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AMDAR Temperature Bias

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Summary and purpose of document

This document presents a methodology on determining temperature biases using numerical weather prediction data. Additionally, a possible source of the bias is briefly investigated, by focusing on its relation to the Mach number.

ACTION PROPOSED

The Meeting is invited to read, comment and offer suggestions on information and recommendations presented.

References:

1. Ballish, B. A., and K. V. Kumar, 2008: Systematic Differences in Aircraft and Radiosonde Temperatures, BAMS, 89, 1689-1707
2. Benjamin, S. G., and B. E. Schwartz, and R. E. Cole, 1999: Accuracy of acars wind and temperature observations determined by collocation, WAF,14,1032-1038
3. Cardinali, C., and L. Rukhovets, and J. Tenenbaum, 2004: Jet Stream Analysis and Forecast Errors Using GADS Aircraft Observations in the DAO, ECMWF, and NCEP Models, MWR, 132, 764-779
4. Drue, C., and W. Frey, and A. Hoff, and Th. Hauf, 2007: Aircraft type-specific errors in AMDAR weather reports from commercial aircraft, QJRMS,134,229-239
5. Painting, J. D., 2003: WMO AMDAR reference manual, WMO-no.958
6. Final Report of “Workshop on Aircraft Observing System Data Management”, Geneva, Switzerland, 5 – 8 June 2012

Appendix:

A. Temperature correction using FOQA data and NWP
B. Temperature correction using Mode-S EHS and NWP

AMDAR Temperature Bias

Background

The error characteristics of AMDAR temperature observations have been examined in a number of studies. A warm bias has been reported by Ballish and Kumar (2008). Drüe et al. (2007) observed aircraft type dependent systematic temperature errors. In general, the standard deviation of AMDAR temperatures versus radiosonde temperature or AMDAR temperature observations very close to each other is around 0.6K (Benjamin et al., 1999). The formal error is slightly smaller, 0.4K (Painting, 2003). ECMWF has introduced an aircraft and flight phase dependent temperature correction (Cardinali et al. 2004). Specifically, the ECMWF assimilation results show much better fit of the analysis and forecast to both radiosonde and GPS radio-occultation data, but there was no significant impact on forecast skill.

Estimation of the temperature bias

Determining biases requires an estimation of the truth, or at least a good approximation. Radiosonde observations are generally regarded as the truth however these observations have also issues with biases. Another issue using radiosonde observations is that these observations are sparse and thus collocation in space and time will be hard. Model temperatures may overcome this issue, although using a model temperature as “truth” is not straightforward. The model temperature can be biased due to for example assimilation of “biased” observations. The quality of the model may also differ from areas with low number of observations to areas with dense observation. Nevertheless, using a model as a reference may reveal biases for different observing systems. The model output used should have a forecast lead-time of at least the assimilation cycle to avoid unfair comparison of observations used in the assimilation step. Furthermore, the model temperature should be interpolated to the location of the observation both in space and time. We therefore recommend the following when a model is used as a reference.

1. Use an operational global model (e.g. ECMWF)
2. Use forecast lead-time of at least the assimilation cycle
3. Space and time interpolation
    a. Perform a linear interpolation in time,
    b. Bilinear in horizontal space, and
    c. log linear in pressure
4. Use at most forecast increments of 3 hours, preferable 1 hour
5. Interpolate between forecast from the same analysis

Investigation of temperature bias using additional aircraft data

The measurement of the (static air) temperature depends on the reported Mach number (see Painting, 2003) and a so-called recovery factor and the measured total air temperature. As is shown in Appendix A, the board computer in an aircraft can store these parameters which imply that the dependence of the static air temperature on Mach number and total air temperature can be investigated (see Appendix A).

It is therefore recommended to investigate the possibility to obtain these parameters for a (large) number of flights from known AMDAR aircraft by contacting the airlines of these aircraft. Using a model temperature as a reference the recovery factor can be estimated. There is a mutual benefit for the meteorological community and the airlines to improve the air temperature measurement.

Investigation of temperature bias using collocation with air traffic control data

Measurements of Mach number can also obtained by collocation with Mode-S EHS. Appendix B gives an example of the E-AMDAR aircraft for which the tail-numbers are known, such that a unique match could be made. Using the Mach number and additionally model temperature as a reference, a temperature correction depending on the Mach number could be found for each aircraft individually.

It is thus recommended to share the tail-numbers of, preferably all, AMDAR aircraft such that a good indication of the dependence of temperature bias on the Mach number can be found.

