Analysis and preprocessing of Czech Mode-S observations

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1 Introduction

Modern surveillance techniques allows air traffic controls (ATC) to collect a large number of flight parameters from aircraft in real time. Among the available communication techniques, Mode-S (selective mode communication between ATC and airplane) is realized with a ground requesting radar (the so-called secondary radar), transponders on board the aircraft, and Mode-S ground sensors to collect the replies. These systems are of interest for meteorology because it is possible to extract meteorological information. This can be done either by using mandatory Mode-S data, the Enhanced Surveillance (EHS) parameters which are available in any Mode-S system (de Haan, 2011) or by directly requesting wind and temperature messages contained in a non-mandatory Mode-S data register Meteorological Routine Air Report (MRAR) (Hrastovec and Solina, 2013; Strajnar, 2012).

Both Mode-S EHS and MRAR methods have their advantages and disadvantages. A great advantage of Mode-S EHS observations is that EHS parameters are available in any Mode-S equipped ATC system and from all Mode-S equipped aircraft. However, the computation is indirect, especially for temperature, which can only be computed through speed of sound equation from Mach number and airspeed (de Haan, 2011). The wind is computed from a vector difference between air speed (including heading) and ground speed. The magnetic heading in particular has been shown to include aircraft type specific biases. A correction procedure was proposed by (de Haan, 2011) and then refined in (de Haan, 2013). On the other hand, Mode-S MRAR includes direct wind and temperature observations and whose quality was shown to be the same as the quality of Automated Meteorological Data Relay (AMDAR) on the AMDAR-equipped aircraft (Strajnar, 2012). However, because this data are not mandatory in a standard Mode-S system, the ATC radars must be configured to interrogate an additional MRAR register containing this data (where this is possible at all with respect to the density of air traffic). The support for MRAR also depends on the type of the transponder on board the aircraft. In the Slovenian case (Strajnar, 2012), MRAR was available from 5% of all Mode-S reports.

Since few years, Mode-S observations (both EHS and MRAR) have been collected by Air Navigation Services of Czech Republic (ANS-CZ). The data was recently made available for evaluation also to Czech Hydrometeorological Institute (CHMI). This work is devoted to a basic analysis and preprocessing of these Mode-S observations. We first describe the data and provide examples of flight profiles. As a next step, raw Mode-S MRAR and Mode-S EHS (as computed for the moment at ANS CZ) are compared to AMDAR in a colocation study. A further evaluation is provided by a comparison to ALADIN/CZ numerical weather prediction model. This comparison enables an evaluation for each Mode-S observation (also non-AMDAR equipped aircraft). Description of scripts, software and data can be found last in the Appendix A.

2 Data description

2.1 Mode-S data set

The Czech Mode-S data includes 3 Czech Mode-S radars Praha/Ruzyně, Písek (Jince) and Buchtův kopec (Sněžné). Those provide Mode-S EHS every 4 s and Mode-S MRAR every 10 seconds. Mode-S EHS is also available form 2 additional radars near Auersberg

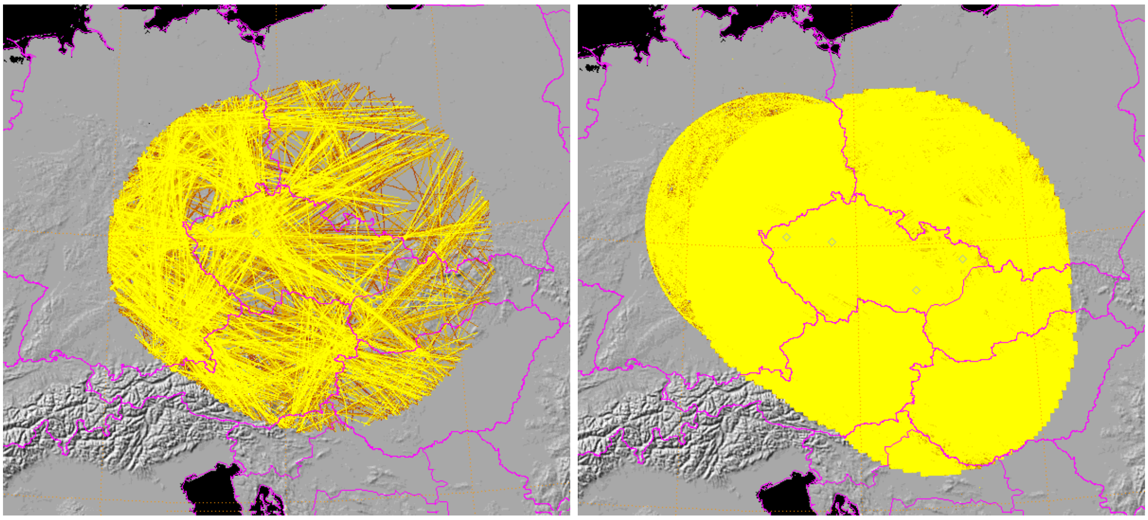

Figure 1: (left) Mode-S MRAR and (right) Mode-S EHS coverage in 24 hours (from Jan Kráčmar and Jiří Frei, ANS CZ). Note the much higher density and slightly larger extent of Mode-S EHS.

(D) and Bratislava (SK). The horizontal coverage is shown in Fig. 1. There are around 3.5 million Mode-S EHS and around 140 thousand Mode-S MRAR observations per day. The time period used for analysis is 12 June - 9 July 2015.

2.2 ICAO aircraft addresses

Within Mode-S, ICAO address is provided as an unique aircraft identification. It is assigned by flight authorities in each country. Consequently, no centralized public database is publicly available. It is possible to relate ICAO address with aircraft information by online resources (e.g. various live flight tracking or plane spotter websites). Another possibility is to retrieve aircraft information from flight plans available at ATC. We used a combination of both to identify as many ICAO addresses as possible (more than 8000 of around 9000 different aircraft). Figure 2 shows the distribution of Mode-S EHS by aircraft type (without detailed subtypes). It can be noted that most frequent type is Boeing 737 followed by Airbus 320,319 and 321. The most frequent aircraft reporting Mode-S MRAR is Canadair Regional Jet (CRJ).

2.3 Flight profiles

The easiest way to observe properties of Mode-S data sets is by plotting profiles of measured variables during the flight. Figure 3 shows an ascent and a descent of a CRJ aircraft which provides both Mode-S EHS and Mode-S MRAR observations. For wind, a good agreement between Mode-S EHS and MRAR can be seen, although there is a small systematic difference (smaller wind speeds in EHS observations). MRAR wind time series seems to be slightly more smooth, but oscillations of about 1-2 m/s can be observed both types. In the case of temperature (right part of Fig. 3), EHS is much more noisy and oscillates around MRAR values.

