Radiation Dry Bias of the Vaisala RS92 Humidity Sensor

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(Manuscript received 11 April 2006, in final form 18 September 2006)

ABSTRACT

The comparison of simultaneous humidity measurements by the Vaisala RS92 radiosonde and by the Cryogenic Frostpoint Hygrometer (CFH) launched at Alajuela, Costa Rica, during July 2005 reveals a large solar radiation dry bias of the Vaisala RS92 humidity sensor and a minor temperature-dependent calibration error. For soundings launched at solar zenith angles between 10° and 30°, the average dry bias is on the order of 9% at the surface and increases to 50% at 15 km. A simple pressure- and temperature-dependent correction based on the comparison with the CFH can reduce this error to less than 7% at all altitudes up to 15.2 km, which is 700 m below the tropical tropopause. The correction does not depend on relative humidity, but is able to reproduce the relative humidity distribution observed by the CFH.

1. Introduction

Vaisala is the largest manufacturer of radiosondes, and with their recent RS92 model a new generation of radiosondes is introduced. This model replaces the older RS80 radiosonde and, to a smaller extent, the RS90 model. The two relative humidity (RH) sensors (A and H Humicaps), which had been available with the RS80, were well characterized and have been compared with reference instruments in simultaneous soundings. The RS80-A had a calibration-based dry bias (e.g., Miloshevich et al. 2001) and, like the RS80-H, a contamination dry bias (Wang et al. 2002). This contamination-induced dry bias was corrected by a change in the packaging introduced in June 2000. Miloshevich et al. (2004) investigated the time lag of these sensors and a possible correction, which has been validated to down temperatures of −70°C (Miloshevich et al. 2006).

The RS90 radiosonde was introduced in 1997 but never attained a large market share. The RS90 temperature and humidity sensors are similar to the RS92 sensors; however, differences exist and the results presented here are likely not applicable to the RS90 humidity sensors.

The RS92 radiosonde was first introduced in 2003 and an operational characterization of its humidity sensor took place in November 2003 as part of the Atmospheric Infrared Sounder (AIRS) Water Vapor Experiment (AWEX). The main goal of this experiment was to evaluate the performance of several tropospheric water vapor profiling instruments (Whiteman et al. 2006), and among other efforts conducted simultaneous observations of the Vaisala RS92 radiosonde and the Cryogenic Frostpoint Hygrometer (CFH), which is currently built at the University of Colorado (Vömel et al. 2007a, hereafter VDS). The CFH measures water vapor between the surface and the middle stratosphere and can be regarded as a reference standard, in particular for radiosonde observations. AWEX, as well as the Lapland Biosphere–Atmosphere Facility (LAPBIAT) Upper Troposphere Lower Stratosphere (LAUTLOS)

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DOI: 10.1175/JTECH2019.1

campaign in Sodankylä, Finland, in February 2004, which focused on stratospheric and upper-tropospheric water vapor instrument comparisons (e.g., Vömel et al. 2007b, conducted nighttime soundings and did not investigate the influence of solar radiation on the humidity observations. However, these observations can be used to assess the calibration accuracy of humidity sensors in the absence of solar radiation. The AWEX campaign revealed a calibration dry bias of up to 10%–30% at cold temperatures, for which Miloshevich et al. (2006) provided correction factors.

Smout et al. (2000) noted significant diurnal differences in the RS90 RH measurements, resulting from solar heating of the RS90 humidity sensors. Diurnal differences in RH measurements were also found at the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program's research sites. Turner et al. (2003) developed a correction for RH profiles, in which the comparison of the column-integrated precipitable water vapor (PWV) derived from these soundings with PWV derived from microwave radiometer measurements provides a constant scaling factor that is applied to the entire profile. Miloshevich et al. (2006) pointed out that the ARM RS90 daytime observations typically show a scaling factor of 6%–8% above the nighttime scaling, indicating that the radiosondes have a daytime dry bias in the precipitable water vapor of this magnitude, which is likely due to a radiation error. This daytime scaling factor is about twice that found by Turner et al. (2003) for the RS80-H humidity measurements.

In July 2005, the Ticosonde 2005 intensive observation campaign took place at Alajuela, Costa Rica. Its goal was to study the atmospheric dynamics of the tropical atmosphere, and in particular the tropical tropopause layer using 4-times-daily radiosondes launched over the course of 2 months. As part of this campaign 24 soundings were launched consisting of the CFH and the Vaisala RS92 radiosonde, which provided both daytime and nighttime comparisons for the humidity observations of these instruments. Here we report on the vertical dependency of the Vaisala RS92 daytime dry bias and offer an update to the nighttime calibration correction factors provided by Miloshevich et al. (2006).

2. Instrumentation

a. The frost-point hygrometer

The CFH is a reference instrument for water vapor observations (VDS). It is based on the chilled-mirror principle and measures the temperature of a mirror that carries a dew or frost layer that is maintained in equilibrium with the ambient water vapor. Under this condition the mirror temperature is equal to the ambient dewpoint or frost-point temperature and the water vapor mixing ratio and relative humidity can be calculated using a variation of the Clausius–Clapeyron equation. In this work relative humidity follows the meteorological convention of relative humidity, defined as the ratio of vapor pressure to saturation vapor pressure over liquid water.

The measurement uncertainty of the CFH is about 0.5°C in dewpoint or frost-point temperature. At the surface and under tropical conditions, this translates to roughly 3.5% of the RH percentage value and increases to about 9% at the tropical tropopause (VDS).

The instrument measures the mirror reflectivity using a phase-sensitive detector, which by design is insensitive to sunlight. Therefore, condensate detection and frost-point control are not influenced by daylight and the performance is the same for measurements during either the day- or nighttime (VDS).

The CFH is capable of measuring water vapor inside clouds, but may occasionally suffer from an artifact, in which the optical detector collects water or ice. This condition leads to a malfunction of the instrument controller, which is easily identified in, and always screened out from, the data (VDS). Observations inside liquid water clouds can be used as in situ references because the relative humidity is expected to be very close to 100%.

