Impact of Vaisala Radiosonde Humidity Corrections on ARM IOP Data

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Introduction

Radiosonde humidity measurements are fundamentally important to a variety of applications, including radiative transfer calculations, validation of remote-sensor retrievals, parameterization of cloud processes, and initialization of (or assimilation into) numerical models. Vaisala radiosondes, used by the Atmospheric Radiation Measurement (ARM) Program and extensively throughout the world, are known to have accuracy limitations that result from several identified sources of measurement error (Miloshevich et al. 2001a). A systematic dry bias in Vaisala radiosonde humidity measurements has been noted in comparison to satellite water vapor retrievals (Soden and Lanzante 1996) and Raman lidar measurements (Ferrare et al. 1995), and in underpredicting clouds and precipitation in a numerical weather prediction model (Lorenc et al. 1996). The concurrent observations that variability exists in the accuracy of the ARM radiosonde humidity measurements when radiosondes from different calibration batches are used (Lesht 1999), and that unrealistically dry tropical boundary layers were frequently observed in the radiosonde data during the Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA-COARE) (Zipser and Johnson 1998), led to a substantial effort by Vaisala and the National Center for Atmospheric Research (NCAR) to identify the sources of the measurement inaccuracy and develop corrections (Wang et al. 2002).

The correction approach used in the present study is based on laboratory measurements of the humidity sensor response characteristics conducted by Vaisala. The sources of the humidity measurement error fall into two classes: a “time-lag error” that results from slow response of the sensor to a changing ambient humidity field at cold temperatures, and several “bias errors” that produce a dry bias in the measurements. The corrections are described in the next section, followed by validation of the correction approach using an accurate measurement standard, and analysis of the impact of the corrections on radiosonde humidity data from five ARM intensive operational periods (IOPs).

Humidity Correction Approach

The time-lag correction is a numerical inversion algorithm that calculates the "ambient" humidity profile from the measured humidity and temperature profiles based on laboratory measurements of the sensor time-constant (63% response time) as a function of temperature (Miloshevich et al. 2001b). The time-constant of the RS80-H humidity sensor is about 6 s at –20°C, 30 s at –40°C, and 200 s at –70°C. Although the sensor may respond only partially to changes in the ambient humidity, the "information" about the ambient humidity profile is contained in the measurements and can be recovered using the known temperature-dependence of the time-constant.

An earlier version of corrections for several of the bias errors has previously been applied to the ARM data (Lesht 1999), with the result that differences in water vapor measurements between the radiosondes and other instruments were reduced. A detailed study of the development of the bias corrections has recently been completed by Wang et al. (2002), which is the source of the bias correction equations used in the present study. These bias corrections are summarized below, and their functional dependences are shown in Figure 1.

- *Temperature-dependence correction*: Addresses inaccuracy at cold temperatures in the Vaisala equation that gives the temperature-dependence of the sensor calibration. This is a data processing inaccuracy rather than an inherent limitation of the sensor.

- *Contamination correction*: Compensates for the tendency of non-water molecules from plastics in the radiosonde packaging material to occupy binding sites in the sensor polymer and render them unavailable to water molecules, leading to a dry bias in the measurements. Radiosondes produced after May 2000 are supposedly no longer subject to contamination due to the introduction by Vaisala of a sealed sensor cover that is removed just before launch.

- *Sensor-aging correction*: Compensates for normal long-term drift in the sensor calibration.

Validation of the Correction Algorithm

The performance of the correction algorithm is evaluated by comparing corrected Vaisala RS80-H humidity measurements with simultaneous measurements from the reference-quality balloon-borne cryogenic hygrometer operated by the National Oceanic and Atmospheric Administration Climate Modeling and Diagnostics Laboratory (NOAA/CMDL) (Vömel et al. 1995). The NOAA hygrometer is a fast-response instrument (relative to the RS80-H at cold temperatures), whose fractional uncertainty in the measured relative humidity (RH) varies from 0.06 at 0°C to 0.10 at –70°C, which is about ±6% RH at ice-saturation, decreasing linearly with decreasing RH (Miloshevich et al. 2001a).

