Mode-S EHS and Mode-S MRAR together. Otherwise, we refer to the specified type by its subtype EHS (alternatively Mode-S EHS), MRAR (alternatively Mode-S MRAR) respectively.

1.3 AMDAR

The AMDAR system is considered the traditional variant of aircraft measurements. It consists of the hardware and software on board of the airplane. The original purpose of the AMDAR system was to transmit the navigation information as well as the meteorological observations to ensure the safety of the flight and also to facilitate easier flight planning. The accuracy for AMDAR observation accuracy is defined in the AMDAR reference manual [7]. The error for wind speed was determined to 2-3 m/s and 0.3-0.45 K for temperature.

It is important to add that the same equippment on board is used for AMDAR and for MRAR measurements, if available. The temperature is measured by inmersion thermometer probe and the pressure by Pitot probe. The difference is in the information which is provided by the on board computer and which is calculated or analysed at ATC or meteorological services. Except of that, the Mode-S MRAR is reported with higher frequency and AMDAR are averaged over 10 - 30 seconds by on board computer and only averaged values are transmitted to ATC. Besides, the AMDAR reports are available if the aircrafts possess the accurate system on board and the reports are then emitted automatically. The MRAR reports are available if the airborne system is configurated to send them and also the TAR is configurated to interrogate those reports.

2 Quality control of Mode - S data

According to literature, there exist two methods to check the quality of Mode-S data, namely a validation with respect to NWP and a collocation method [9].

Here, the validation with respect to NWP method was chosen. This method is based on assimilation of analysed dataset into the model and calculation the differences between the observations and the first guess at the observation points. We assume the first guess is precise enough, so the departures will show the uncertainity of the observations. However, we can not forget that the differences are caused by observation error together with model error, which is unknown. Despite of that, this method is generally used for quality control. Some examples can be found in these studies [2], [9] or [14] that tackle the quality of Mode-S data in Europe.

2.1 Parameters of the NWP model of reference

In this study the ALADIN (Aire Limitée Adaption Dynamique et dévelopement InterNational) NWP system was used, namely the AROME (Applications of Research to Operations at MEsoscale) canonical model configuration.

The system operationally used at Slovak Hydrometeorological Institute (SHMU) usually denoted as ALADIN/SHMU or ALARO/SHMU has 63 vertical levels and resolution of 4.5 km horizontally. The time step is 180 seconds. The latest improvements of ALADIN/SHMU based on the code version CY40t1_bf07 operationally used from 2017 were presented in [4].

The AROME/SHMU canonical model configuration used in this work has the resolution of 2.0 km, so it is a non-hydrostatic convective-scale limited area model (LAM), as presented in [13]. There are 73 vertical layers. It covers the area of Slovak republic and near vicinity. A comparison of model configurations used at SHMU are shown in table 3.

Table 3: Model configurations used at SHMU.

	ALADIN/SHMU	AROME/SHMU
status	operational	experimental
code version	CY40T1bf07_export	CY40T1bf07_export
coupling model	ARPEGE/IFS	ALADIN/SHMU
horizontal resolution	4.5 km	2.0 km
vertical levels	63	73
time step	180 s	144 s

The selection of AROME/SHMU model for the purpose of this study is based on various reasons. This canonical model configurations is suitable for experiments aimed to test the impact of Mode-S data. The driving ALADIN model catches the mesoscale patterns. On the contrary, the AROME/SHMU with twice finer resolution is able to simulate convective scale patterns and more accurately describes the local atmospheric phenomena.

2.2 Parameter of the analysed dataset

The data analysed in this report was provided by LPS SR. The sample consists of measurements from January to February 2018 from 4 different TARs, as listed in the table 4 below. The availability of the data is not the same for every country. In Slovakia the TARs are set to be able to query the Mode-S EHS messages only. Whilst in Czech republic, the TAR is predetermined to request both possible data types EHS and MRAR, it means the radars query on two different transmition frequencies. However, the possibility of gathering MRAR reports requires a special transponder on board of the airplane, which is not installed on each of those crossing the air space covered by these radars. For that reason, the MRAR reports are less frequent than EHS reports. From Vienna TAR onlyv MRAR data was obtained. This radar is adapted to recieve information from registers 4.4, 5.0 and 6.0, but the registers 5.0 and 6.0 from Vienna does not contain all the information needed to derive the meteorological parameters. The whole dataset was provided thanks to the cooperation between LPS SR and Czech and Austrian ATCs.

Table 4: Geografical position of TARs which the data was taken from.

Radar	data	latitude	longitude
Malý Javorník (JAVOR)	EHS	N48°15′	E17°09′
Mošník (MOSNIK)	EHS	N48°47′	E21°32′
Buchtův kopec (BUKOP)	EHS, MRAR	N49°40′	E16°08′
Vienna (VIENNA)	MRAR	N48°07′	E16°34′

The AMDAR measurements were chosen as the reference dataset. These were obtained from CHMI.

The filters for the uncomplete data (at least one parameter from temperature, wind speed or wind direction was missing due to not being reported for any reason) were applied and the data was thinned. The measurements after filters are available approximately once per minute from each detected aircraft (the time criterion was applied only to EHS). This is convenient to NWP because excessive overfilling by data does not lead to improvements in forecasts.

As there are aircrafts that fly across our air space regulary as well as some that passed only few times, it is interesting to consider the number of all the observations and the number of observations that belong to particular aircrafts. The aircraft identification is the ICAO address. It is a unique code involved in the transmitted messages. Its aim is to differentiate them as there are many collected at the same time by one TAR while they proceede from different airplanes. The total amounts of observation in the studied sample are enumerated in the following table 5. It is necessary to mention that there exists an intersection of different TARs that transfer the same kind of reports, because of the overlapped coverage of the radars.

Table 5: 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 frequency of EHS measurements data from all aircrafts together is 80 reports per minute. The reporting frequency for a single aircraft from the available data sample is approximately 1 report per minute. When this dataset was created by LPS SR, this was thinned with the thinning time interval of one minute, because of very big amounts of the EHS data. In case of MRAR data, the frequency of all data is 2 reports per minute. The number of observations is subject to current air traffic, it is consistently smaller at night. There are several cases during the studied two months period, where no MRAR measurements were available $\pm$ 3 h around midnight.

2.2.1 Preprocessing of the whole dataset

The studied dataset of Mode-S data was provided in daily csv (commma separated values) formatted files. Then a conversion from csv formatted files into specific format denoted "obsoul" was done. The obsoul format is directly read by the AROME/SHMU model assimilation scripts. At this step, some criteria for eliminating unnecessary data were applied. The selection avoided the latter use of uncorrect data by setting limits to highest and lowest possible observed value of temperature and the highest possible wind speed. Also, the data produced by airplanes that have already landed were excluded. The vertical position is provided in hektofeets which denote the flight level. A conversion to meters is done.