The CFH is interfaced with an electrochemical concentration cell (ECC) ozonesonde and currently uses a Vaisala RS80 radiosonde as data transmitter. Thus, every CFH payload provides observations of water vapor, ozone, pressure, temperature, and wind between the surface and the middle stratosphere.

b. Vaisala RS92 humidity sensor

The Vaisala RS92 humidity sensor is a thin-film capacitor that directly measures relative humidity. It has two independent sensors, which are alternately measuring and being heated, eliminating coating of the sensor by ice or liquid inside clouds. The calibration setup for this humidity sensor has been significantly improved, which provides a stable and repeatable calibration. However, in contrast to the RS80 humidity sensor, the RS92 sensor does not have a radiation shield and is therefore more susceptible to solar heating.

The RS92 radiosondes used as part of this study went through the standard ground check procedures and preconditioning. The sondes were attached to the CFH payload, but used their own telemetry system and the operational Vaisala processing system. The two different data streams were matched as a function of time, eliminating potential errors in matching the data by pressure or altitude. Great care has been taken to eliminate minor differences in the launch detection by matching the time at which the tropopause was observed by each instrument.

3. Observations and discussion

The Ticosonde 2005 project was a combined radiosonde and CFH water vapor and ozonesonde program, which took place at Alajuela in the boreal summer of 2005. Vaisala RS92 radiosondes were launched every 6 h between 16 June and 24 August 2005; CFH water vapor and ECC ozonesondes were launched daily at local noon (1800 UTC) between 8 and 25 July, and additionally at local midnight (0600 UTC) between 21 and 25 July. Each of these CFH/ECC payloads carried the noon or midnight RS92 radiosonde. The soundings typically reached an altitude of 28 km, with good CFH water vapor up to about 25 km. These observations provide a direct in situ comparison of CFH and RS92 as a function of altitude as well as time of day.

a. *Nighttime observations*

Figure 1 shows an example of a nighttime sounding with humidity profiles obtained simultaneously by the CFH, the Vaisala RS80-A, and the Vaisala RS92. The figure indicates generally good agreement between the CFH and the Vaisala RS92, with minor differences in the upper troposphere, which are reduced by the time-lag correction (see below). The Vaisala RS80-A humidity sensor shows a dry bias in the upper troposphere, which has been studied previously (e.g., Miloshevich et al. 2001) and will not be investigated here further. Note that the RS92 profile reproduces several layers showing saturation or supersaturation over ice, seen in the CFH profile.

The Vaisala RS80 temperature, which is part of the CFH data stream, was used to calculate the RH from the CFH dewpoint or frost-point measurement. The difference between the RS80 and RS92 temperatures on this payload is shown in Fig. 2. The average difference between these two temperature observations is $-0.01° \pm 0.2°C$ for nighttime and $0.13° \pm 0.3°C$ for daytime measurements. This result is consistent with previous studies, which compared RS80 and RS90 temperature measurements (Luers 1997). This temperature measurement difference is neglected in the calculation of RH, but is taken into account in the CFH RH uncertainties (VDS).

The spike in the daytime temperature difference at

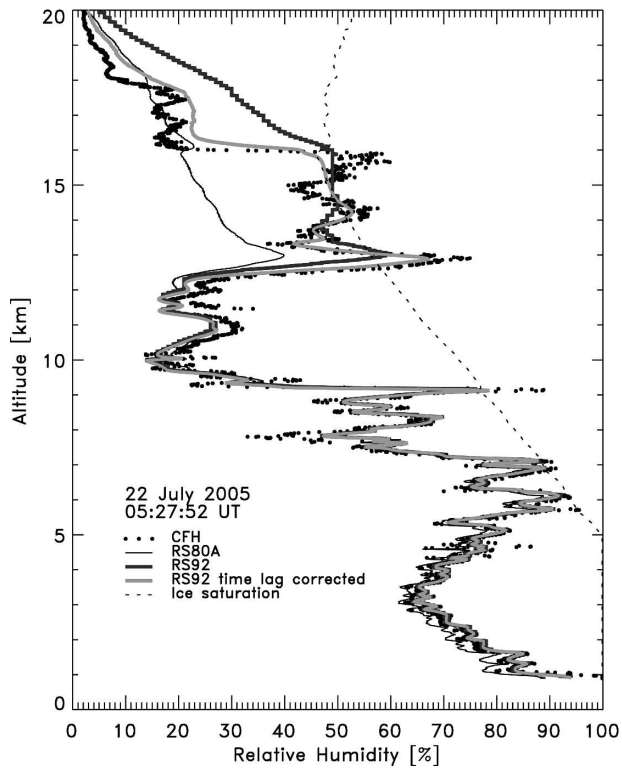

FIG. 1. Nighttime simultaneous relative humidity profiles measured by CFH, Vaisala RS80, and Vaisala RS92 on 22 Jul 2005.

16.5 km is an artifact caused by the Vaisala processing system, which rejects observations if the balloon ascent rate is faster than 12 m s^{-1}. The spike in the nighttime temperature difference at 19.5 km is also caused by the Vaisala processing system, although the reason is not clear. Either result does not represent a sensor failure of either sonde.

For consistency with the Vaisala RH measurement, the equation by Hyland and Wexler's (1983) was used to calculate the saturation pressure of water vapor over liquid and to calculate the partial pressure over liquid for the sounding phase, where the mirror condensate is liquid. For the sounding phase during which the condensate phase is solid, Goff and Gratch (1946) are used to calculate the partial pressure over ice. For the ice phase the difference between the different vapor pressure formulations, in particular between Goff and Gratch (1946) and Hyland and Wexler (1983), is small and negligible for the differences under consideration here.