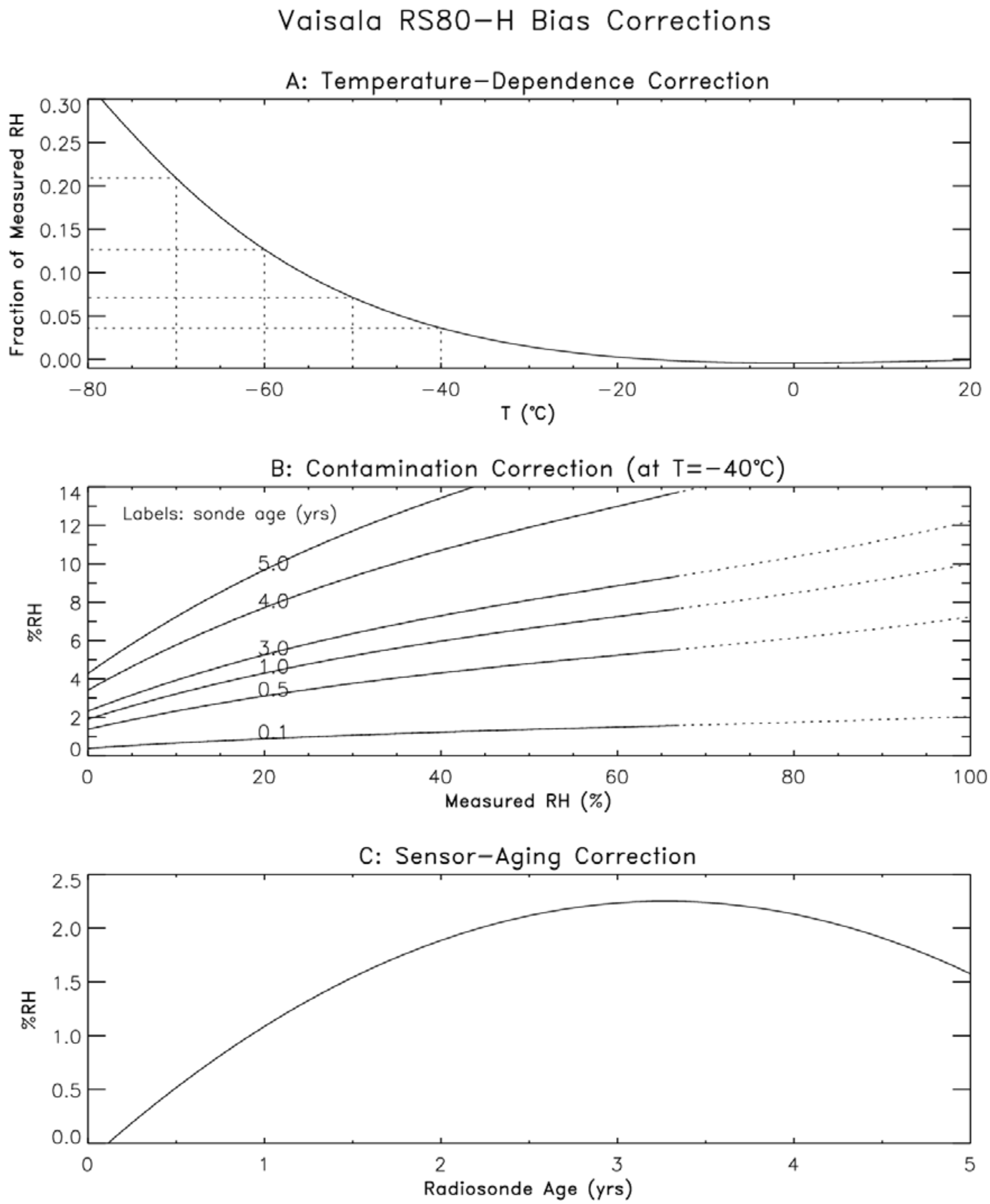

Figure 1. Functional dependences for the Vaisala RS80-H RH bias corrections used in this study. (A) Temperature-dependence correction (as a fraction of the measured RH) versus temperature. (B) Contamination correction (%RH) versus measured RH for radiosondes of the labeled ages (solid curve below ice-saturation, dashed above ice-saturation). The correction is shown for -40°C, but is only weakly dependent on temperature. (C) Sensor-aging (long-term stability) correction (%RH) versus radiosonde age.