Another example of temperature profile demonstrates sensitivity of EHS temperatures on ground speed (which is an input in EHS calculations, Fig. 4). Figure shows MRAR

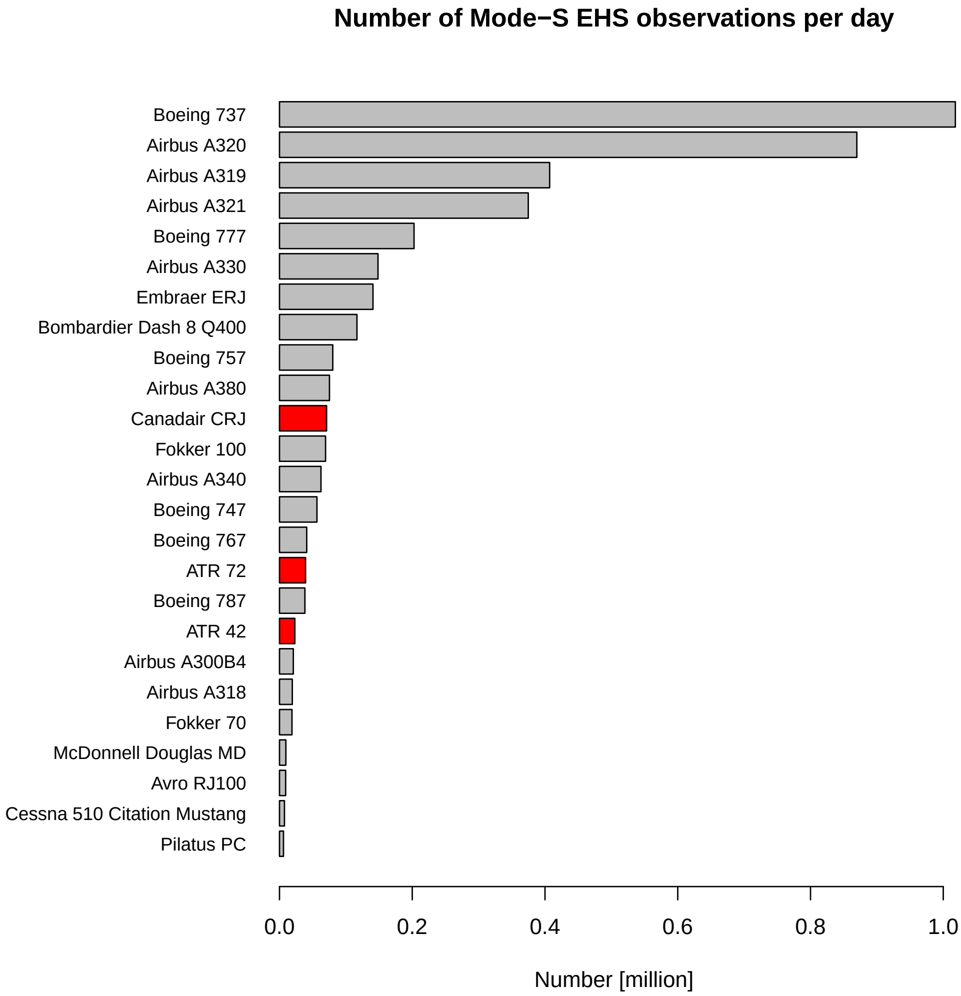

Figure 2: Number of Mode-S EHS observations from different aircraft types (only the 25 most frequent are shown). The aircraft which also provide MRAR are plotted in red.

temperature profile in blue and EHS temperatures in green. The oscillations of EHS temperature in this case are large (5-10 K). There are also some unphysical values which are related to errors in ground speed values (red line). The ground speed is constantly decreasing over time but there are a few zero values in the time series, causing unrealistic temperature calculation. A filtering would be needed to remove such ground speeds from the data set. A time smoothing is also suggested to suppress oscillations in EHS temperature (as already done by de Haan (2011)). EHS temperature calculation may especially be problematic at low ground and air speeds.

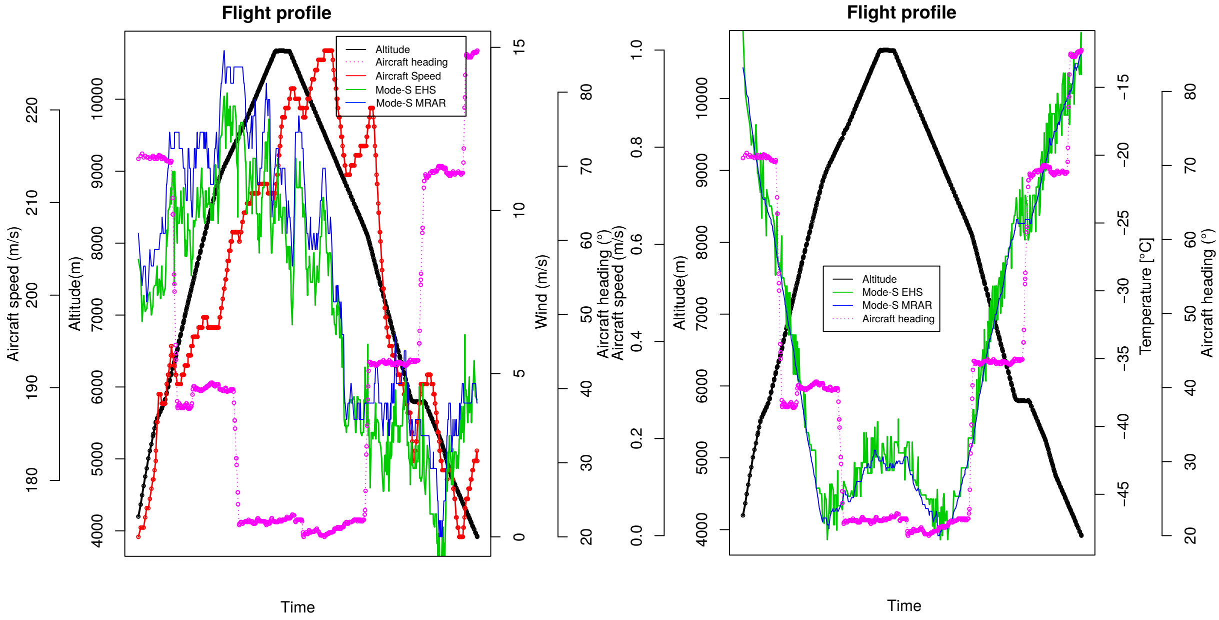

Figure 3: Evolution of (left) wind and (right) temperature (and other parameters) during ascent and descent. Mode-S EHS is shown in green, Mode-S MRAR in blue.