The assimilation procedure was used for further processing. For the validation of Mode-S data with respect to NWP, the 6 h cycling was run. The analysis time was set to 00, 06, 12 and 18 UTC. The assimilation windows, it means the time span the observations proceed from, was set to ± 3 hours for MRAR and only $\pm 1,5$ hours for EHS, because of the very high density of EHS observations in time. To achieve this, the observations were parsed into 6 h or 3 h long timesteps for MRAR or EHS data respectively. In more detail, if the analysis time was set to 00 UTC, the observations for this time were taken from 21:00 UTC until midnight from the previous day and from 00 UTC to 03:00 UTC, in case of MRAR data. For EHS observations the observations were taken in the same fashion from 22:30 UTC from the previous day until 01:30 UTC for the date of the analysis time.

3 Results and discussion

3.1 Validation of Mode-S and AMDAR with respect to NWP

In this section, the results of validation of Mode-S and AMDAR with respect to NWP are presented. The observed values of temperature, wind speed and wind direction (or calculated from other observed quantities, in case of EHS data, see detailes in section 1.1) were compared to model first guess fields. Then, the obtained differences were statistically analysed. The results are presented for AMDAR, EHS and MRAR data separately, in this order respectively.

The statistical tools exploited in this section were developed by B. Strajnar in frame of RC LACE stay [11] at CHMI, Prague. These tools together with the know how on statistical analysis of Mode-S data were forwarded to the author during the research stay at CHMI, Prague supported by RC LACE.

The three dimensional variational analysis (3D-Var) assimilation performs the interpolation of model variables into the positions of the observations. These are easily known as each observation (including aircraft reports) contains its position (latitude, longitude, pressure altitude). The final differences, calculated as the observations minus first guess, proceed from the same spots. From here, the notation observations minus first guess (OMG) for these differences will be used.

The above mentioned observations minus first guess departures were statistically evaluated. The mean value and standard deviations were calculated. The mean ($\bar{x}$) of a statistical sample is obtained by formula (4), where (N) is the total number of elements in the sum and (x_i) are the individual elements of the sample. The bias is represented by the deviation of the mean from 0. If the bias is different from 0, a systematic error exists there and the observations are systematically deviated from the model first guess. An indication of a randomly and normally distributed data is the bias equal to 0. However, the bias can be equal to 0 even if the observations are deviated to both sides from the mean value, in the same measure. This can be detected from the standard deviation values, calculated according to formula (5). The standard deviation defines the spread of the observations in the sample and their distances from the mean value.

$$\bar{x} = \frac{1}{N}\sum x_i \tag{4}$$

$$STD = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N-1}} \tag{5}$$

3.1.1 Temperature

First, the results for the temperature measurements for AMDAR, EHS and MRAR respectively are presented. The histograms show the distribution of the OMG departures for different types of data and studied variables. For each data type, a vertical profile of mean value, standard deviation (STD) and number of observations is also presented.

The raw AMDAR data was checked for gross errors. The STD was calculated for the whole dataset of AMDAR temperature OMG departures and values out of the interval $< -2\ STD; 2\ STD >$ were excluded. Only then the basic statistics (mean value and standard deviaton) for the restricted dataset were calculated.

Figure 1a depicts the distribution of AMDAR OMG departures over the whole period of two months Jan-Feb 2018. The ploted data is already after the gross error check described above. The bins in the histogram are of 0.2 K wide, the horizontal axis displays the temperature in K and the vertical axis represents the number of observations. The total amount of the observations plotted here is 208 933. It is almost 97% from the raw data before gross error check. The distribution is nearly gaussian, slightly assymetric with more observations on the negative side. The mean calculated for this data sample is -0.03 K. For comparison de Haan [2] reached 0.2 K bias in his study. On the other hand, the WMO standards [15] define the accuracy of ± 1 K for temperature observations.

The vertical distribution of AMDAR OMG departures in figure 1b consist of three plots. The whole column of atmosphere where observations were present (from 1 050 hPa to 150 hPa) was divided into 18 layers of 50 hPa. The mean and STD were calculated for each layer and are depicted in figure 1b. The most left plot displays the vertical profile of the mean value calculated for different vertical layers and the middle stands for the STD vertical distribution. The bias is mostly negative in the layer with most observations and the STD there is a bit over 1 K. The right panel is again a histogram of number of observations plotted for each vertical layer. There is an interesting point to notice, the global maximum of the number of observations proceeds from the 900 - 850 hPa layer. It might be induced by higher reporting frequency compared to other layers.

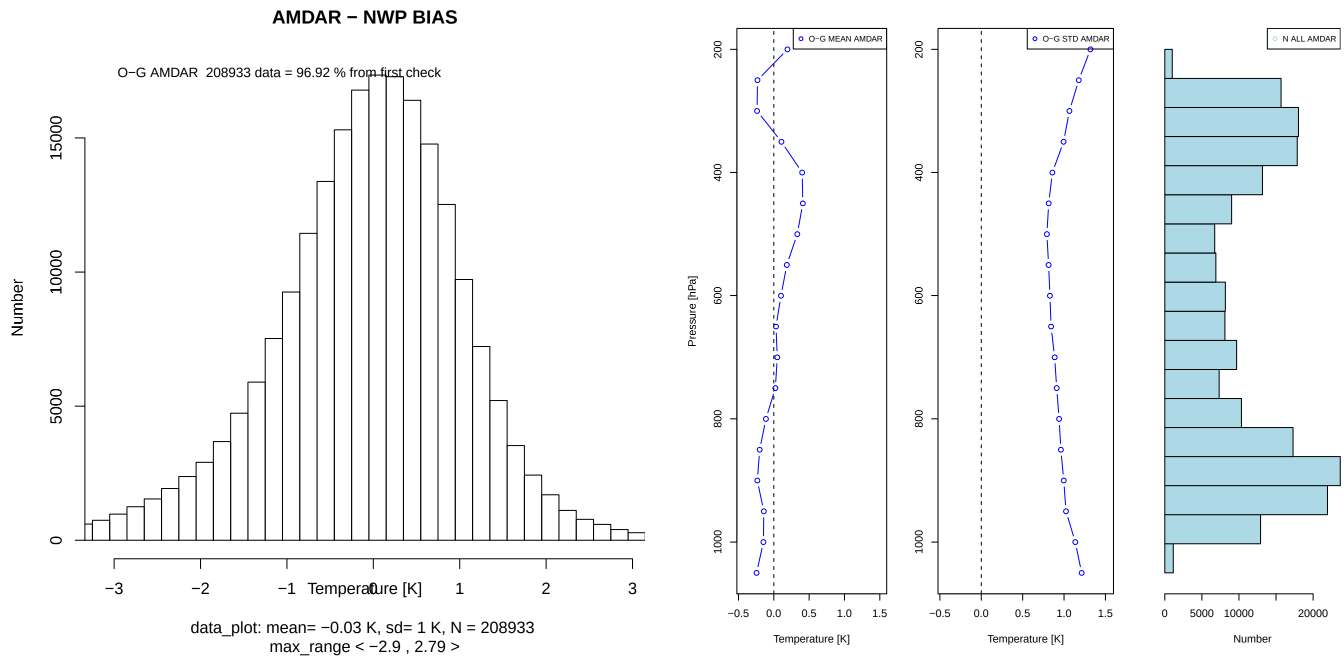


Figure 1: (a) Distribution of AMDAR OMG departures for temperature after the gross error check. (b) Vertical profile of AMDAR OMG departures for temperature after the gross error check. The left panel depicts the vertical profile of the mean value, the STD is plotted in the middle panel and the right panel shows the vertical profile of the number of observations.

