Correction of Humidity Bias for Vaisala RS80-A Sondes during the AMMA 2006 Observing Period

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ABSTRACT

During the African Monsoon Multidisciplinary Analyses (AMMA) program, which included a special observing period that took place over West Africa in 2006, a major effort was devoted to monitor the atmosphere and its water cycle. The radiosonde network was upgraded and enhanced, and GPS receivers deployed. Among all sondes released in the atmosphere, a significant number were Vaisala RS80-A sondes, which revealed a significant dry bias relative to Vaisala RS92 (a maximum of 14% in the lower atmosphere, reaching 20% in the upper levels). This paper makes use of a simple but robust statistical approach to correct the bias. Comparisons against independent GPS data show that the bias is almost removed at night, whereas for daytime conditions, a weak dry bias (5%) still remains. The correction enhances CAPE by a factor of about 4 and, thus, becomes much more in line with expected values over the region.

1. Introduction

Dry biases encountered from Vaisala RS80 measurements made during the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) over the "warm pool" of the tropical western Pacific Ocean have been a major issue. They have a dramatic impact on operational numerical weather prediction (NWP) and on all research activities related to the water cycle. It took several years to produce an RS80 humidity "corrected" dataset useable by researchers (Wang et al. 2002), and the RS80 dry bias is still an issue in operational NWP.

The international African Monsoon Multidisciplinary Analyses (AMMA) program (Redelsperger et al. 2006) aims to improve our understanding of the West African monsoon and its variability, from daily to intraseasonal time scales. Since 2004, AMMA scientists have been working with operational agencies in Africa to reactivate silent radiosonde stations, to renovate unreliable stations, and to install new stations in West Africa (Parker et al. 2008), where 21 stations are now active. During the period June–September 2006, some 7000 soundings were made, representing the greatest density of radiosondes ever launched in the region—greater even than during the Global Atmospheric Research Programme (GARP) Atlantic Tropical Experiment (GATE) in 1974. To complete the experimental design, around 500 additional soundings were launched from three research vessels in the Gulf of Guinea and the east Atlantic, from aircraft and from driftsondes. Simultaneous to this upgrading, six AMMA ground-based global positioning system (GPS) stations were operating during the Special Observing Period (SOP), allowing two north–south transects (Bock et al. 2008).

The monitoring of the AMMA radiosonde network by NWP centers [the European Centre for Medium-Range Weather Forecasts (ECMWF) and Météo-France] and first comparisons of Integrated Water Vapor (IWV) derived from independent GPS data revealed (Bock et al. 2007) that many humidity radiosonde measurements were negatively biased (dry bias). This may be explained by the fact that a large number of the sondes released during the AMMA 2006 SOP were

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Vaisala RS80-A sondes, known to have significant dry bias. The bias magnitude depends on several factors (e.g., temperature, relative humidity, the sonde's age, etc.) and may reach up to 30% relative humidity in the low troposphere. The dry bias partly results from the contamination of the humidity sensor during its storage, from out-gassing of the packaging material, and increases with sonde age (Wang et al. 2002; Roy et al. 2004; Miloshevich et al. 2004). More recent sonde types (analog RS90 and digital RS92) do not suffer from this type of contamination-related bias problem. They are generally within 4% of a reference at night (Nash et al. 2005). Nevertheless, another dry bias source for daytime resulting from the solar heating of the humidity sensor has been described recently (Vomel et al. 2007; Yoneyama et al. 2008). Miloshevich et al. (2004) also identified a time-lag (TL) error (due to sensor slow response) and a temperature-dependence (TD) error (inaccuracy in the calibration method) mainly affecting humidity at very low temperature.

Documentation of the Vaisala RS80-A bias and various attempts to correct it can be found in the literature, but few address the continental tropical context, although the humidity field is a key parameter for the tropics. TOGA COARE was the first large field campaign in which RS80 humidity biases were extensively documented. Wang et al. (2002) proposed a bias correction algorithm valid for RS80-A and -H without the sensor boom cover introduced in 2000 for all RS80s; the dry bias was estimated to be 2% in the lower and midtroposphere, and reached 15% above 300 hPa. However, it should be noted that the approximately 8000 released RS80 sondes were almost brand new (manufactured 4 months before the first day of the experiment). Extensive documentation of the RS80 humidity bias and correction were proposed later using microwave radiometer validation in the framework of the Atmospheric Radiation Measurement (ARM) Program (Turner et al. 2003), but for midlatitudes.