Because there is a known time lag in the Vaisala radiosonde humidity measurements at colder temperatures, a time-lag correction (Miloshevich et al. 2004) was applied to all RS92 observations in the analysis below. The impact of the time-lag correction on the

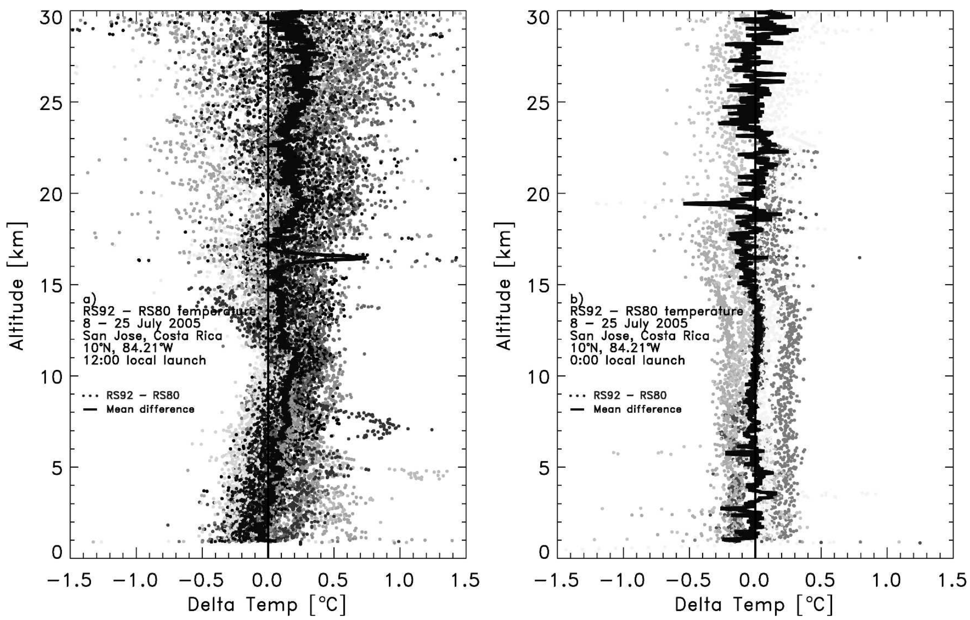

FIG. 2. Difference between the Vaisala RS80 and Vaisala RS92 temperatures.

Vaisala RS92 data is also shown in Fig. 1 and discussed in detail in section 4c. All RH differences used in this study are relative differences (%) defined as $\Delta_{rel}RH = (RH_{RS92} - RH_{CFH})/RH_{CFH} \times 100$. The relative difference of the nighttime observations is shown in Fig. 3 as a function of temperature. The data were limited to observations below the tropopause, because stratospheric RH measurements by radiosondes in the Tropics are considered meaningless for our purposes. The combined uncertainty of the CFH plus the RS92 is denoted by the dashed line. Figure 3 indicates that there is a minor dry bias that reaches roughly 6% at a temperature of −55°C. This dry bias is within the measurement uncertainty and is not significant. Below −55°C the character changes to a significant wet bias, which reaches a value of 13% at −70°C. The apparent dry bias at temperatures below −75°C is a result of only one sounding and not is sufficient to evaluate the calibration accuracy. It has been ignored in the analysis.

The LAUTLOS campaign at Sodankylä in February 2004 used both the old National Oceanic and Atmospheric Administration/Climate Modeling and Diagnostic Laboratory (NOAA/CMDL) hygrometer (Vömel et al. 1995) and an early version of the CFH. Fourteen soundings were launched in total, and all of them carried a number of different humidity sensors, including the Vaisala RS92. Of these soundings, 11 produced nighttime data useful for the comparison here. The NOAA/CMDL hygrometer performance in the troposphere is not as good as that of the CFH, and the early CFH version used during LAUTLOS had some minor technical difficulties (VDS), leading to an uncertainty that is slightly larger than that during Ticosonde 2005. Figure 4 shows the nighttime comparison between these sondes and the RS92. The data in this comparison largely confirm the result of the Ticosonde 2005 campaign. In particular, they indicate that there is a change in character of the comparison at temperatures below −55°C, although not as strongly, which may be

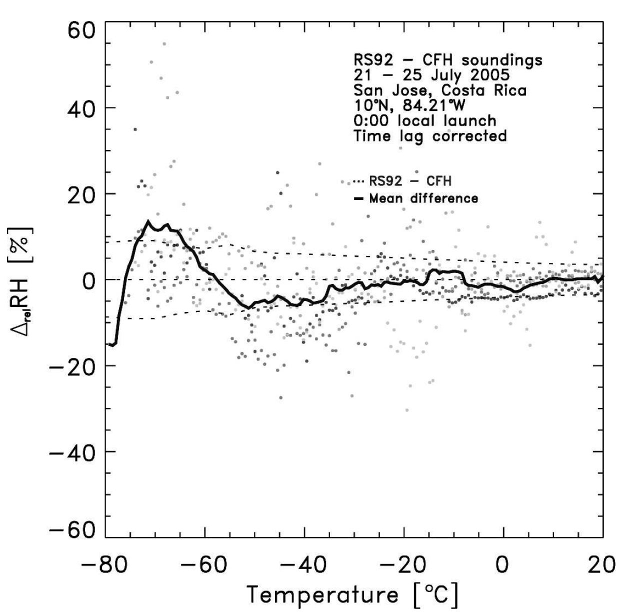

FIG. 3. Relative difference between the Vaisala RS92 and CFH nighttime RH.

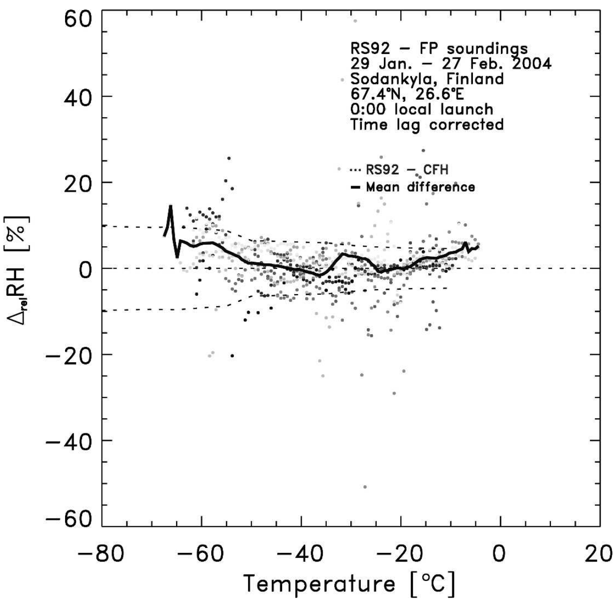

FIG. 4. Relative difference between the Vaisala RS92 and CFH or NOAA/CMDL nighttime RH during the LAUTLOS campaign at Sodankylä, 29 Jan–26 Feb 2004.

related to the much-warmer tropopause temperatures and the limited amount of tropospheric data below −55°C.

