In Situ Validation of a Correction for Time-Lag and Bias Errors in Vaisala RS80-H Radiosonde Humidity Measurements

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Introduction

Radiosonde relative humidity (RH) measurements are fundamentally important to Atmospheric Radiation Measurement (ARM) Program goals because they are used in a wide variety of both operational and research applications, including initialization of numerical models and evaluation of model results, validation of remote-sensor water vapor retrievals, construction of water vapor climatologies and studies of climate trends, parameterization of cloud processes, and as input to radiative transfer calculations. A systematic dry bias in Vaisala radiosonde humidity measurements has been noted in comparison to Raman lidar measurements (Ferrare et al. 1995) and satellite water vapor retrievals (Soden and Lanzante 1996), and in underpredicting clouds and precipitation in a numerical weather prediction model (Lorenc et al. 1996). Direct observations of bias error in Vaisala radiosonde humidity measurements have also been reported: dual-radiosonde launches at the Oklahoma ARM site showed offsets between radiosondes from different calibration batches that measured the same air (Lesht 1998); unrealistically dry tropical boundary layers were frequently observed during the Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response (TOGA-COARE) experiment (Zipser and Johnson 1998); and humidities far below ice-saturation were measured in cirrus clouds when simultaneous measurements of detailed ice crystal characteristics indicated that the crystals were pristine and therefore actively growing in an ice-supersaturated environment (Miloshevich et al. 2001a).

Laboratory measurements conducted by Vaisala led to the development of corrections for two primary sources of bias error: (1) inaccurate calibration of the temperature-dependence of the sensors at cold temperatures; and (2) contamination of the sensor polymer by non-water molecules from the radiosonde packaging material in radiosondes produced before May 2000 (Wang et al. 2002). The temperature-dependence correction is proportional to the measured humidity, and increases with decreasing temperature below about -30°C. The contamination correction is a function of the measured humidity and the age of the radiosonde. These bias corrections have been included in a numerical correction algorithm for sensor time-lag error, which is caused by slow sensor response at cold temperatures (Miloshevich et al. 2001b, 2002). The time-lag correction is a numerical inversion algorithm that calculates the ambient ("true") humidity from the measured humidity and temperature profiles, based on Vaisala's measurements of the sensor time-constant as a function of temperature. The time-lag effect and its dependence on temperature are illustrated in Figure 1 for both RS80-H and RS90 radiosondes.