The example profile in Figure 2 shows that the radiosonde data corrected for the time-lag and bias errors (red) compares remarkably well with the hygrometer data (purple), in terms of both absolute accuracy and recovery of vertical structure in the profile. Of the 24 comparison soundings studied, about 75% are generally similar to Figure 2 and give high confidence that the physical basis of the correction approach is sound and the accuracy of the radiosonde data is markedly improved. The remaining 25% of comparisons show that the corrected radiosonde data still contain a residual dry bias, although the time-lag correction performs well in all cases as judged by recovery of the vertical structure in the humidity profile. The soundings that contain a residual bias are from “young” radiosondes that have a small contamination correction, whereas the soundings like Figure 2 are from “old” radiosondes that have a larger contamination correction. The contamination correction was empirically derived from a small dataset with large variability, and no information was available for radiosondes less than 0.46 years old (Wang et al. 2002). Furthermore, the contamination process is probably influenced by the temperature at which the radiosondes are transported and stored. It is by far the most uncertain of the corrections. We theorize that the young radiosondes were, in reality, more influenced by contamination than is indicated by the correction, and recent NOAA data (radiosondes manufactured after May 2000) may soon be available to test this hypothesis.

Impact of Humidity Corrections on ARM IOP Data

The correction algorithm was applied to soundings from the ARM-FIRE Water Vapor Experiment (AFWEX). Frequency distributions were constructed for the percentage change in precipitable water vapor (ΔPWV) due to the corrections, for both the total column and for 1 km thick layers. The mean and standard deviation of the frequency distributions are shown as a function of altitude in Figure 3. Results for the combined time-lag and bias corrections are shown in the top panel, and results for the bias corrections alone are shown in the bottom panel. All radiosondes used in this experiment were less than a few months old and were manufactured after May 2000, thus the contamination correction is zero and the total bias correction is almost entirely due to the temperature-dependence correction.

The bias correction (Figure 3, bottom panel) increases with decreasing temperature to about ΔPWV=13% at the tropopause (between 11 and 14 km altitude for these soundings), with little variability between soundings. The time-lag correction (difference between panels) broadens the ΔPWV distribution substantially as the temperature decreases, because it depends on the humidity *gradient* (examine Figure 2), which can vary considerably between profiles at a given altitude. The time-lag correction has minimal effect on the *mean* ΔPWV below about 8 km, but in the upper troposphere (UT) the time-lag correction contributes a modest increase in the mean ΔPWV. In the lower stratosphere (LS) the time-lag correction contributes a large *decrease* in the mean ΔPWV. The only way that the time-lag correction can contribute a bias to the mean ΔPWV is if humidity gradients at a given altitude are consistently in the same direction. This situation commonly occurs at the tropopause, where the humidity typically decreases from relatively high values in the UT (often at or above ice-saturation) to very low values in the LS. The sensor responds slowly to the decreasing humidity above the tropopause, so the measurement is too moist for about 3 time-constants (about 600 s at –70°C, or 3 km for a typical ascent rate of 5 m/s). Finally, the total-column PWV is essentially zero (for the AFWEX dataset), because most of the water vapor resides in the low- and mid-troposphere where the time-lag and