This short review on the RS80-A humidity bias correction issue indicates that a general algorithm suitable for AMMA RS80-A sondes does not exist. Thus, the scope of this paper is twofold: first, we propose an original well-suited algorithm to correct on a statistical basis the RS80-A humidity bias with respect to the RS92 sondes (better quality) and, second, we evaluate the correction applied to RS80-A radiosondes against independent GPS collocated data. The AMMA observational network is presented in section 2. In section 3, the statistical correction approach is described. Section 4 is devoted to correction evaluation. In section 5, results are summarized and suggestions for future work are given.

2. AMMA 2006 RS and GPS networks

Various types of sondes have been used for AMMA: Vaisala (RS80-A and RS92) from Finland, Modem (M2K2) from France, and Graw (DFM-97) from Germany. Figure 1 presents the radiosonde locations over West Africa, together with the sonde-type information. Stations using Graw and Modem sondes launched only a single type of sondes. But for sites using Vaisala sondes, both types (RS80-A and RS92) were used in some cases. In that case, the strategy was to alternate periods of homogeneous observations performed with one sonde type, either RS80-A or RS92. The Niamey site was an exception, with a "staggered sampling" during the 2006 intensive observations periods IOP1 (20–30 June) and IOP2 (1–15 August). To monitor the water budget, eight soundings per day were performed during these periods at Cotonou, Parakou, Niamey, Agadez, Tamale, and Abuja (gray area on Fig. 1).

In Niamey the staggered sampling consisted of launching RS92 at synoptic hours (0000, 0600, 1200, 1800 UTC) and RS80-A at intermediate hours (0300, 0900, 1500, 2100 UTC); the RS92 sondes were manufactured in 2005 (1 yr old) and RS80-A between 2002 and 2005. IOP1 and the beginning of IOP2 in Niamey were characterized by fair weather conditions (except on 3 August); moderate to strong convection was observed in the second half of IOP2 (6–15 August 2006, with a maximum convective activity on 10 August 2006).

A total of seven GPS ground stations were collocated with radiosondes, offering unique comparison opportunities.

3. Bias correction

The usual approach for estimating sonde biases is comparing them with a reference measurement at the same location, but such coincident measurements were not available in AMMA. Here an alternative approach is proposed that takes advantage of the staggered sampling at Niamey over 25 days. Owing to the use of the hypothesis of homogeneity for encountered weather conditions over this period, the difference between humidity probability distribution functions (PDFs) of RS80-A and RS92, results only from the differential bias between the two measurements. The cumulative distribution function (CDF) matching method provides an easy way to compute this differential bias as the translation function between the CDFs. CDF matching is widely used in imagery preprocessing (Richards and Jia 1999) and has also been used in meteorology (Anagnostou et al. 1999; Reichle and Koster 2004). Here the