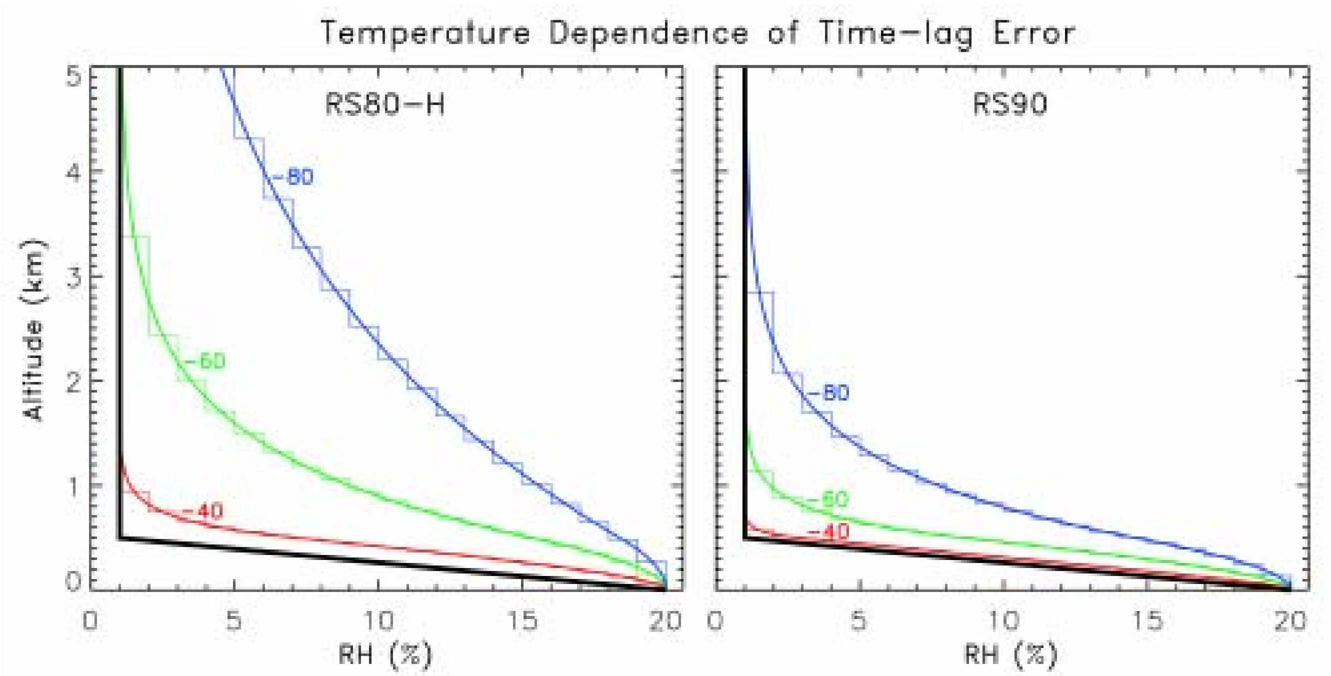

Figure 1. Simulated Vaisala RS80-H and RS90 humidity measurements (colored curves) for a prescribed linear decrease in the ambient ("true") humidity (black curve), at three constant temperatures. The altitude scale assumes a radiosonde ascent rate of 5 M s^{-1}. Stairstep curves show the simulated measurements if data are recorded with a resolution of 1% RH, as with ARM and other standard Vaisala data. The time-lag correction involves the inverse procedure of calculating the ambient humidity from any of the colored curves, after employing various numerical techniques to calculate a smooth and continuous, noise-free time series of measurements from the low-resolution data.

This study evaluates the time-lag/bias correction algorithm by comparing 40 RS80-H radiosonde soundings with simultaneous measurements from the relatively fast-response National Oceanic and Atmospheric (NOAA)/Climate Monitoring and Diagnostics Laboratory (CMDL) balloon-borne cryogenic hygrometer (Vömel et al. 1995). The fractional uncertainty in RH values calculated from the NOAA hygrometer frostpoint measurements increases with decreasing temperature from 0.06 at 0030°C to 0.10 at -70°C (Miloshevich et al. 2001a).

Validation of the Correction Algorithm

Four of the radiosonde/hygrometer comparisons that span the range of radiosonde ages from 0.2 to 6.7 years illustrate two general characteristics of the algorithm performance (Figure 2). Comparison of the corrected radiosonde data (red) with the hygrometer data (dark blue) shows that the time-lag correction is remarkably successful in recovering vertical structure in the humidity profile that had been highly “smoothed” by slow sensor response at cold temperatures. The “information” about the vertical structure is present in the slope of the original data and is recovered by the time-lag correction. The accuracy of the laboratory time-constant measurements and their validity under operational conditions are also verified by Figure 2 (and by the other 36 profiles, which are generally similar). The second main conclusion from Figure 2 is that a residual bias relative to the hygrometer remains in some of the corrected radiosonde profiles. The residual bias appears to be an offset whose magnitude depends on the radiosonde age, where “young” radiosondes are undercorrected (Figure 2a), and “old” radiosondes are overcorrected (Figure 2d). The cause of this residual bias is found in the age-dependent factor of the contamination correction, as will be shown shortly.

The RH difference between corresponding radiosonde and hygrometer measurements is shown as a function of temperature for all 40 soundings in Figure 3, before and after correction. The corrections mostly remove the temperature-dependent mean bias from the uncorrected data, leaving a small moist bias relative to the hygrometer of 1% to 2% RH that is independent of temperature, except for the -60° to -65°C temperature bin (perhaps because it contains contributions from relatively few soundings). The 68th percentile curves (which are analogous to the standard deviation, but are more appropriate for an asymmetric distribution) indicate that the variability in the comparison is considerably reduced at cold temperatures, mainly due to the more accurate vertical structure of the corrected profile. However, variability actually increases over much of the temperature range, which is shown below to result from the age-dependent residual bias seen in Figure 2.