Table 1 shows the empirical correction factors, which can be derived from these nighttime soundings. Nighttime RH values are multiplied by these correction factors to achieve a better agreement with the CFH reference measurement. These correction factors will also be used in the daytime radiation correction, which is discussed below. Because of the small dataset, these factors are just given as a function of temperature and not as a function of RH as well.

Within the uncertainties, the difference above −55°C is consistent with the results obtained during AWEX. However, the change to a wet bias is different than the AWEX results and may have been caused by a change in the RS92 calibration, which went into effect in early 2004 (A. Paukkunen, 2004, personal communication). This RS92 calibration update may have replaced a small calibration-related dry bias at cold temperatures by a small but significant moist bias. The AWEX results should not be applied for sondes produced after early 2004.

TABLE 1. Empirical RS92 calibration correction factors (cfs) and their uncertainties derived from nighttime soundings

T	cf	σ
0	0.98	±0.02
−30	0.98	±0.06
−50	0.94	±0.03
−60	1.04	±0.06
−70	1.13	±0.06

b. Daytime observations

Daytime CFH and RS92 RH observations during Ticosonde 2005 show significant and strongly altitude-dependent differences. Figure 5 shows as example the sounding on 16 July 2005. The time-lag correction of the RS92 data becomes noticeable above around 12 km and enhances some vertical features also detected by the CFH. However, it does not remove the overall difference seen in this comparison. While the minor calibration-related differences play a role during the daytime as well, the observed differences are dominated by a solar radiation–induced dry bias. In this case the RS92 data miss all layers showing saturation or supersaturation over ice, which are identified in the CFH data. The average dry bias increases from about 9% at the surface to about 50% at an altitude of 15 km (Fig. 6). This means that the Vaisala RS92 radiosonde will underestimate the amount of water vapor in the tropical upper troposphere by up to a factor of 2.

Figure 7 shows the 100-m-averaged RH distribution in the 1–5- (the surface elevation is 920 m) and the

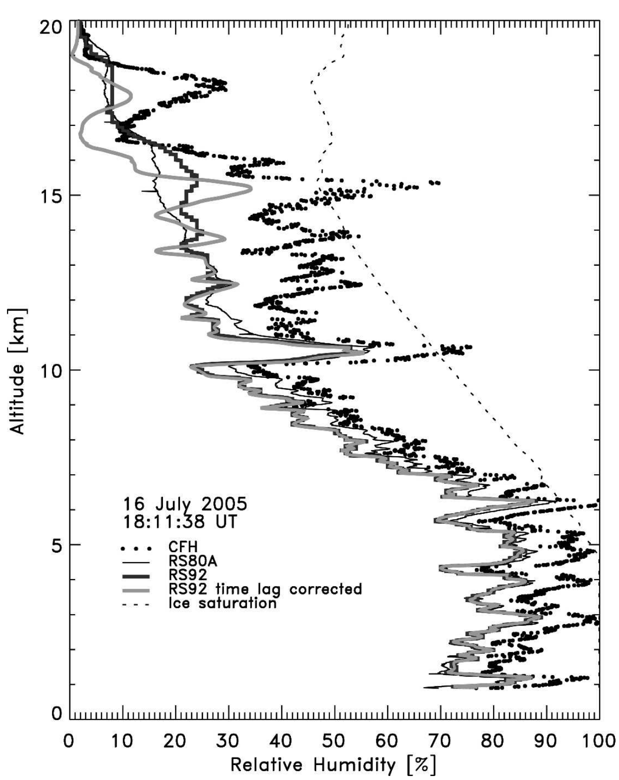

FIG. 5. Daytime simultaneous relative humidity profiles measured by CFH, Vaisala RS80, and Vaisala RS92 on 16 Jul 2005.

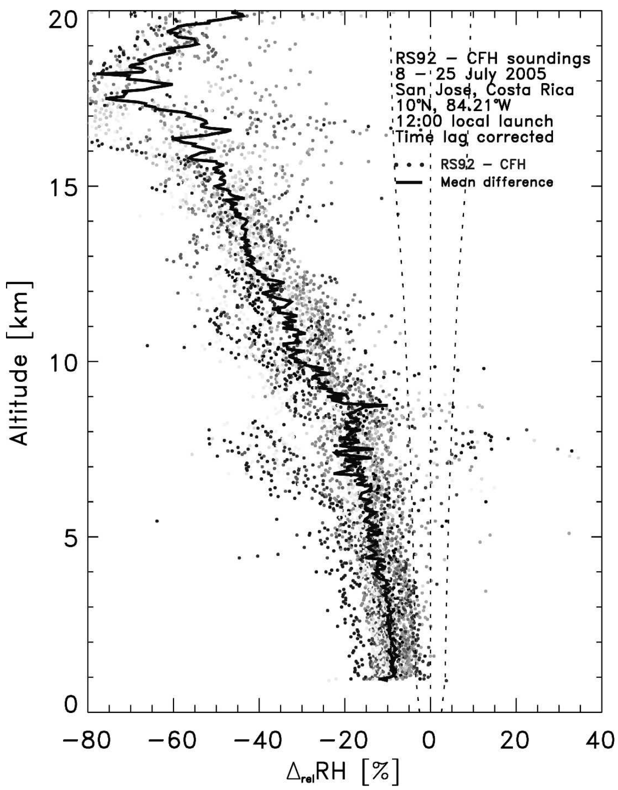

FIG. 6. Relative difference between the Vaisala RS92 and CFH daytime RH.