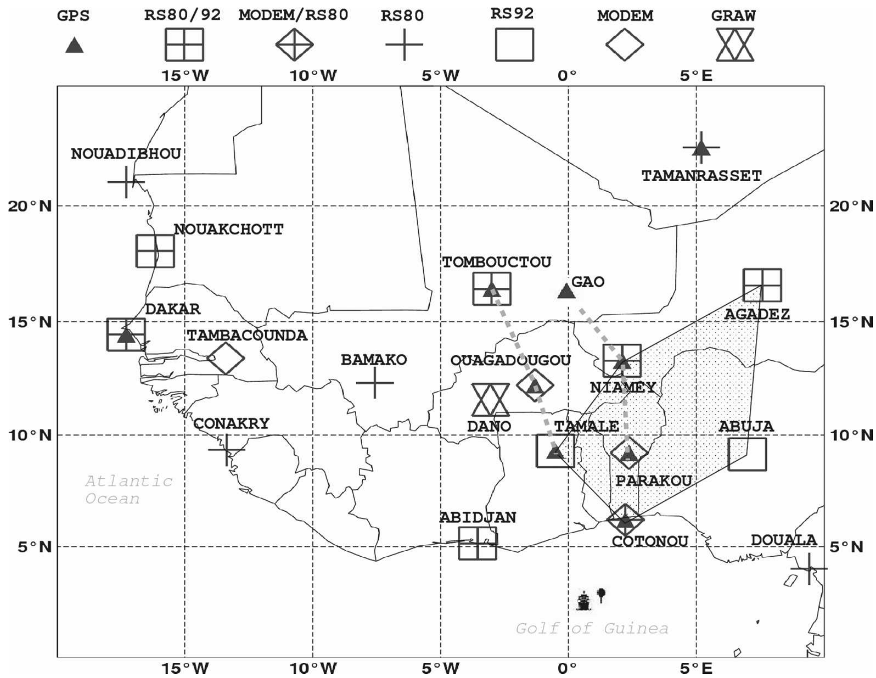

FIG. 1. AMMA RS stations and GPS networks over West Africa for SOP 2006. Shaded area corresponds to the stations performing eight launches per day during the IOPs. Dashed lines indicate the north–south GPS transects.

matching is performed between the RS92 and RS80-A CDFs. Computations are performed for 20°C-wide temperature layers between +40°C and –80°C, so that the differential bias is a function of both relative humidity RH (computed against water) and temperature *T*. Because sondes behave differently between day and night, the staggered sampling at Niamey is partitioned into four homogeneous datasets:

- RS80_D: 0900 and 1500 UTC launches (37 soundings) and
- RS92_D: 1200 and 1800 UTC launches (36 soundings) for daytime,
- RS80_N: 2100 and 0300 UTC launches (33 soundings) and
- RS92_N: 0000 and 0600 UTC launches (34 soundings) for night.

The CDF matching between the RS80_D and RS92_D datasets provides the RS80-A bias function relative to RS92 for daytime (similarly for night). Because raw radiosonde measurements at 1-Hz frequency are used, one sounding provides approximately 3000 humidity points. Due to the high vertical variability of humidity, statistics appeared representative. The resulting bias of the CDF matching is computed for each percentile of the CDF for each temperature layer, so that each bin (percentile) is built from the same number of data points for a given level (from about 500 points for a percentile in the +40°/+20°C layer up to about 2500 points in the –60°/−80°C layer). To build the correction table, the bias is linearly interpolated from the irregular grid onto a regular RH grid (10% interval) with 0% differential bias boundary conditions at RH = 0% and 100%. Each RS80-A humidity sounding data is then corrected using a bilinear interpolation from the four closest points of this correction table.

Figure 2 provides the structure of the RS80-A humidity bias relative to RS92 as computed with the CDF matching technique for the Niamey learning dataset (IOP12). Ninety percent of RS80-A humidity measurements are located between the two dashed lines, with no observation to the right. The RH (relative to liquid water) decreases below 0°C, as expected, with evidence of supersaturation relative to ice between 0° and –40°C. RS80-A soundings are almost always drier than those of RS92. At low levels the differential bias reaches maximums of 10% and 14% at day and night, respectively. At midlevel (between 0° and –40°C) the behavior is different for day and night, with weaker values for night (~8%) than for daytime (maximum of 12%). At upper levels, the bias is the largest (>20%). At midlevels the daytime differential bias maximum is not fully