The same steps were performed to check the EHS dataset for gross errors. In figure 2a the scale for the vertical and also the horizontal axis is different from the previous case, as it is set according to the 2 STD criterium. There remained 99.99 % of the raw data after the gross error check. The following figure 2a displays the histogram for EHS OMG departures for temperature. The bias is again negative, although larger than for AMDAR. The STD is worse than for AMDAR too. This time, the entire sample counts for 14 millions of observations over 2 months period, the dataset is then statistically much more robust.

For comparison, Strajnar [12] analysed an EHS sample of randomly chosen 10% of 10 months period. Those data were collected and preprocessed by Royal Netherlands Meteorological Institute (KNMI). He reached the mean of 0.02 K and STD of 0.99 K. The large difference from the results of this work are probably caused partially by a distinct preprocessing method and mainly by the relatively big amount of deviated observations near the ground.

The vertical profile in figure 2b shows that the mean for temperature is oscillating around 0 K, only near the ground the mean is nearly 1.5 K. The STD reflects the profile and the biggest value 10.5 K is observed in the lowest layer 1050 - 1000 hPa. This may be induced by distortion of measurements near the ground due to large gradient of aircraft speed and the Mach number. The derivated quantities are then affected. This problem appeared also in Strajnar‘s study [12], although in a smaller measure. From the 950 hPa level, the STD value is quite stable. The maximum of the measurements is observed in the 250 - 200 hPa level, where the most of the comercial aircrafts fly.

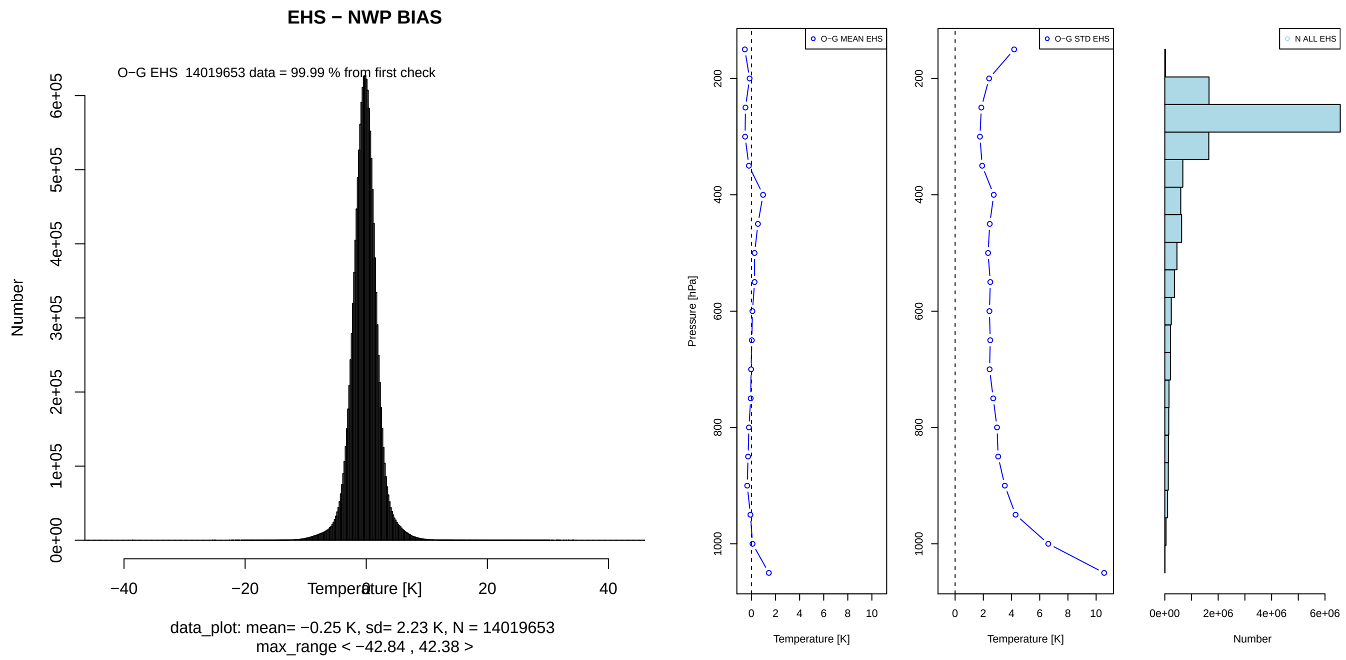


Figure 2: (a) Distribution of EHS OMG departures for temperature after the gross error check. (b) Vertical profile of EHS OMG departures for temperature after the gross error check. The left panel depicts the vertical profile of the mean value, the STD is plotted in the middle panel and the right panel shows the vertical profile of the number of observations.

In figure 3a is the histogram of MRAR OMG departures for temperature. In case of MRAR data, only less than 95% remained from the first gross error check, after applying the 2 STD criterium. The histogram has almost normal distribution and it is slightly assymetric in a similar way like the AMDAR OMG departures. The MRAR OMG departures are biased, the mean for this data sample was determined to 0.3 K and STD is 1.17 K. In this work, the results for quality of MRAR data were much better than e.g. in Hrastovec and Solina‘s study [6], where they assessed the average OMG departures to 0.4 K and STD to 2.1 K. Similarly, the study by CHMI [14] presented results for mean 0.79 K and STD 1.19 K for MRAR OMG departures, although in this case, they calculated the statistics per aircraft type. So they first aggregated the observed values according to the ICAO address and only these results were presented in their study.

From the vertical profile in figure 3b of MRAR OMG departures, a slight warm bias near the ground is detectable, similarly to the EHS data. The mean for the 250 - 200 hPa layer with most observations is only 0.15 K and the STD is 1.25 K there. The vertical profile of the mean value oscillates much more than in case of EHS or AMDAR observations, but the STD remains steady.