The dependence of the residual bias on radiosonde age is investigated by calculating the mean (profile-average) RH difference between corresponding radiosonde and hygrometer measurements for each of the 40 profiles (Figure 4). Before applying corrections, the mean dry bias for the dataset as a whole is -6.4% RH and the variability between soundings of a given age is about ±6% RH, and both are independent of the radiosonde age. After correction, the residual bias is seen to depend on the radiosonde age, where young radiosondes are undercorrected and old radiosondes are overcorrected, consistent with the cases shown in Figure 2.

The contamination correction given by Wang et al. (2002) is the product of two polynomials, one dependent on humidity, and the other dependent on the radiosonde age. The RS80-H contamination correction is shown as a function of radiosonde age in Figure 5 for four different values of the measured humidity, where circles indicate the five radiosonde ages that were used to derive the correction, and asterisks indicate the ages of the radiosondes in the NOAA dataset. The contamination correction was derived from a statistically small dataset, especially for radiosondes outside the age range 0.5 to 2.75 years. The polynomial fit contains an artificial peak at age 5 years that leads to overcorrection of radiosondes in the age range 3 to 5.5 years and undercorrection of radiosondes older than 5.5 years.

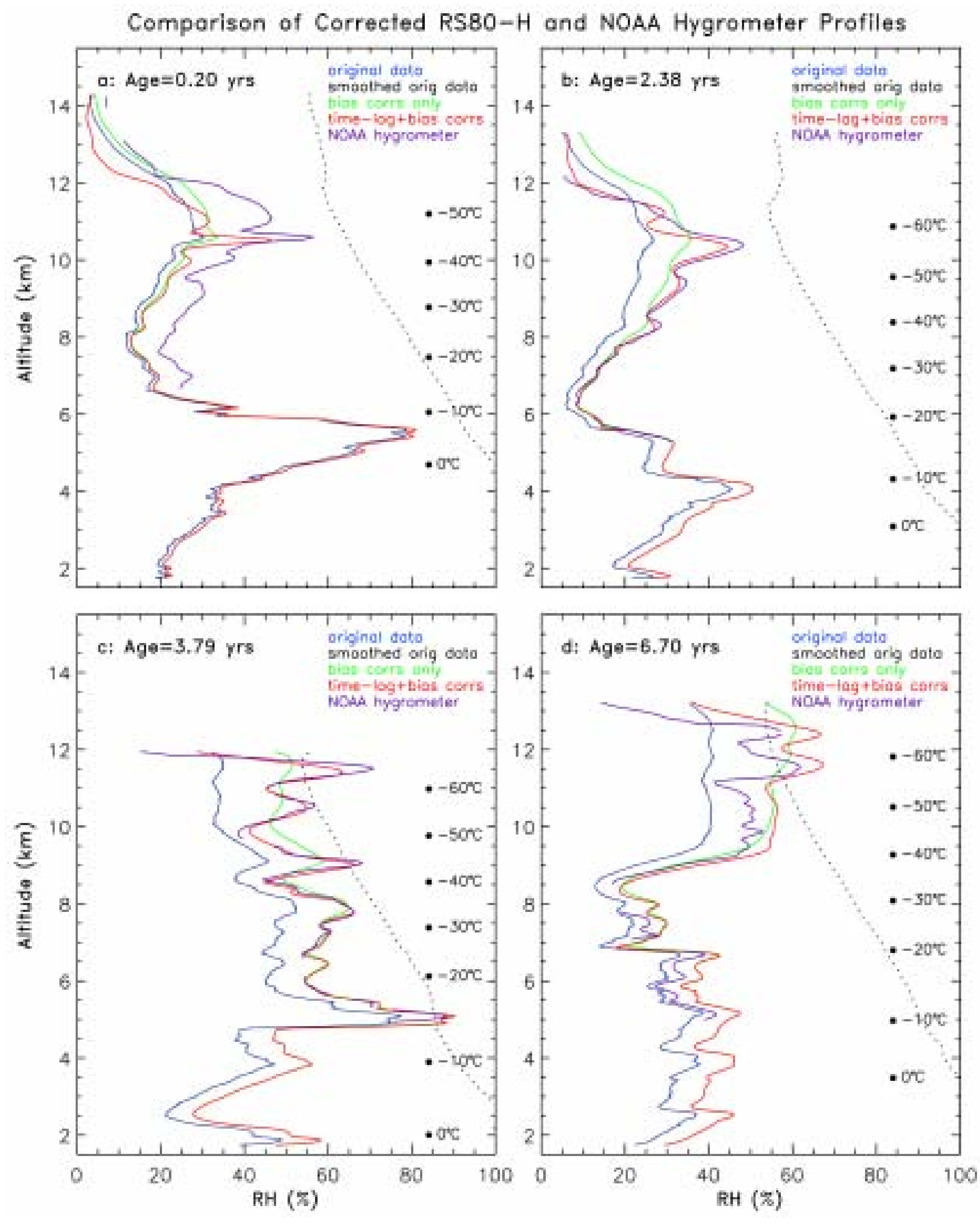

Figure 2. Four soundings comparing Vaisala RS80-H humidity measurements after correction for time-lag, temperature-dependence, and contamination errors (red) with simultaneous measurements from the NOAA/CMDL cryogenic hygrometer (dark blue). Other curves are: original radiosonde measurement (light blue, beneath black), smoothed radiosonde measurements (black), radiosonde measurements corrected for only the bias errors (green), and the ice-saturation curve (dashed). Panels are labeled with the age of the radiosonde at launch.

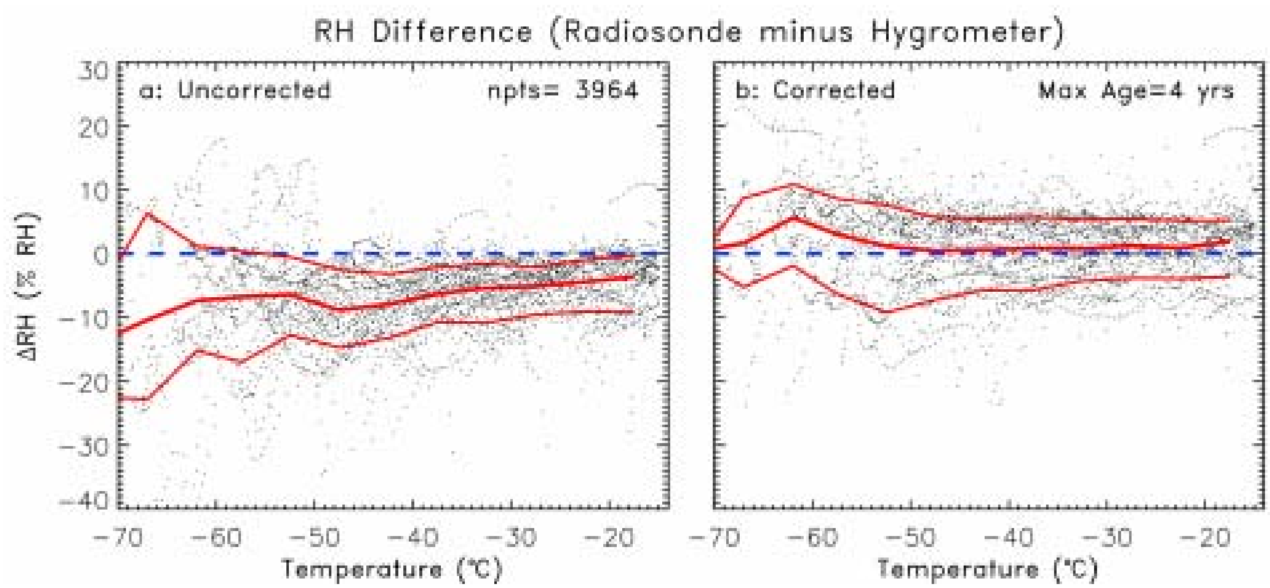

Figure 3. RH difference between simultaneous Vaisala RS80-H and NOAA hygrometer humidity measurements from 40 profiles, shown as a function of temperature, (a) before and (b) after correction for time-lag, temperature-dependence, and contamination errors. Data are excluded if the temperature is warmer than -15°C or the altitude is above the tropopause. Red curves are the mean in 5°C temperature bins and the 68th percentile above and below the mean. The radiosonde age used to calculate the contamination correction was limited to a maximum of 4 years, as discussed in the text.