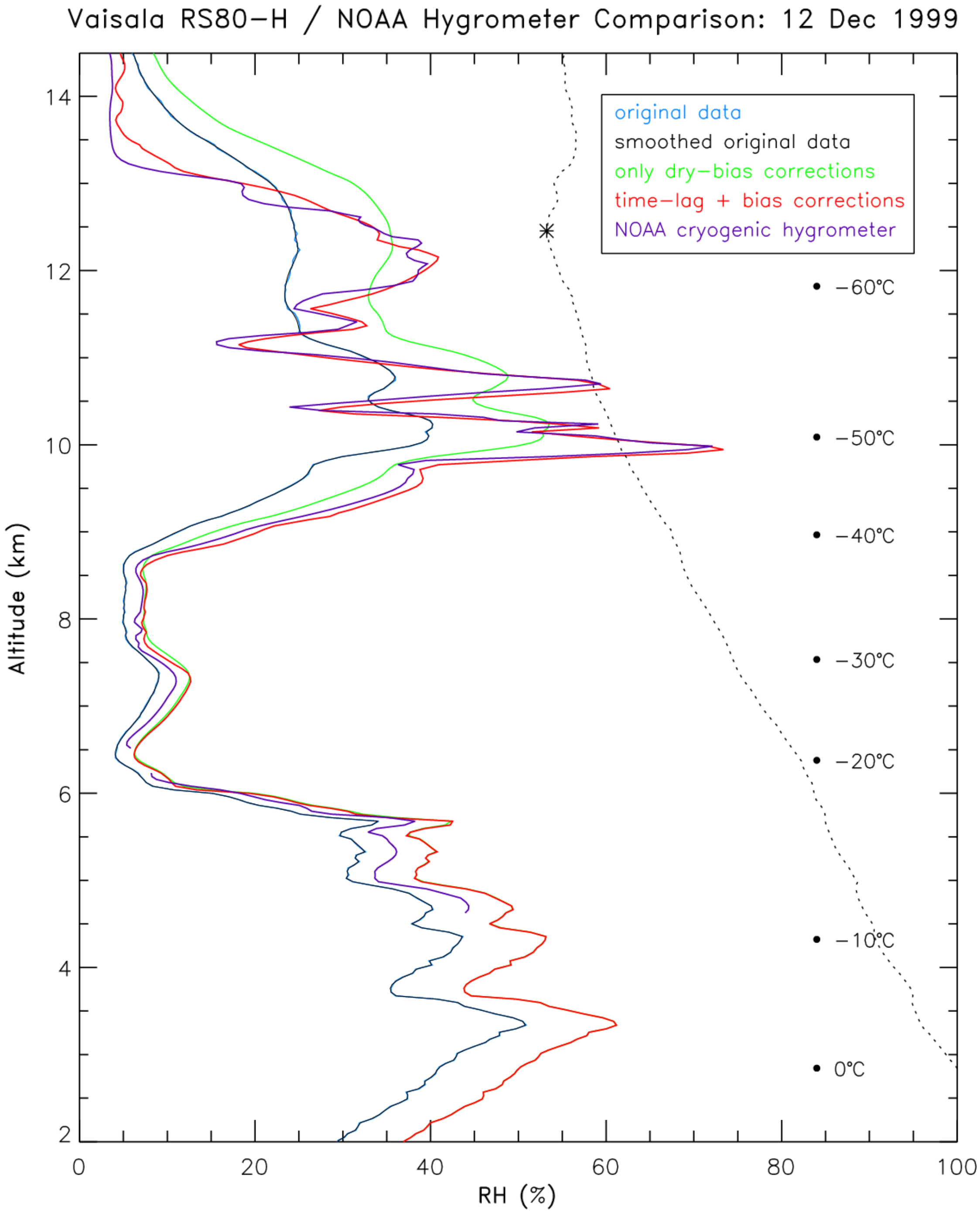

Figure 2. Comparison of humidity profiles measured simultaneously by the NOAA/CMDL balloon-borne cryogenic hygrometer (purple) and by a Vaisala RS80-H radiosonde (light blue, beneath black). The radiosonde data are first smoothed (black), then corrected for the three bias errors discussed in the text (green), and finally corrected for time-lag error (red). The dashed curve is ice-saturation, and the asterisk indicates the tropopause.