Appendix A

Temperature correction using FOQA data

Bias corrections based on model comparison may result in good temperatures, however the cause of the bias will not be revealed. From (Painting,2003) we learn that corrections are applied to the measured temperature to estimate the static air temperature (T_0), the temperature of the free airstream. Following Painting (2003), the temperature (T_1) measured by the temperature probe is close to the theoretical value of Total Air Temperature that would occur with perfect adiabatic compression of the free airstream at the sensor probe. The correction of T_1 using Mach, γ=1.4 and recovery factor λ to estimate the static air temperature is,

$$T_0 = T_1/(1 + \lambda(\gamma -1)/2 \, Mach^2) \quad (1)$$

The value of λ is around 1, with Paining giving an example of λ=0.97. In the following we exploit methods to determine whether these corrections are correct.

Temperature corrections using reports of T_0, T_1, Mach and ECMWF

Since the measurement of temperature depends a correction using the Mach which includes a recovery factor, biases might be introduced. Investigation in this correction might reveal the origin of bias. The current onboard aircraft computer stores a lot of information during the flight for offline aircraft and flight performance evaluation. For example Flight operational quality assurance (FOQA) data can contain information on fuel consumption and other flight characteristics. This data set can also contain the T_0 and T_1. Royal Dutch Airline (KLM) made two FOQA flight information data sets available for research purposes, both containing T_0 and T_1. The flight tracks are shown below.

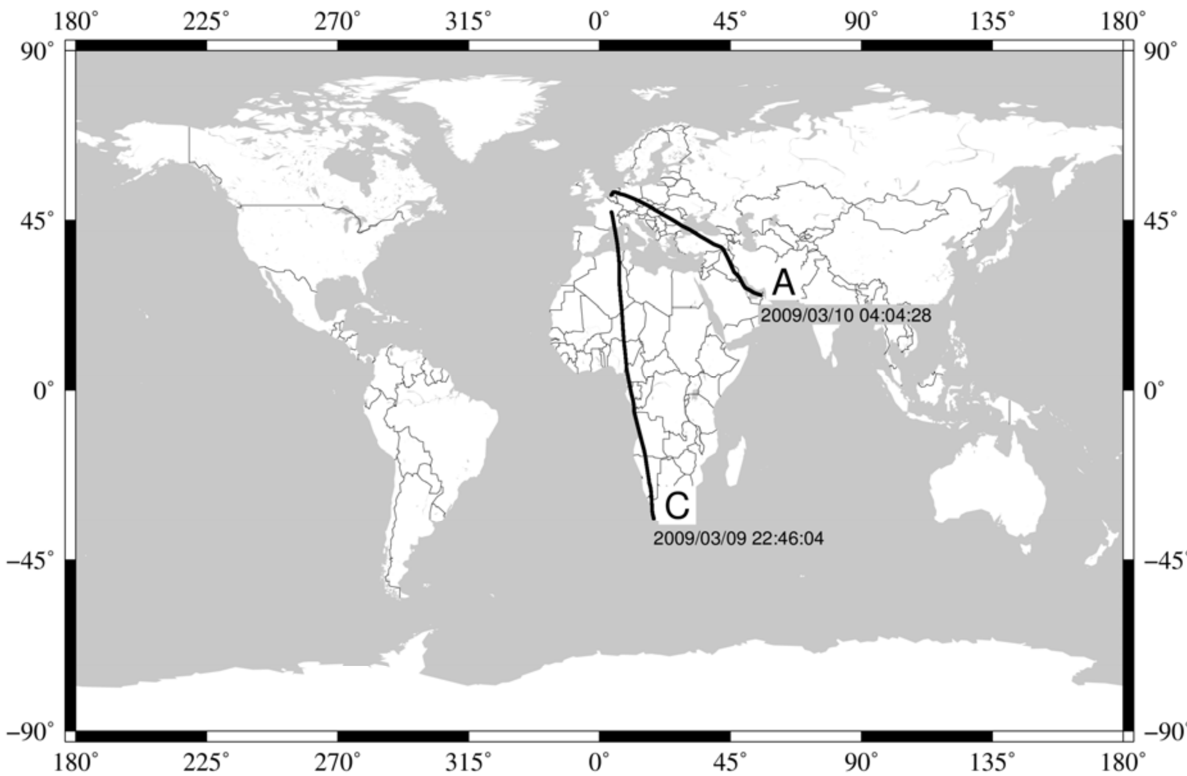

Figure 1 : Locations of FOQA data; both aircraft are landing at Amsterdam Airport Schiphol.