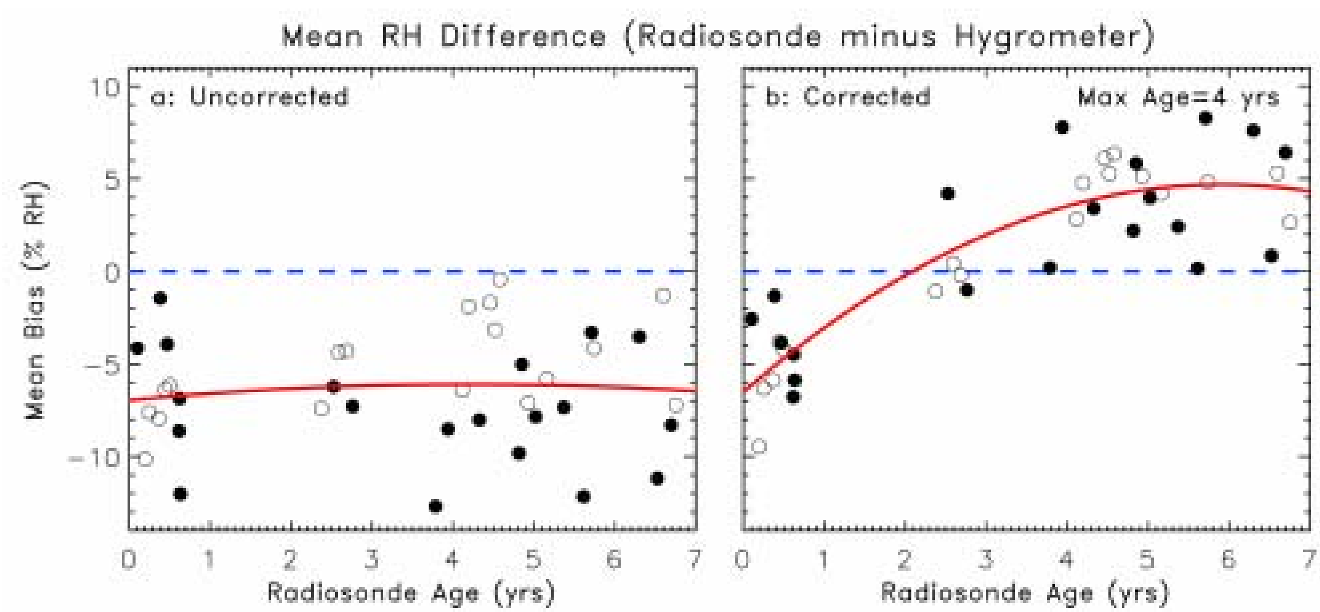

Figure 4. Circles show the mean (profile-average) RH difference between corresponding RS80-H and hygrometer measurements for each of the 40 profiles as a function of radiosonde age, (a) before and (b) after (right) correction. Open circles indicate that the mean humidity measured by the hygrometer was <30% RH, and closed circles indicate that the mean humidity was >38% RH. The solid curve is a polynominal fit for reference.

The age used to compute the contamination correction for the 6.7-year-old radiosonde shown in Figure 2d was arbitrarily set to 4 years for demonstration purposes, because the calculated contamination correction was actually negative (it was this observation that initiated further investigation of the contamination correction). A maximum radiosonde age of 4 years was also used to calculate the contamination correction for the older radiosondes in Figures 3 and 4, but Figure 4b shows that radiosondes older than about 3 years are still overcorrected, as might be expected based on Figure 5. The contamination correction for radiosondes younger than 0.5 years is also in question, and it is impossible to distinguish whether the contamination process is gradual (as assumed by the polynomial fit), or whether contamination might occur rapidly and reach the “saturation” amount suggested by constant contamination in the age range 1 to 3 years.