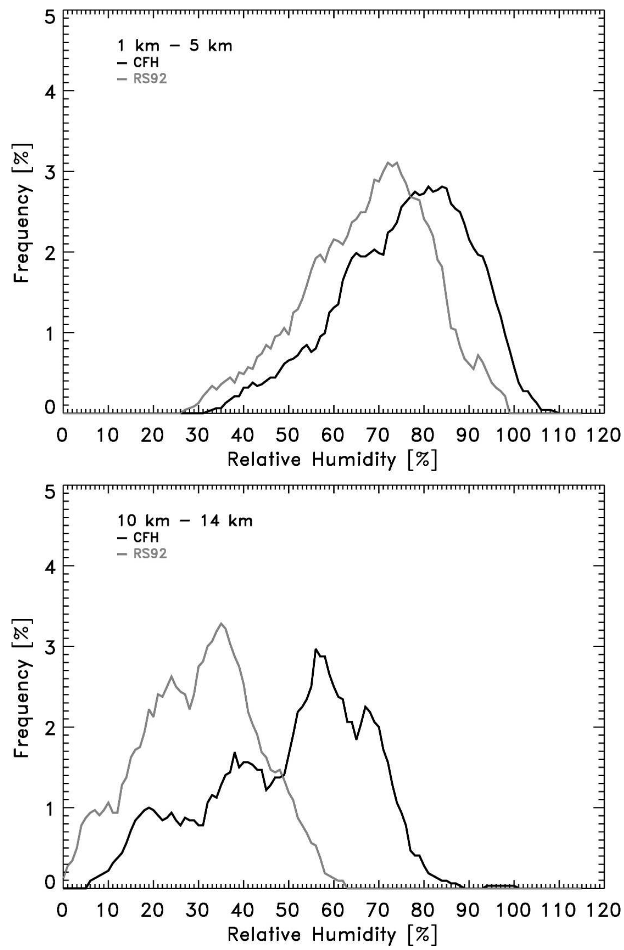

FIG. 7. Distribution of daytime RH averaged in 100-m layers for the (top) 1–5- and (bottom) 10–14-km layers.

10–14-km layers for both CFH and RS92. While the dry bias in the lower troposphere merely leads to a slight shift of the RH distribution, the dry bias in the upper troposphere also changes the shape of the RH distribution. In the lower layer the CFH observations show values above 100% RH (up to 110%, which is discussed below), whereas the RS92 observations completely failed to detect saturation during daytime observations despite frequent passage through the clouds.

4. Discussion

The daytime observations show a very strong dry bias, which is a combination of a very large radiation error and the slight calibration error. The cause of this radiation error is most likely solar heating of the sensor, which as a result will report a lower relative humidity. This radiation error is larger than that for the RS80 (Smout et al. 2000) because of the absence of a protective cap, which had been part of the RS80 humidity sensor. The absence of this protective cap exposes the sensing elements to direct sunlight, and the integrated heating elements make each of the two RS92 RH sensors significantly larger than the single RS80 sensor, providing more surface area that can be radiatively heated. The absence of the cap also increases the airflow across the sensor and reduces heating of the air, which is in contact with the sensor. Therefore, it is likely that the temperature of the sensor itself increases, leading to a drier RH reading.

This solar radiation error depends on the energy input into the sensor, which is a function of the solar zenith angle and the sensor orientation. It is somewhat counteracted by forced cooling as the sensor rises, which depends strongly on the ambient pressure and decreases with altitude. The calibration error, on the other hand, is most likely a function of the ambient temperature alone, while the time-lag error is a function of both ambient temperature and rise rate. These errors are convolved in the daytime comparison, and the average difference shown in Fig. 6 should, therefore, not be used directly as a correction factor. To be able to use these results at locations outside the Tropics, these errors have to be deconvolved.

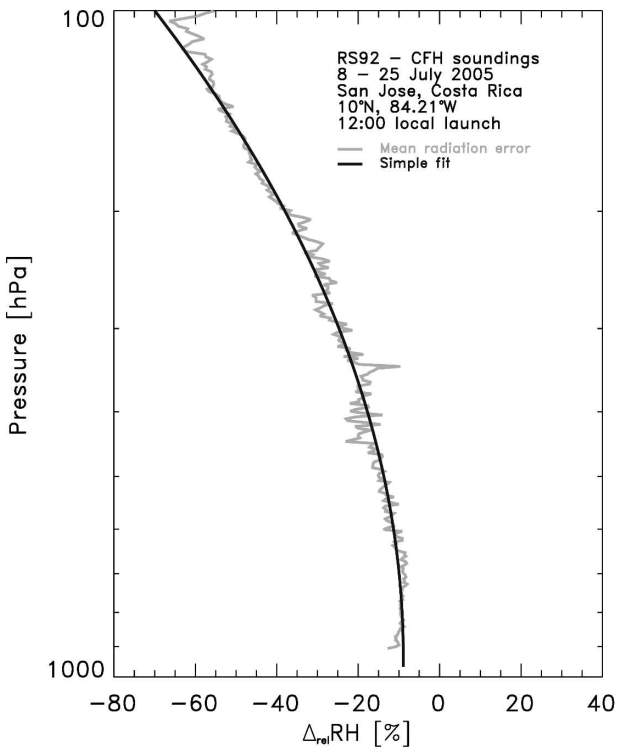

FIG. 8. Mean radiation error as a function of pressure.

a. Dry bias correction

The time-lag error was corrected using the results of Miloshevich et al. (2004). To extract the pressure-dependent radiation correction, the temperature-dependent calibration correction was then applied to the time-lag-corrected RS92 data and the average relative difference between the calibration-corrected RS92 and CFH data was calculated. The result is shown in Fig. 8. A simple fit can be derived, which gives the radiation error correction factor as a function of pressure altitude. It has the form

$$c_{\text{rad}}(P) = -0.121\,58 \ln(P)^2 + 1.664 \ln(P) - 4.7855, \quad (1)$$

where P is given in hectopascals. Using this correction factor, the corrected RH values can be derived as

$$\text{RH}_{\text{corr}} = \frac{\text{RH}_{\text{TL}}}{c_{\text{rad}}(P)[c_{\text{cal}}(T)]}, \quad (2)$$

where RH_{TL} is the time-lag-corrected humidity profile, $c_{\text{rad}}(P)$ is given in Eq. (1), and $c_{\text{cal}}(T)$ is the temperature-dependent calibration correction given in Table 1. This correction scheme may also be used with the original relative humidity profile instead of the time-lag-corrected profile, which leads to a small degradation in the uppermost troposphere, which is discussed in section 4c.