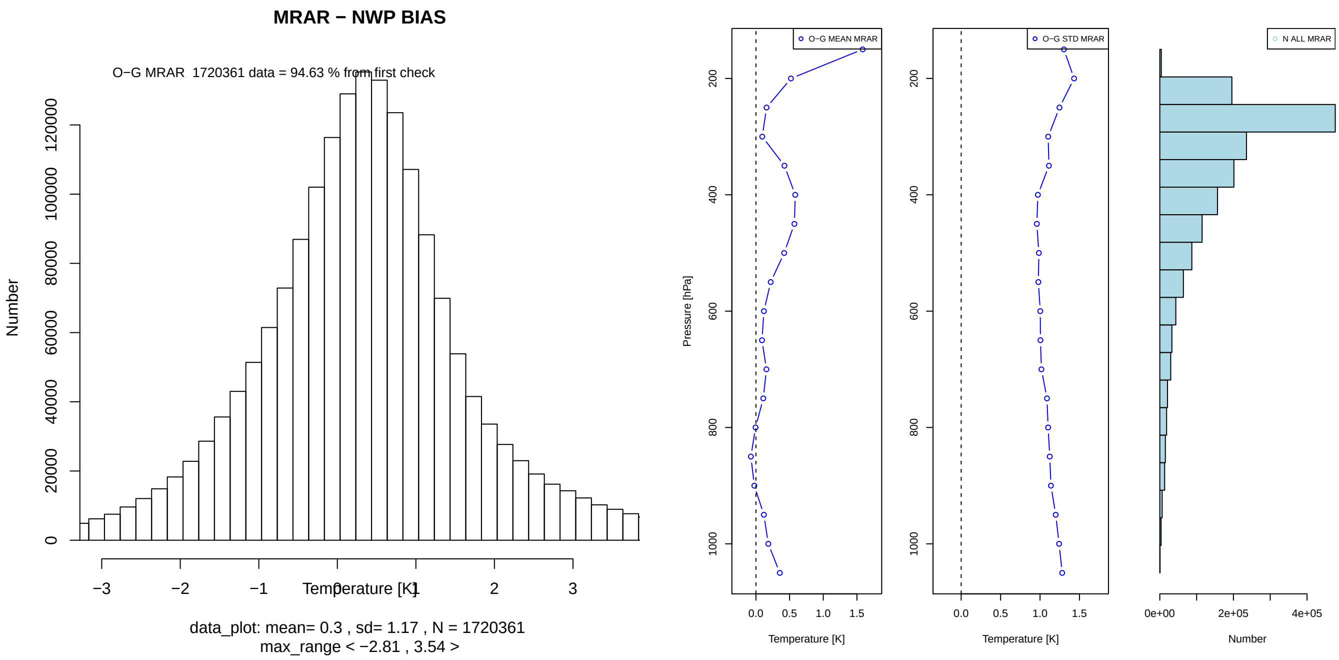


Figure 3: (a) Distribution of MRAR OMG departures for temperature after the gross error check. (b) Vertical profile of MRAR OMG departures for temperature after the gross error check. The left panel depicts the vertical profile of the mean value, the STD is plotted in the middle panel and the right panel shows the vertical profile of the number of observations.

3.1.2 Wind speed

As well as for the temperature measurements, the gross error check was performed for wind speed. The OMG departures are calculated for u, v components of the wind, so the wind speed was determined before the statistical analysis, according to the equations (3). The 2 STD criterium was calculated separately for each quantity, that is one of the reasons why the numbers of all the studied observations are different for various variables. Another one is that the there are two independent sensor on board to measure wind related quantities and temperature, so there are occasions when only one of them reports the data or one can be out of service or there is just a modified configuration of the sensor, as Strajnar [9] presumes.

Figure 4a depicts the histogram of the OMG departures for AMDAR data. As was expected, the distribution is normal, with a very light assymetry to positive values, which is reflected in a positive mean 0.1 m/s. The observed negative values represent the situations, where the observed value of wind speed was smaller than the value predicted by the model. The STD was determined to 2.53 m/s. The number of observations is less than for AMDAR observations, only 203 060. This is the 95.8% of raw data.

Concerning the vertical profile in figure 4b, the mean is negative only for the lowest layers below 800 hPa. The STD is slowly increasing with height. Bučánek [1] revealed, that the AMDAR wind observation error depends on air temperature, Mach number, but it also increase with inclination of the aircraft when maneuvering and with ascent. The number of observations of AMDAR OMG departures for wind speed, likewise those for temperature, has the maximum in 900 - 850 hPa layer.

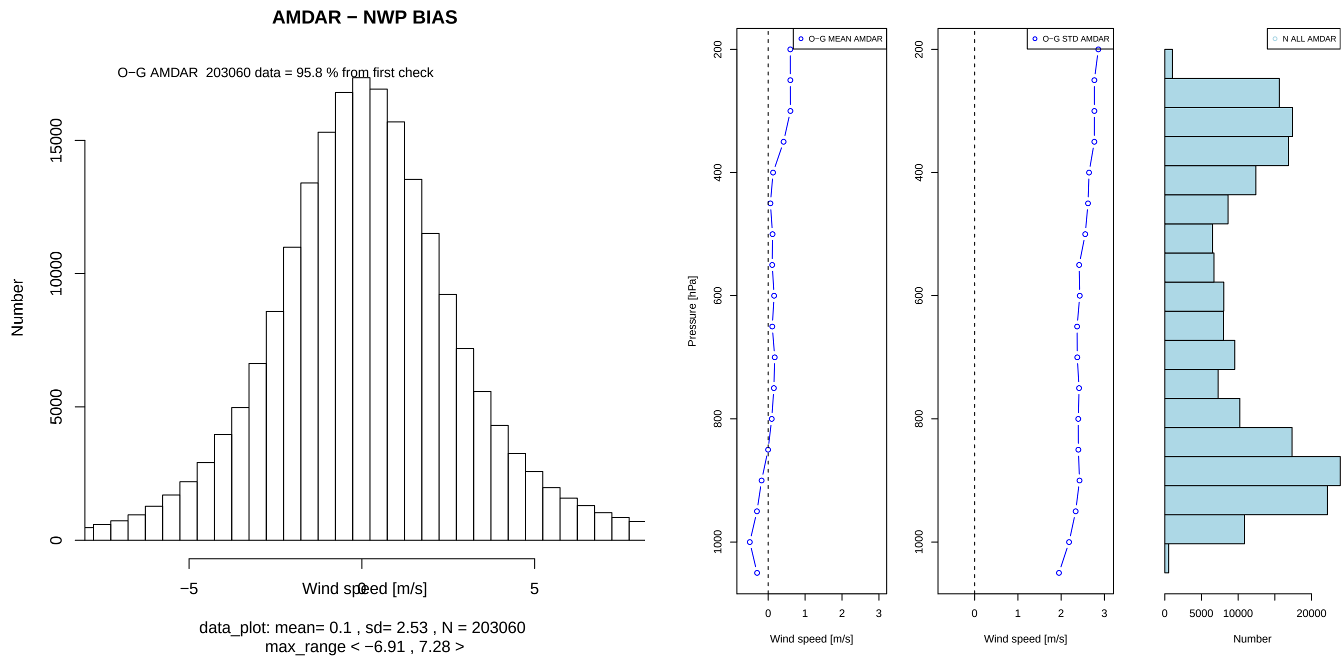


Figure 4: (a) Distribution of AMDAR OMG departures for wind speed after the gross error check. (b) Vertical profile of AMDAR OMG departures for wind speed after the gross error check. The left panel depicts the vertical profile of the mean value, the STD is plotted in the middle panel and the right panel shows the vertical profile of the number of observations.