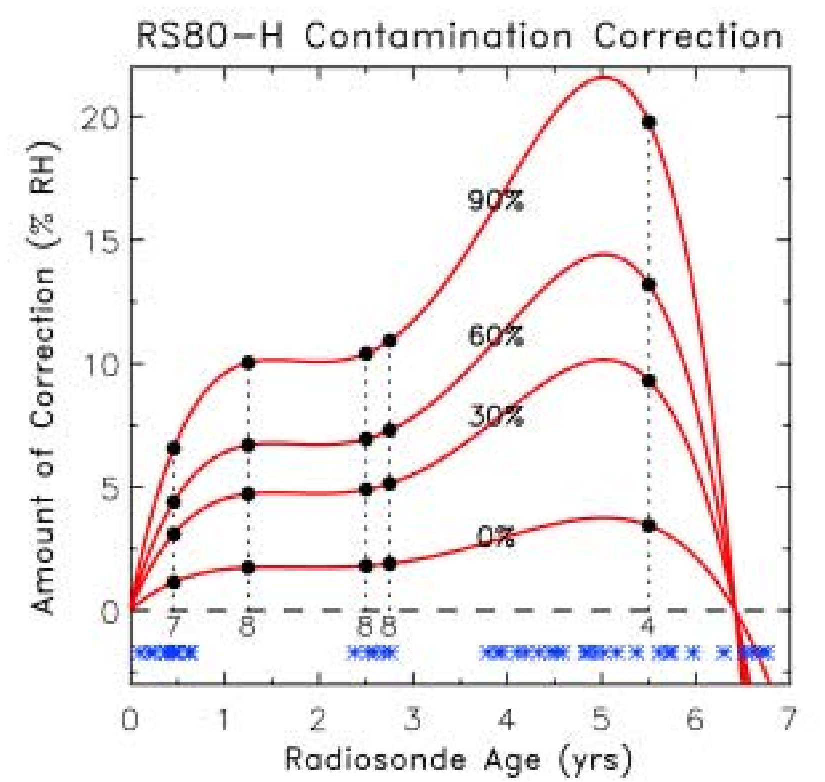

Figure 5. Contamination correction as a function of radiosonde age at +20°C for RS80-H radiosondes, from Wang et al. (2002). Curves show the amount of correction for the labeled humidity values. Dots and vertical dashed lines indicate the ages of the radiosondes that were tested by Vaisala and used to derive the contamination correction (number of radiosondes tested is also indicated). Asterisks show the ages of the 40 radiosondes in the NOAA dataset.

The contamination process involves the occupation of binding sites in the sensor polymer by non-water molecules from the radiosonde packaging material, making these sites unavailable to water molecules and leading to a dry bias in the measurements. We propose that contamination reaches a constant “saturation” level where all susceptible binding sites have been contaminated, which is supported by both the constancy of the contamination correction in the age range 1 to 3 years as derived from the Vaisala data (Figure 5), and also by the absence of an age-dependence in the uncorrected NOAA data

(Figure 4a). The single datapoint at age 5.5 years in Figure 5 suggests that contamination may again increase after age 3 years, but this behavior seems implausible, and these few radiosondes might instead be an indicator of the large variability in contamination caused by such factors as storage temperature (e.g., the outgassing of contaminants and consequent saturation level are likely to increase with increasing maximum temperature reached during storage). The undercorrection of radiosondes younger than 1 year in the NOAA dataset (Figure 4b) also suggests that contamination may reach its saturation value quite rapidly.