From this information the used recovery factor is deduced and, using auxiliary temperature information from the ECMWF model, an estimate of the recovery factor can be made assuming this auxiliary temperature is the truth. The figure below shows the factor λ as based on the FOQA data (blue dots) and ECMWF temperature (red dots). This factor is determined using the reported Mach number and T_1 together with the reported T_0 and ECMWF temperature, respectively using equation (1) and γ=1.4.

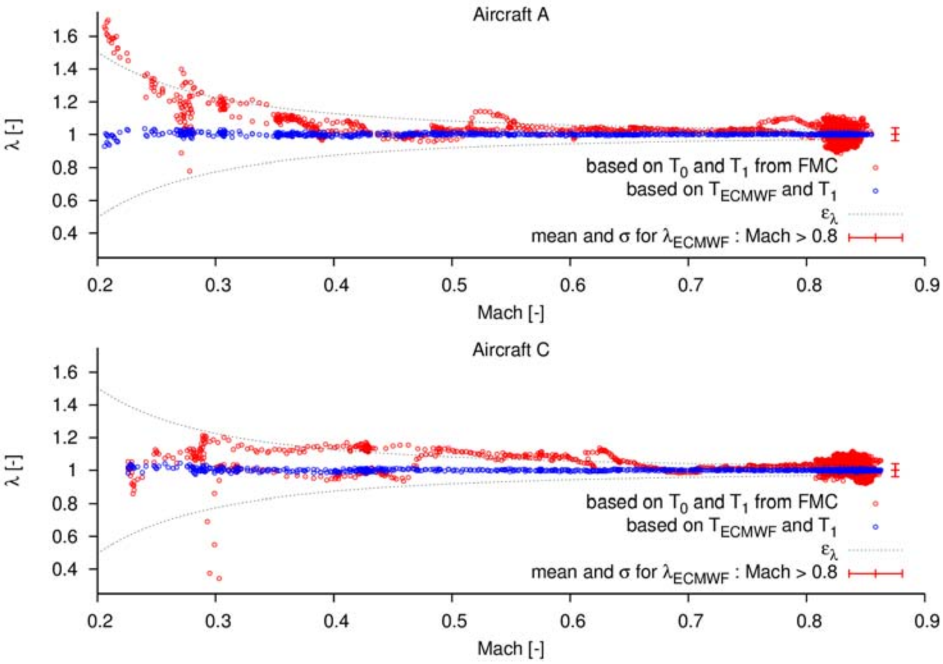

Figure 2 : Estimation of the recovery factor λ using FOQA data (blue dots) and a combination of FOQA and ECMWF (red dots).

The dashed lines in the above figure represent the estimate of error in determining λ based on an error ε in temperature (ε_T) and error in Mach (ε_M). This term is estimated using a Taylor expansion of $\lambda = 2/(\gamma -1)\,(T_1/T_0 - 1)/\mathrm{Mach}^2$ around λ_0=1, that is

$$\varepsilon_\lambda \approx d\lambda/dT_0\ \varepsilon_{T0} + d\lambda/dT_1\ \varepsilon_{T1} + d\lambda/d\mathrm{Mach}\ \varepsilon_M$$

$$\approx 2/(\gamma -1)/\mathrm{Mach}^2\ (\varepsilon_{T1}/T_0 - \varepsilon_{T0}\ T_1/T_0^2\ ) + \lambda_0\ \varepsilon_M/\mathrm{Mach}$$

$$\approx 2/(\gamma -1)/\mathrm{Mach}^2\ (2\varepsilon_T/T) + \varepsilon_M/\mathrm{Mach} \approx 0.02/\mathrm{Mach}^2 + 0.001/\mathrm{Mach},$$

where we used approximations for the temperature $T_0 \approx T_1 \approx T \approx 250$K, the temperature error $\varepsilon_{T0} \approx \varepsilon_{T1} \approx \varepsilon_T \approx 0.5$K and the Mach error $\varepsilon_M \approx 0.001$.

Although it is expected that the recovery factor is close or below 1, we see that for there are values with recovery factors larger than 1. The majority of the observations are at high Mach numbers (around Mach 0.85), while the low Mach numbers are from the ascending and descending flight phase. Clearly due to the temperature difference between the model and the measured (i.e. corrected T_1) temperature, the factor increases for decreasing Mach number for aircraft A. Note that both descending and ascending points are plotted. The value of the factor attains values of 1.5 at low Mach numbers. These values are still within the error margins, however may also related to issues with the recovery factor. For Aircraft C, the recovery factor based on ECMWF temperatures shows to have smaller deviation from the value 1.