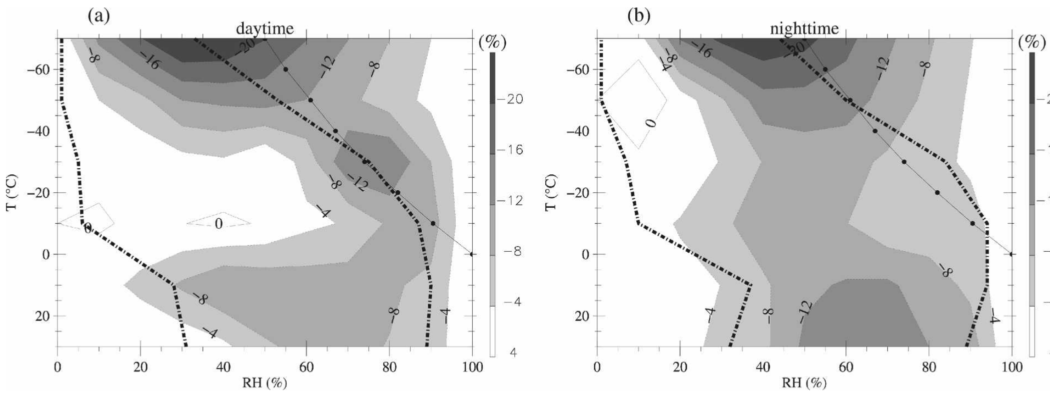

FIG. 2. Bias (shading) for (a) day and (b) night of the Vaisala RS80-A sondes relative to RS92 sondes at Niamey for the learning sample. The axes are temperature and relative humidity as observed by RS80-A sondes. Superposed dashed lines correspond to first and last percentiles (10% and 100% RS80-A CDF isolines, respectively). The thin line with dots represents the saturation line relative to ice.

understood. As it corresponds to moist conditions close to the saturation relative to the ice, it could be an artifact due to RS80-A icing within cloudy systems. Indeed, contrary to RS92, RS80-A sondes do not have a twin humidity probe alternatively heated to remove icing.

4. Bias correction evaluation

a. *Evaluation against the GPS independent dataset*

The bias correction procedure is now evaluated by comparing IWV computed from the radiosondes to the independent GPS measurements at Niamey for IOP1 and -2 (Fig. 3). The accuracy of GPS IWV estimates is about 1–2 kg m^{-2}, and the bias at individual sites is $<\pm 1$ kg m^{-2} (Bock et al. 2007).

Clearly, RS80-A strongly underestimated the IWV for the whole range of observed values (25–55 kg m^{-2}), with larger differences at daytime (-7.9 kg m^{-2}) than at night (-5.5 kg m^{-2}). RS92 quality is better (Table 1), with a low dry bias at daytime (-0.9 kg m^{-2}) and a weak moist bias at night (1.8 kg m^{-2}). The correlation slope for RS92 is slightly greater than 1. Both types of sonde have a similar correlation ($\sim$0.94) with IWV, except for RS80-A at night (0.91). Comparison of RS80-A IWV with GPS as a function of sonde age did not show a clear relationship.

The scatterplots after correction (RS80-A*) resemble those of RS92 (see Fig. 3 and Table 1). The correction drastically improves the bias, correlation, and slope (closer to 1). This independent comparison with GPS shows that the CDF matching performs well. It is not surprising that the RS80-A* is close to the RS92, because the test was performed with the same learning sample used to compute the differential bias.

We now check that this correction can be applied to other sites with different climatic conditions. The Timbuktu (17°N) and Dakar (15°N) sites are selected as collocated series of GPS and RS80-A soundings were available at each site for the period June–September 2006. In all cases, the magnitude of the bias is reduced (Table 1). For night it efficiently corrects the dry bias and even moistens a little too much, which is an RS92 characteristic. For daytime a weak dry bias (5%) remains after correction at Dakar and Niamey. It is worse at Timbuktu (bias after correction is close to 8%). Although efficient, this correction is only a first step. The next step will concern the correction of RS92 biases on the basis of previous studies. Table 1 indicates that the RS80-A* measurements are closer to GPS at night than at daytime. This is consistent with the fact that RS92 sondes are more accurate at nighttime, when they are not affected by the daytime radiative dry bias. Thus, the second step of the correction will concern this solar-elevation-dependent dry bias.

b. *Physical evaluation*

The impact of the humidity correction (e.g., Guichard et al. 2000; Cieselski et al. 2003) can be important on physical parameters derived from the soundings, such as the convective available potential energy (CAPE). Figure 4 presents the CAPE time series for IOP2. Without any correction the CAPE evolution (dashed line) exhibits a huge 6-h oscillation due to the dry bias of RS80-A compared to RS92 alternately launched. The correction procedure reduces the CAPE difference within the two datasets, allowing a better temporal consistency. Lower CAPE on 3 and 6 August