For the wind speed EHS measurements, there were more outliers observed. Only 99.65% of raw observations remained after gross error check according to 2 STD criterium. The distribution displayed in figure 5a is assymetric to positive values, so the values predicted by the model were more frequently larger than those measured by aircrafts. The depicted results were compared to Strajnar‘s study [12]. As he adopted a different preprocessing method, he achieved the mean value 0.27 m/s and STD 2.43 m/s. On the other hand, in this work the whole datased from the 2 months period was analysed, while he randomly chose only 10% of 10 months period.

The most biased data are from the lowest layer 1050 - 1000 hPa, where the STD reaches approximately the double of the rest layers. The reason is expected to be due to distorted observations because of rapid changes of temperature near the ground. Note that for the derivation of wind speed of EHS data, the direct observation of temperature is indispensable. The lowest layer contains around 5 000 observations, similarly to the temperature observations at this altitude. The vertical profile for EHS wind speed OMG departures is presented in figure 5b.

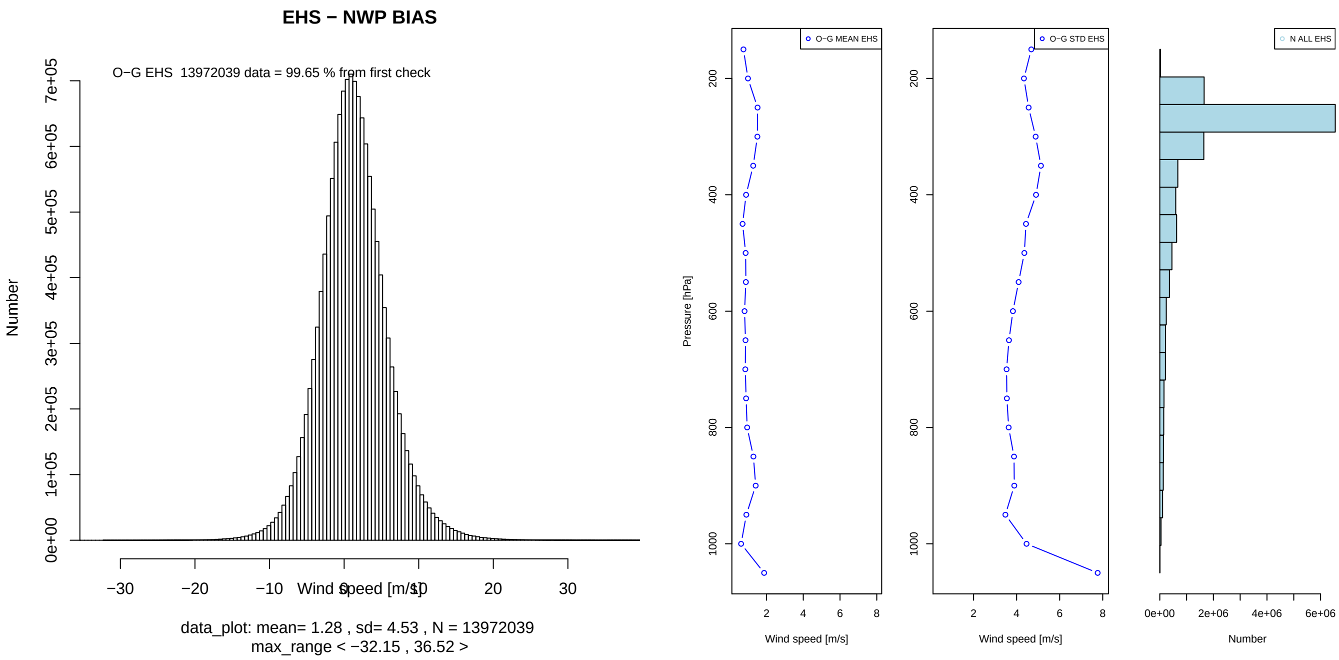


Figure 5: (a) Distribution of EHS OMG departures for wind speed after the gross error check. (b) Vertical profile of EHS OMG departures for wind speed after the gross error check. The left panel depicts the vertical profile of the mean value, the STD is plotted in the middle panel and the right panel shows the vertical profile of the number of observations.

The MRAR OMG departures for wind speed are diplayed in figure 6a. There remained 94.61% data from the gross error check. The resultant observations have nearly normal distribution, lightly assymetric to positive values as well as the EHS data. The mean is negative only near the ground, below the 950 hPa level. The mean of the dataset is also positive 0.61 m/s. The STD increases with height from 2.75 m/s to 3.79 m/s, this tendency was also observed by Strajnar in [9]. The lowest layer is an exception, the STD is 3.15 m/s.