Figure 6 shows the mean RH bias as a function of radiosonde age (as in Figure 4), and Figure 7 shows the RH difference between corresponding datapoints as a function of temperature (as in Figure 3), except that all radiosondes are treated as if they are 1 year old (i.e., age-independent contamination). This assumption represents the hypothesis that contamination occurs rapidly and reaches a saturation level given by the constant region in Figure 5. (Note that it makes little difference which age in the range 1 to 3 years is used to represent the contamination, since the polynomial fit is essentially constant throughout this range for all humidities.) Figure 6 shows that the mean residual bias of the older radiosondes is reduced to approximately zero on average, and the range of variability between soundings is reduced to about ±4% RH. The NOAA dataset is consistent with the proposed constant contamination for radiosondes older than about 1 year. The humidity-dependence in the original Wang et al. (2002) contamination correction appears to be consistent with the NOAA dataset, as judged by roughly equal effectiveness in correcting generally moist or generally dry soundings (solid vs. open circles in Figure 6). The residual bias for young radiosondes is only partially eliminated even by assuming that full contamination occurs prior to launch. The persistence of a dry bias suggests that these radiosondes may be more contaminated than average, either by chance, or due to several changes over time in the type of desiccant used by Vaisala, or due to exposure to higher temperatures, or due to other non-contamination bias errors. Figure 7 shows that the corrections reduce the mean dry bias of the uncorrected radiosonde measurements from a temperature-dependent value in the range of 5% to 10% RH to a corrected mean bias that is generally <2% RH. The variability as given by the 68th percentile curves is also reduced, partly due to recovery of vertical structure in the radiosonde profiles by the time-lag correction and partly due to reduction in the residual bias by modification of the age-dependence of the contamination correction.

Summary

Corrections for time-lag, temperature-dependence, and contamination errors were applied to 40 Vaisala RS80-H radiosonde humidity soundings. Comparison of the corrected radiosonde profiles with simultaneous measurements from the reference-quality NOAA/CMDL cryogenic hygrometer shows that the time-lag correction successfully recovers vertical structure in the humidity profile that had been smoothed by slow sensor response at cold temperatures, and gives confidence that the physical basis of the time-lag correction approach is sound.

Statistical analysis of the difference between corresponding radiosonde and hygrometer measurements (Figure 7) shows that the corrections reduce the mean dry bias in the uncorrected radiosonde measurements from about 4% RH at -20°C and 10% RH at -70°C to about ±2% RH at all temperatures. An age-dependent residual bias revealed a problematic polynomial fit in the contamination correction (Figure 5), and also led to a greater appreciation of the large variability in contamination that naturally