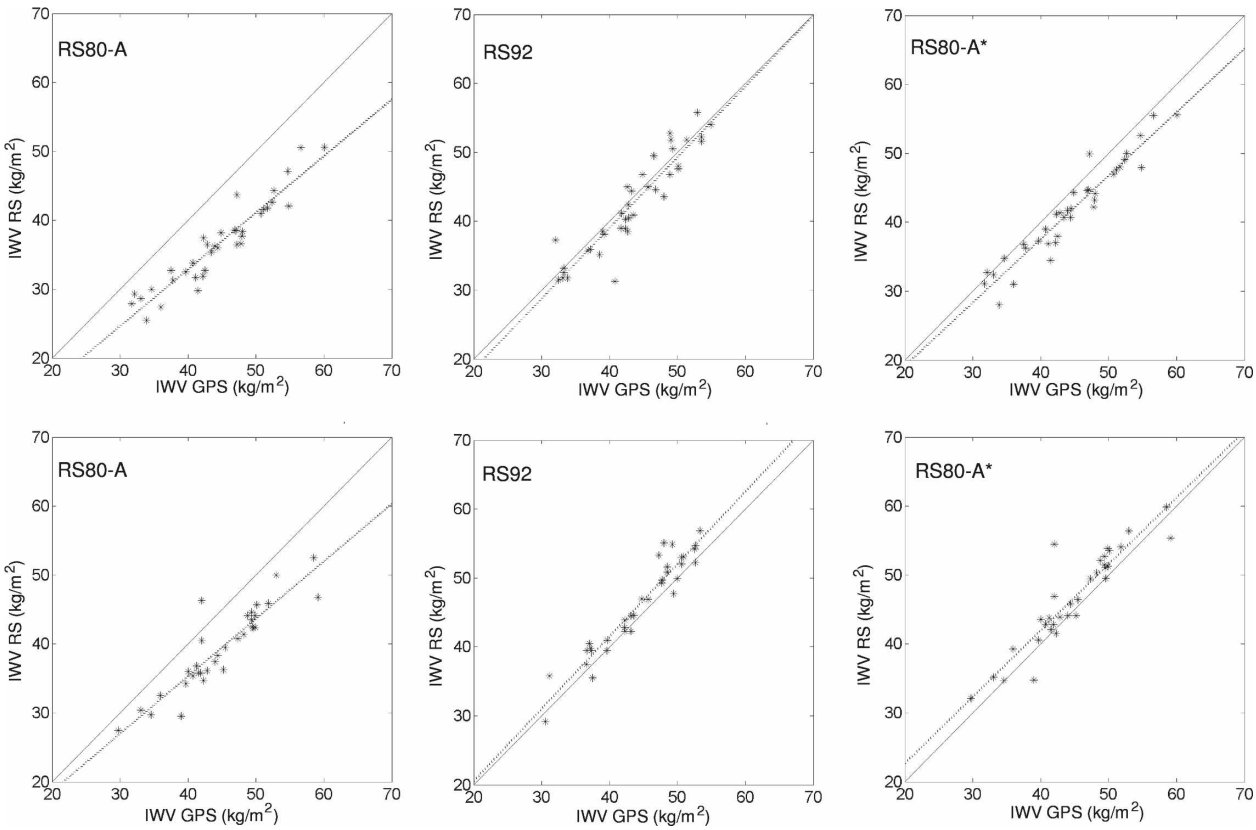

FIG. 3. Scatterplots of IWV from GPS against IWV from Vaisala sondes at Niamey for (top) day and (bottom) night: (left) RS80-A, (middle) RS92, and (right) RS80-A*.

2006 is linked to the passage of strong convective systems (not shown). On 7 August, when scattered convection occurs, corrected time series still oscillate, which suggests that the correction may be too weak for this day.

CAPE mean values analyzed at different locations confirm that the correction applied to RS80-A data dramatically increases their mean CAPE to more realistic values: 279–1241 J Kg^{-1} at Niamey, 270–737 J Kg^{-1} at Timbuktu, and 191–901 J Kg^{-1} at Dakar.