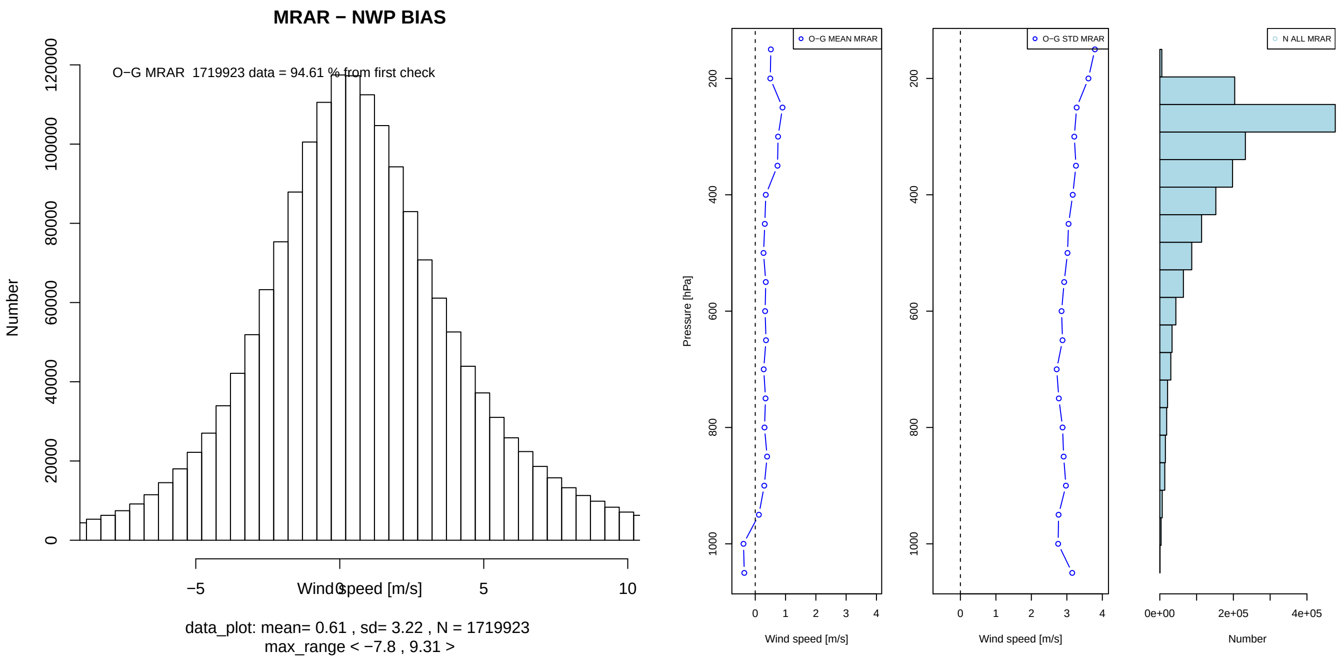


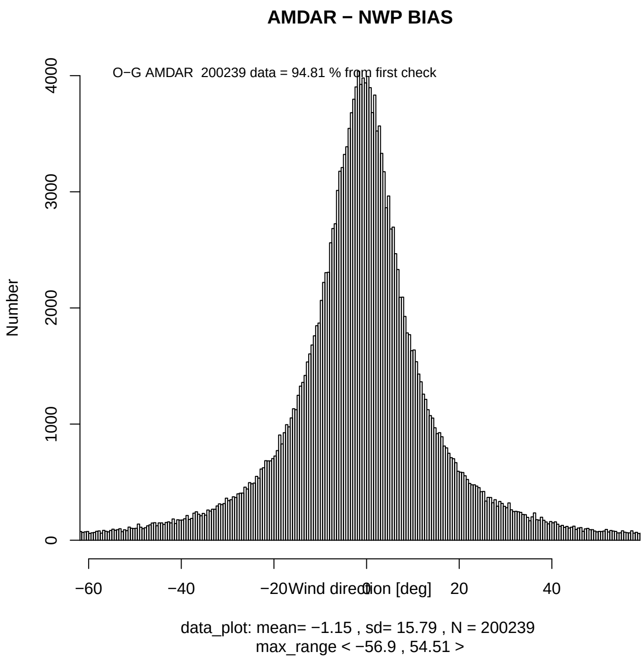
Figure 6: (a) Distribution of MRAR OMG departures for wind speed after the gross error check. (b) Vertical profile of MRAR OMG departures for wind speed after the gross error check. The left panel depicts the vertical profile of the mean value, the STD is plotted in the middle panel and the right panel shows the vertical profile of the number of observations.

3.1.3 Wind direction

Before the statistical analysis was performed, the wind direction had to be calculated from wind u, v components following the formulas (3). Then the gross error check was done, again separately for wind direction OMG departures applying the 2 STD criterium. The wind direction is in general very variable quantity, so the measuring accuracy is naturally much lower than for the previous parameters. From the character of the atmospheric flow, the variability of direction decreases with height.

First, the AMDAR OMG departures for wind direction were analysed in figure 7a. Compared to temperature or wind speed, most outliers were detected in wind direction OMG departures, only 94.81% of raw data remained after first gross error check. The distribution is very spread, approximately ± 55 degrees. That leads to STD of 15.79 degrees. The histogram is biased to negative values and the mean calculated for the entire sample is -1.15 degrees.

The vertical profile shown in figure 7b is very accurate. The mean belongs to $< -1; 0 >$ degrees interval for the big part of the profile, except the lower layers. The precision is similarly detectable in the STD profile, which is quite stable for the highest level and it increases while descending nearer to the ground. The number of observations shows the typical profile for AMDAR data.



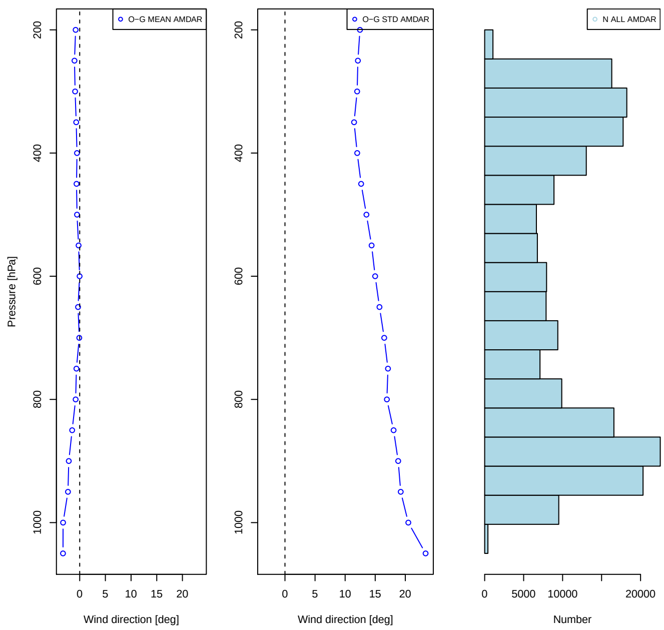


Figure 7: (a) Distribution of AMDAR OMG departures for wind direction after the gross error check. (b) Vertical profile of AMDAR OMG departures for wind direction after the gross error check. The left panel depicts the vertical profile of the mean value, the STD is plotted in the middle panel and the right panel shows the vertical profile of the number of observations.

The EHS OMG departures displayed in figure 8a are of similar range as for the AMDAR data. The mean value is even better than for AMDAR observations, only 0.78 degrees. The STD reaches 16.43 degrees. E.g., the bias is much lower than the one observed by de Haan in [2].

The vertical profile of the EHS OMG departures is more biased in the lowest levels. The STD deviation decreases with height, what can be caused also by a much larger amount of observations in the highest levels compared to the number of observations near the ground. E.g., in the 1050 - 1000 hPa layer, only 3 158 observations were registered. This is 0.05% of the number of observations in the most numerous layer between 250 - 200 hPa.