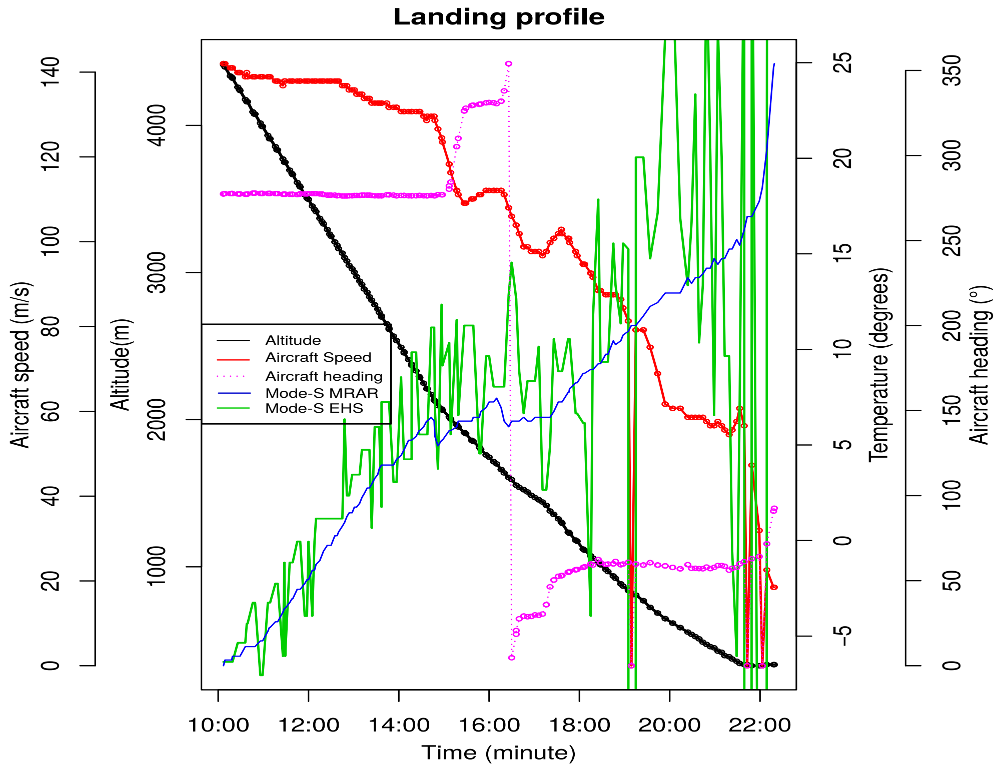

Figure 4: Evolution of EHS and MRAR temperatures and other reported parameters during descent. Aircraft is ATR 42, Czech Airlines.

3 Colocation of AMDAR, Mode-S EHS and Mode-S MRAR

To validate Mode-S observations other meteorological observations which are close in space and time are needed. An ideal observational reference for Mode-S is AMDAR

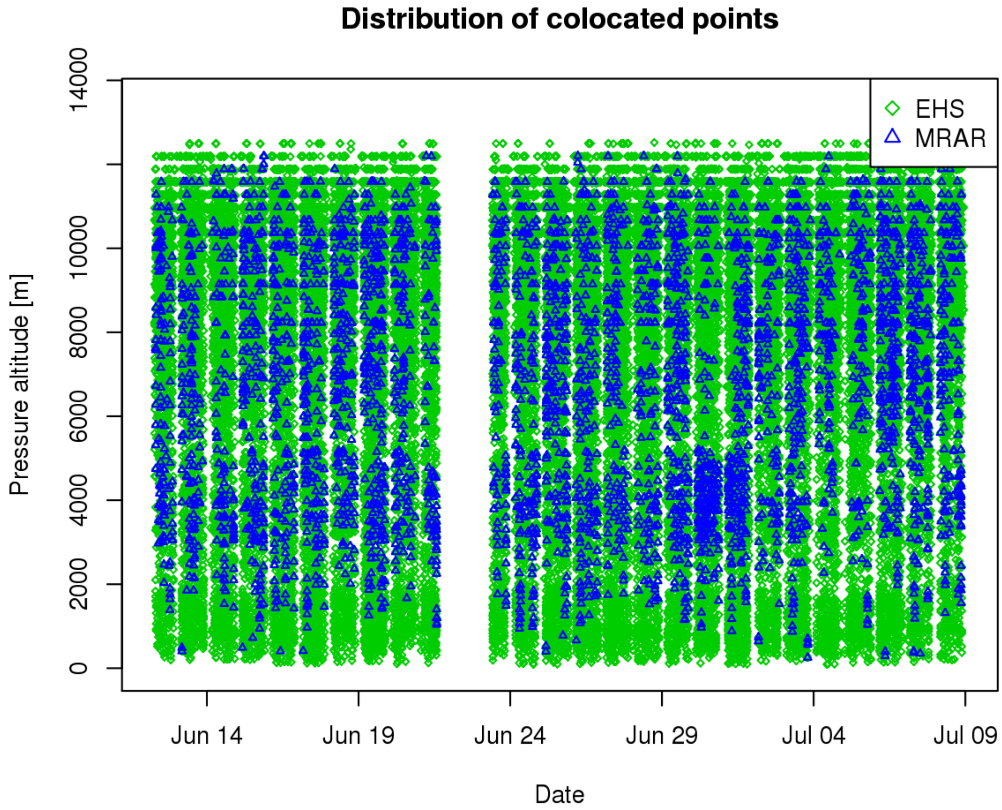

Figure 5: Vertical and temporal distribution of colocated points.

which is available on several types of aircraft. Although AMDAR and Mode-S observations originate from the same sensors, they differ due to the preprocessing or simply the reporting frequency and temporal averaging. Such a comparison can not highlight possible systematic instrumental errors affecting both observation sources.

To find Mode-S EHS/MRAR and AMDAR observation pairs (colocated observations) we allowed a time mismatch of 30 s, maximal height difference of 50 m and 10 km horizontal separation. Such a tolerance is essential because AMDAR reports are not available so frequently as Mode-S. Due to preprocessing (e.g. smoothing or averaging) the exact time and space of the AMDAR measurement does not fully agree with flight data from Mode-S. If more possible pairs are found within these criteria the closest in space is selected. Figure 6 shows time and space distribution of colocated observation pairs. There were around 73200 EHS - AMDAR pairs and around 4850 MRAR - AMDAR pairs, slightly depending on the variable.

3.1 General difference statistics

A general comparison between AMDAR and Mode-S is shown in Fig. 7. The difference between Mode-S and AMDAR are mostly normally distributed. The spread of differences against EHS is much larger than the spread against MRAR, both for wind and temperatures. The wind difference distribution even shows a two peak distribution. To verify this result, the statistics are shown against the subset of MRAR observations (around