All daytime soundings at Alajuela were launched near local noon, with solar zenith angles on ascent between 10° and 30°. There is insufficient information to evaluate the solar zenith dependency at higher solar zenith angles. While the data are sufficient to estimate a radiation correction factor as a function of pressure, there are not enough data to estimate the contribution of the rise rate. The balloons launched in this study had a typical ascent rate of 6–7 m s^{-1}, which is significantly faster than the typical ascent rate of a standard radiosonde. Forced cooling of the sensors is therefore somewhat stronger compared to a regular sounding, and the radiation error correction suggested here is likely a conservative estimate.

Forced cooling becomes an inefficient process at lower pressures. In that region the radiative correction factor should reach a constant value, which depends on solar zenith angle only and no longer on pressure. The simple fit described here does not capture this limit and our data are insufficient to determine this limit quantitatively, because solar zenith angle dependency, the limitation of reported RS92 RH to integer values, and instrument-to-instrument variability become dominating factors in the upper troposphere and lower stratosphere. As a simple solution to this problem, the radiation correction factor is limited to the value $c = 0.44$, which is reached at 130 hPa.

b. Residual error after correction

The quality of the correction proposed here is described by the residual error, which is defined as the average difference between the corrected RS92 and the CFH measurements. It allows an evaluation of the error remaining after all corrections and an evaluation of the vertical range over which this correction can produce meaningful results. The residual error applies to the entire dataset, because it averages over the sonde-to-sonde variability. The residual error for individual profiles is larger, and the scatter of data points around the mean (shown in Fig. 6) represents the variability of the residual errors that may be expected for individual profiles. Figure 9 shows the residual error for the Ticosonde 2005 dataset and its standard deviation. Using all corrections it is less than 7% up to an altitude of 15.2 km, with a maximum standard deviation of 22% (Fig. 9b). This error is well within the combined uncertainty of the CFH and the RS92, and can be considered as measurement error. The average tropopause height during this campaign was 15.9 km. Between 15.2 km and the tropopause, the residual error and its standard deviation begin to increase strongly and show large

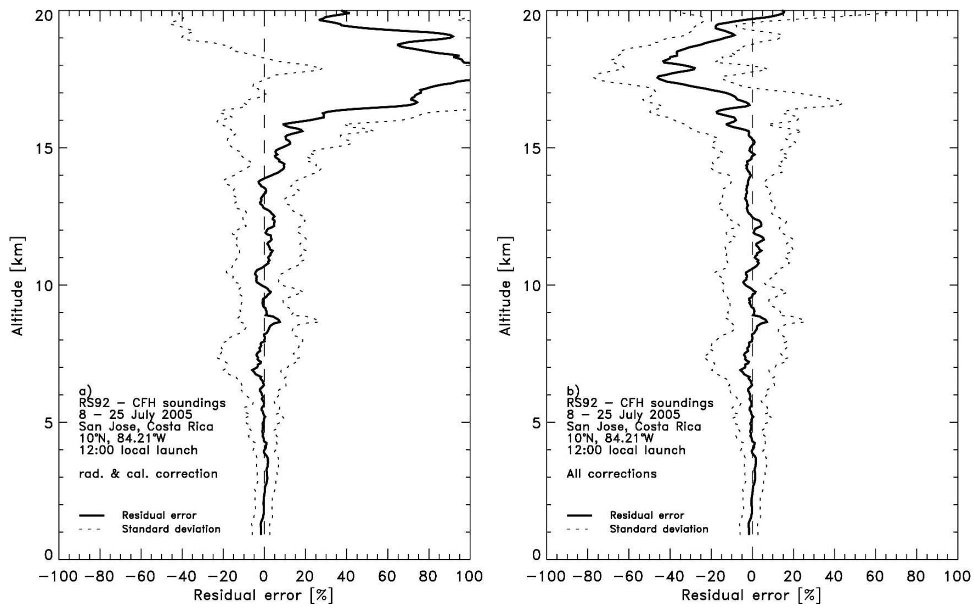

FIG. 9. Residual error: (a) after applying radiation and calibration correction, and (b) after applying radiation, calibration, and time-lag correction.

variations. This region typically showed a significant change in lapse rate, which is one indicator for the lower limit of the tropical tropopause layer (e.g., Selkirk 1993; Highwood and Hoskins 1998). The pressure at 15.2 km is about 130 hPa, which is one reason why this level was chosen to limit the radiation correction. Figure 9 clearly shows that the variations in the residual error above this level are no longer explained by a simple monotonic dry bias. Both the residual error and its standard deviation become large in the lower stratosphere. Given that the natural atmospheric variability of water vapor in this region is small, this large error implies that the corrected RH values do not contain any significant amount of information, and that water vapor concentrations derived from the corrected RH measurements do not improve the knowledge beyond a climatological mean value derived by other, more accurate, measurements like the CFH. Therefore, the RS92 humidity sensor using the corrections described here does not provide useful water vapor measurements in the tropical tropopause layer or above. However, up to this level, the measurements are significantly improved by these corrections.

c. *Importance of the time-lag correction*

The time lag of the RS92 humidity sensor is most significant at cold temperatures. Figure 9a shows the residual error for the data corrected for solar radiation and calibration error only, but not for time-lag error. Figure 9b shows that the contribution of the time-lag correction in the corrections described here becomes noticeable above 14 km ($T < -68°C$). The use of the small calibration correction and large radiation correction on tropical Vaisala RH data, which have not been time lag corrected, will produce very good results up to about 14 km and a wet bias of up to 17% at 15.2 km. Below 14 km, the residual errors for non-time-lag-corrected data are nearly identical to data that had the additional time-lag correction.