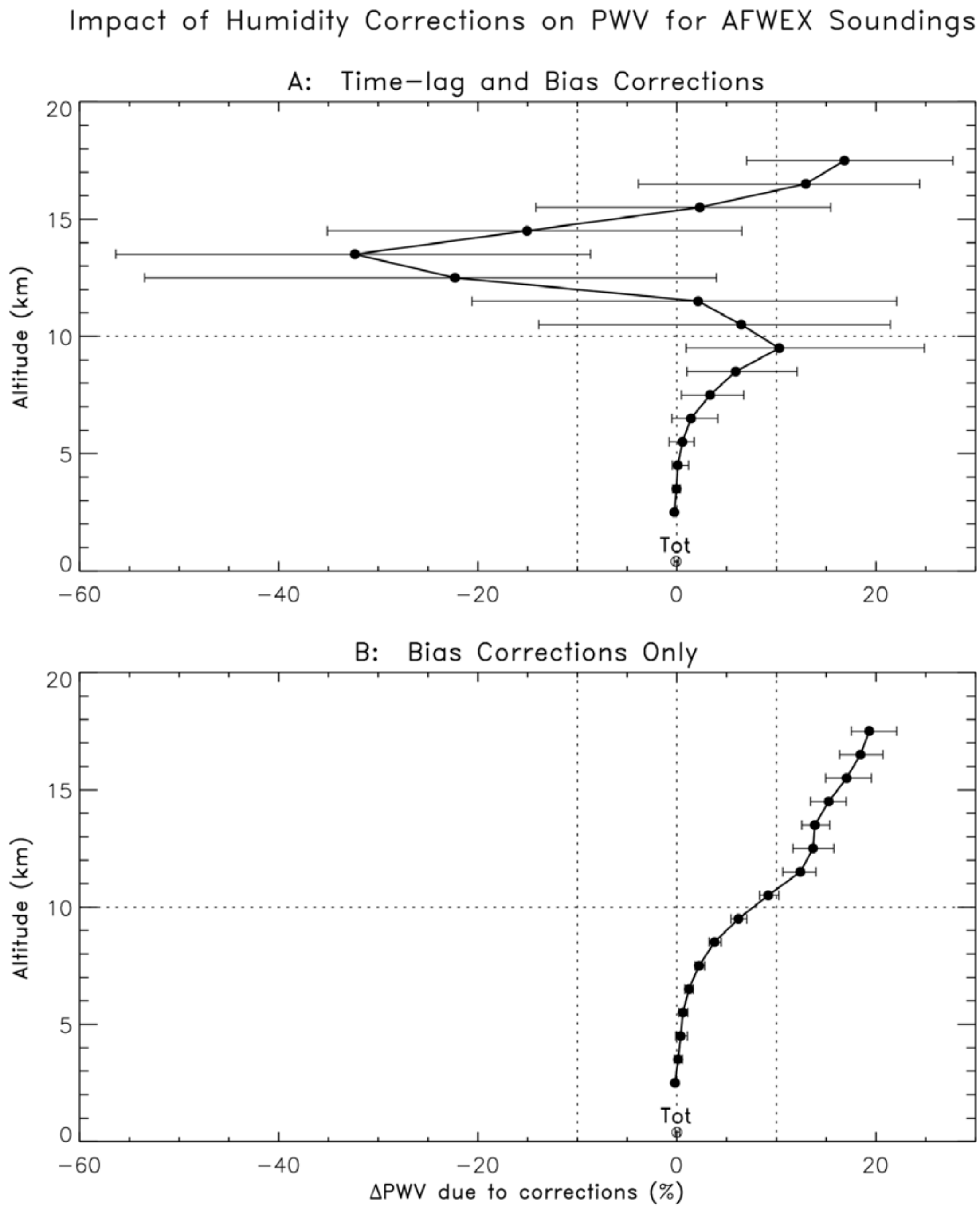

Figure 3. Mean (dots) and standard deviation (bars) from the frequency distribution of percentage change in ΔPWV that resulted from applying the humidity corrections to 135 soundings from the ARM Southern Great Plains (SGP) site central facility (CF) during the November-December 2000 AFWEX experiment. ΔPWV was calculated for 1-km-thick layers and plotted as a function of altitude. The total-column ΔPWV is labeled “Tot.” The top panel shows ΔPWV if the time-lag and bias corrections are applied, and the bottom panel shows ΔPWV if only the bias corrections are applied. Reference lines (dashed) are drawn at ΔPWV=0% and ±10%, and at 10 km altitude.

temperature-dependence corrections have little impact. Also, the large negative *percentage* correction in the LS is less significant for most purposes than the smaller positive percentage correction in the UT, because the UT contains much more water vapor than the LS.

The correction algorithm was also applied to several other ARM IOP datasets, although the quality assessment performed for the AFWEX dataset has not yet been performed for the other datasets. The percentage change in PWV due to the combined time-lag and bias corrections is shown in Figure 4 for five ARM IOP datasets. All of the datasets share the general characteristics described above for the AFWEX dataset, with a few notable exceptions. The reversal of the increase in ΔPWV with increasing altitude in the tropopause region is less pronounced in the other datasets, for reasons that are being investigated. One likely contributing factor is the possibility of a seasonal dependence for characteristics (magnitudes and gradients) of the ambient humidity and temperature profiles; AFWEX occurred in December whereas the other IOPs occurred in September. The radiosondes used in all IOPs except AFWEX were subject to the contamination error, which also affects the lower troposphere and thereby increases the total-column PWV. During the 2000 IOP, older radiosondes (often >3 yrs) were used with data system "B," resulting in a large contamination correction, an average increase of 18% in the total-column PWV, and increases in PWV that often exceed 50% in the mid-troposphere and above.

Summary

Corrections for sensor time-lag and for three dry-bias errors were applied to Vaisala RS80-H radiosonde humidity data from five ARM IOPs. Comparison of corrected soundings with simultaneous measurements from the NOAA/CMDL cryogenic hygrometer give high confidence that the physical basis of the correction approach is sound and markedly improves the accuracy of the radiosonde data. Both the magnitude of the correction and its variability between soundings increase with decreasing temperature throughout the troposphere. The most reliable corrected data are from radiosondes manufactured after May 2000, when production changes at Vaisala eliminated the need for the most uncertain of the bias corrections. These results must be considered preliminary because several details of the correction algorithm remain to be finalized, although the general observations made in this paper are not likely to change.