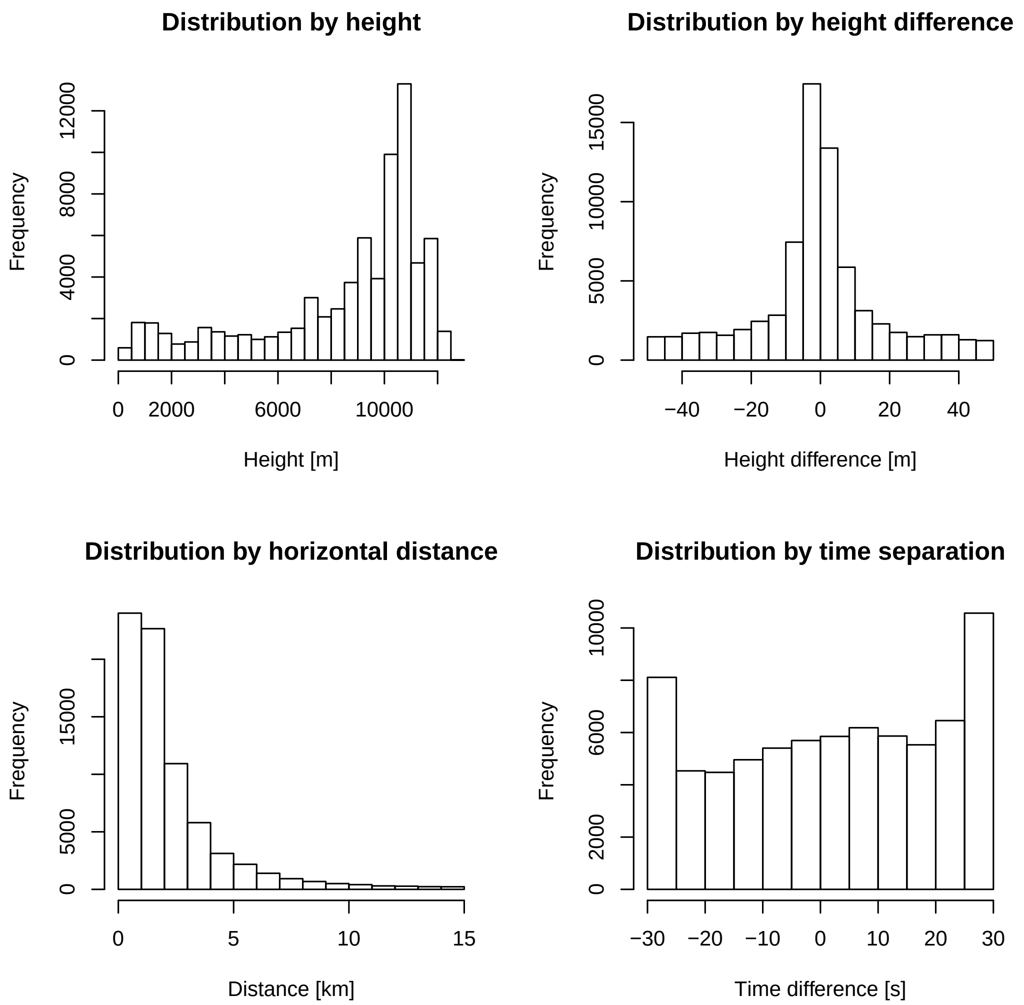

Figure 6: Distribution of Mode-S EHS/MRAR - AMDAR matches by (a) height, and (b) vertical, (c) horizontal and (d) time separation.

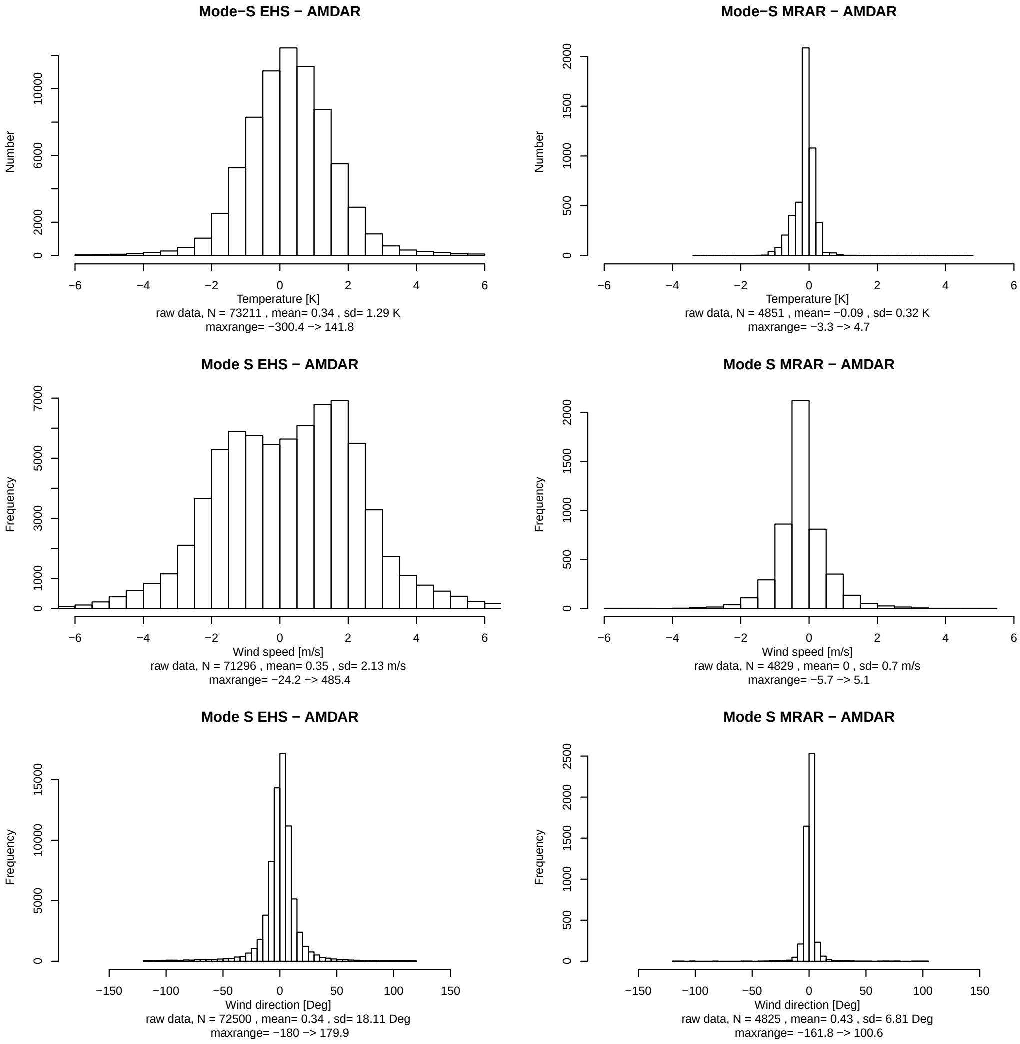

Figure 7: Histograms of (left) Mode-S EHS and (right) Mode-S MRAR - AMDAR differences. Shown are (top) temperature , (middle) wind speed and (bottom) wind direction. To compute histograms, only the displayed value range is shown and extreme values are indicated below the plots.

4850 cases, 8). Here, the calculation is made for the same aircraft reporting both kinds of observations. While most of the distributions do not change, wind speed for EHS seems to become somewhat biased. This may be linked to the type of the aircraft (in this case mostly CRJ as explained later) and the errors in either ground or air speed or magnetic heading.

3.2 Type dependent statistics

The colocated observations stem from different aircraft types. Figure 9 presents the distribution of collocated data set between different aircraft types. It can be observed that colocated Mode-S EHS observations come mostly from Airbus A319, A320 and A321, and that Mode-S MRAR comes from CRJ aircraft. It is important to keep in mind that the colocation result will be limited only to these aircraft types.