A better characterization of the RS92 humidity sensors at very cold temperatures below −70°C and at very low humidities, as well as an improvement of the radiation dry bias, may improve this in the future. However; significantly more work is required at this point.

d. *Impact of the correction*

The RH distributions shown in Fig. 7 were recalculated using the corrected Vaisala data and are shown in Fig. 10. At the lower layer, the CFH RH distribution is recreated remarkably well; in particular, saturation in clouds is recreated. In fact, the somewhat questionable supersaturation values shown by the CFH are recreated by the corrected RS92 data, with nearly the same shape as for the CFH observations. This may indicate that these values are not influenced by either humidity sensor, but rather by a cold bias of the temperature sensor inside the clouds. However, the questionable supersaturation values may also be a result of the instrumental uncertainty for a Gaussian-type distribution of both the measurements for the CFH the correction uncertainty

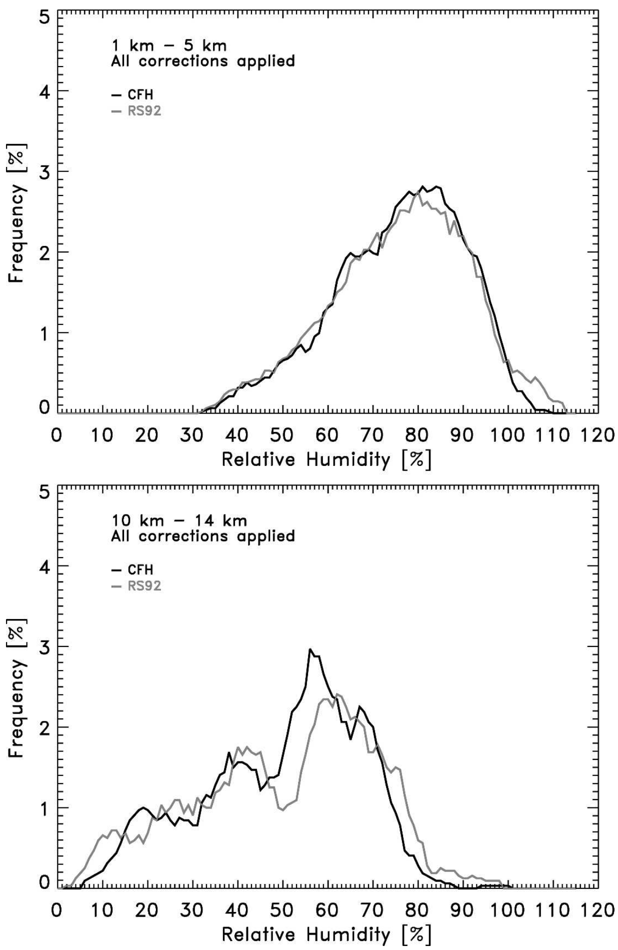

FIG. 10. Distribution of corrected daytime RH averaged in 100-m layers for the (top) 1–5- and (bottom) 10–14-km layers.

for the corrected RS92 data. The upper layer also shows significant improvement, and the general shape of the RH distribution measured by the CFH is reproduced by the corrected RS92 data. The fact that the shape of the RH distribution is reproduced reasonably well supports the implicit assumption that there is no significant RH dependency in these corrections. Some residual errors remain, however, particularly at the very dry end of the distribution as well as in the location of the peak around 60% RH. These might be related to an incomplete treatment of solar zenith angle and rise rate and a residual RH dependency, as well as instrumental variability.

The dry bias in PWV is largely determined by the dry bias in the lowest parts of the sounding profile. Before correction, the average dry bias in PWV is 11%, which is larger than the bias in PWV found in the comparison with microwave radiometers at the ARM. The time-lag correction does not influence the bias in PWV, because it affects only the upper troposphere, where the contribution to PWV is minimal. The radiation correction reduces this average dry bias to 1.0%. The dry bias for the RS92 nighttime comparisons without corrections is 2.0%, based on the four nighttime soundings used here.

e. Application to RS90 and changed RS92 sonde versions

The corrections proposed here most likely do not apply to data obtained with the RS90 radiosonde. There are only four soundings that compare the RS90—two using the CFH and two using the older NOAA/CMDL hygrometer, which does not perform as well in the troposphere (e.g., Vömel et al. 2007b). In addition, Smout et al. (2000) noticed that there were batch differences between different RS90 sondes as well as differences resulting from launch preparation procedures. Together, these effects significantly reduce the data quality for the RS90 comparisons and make a quantitative study of the radiation dry bias impossible, given the small number of soundings. Nevertheless, these soundings strongly suggest that the radiation error of the RS90 may not be as large as that of the RS92. This may indicate that there are some physical differences between the RS90 and RS92 humidity sensors, which would imply that future changes in the RS92 humidity sensor design could strongly affect the radiation dry bias of this sensor.

During the World Meteorological Organization (WMO) radiosonde intercomparison at Mauritius in February 2005 (see information online at http://www.wmo.ch/web/www/IMOP/reports/2003-2007/RSO-IC-2005_Final_Report.pdf), Vaisala tested a modified version of the RS92, which had improved radiation shielding of the humidity sensor arm over the production model. These results indicate that the radiation dry bias of this RS92 version is lower than that of the current operational model, which was used in our study. However, preliminary results of comparisons using RS92 radiosondes sold in 2006 indicate that this version is affected similarly as the version used in this study.

The Mauritius intercomparison also indicated a slight moist bias compared to the Snow White hygrometer for some RS92 sondes at cold temperatures in nighttime soundings. This discrepancy was attributed to the termination of the pulse heating of the sensors at −40°C. Sondes for which the termination of the pulse heating had been changed to −60°C showed significantly less discrepancies. Production models of the Vaisala RS92 had the termination of pulse heating at −40°C until the middle of 2005, which included the RS92 sondes used here. In the middle of 2005 the termination in production models was changed to −60°C. We suspect that the slight wet bias that was observed at −70°C may not be reproduced with current production models.

5. Summary and conclusions

Simultaneous measurements of relative humidity by Vaisala RS92 radiosondes and the reference CFH instrument reveal a minor calibration error in nighttime measurements and a large radiation dry bias in daytime measurements. These soundings provide data on the altitude dependency of this radiation dry bias, which reaches values of up to 50% at 15 km in the tropical upper troposphere. The dry bias is a function of pressure and is expected to be more significant in tropical than in polar regions, because the tropopause is significantly higher in the Tropics, thereby limiting the vertical range in which radiosonde RH data should be considered. At high latitudes the solar zenith angle is also lower, which is also expected to lead to a lower-radiation dry bias.