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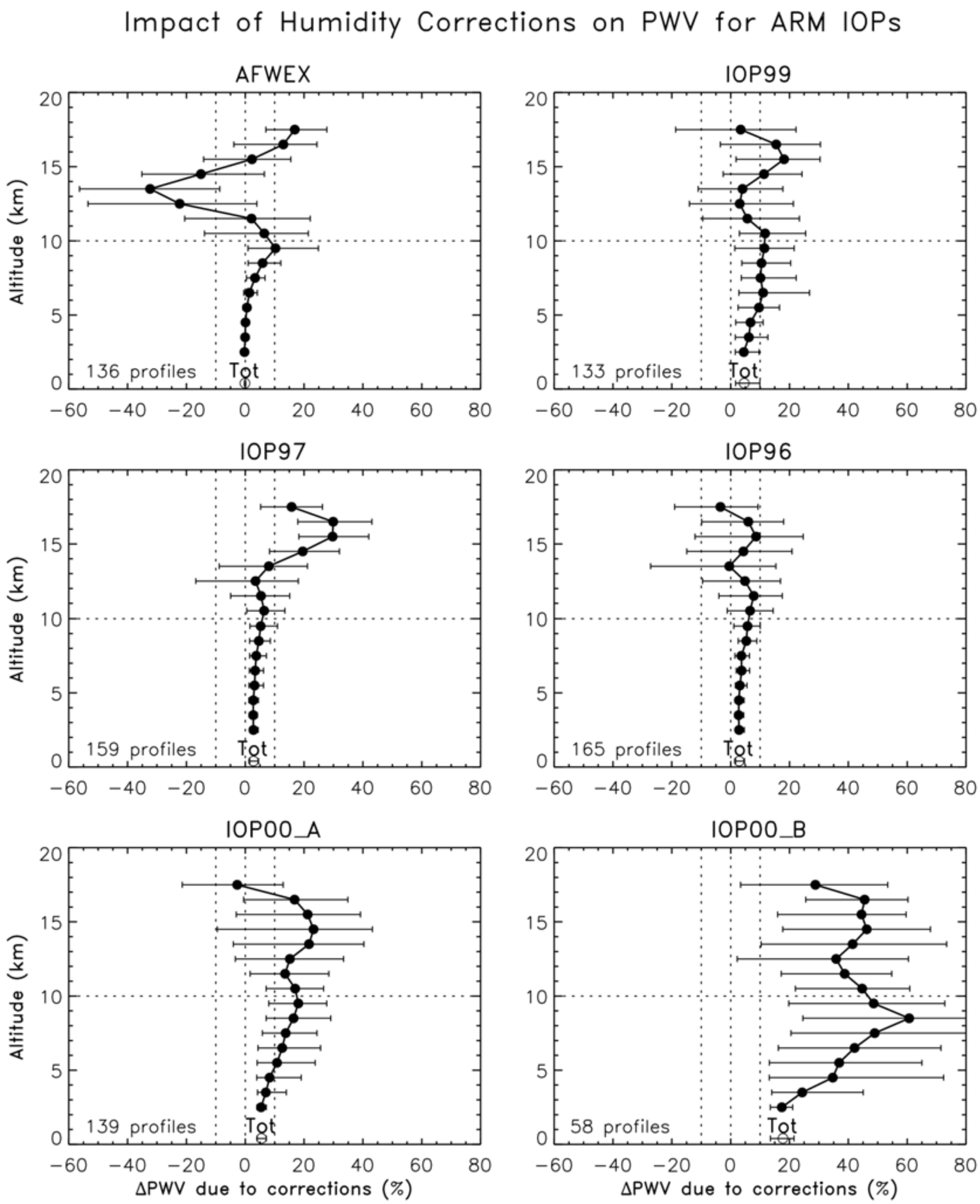

Figure 4. Mean (dots) and standard deviation (bars) from the frequency distribution of percentage change in ΔPWV that resulted from applying the time-lag and bias humidity corrections to soundings from the ARM SGP site CF for several IOP datasets. ΔPWV was calculated for 1-km-thick layers and plotted as a function of altitude. The total-column ΔPWV is labeled "Tot." The 2000 IOP (IOP00) is shown as two separate datsets because radiosondes used with one of the two data systems (B) were in many cases from an older batch. Reference lines (dashed) are drawn at ΔPWV=0% and ±10%, and at 10 km altitude.

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