In Figs. 10,11,12 the differences are shown separately for aircraft types. Because the

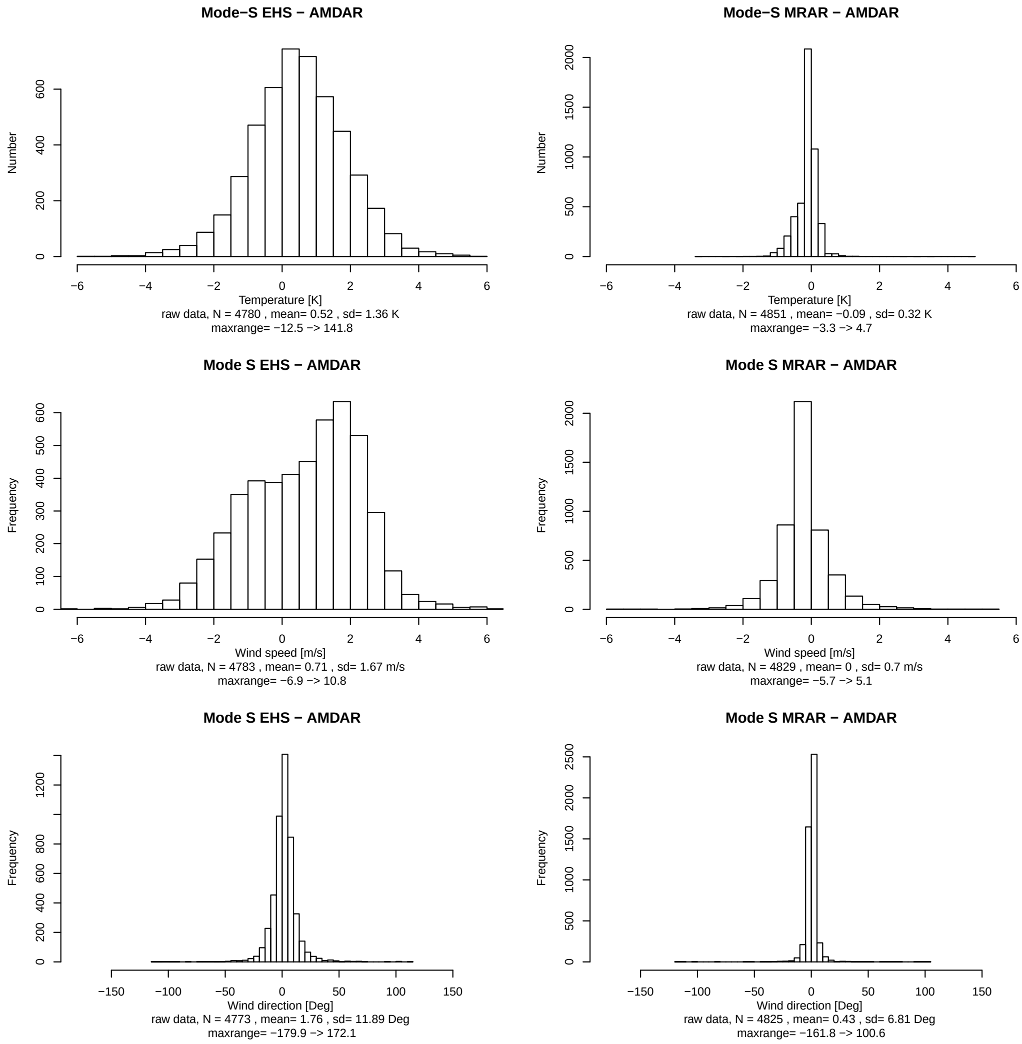

Figure 8: Same as Fig. 7 except that Mode-S EHS comparison is only displayed for the subset where MRAR is also available.

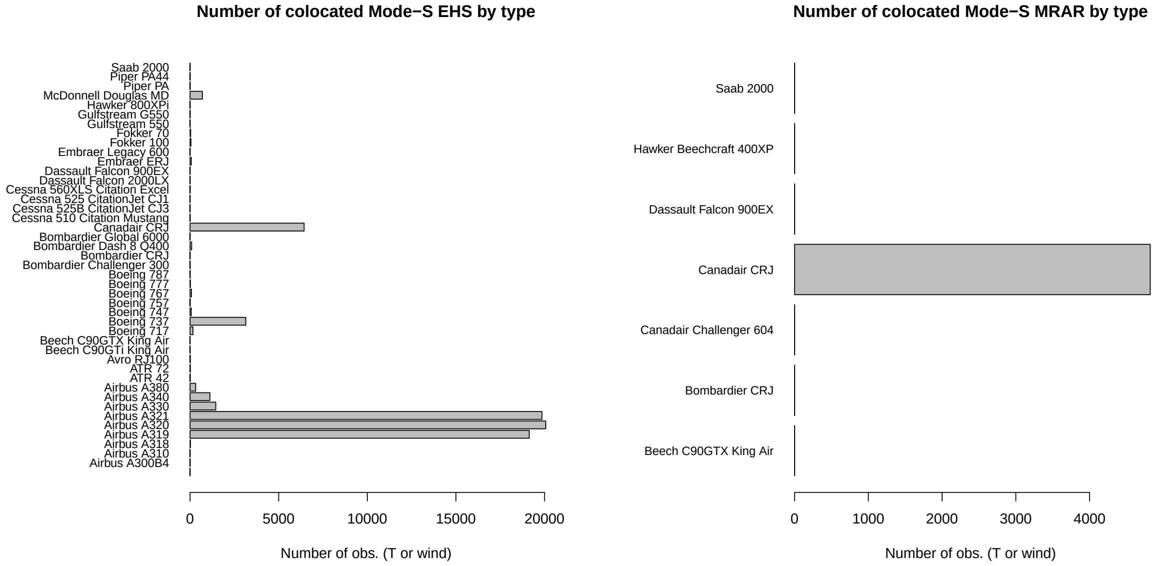

Figure 9: Number of (left) Mode-S EHS and (right) Mode-S MRAR by aircraft type.

MRAR colocated set is dominated only by CRJ, these plots are shown only for Mode-S EHS. The interpretation should be limited to the above mentioned Airbus types and CRJ because the other types are rarely colocated with AMDAR over the region. A large temperature error standard deviations of around 10 K can be seen for A319-A321 while their biases are reasonable but positive. A large warm bias appears for A318. In the case of wind speed, the errors of A319 seem to be larger that for the other Airbuses and they also include significant biases.

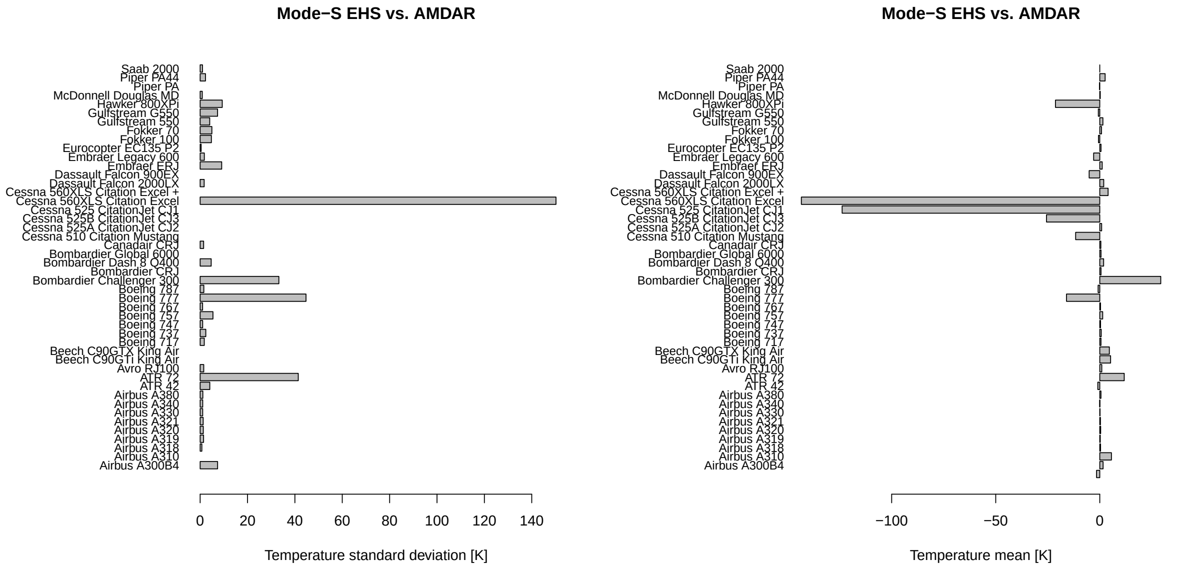

Figure 10: (left) Standard deviation and (right) mean temperature difference between Mode-S EHS and AMDAR by aircraft type.