TABLE 1. Number of radiosoundings, IWV bias, rms, correlation, and slope relative to IWV GPS independent estimates for the various datasets (RS92, RS80-A uncorrected, RS80-A*corrected) and mean observed GPS IWV (kg m^{-2}) at three locations.

Location	Time	No.	Dataset	Bias	Rms	Correlation	Slope	Mean IWV
Niamey	Day	38	RS92	−0.9	2.7	0.93	1.03	43.4
		36	RS80-A	−7.9	2.1	0.94	0.82	44.5
			RS80-A*	−2.8	2.1	0.96	0.92	
	Night	34	RS92	1.8	2.1	0.95	1.05	44.4
		33	RS80-A	−5.5	2.8	0.91	0.83	44.8
			RS80-A*	1.8	2.7	0.92	0.96	
Timbuktu	Day	68	RS80-A	−8.2	2.4	0.93	1.06	40.6
			RS80-A*	-3.4	2.6	0.92	0.89	
	Night	42	RS80-A	−4.8	2.4	0.96	0.94	38.7
			RS80-A*	−1.6	2.4	0.96	0.78	
Dakar	Day	23	RS80-A	−5.9	2.1	0.94	0.84	35.2
			RS80-A*	−1.7	2.3	0.94	0.98	
	Night	31	RS80-A	−5.0	2.0	0.96	0.88	37.2
			RS80-A*	0.8	2.5	0.96	1.08	

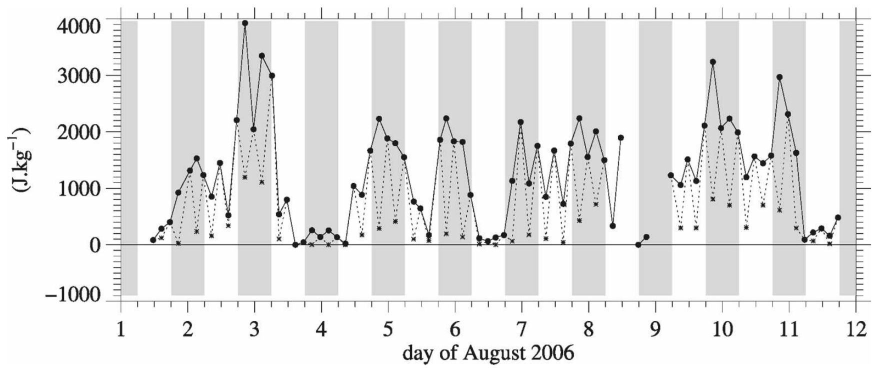

FIG. 4. Time evolution of CAPE at Niamey for IOP2. The solid line is for corrected data (staggered RS92 and RS80-A*), the dashed line for uncorrected data (staggered RS92 and RS80-A). The shading is for night, unshaded for day. Values are for a 40-m-thick layer pseudo-adiabatically lifted from 70 m AGL (only positively buoyant layers are considered).

5. Conclusions

A huge observational effort has been made during AMMA by upgrading the West African radiosonde network and increasing the launch frequency up to eight sondes per day during IOPs at specific sounding sites. Among the sondes launched during SOP 2006, it appears that many of the RS80-A sondes were old (up to 9 yr old) and affected by a large dry bias. A simple and robust statistical method is able to diagnose the bias relative to the RS92 thanks to the staggered radiosonde sampling at Niamey during the IOPs. Validation against independent GPS data and computation of CAPE show substantial improvement at night and, to a lesser extent, at daytime.

The final step will be to apply to the RS92 and "RS80-A corrected" data an RS92 correction along the lines of that proposed by Vomel et al. (2007) and Yoneyama et al. (2008). Investigation of the behavior of the other sondes (Modem, Graw) will be carried out. These further corrections are expected to be smaller than the large ones estimated for RS80-A.

The treatment of all AMMA radiosondes in order to remove the humidity bias is a key issue, prior to reanalysis and scientific exploitation of the AMMA observation periods. This is also a general issue, since such biases affect operational radiosondes as well, especially in the tropics, and may dramatically impact NWP skill and satellite calibration. The statistical approach proposed in this paper may be adapted to monitor and correct operational radiosonde data.

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