Appendix B

Bias corrections using Mach number from Mode-S EHS observations and HIRLAM
Mode-S Enhanced Surveillance data is available in designated air space where the tracking and ranging air traffic surveillance radar is Mode-S EHS enabled. At present, this in Belgium, Dutch German and Slovenian air space the case. All air craft are actively interrogated by the TAR radar on which the aircraft responds with an unique ICAO 24-bit identifier, and amongst other the Mach-number.
Knowing the connection between AMDAR identifier and the ICAO identiefer collocations in space and time can be made using the following thresholds: distance between AMDAR and Mode-S EHS is smaller than 5 km; the height difference is smaller than 200m and observation time difference is less than130s. At present, matching AMDAR and ICAO identifiers was done for a subset of E-AMDAR aircraft.
NWP temperature from operational HIRLAM run was used as a reference, with minimal forecast time of 3 hours, hourly interpolated.
The plot below shows the fractional difference of AMDAR and HIRLAM temperatures with respect to the reported Mode-S EHS Mach number from the Belgium, German and Dutch ai space, over the period from 27 January 2014 to 10 February 2014, collocated. Some aircraft show to have a Mach number related signal. Others show no signal.

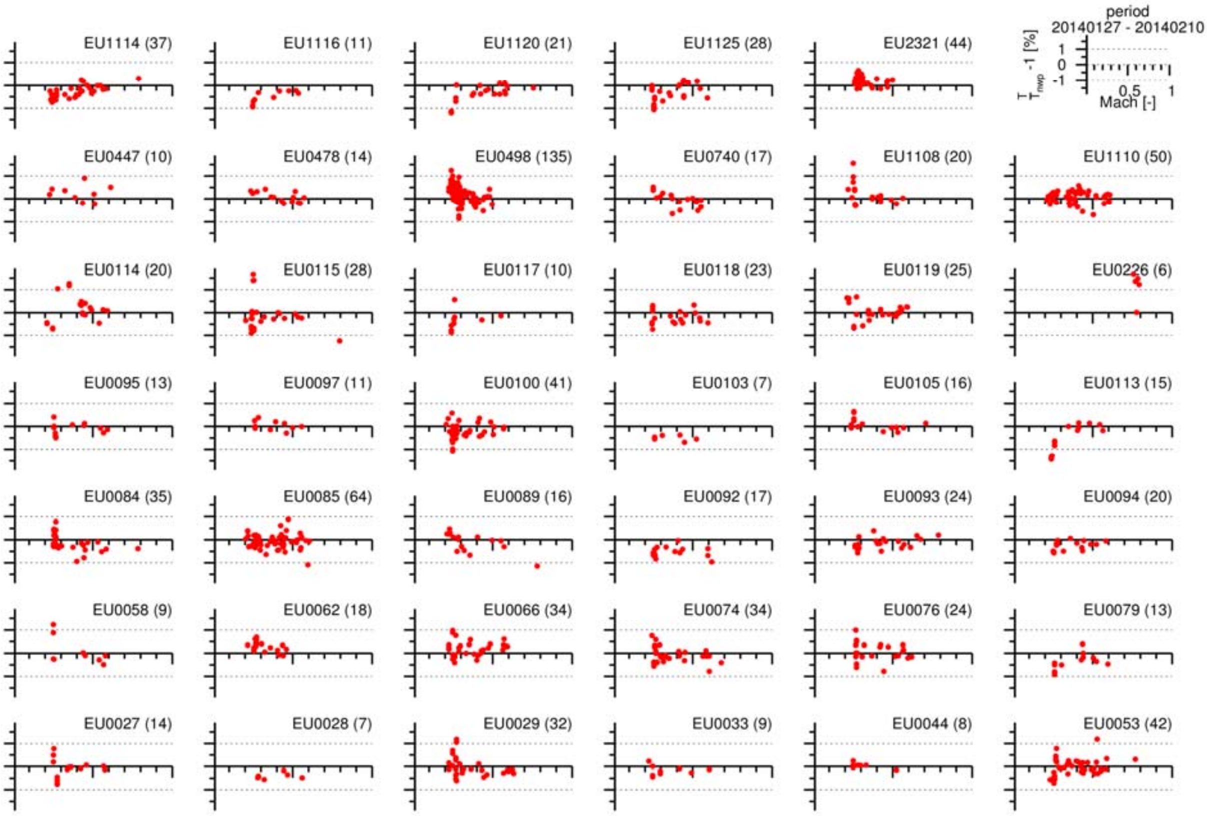

Figure 3 : Fractional difference (in percent) of observed AMDAR temperature and HIRLAM temperature with respect to the Mach number as reported by Mode-S EHS; number in brackets denotes the number of plotted data points.