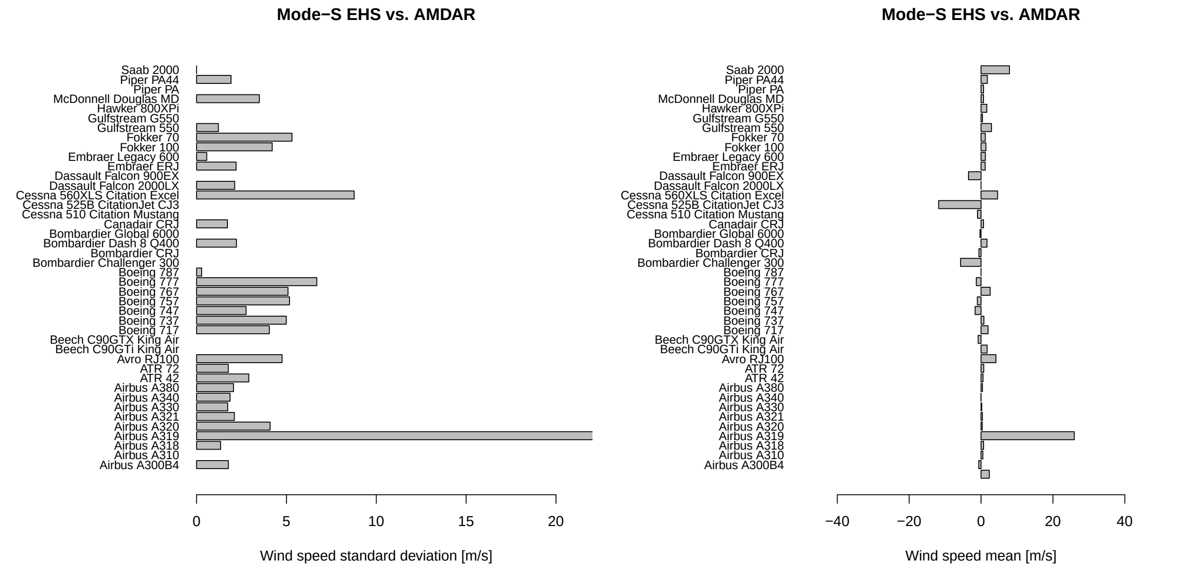

Figure 11: (left) Standard deviation and (right) mean wind speed difference between Mode-S MRAR and AMDAR by aircraft type.

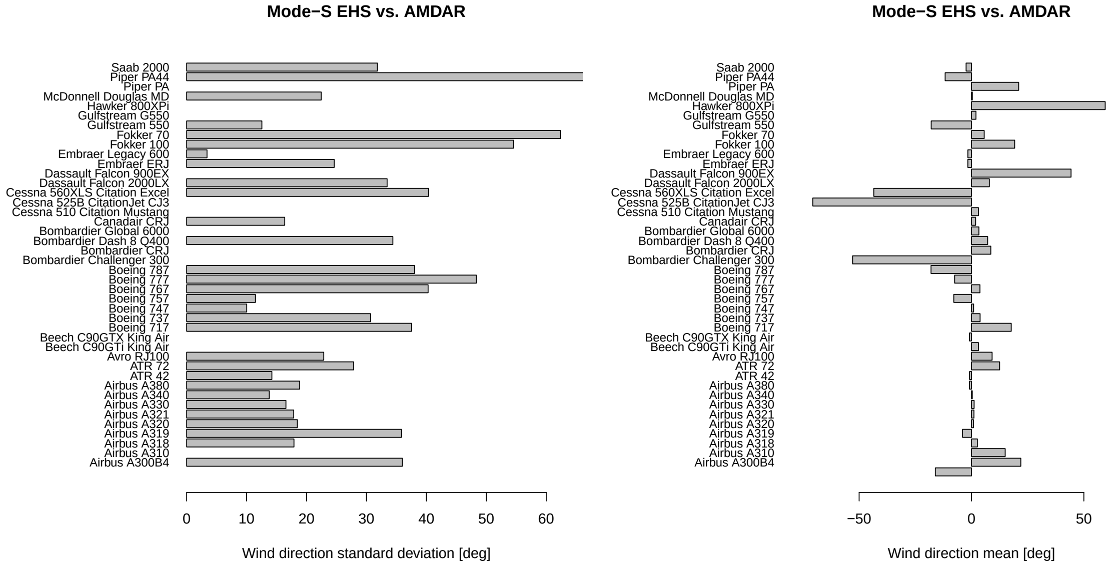

Figure 12: (left) Standard deviation and (right) mean wind direction difference between Mode-S MRAR and AMDAR by aircraft type.

Table 1: Thresholds used to generate white list of aircraft reporting Mode-S MRAR.

variable	number of observations	mean	std.
temperature (K)	3000	< 1 K	< 2 K
wind speed (m/s)	3000	< 1 m/s	< 5 m/s
wind direction (deg)	3000	$< 10°$	$< 100°$

4 Validation against NWP

The comparison against AMDAR offers a good observations reference to Mode-S data but is limited to AMDAR-equipped aircraft. An evaluation of data from all aircraft is possible only by comparison against NWP model. This allows sufficiently large samples for each single aircraft and therefore a reliable error estimates. However, such a comparison is limited by forecast and model errors. In this study we used ALADIN/CZ forecasts of various lengths, depending on the hour of day. As ALADIN/CZ performs an analysis every 6 hours, we used forecasts of lengths 6-11 hours. Analysis was avoided because AMDAR observations are also used, which may in some cases prevent fair comparison. We assume that the method is robust with respect to slight decrease of the quality of forecasts with range. To find the model counterpart of each Mode-S observation we used screening configuration of the ALADIN model (e002) and saved obs-minus-guess departures stored in the observational database (ODB).

The analysis was first performed for Mode-S MRAR. Partly following Strajnar et al. (2015), criteria were defined to regard measurements from an aircraft as of a good quality (Table 1). Because wind speed and direction are measured separately by measuring air speed and heading, criteria with respect to those wind variables were preferred over u and v wind components. To achieve this, the wind departures were first recalculated from observations and u and v component differences which are output of screening.

Figure 13 shows difference statistics computed from aircraft on the white list, distributed by type. For example, the turboprop ATR aircraft (often flying in the Czech airspace and reporting MRAR) are not of sufficient quality and thus not displayed. The final white list includes 127 aircraft addresses for temperatures and 116 addresses for wind.