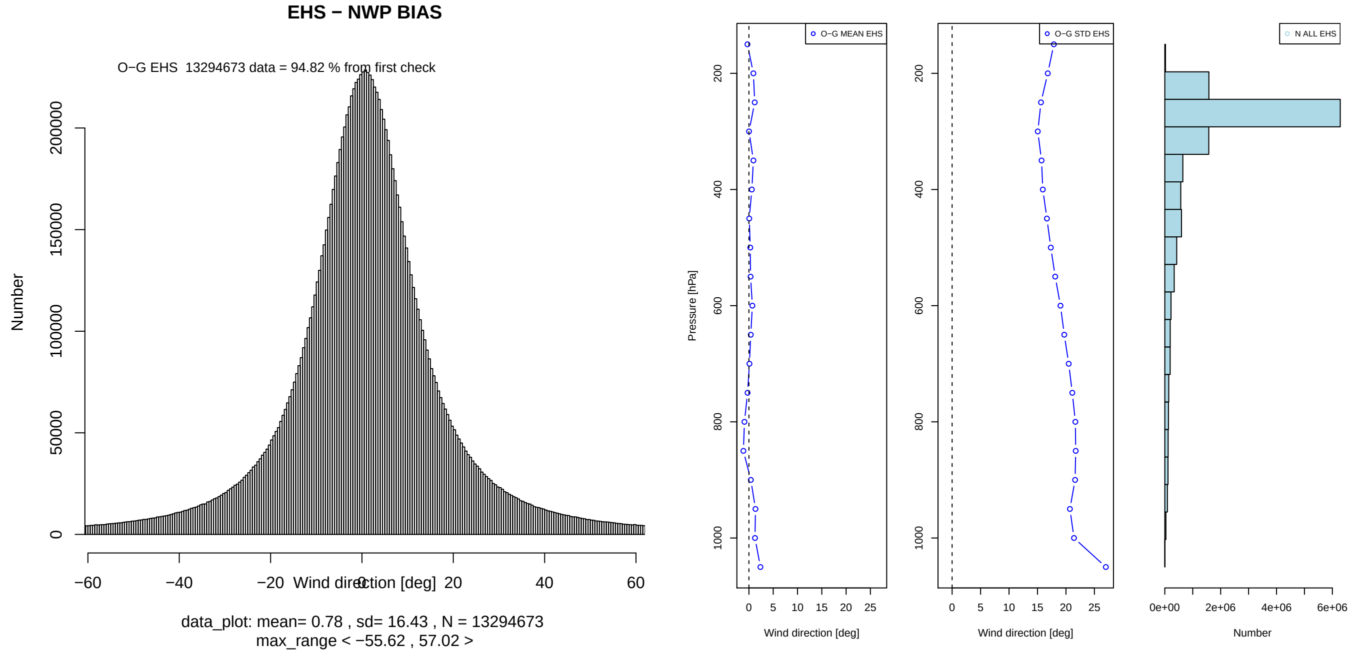


Figure 8: (a) Distribution of EHS OMG departures for wind direction after the gross error check. (b) Vertical profile of EHS OMG departures for wind direction after the gross error check. The left panel depicts the vertical profile of the mean value, the STD is plotted in the middle panel and the right panel shows the vertical profile of the number of observations.

The distribution of MRAR OMG departures for wind direction is slightly assymetric to negative values. The mean was determined to -0.59 degrees and the STD 14.37 degrees, what is comparable to the EHS results. The range of plotted data selected after the gross error check is approximately the same as for the EHS and AMDAR - the reference dataset.

The vertical profile of OMG departures is very similar to the EHS vertical profile, mainly for STD. In the lower layers, the positive bias is dominant, whilst in case of EHS the negative mean was frequent. According to Strajnar‘s study [9], the STD was expected to increase with height but the result presented here is opposite.

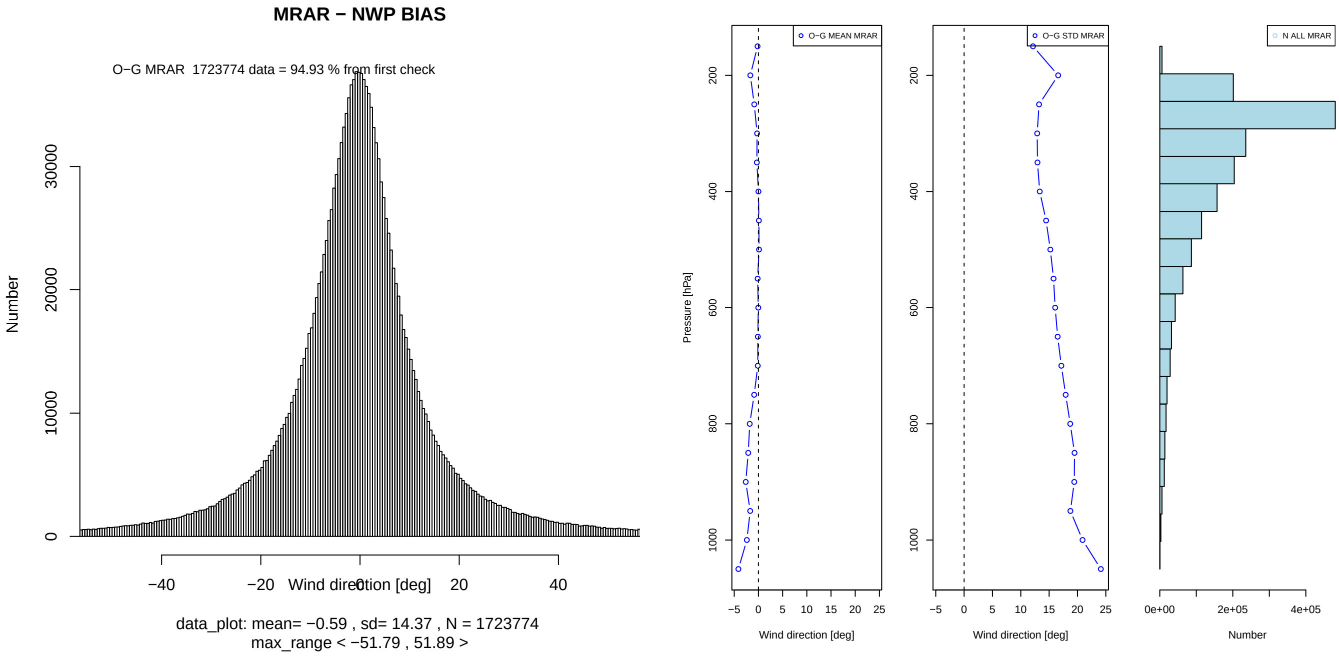


Figure 9: (a) Distribution of MRAR OMG departures for wind direction after the gross error check. (b) Vertical profile of MRAR OMG departures for wind direction after the gross error check. The left panel depicts the vertical profile of the mean value, the STD is plotted in the middle panel and the right panel shows the vertical profile of the number of observations.

3.1.4 Summary of the results from validation method with respect to NWP

The statistics presented in this report consist of the distribution analysis of OMG departures for the three studied data sample in particular for temperature, wind speed and wind direction separately. A summary of the results displayed in previous graphs is presented here in the table 6.

Obviously, the best quality was reached in the analysis of temperature OMG departures, where all the three datatypes have the mean value less or equal than ± 0.3 K. The STD for AMDAR data was equal to 1.0, that represents a very good distribution of nearly gaussian shape. The spread of MRAR (STD = 1.17 K) data is very close to AMDAR (STD = 1.00 K), although the mean value is shifted to positive values. The MRAR data temperature dataset achieved the lowest spread compared to other previous studies cited in this work.

The EHS data is the most numerous from the three compared aircraft data types. The MRAR measurements result more precise than EHS in terms of STD comparison, also because the results obtained here were better than in previous similar studies.

The wind speed statistics for MRAR were comparable to the values obtained for AMDAR. However, the AMDAR results in this study were more biased than results from other similar works. The mean value and the STD for EHS is approximately the double of the AMDAR values presented here. Estimating the wind direction OMG departures for the three datasets, the MRAR data reached the lowest spread and mean value closest to 0. But comparing the same results to similar studies performed e.g. in Czech Republic, the results are not satisfactory.