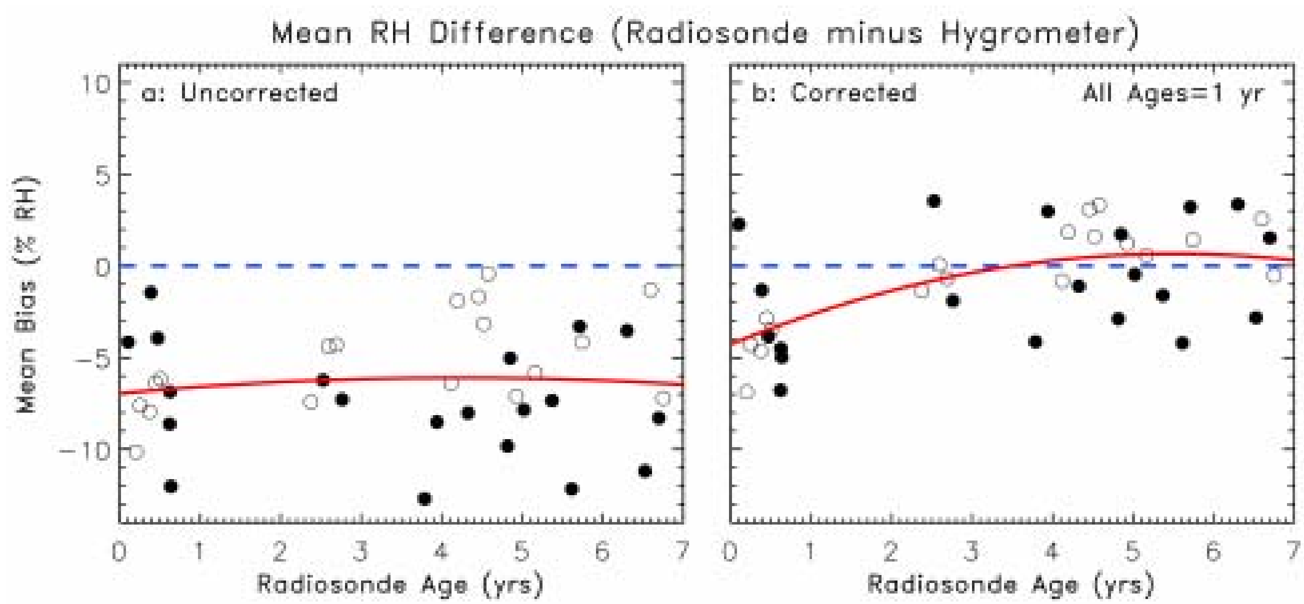

Figure 6. Mean (profile-average) RH difference between corresponding RS80-H and hygrometer measurements before and after correction, as in Figure 4 except that a radiosonde age of 1 year was used in all cases to calculate the contamination correction.

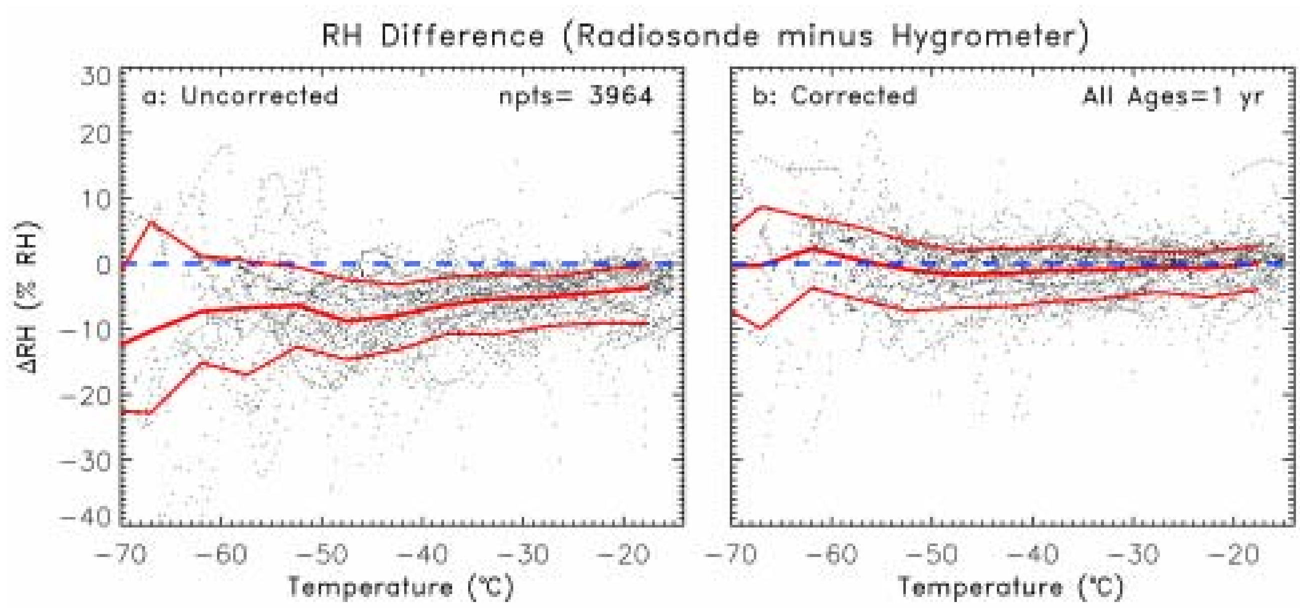

Figure 7. RH difference between simultaneous RS80-H and hygrometer measurements before and after correction, as in Figure 3 except that a radiosonde age of 1 year was used in all cases to calculate the contamination correction.

arises from the complexity of the contamination process. The NOAA dataset is consistent with the notion that contamination occurs rapidly and reaches a saturation level, which was implemented in the context of the Wang et al. (2002) contamination correction by specifying that the age of all radiosondes is 1 year. Vaisala *may* have reduced or eliminated the contamination problem in May 2000 by introducing a sealed sensor cap that isolates the sensor from contamination prior to launch.

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