The same procedure can also be applied to Mode-S EHS. The aggregation of the statistics takes longer because the data set is large ($>$ 30 GB of data). For temperature, 2036 out of 7278 aircraft pass the criteria defined in Table 1. For wind, the white lists was not yet computed because the model departures are so far only defined for u v components. Figure 14 shows the number of observations per observation type for wind and temperature and Fig. 15 displays the distributions of Mode-S EHS - ALADIN differences computed separately for each aircraft (wind is shown only as u components) within thresholds defined in Table 1. This suggests that for a large part of aircraft the quality of Mode-S EHS is also potentially acceptable. To create a white list of Mode-S EHS observations to be used in data assimilation experiments, the Mode-S - ALADIN differences should be recomputed in the form of wind speed and direction, like in the case of Mode-S MRAR.

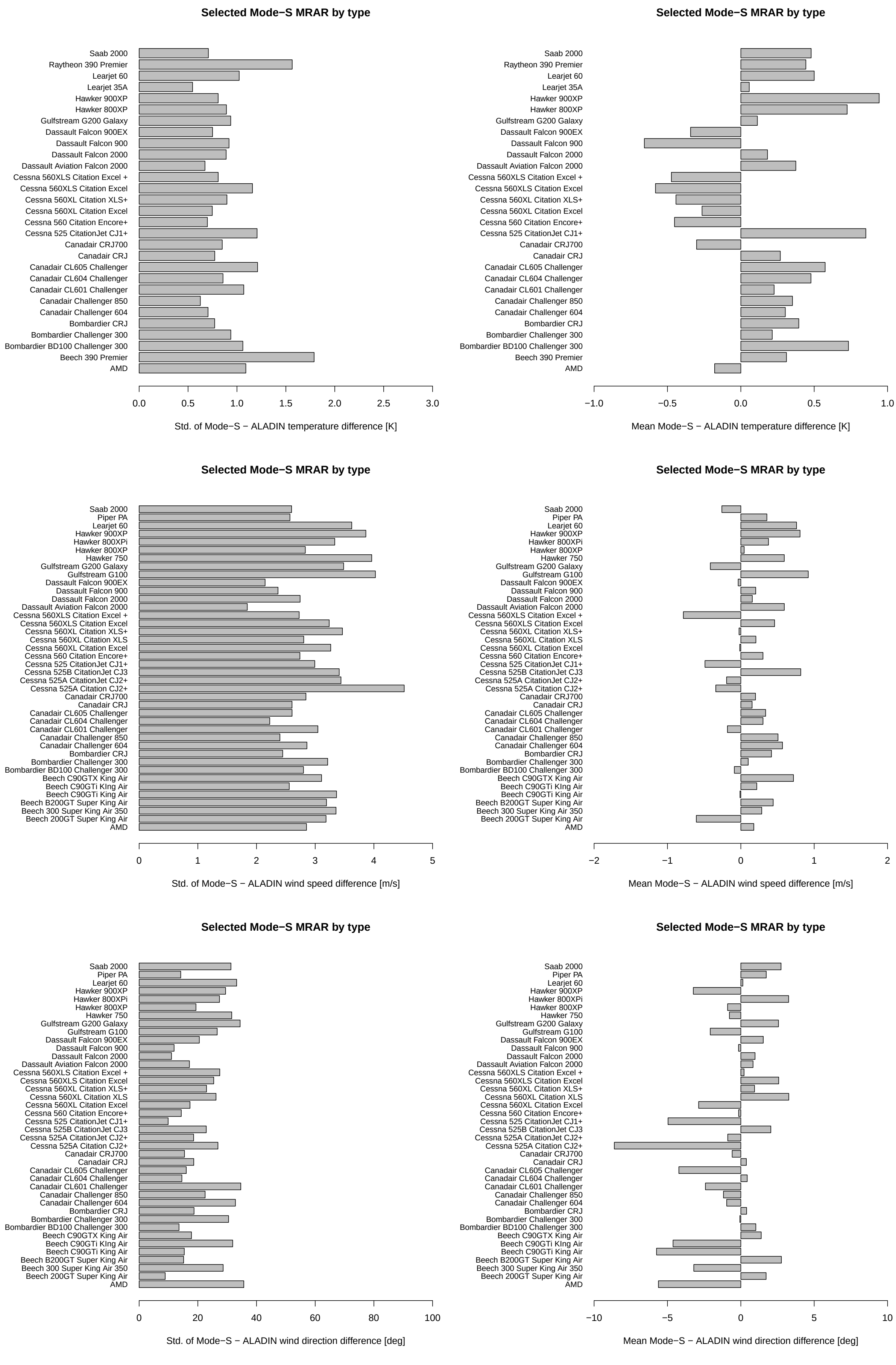

Figure 13: (left) Standard deviation and (right) mean difference between Mode-S MRAR and ALADIN forecast by aircraft type for (top) temperature, (middle) wind speed and (bottom) wind direction.

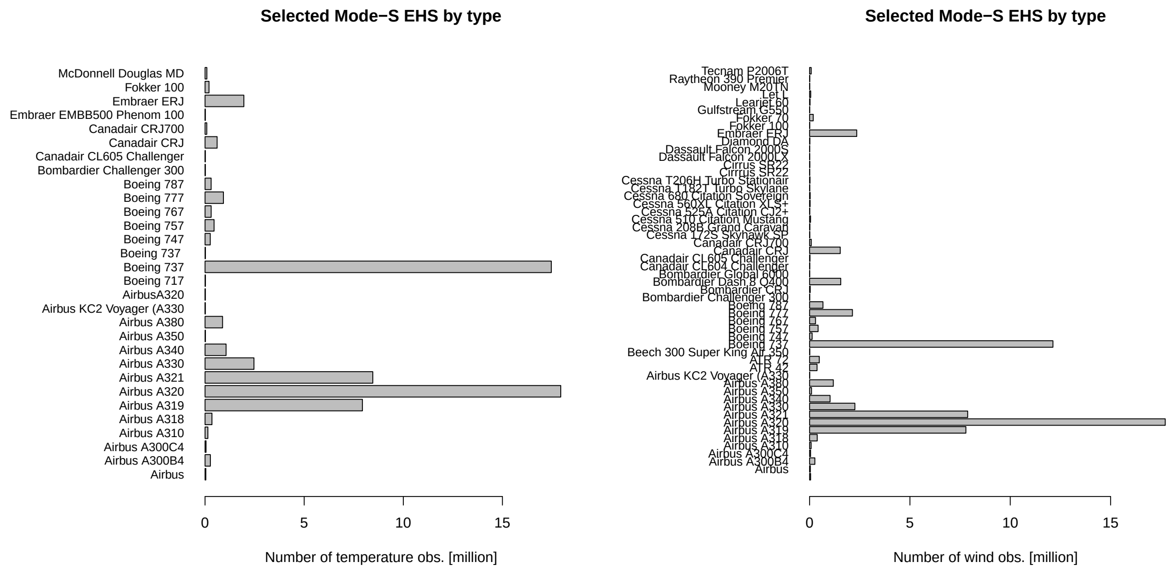

Figure 14: (left) Number of Mode-S EHS (left) temperature and (right) wind observations by aircraft type.