The very good results for temperature, mainly for MRAR data, are beneficial for a more accurate determination of the state of the atmosphere. But the temperature is a large scale parameter that changes only in a small measure in the upper layers of the atmoshpere. On the other hand, the wind is considered a small scale parameter that changes rapidly even in upper layers of the atmosphere, so there is a need to improve the wind speed and direction statistics for more precise forecasting.

Table 6: Summary of temperature, wind speed and wind direction OMG departures results for AMDAR, EHS and MRAR data.

Temperature [K]				
Data type	Number of observations after gross error check		Mean [K]	STD [K]
	Absolute number	Relative number [%]		
AMDAR	208 933	96.92	-0.03	1.00
EHS	14 019 653	99.99	-0.25	2.23
MRAR	1 720 361	94.63	0.30	1.17
Wind speed [m/s]				
Data type	Number of observations after gross error check		Mean [m/s]	STD [m/s]
	Absolute number	Relative number [%]		
AMDAR	203 060	95.80	0.10	2.53
EHS	13 972 039	99.65	1.28	4.53
MRAR	1 719 923	94.61	0.61	3.22
Wind direction [deg]				
Data type	Number of observations after gross error check		Mean [deg]	STD [deg]
	Absolute number	Relative number [%]		
AMDAR	200 239	94.81	-1.15	15.79
EHS	13 294 673	94.82	0.78	16.43
MRAR	1 723 774	94.93	-0.59	14.37

Conclusion

The purpose of this study was first to become aquainted with the quality control methods used to test the Mode-S and AMDAR data. Secondly, these methods were exploited to accomplish a quality assessment of local Mode-S data and their assimilation into the ALADIN/SHMU system, namely AROME/SHMU convective scale canonical model configuration.

The quality control was peformed by validation of collected observations with respect to AROME/SHMU model. The assimilation procedure was exploited. The first guess fields were calculated in downscaling mode. Further the screening 002 configuration executes the quality control and attributes quality indices considering the metadata. The model parameters are interpolated into observation points and observation minus first guess departures were calculated.

The statistical analysis on OMG departures was carried out for AMDAR, EHS and MRAR data analysing the departures for temperature, wind speed and wind direction separately. The results obtained for temperature OMG statistics were comparable to other studies taken as reference. The MRAR temperature OMG departures distribution studied here exceeded the best reached statistics available in cited literature. The wind speed and wind direction statistics results were not satisfactory compared to reference studies in literature. The wide spread and biased results may be caused by different preprocessing of raw data before statistical analysis, by relatively small studied data sample or by incorrect measurements registered by avionics.

The future research should focus on the improvement of the statistics for wind speed and wind direction. The whitelisting method (based on filtering reliable data accomplishing some specified criteria) should be used for a detailed test of the Mode-S data characteristics.

References

[1] Bučánek, A. (2009): *Studie použití dat AMDAR pro jejich asimilaci v NWP modelu ALADIN.* Diploma thesis, Univerzita Karlova v Praze, Matematicko-fyzikální fakulta

[2] De Haan, S. (2009): *Quality assessment of high resolution wind and temperature observations from Mode-S.* KNMI Scientific report, DeBilt, The Netherlands [Retrieved 1 May 2019 from https://www.researchgate.net/publication/239592823_Quality_assessment_of _high_resolution_wind_and_temperature_observation_from_ModeS]

[3] De Haan, S. - Stoffelen, A. (2012): *Assimilation of High-Resolution Mode-S Wind and Temperature Observations in a Regional NWP Model for Nowcasting Applications.* Weather and Forecasting, Vol.27,918-937 American Meteorological Society DOI: 10.1175/WAF-D-11-00088.1

[4] Derková, M. - Vivoda, J. - Belluš, M. - Španiel, O. - Dian, M. - Neštiak, M. - Zehnal, R. (2017): *Recent improvements in the ALADIN/SHMU operational system.* Meteorologický časopis, Vol.20, 45-52, SHMU

[5] EUMETNET (2015): *EUMETNET Aircraft Derived Data Feasibility Study Expert Team.* GIE EUMETNET, c/o L'Institut Royal Météorologique de Belgique [Retrieved 1 May 2019 from http://mode-s.knmi.nl/documents/EUMETNET_ADD_Report_FINAL_v1.0_03102015.pdf]

[6] Hrastovec, M. - Solina, F. (2013): *Obtaining Meteorological Data from Aircraft with Mode-S Radars.* IEEE Aerospace and Electronic Systems Magazine, vol. 28, no. 12, pp. 12-24, Dec. 2013 DOI: 10.1109/MAES.2013.6693664

[7] Painting J. D. (2003): *Aircraft Meteorological Data Relay (AMDAR) Reference Manual.* Technical report WMO-No.958, WMO, Geneva, Switzerland ISBN 92–63–10958–3

[8] Stone, E.K. - Pearce, G. (2016): *A Network of Mode-S Receivers for Routine Acquisition of Aircraft-Derived Meteorological Data.* Journal of atmospheric and oceanic technology,33, 757–768, Met Office, Exeter, United Kingdom DOI: 10.1175/JTECH-D-15-0184.1

[9] Strajnar, B. (2012): *Validation of Mode-S meteorological routine air report aircraft observations.* Journal of Geophysical Research, vol.117, D23110 DOI:10.1029/2012JD018315

[10] Strajnar,B. - Žagar,N. - Berre,L. (2012): *Impact of new aircraft observations Mode-S MRAR in a mesoscale NWP model.* Journal of Geophysical Research: Atmosphere, 120, 3920-3938 DOI: 10.1002/2014JD022654

[11] Strajnar, B. (2015): *Analysis and preprocessing of Czech Mode-S observations.* Report on RC LACE stay, CHMI, Prague, Czech republic [Retrieved 1 May 2019 from http://www.rclace.eu/?page=11]

[12] Strajnar, B. (2017): *Assimilation of Mode-S EHS observations in ALADIN BlendVar.* Report on RC LACE stayCHMI, Prague, Czech republic [Retrieved 1 May 2019 from http://www.rclace.eu/?page=11]

[13] Termonia, P. - Fischer, C. - Bazile, E. - Bouyssel, F. - Brožková, R. - Bénard, P. - Bochenek, B. - Degrauwe, D. - Derkova, M. - El Khatib, R. - Hamdi, R. - Mašek, J. - Pottier, P. - Pristov, N. - Seity, Y. - Smolíková, P. - Spaniel, O. - Tudor, M. - Wang, Y. - Wittmann, C. and Joly, A. (2018): *The ALADIN System and its Canonical Model Configurations AROME CY41T1 and ALARO CY40T1.* Geoscienfific Model Developement, 11, 257-281 DOI:10.5194/gmd-11-257-2018

[14] Trojáková, A. - Benáček, P. - Brožková, R. - Bučánek, A. (2015): *Assimilation of Mode-S observations in ALADIN/CHMI.* [Retrieved 1 May 2019 from http://www.rclace.eu/?page=11]

[15] WMO Commision for Basic Systems (2014): *WMO Integrated Global Observing System. The Benefits of AMDAR Data to Meteorology and Aviation.* Technical report No. 2014-01, Geneva, Switzerland