Some sites, particularly the ARM program sites, regularly scale RH profiles with microwave observations of total precipitable water vapor (Turner et al. 2003). This scaling eliminates the dry bias in the lower parts of the profile, which have the largest contribution to precipitable water vapor. However, this correction will not correct for the middle- and upper-tropospheric dry bias, because these regions contribute little to the precipitable water. Microwave scaling applied after a radiation correction will give improved results, even for solar zenith angles slightly outside the range studied here.

The RS92 radiosonde was introduced in 2003, and the production of the RS80 radiosonde is currently being phased out, with only the National Weather Service (NWS) continuing to use the RS80. Therefore, the RS92 is quickly replacing the RS80 radiosonde, and this radiation error is beginning to affect climate records for Vaisala radiosonde sites (with the exception of NWS sites), as the last stocks of RS80 radiosondes are being spent.

Radiosonde manufacturers should ensure that time series of observations can be continued and are not impacted by instrumental changes. In the case of the introduction of the Vaisala RS92 radiosonde, climatological time series of RH in the middle and upper troposphere will be impacted significantly. However, correction schemes like the one proposed here will be able to improve the RH observations. This highlights the importance of independent characterization of radiosonde observations with any change of instrumentation.

Acknowledgments. This work was supported in parts by the NASA Radiation Sciences Program; the NASA Atmospheric Chemistry, Modeling, and Analysis Program; and the NASA Upper Atmosphere Research Program. The authors thank Oliver Gómez for excellent logistical support; Paulo Manso Salgado, Alexander Cordoba Canales, Luis Zumbado Ramírez, Rodolfo Sánchez González, Carlos Badilla Chávez, Víctor Hernández, Octavio Castillo Vega, and Adolfo Alvarado Gonzalez of IMN; and Edgar Gómez Chaves, Jose Morales Rivera, Rosa Alfaro Solís, Berny Meléndez Alfaro, Aylin Castillo Ovares, Jose Pablo Sibaja Brenes, Ilena Vega Guzmán, Yerling Carranza Jiménez, Jose Pablo Jiménez Oviedo, Victor Hugo Beita Guerrero, Karla Cerna Solano, Rocio Alfaro Avendaño, Gabriela Hernández Hernández, Sebastián Miranda Brenes, and Diana González Orozco for the CFH preparation and launch.

REFERENCES

Goff, J. A., and S. Gratch, 1946: Low-pressure properties of water from −160 to 212 F. *Trans. Amer. Soc. Heat. Ventilat. Eng.,* **52,** 95–122.

Highwood, E. J., and B. J. Hoskins, 1998: The tropical tropopause. *Quart. J. Roy. Meteor. Soc.,* **124,** 1579–1604.

Hyland, R. W., and A. Wexler, 1983: Formulations for the thermodynamic properties of the saturated phases of H_2O from 173.15 K to 473.15 K. *ASHRAE Trans.,* **89,** 500–519.

Luers, J. K., 1997: Temperature error of the Vaisala RS90 radiosonde. *J. Atmos. Oceanic Technol.,* **14,** 1520–1532.

Miloshevich, L. M., H. Vömel, A. Paukkunen, A. J. Heymsfield, and S. J. Oltmans, 2001: Characterization and correction of relative humidity measurements from Vaisala RS80-A radiosondes at cold temperatures. *J. Atmos. Oceanic Technol.,* **18,** 135–156.

——, A. Paukkunen, H. Vömel, and S. J. Oltmans, 2004: Development and validation of a time-lag correction for Vaisala radiosonde humidity measurements. *J. Atmos. Oceanic Technol.,* **21,** 1305–1327.

——, H. Vömel, D. N. Whiteman, B. M. Lesht, F. J. Schmidlin, and F. Russo, 2006: Absolute accuracy of water vapor measurements from six operational radiosonde types launched during AWEX-G and implications for AIRS validation. *J. Geophys. Res.,* **111,** D09S10, doi:10.1029/2005JD006083.

Selkirk, H. B., 1993: The tropopause cold trap in the Australian monsoon during STEP/AMEX 1987. *J. Geophys. Res.,* **98,** 8591–8610.

Smout, R., J. Elms, D. Lyth, and J. Nash, 2000: New technology in upper-air observations. *Proc. TECO-2000 Conf.,* WMO/TD-1028, Beijing, China, World Meteorological Organization, 179–182.

Turner, D. D., B. M. Lesht, S. A. Clough, J. C. Liljegren, H. E. Revercomb, and D. C. Tobin, 2003: Dry bias and variability in Vaisala RS80-H radiosondes: The ARM experience. *J. Atmos. Oceanic Technol.,* **20,** 117–132.

Vömel, H., S. J. Oltmans, D. J. Hofmann, T. Deshler, and J. M. Rosen, 1995: The evolution of the dehydration in the Antarctic stratospheric vortex. *J. Geophys. Res.,* **100,** 13 919–13 926.

——, D. David, and K. Smith, 2007a: Accuracy of tropospheric and stratospheric water vapor measurements by the Cryogenic Frost point Hygrometer (CFH): Instrumental details and observations. *J. Geophys. Res.,* in press.

——, V. Yushkov, S. Khaykin, L. Korshunov, E. Kyrö, and R. Kivi, 2007b: Intercomparisons of stratospheric water vapor sensors: FLASH-B and NOAA/CMDL frost-point hygrometer. *J. Atmos. Oceanic Technol.,* **24,** 941–952.

Wang, J., H. L. Cole, D. J. Carlson, E. R. Miller, K. Beierle, A. Paukkunen, and T. K. Laine, 2002: Corrections of humidity measurement errors from the Vaisala RS80 radiosonde—Application to TOGA COARE data. *J. Atmos. Oceanic Technol.,* **19,** 981–1002.

Whiteman, D. N., and Coauthors, 2006: Analysis of Raman lidar and radiosonde measurements from the AWEX-G field campaign and its relation to Aqua validation. *J. Geophys. Res.,* **111,** D09S09, doi:10.1029/2005JD006429.