5 Conclusions and outlook

In this preliminary evaluation of Mode-S data available over the Czech airspace and surroundings, we demonstrated the observation quality with respect to AMDAR observations and ALADIN NWP model, separately for each reporting aircraft or aircraft type. The difference in availability and quality between Mode-S MRAR and Mode-S EHS was also demonstrated. While Mode-S MRAR observations are of overall good quality even without preprocessing, they can be used for meteorological applications including data assimilation just after the basic data selection based on statistics of differences with respect to ALADIN model.

In the case of Mode-S EHS a larger variability in the data and their errors was observed, and these could be further improved by smoothing the data or applying corrections to temperature wind speed and wind direction, as done at KNMI (de Haan, 2013). It appears that Mode-S EHS generally include a slight warm bias. The possible future steps include:

- checking for unrealistic air speeds resulting in unphysical temperatures in some cases (see Fig. 4)
- temporal smoothing of variables which appear in EHS temperature calculation (Mach number, air speed) and recomputing EHS temperatures, investigating the effect on warm bias
- computation of magnetic heading correction separately for each aircraft and recomputation of EHS wind observations, optional temporal smoothing (currently not performed at KNMI)
- repeated colocation with AMDAR and evaluation of impact of such corrections

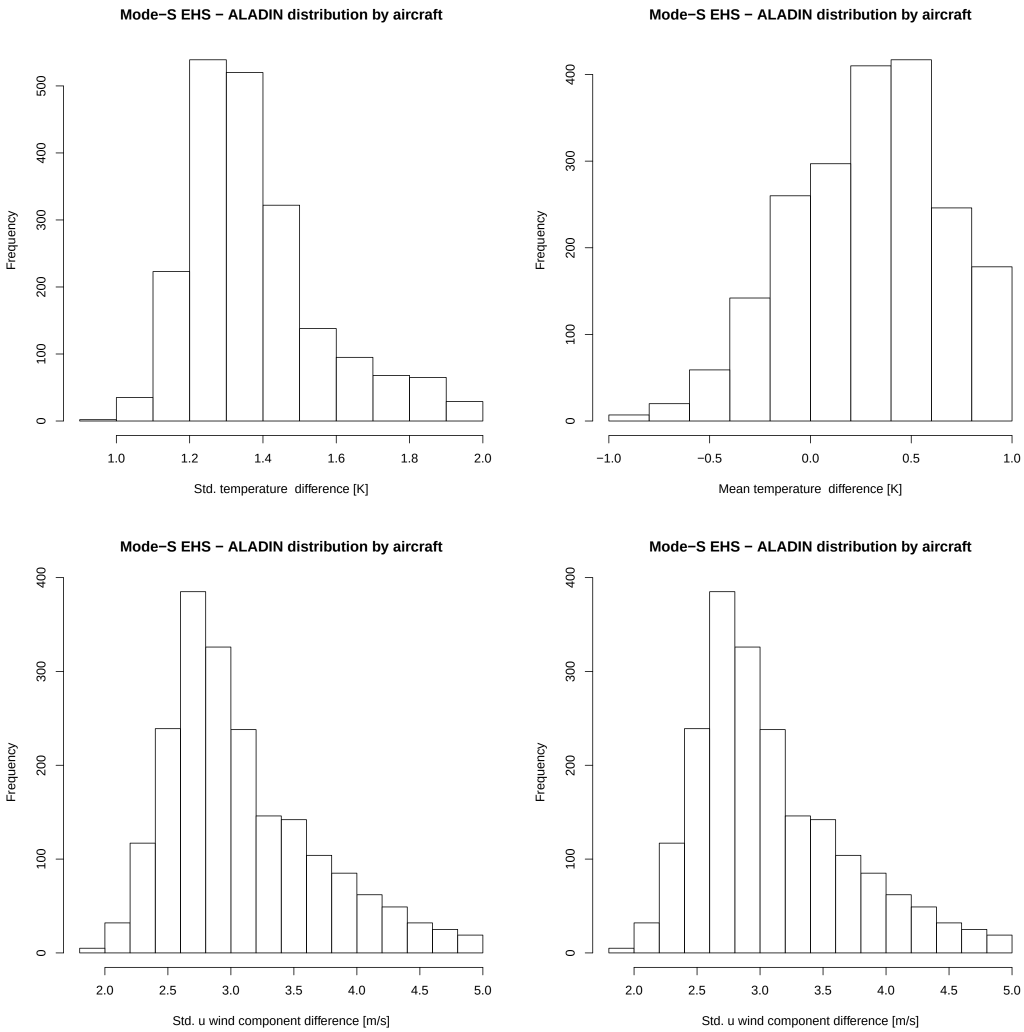

Figure 15: Distributions of (left) standard deviation and (right) mean Mode-S EHS - ALADIN differences computed separately for each aircraft. Shown are (top) temperature and (bottom) u wind component.

- repeated comparison against ALADIN model, recalculation of wind speed and direction difference from wind components and data selection based on thresholds used in Table 1 to generate a white list for EHS observations.

The data assimilation experiments should be carried out first with Mode-S MRAR and then Mode-S EHS. Recent studies suggested that improvements in the first few hours of forecasts can be expected (de Haan and Stoffelen, 2012; Strajnar et al., 2015). As the quality of EHS temperatures were shown to be less than the quality of wind and if this does not improve significantly with further correction it may be reasonable to assimilate EHS winds only on top of all Mode-S MRAR observations.

Acknowledgment

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6 References

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A Scripts and data sets

The following scripts and data sets were prepared on server *yaga*, user *mma*233. The data sets are archived on directory $\tilde{/}work/data/modes$ (Table A). Scripts are located under $\tilde{/}scripts/R$ and $\tilde{/}python$ and possible their sub directories (Table 3).

Table 2: List of data sets.

data set	description
colocated_AMDAR	csv files containing colocated AMDAR, EHS and MRAR observational data
screened_mrar_csv	csv files containing screened MRAR observations
screened_ehs_csv	csv files containing screened EHS observations
mrar_merged_1h	csv files with merged MRAR observations, ALADIN departures and aircraft details
ehs_merged_1h	csv files with merged EHS observations, ALADIN departures and aircraft details
ehs_merged_byICAO	csv files with merged EHS observations, separate file for each aircraft address

Table 3: List of R and python scripts.

script	purpose
profiles.R	plot flight profiles
compute_colocations.R	compute colocated AMDAR and Mode-S points, merge both information and outprint
analyse_amdar_colocation.R	compute and plot statistics from colocated data
analyse_amdar_colocation_by_type.R	compute and plot type-dependent statistics from colocated data
merge_ModeS_ehs_NWP.R	prepare merged data sets for EHS
merge_ModeS_mrar_NWP.R	prepare merged data sets for MRAR
create_whitelists_and_stats_mrar.R	prepare statistics and create white lists for MRAR
create_whitelists_and_stats_ehs.R	prepare statistics and create white lists for EHS (not fully completed)
create_stats_ehs_by_address.R	create files with NWP difference statistics separately for each aircraft address
superobs.R	create smoothed super observations for MRAR (not used in this work)
split_ehs_by_ICAOaddr.py	split EHS data by aircraft registration
create_screened_csv_ehs.py	creation of screened EHS
create_screened_csv_mrar.py	create of screened MRAR
ecma2modescsv.py	combine variables into one row for a single observation, called by the two above scripts