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Performance of the Vaisala RS80A/H and RS90 Humicap Sensors and the Meteolabor “Snow White” Chilled-Mirror Hygrometer in Paramaribo, Suriname

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ABSTRACT

In climate research there is a strong need for accurate observations of water vapor in the upper atmosphere. Radiosoundings provide relative humidity profiles but the accuracy of many routine instruments is notoriously inadequate in the cold upper troposphere. In this study results from a soundings program executed in Paramaribo, Suriname (5.8°N, 55.2°W), are presented. The aim of this program was to compare the performance of different humidity sensors in the upper troposphere in the Tropics and to test different bias corrections suggested in the literature. The payload of each sounding consisted of a chilled-mirror “Snow White” sensor from Meteolabor AG, which was used as a reference, and two additional sensors from Vaisala, that is, either the RS80A, the RS80H, or the RS90. In total 37 separate soundings were made.

For the RS80A a clear, dry bias of between -4% and -8% RH is found in the lower troposphere compared to the Snow White observation, confirming the findings in previous studies. A mean dry bias was found in the upper troposphere, which could be effectively corrected. The RS80H sensor shows a significant wet bias of 2% – 5% in RH in the middle and upper troposphere, which has not been reported before. Comparing observations with RS80H sensors of different ages gives no indication of sensor aging or sensor contamination. It is therefore concluded that the plastic cover introduced by Vaisala to avoid sensor contamination is effective. Finally, the RS90 sensor yields a small but significant wet bias of 2% – 3% below 7-km altitude.

The time-lag error correction from Miloshevich et al. was applied to the Vaisala data, which resulted in an increased variability in the relative humidity profile above 9- (RS80A), 8- (RS80H), and 11-km (RS90) altitude, respectively, which is in better agreement with the Snow White data.

The averaged Snow White profile is compared with the average profiles of relative humidity from the European Centre for Medium-Range Weather Forecasts (ECMWF). No significant bias is found in either the analyses or the forecasts. The correlation coefficient for the Snow White and ECMWF data between 200 and 800 hPa was 0.66 for the 36-h forecast and 0.77 for the analysis.

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1. Introduction

Water vapor is the dominant greenhouse gas and it plays an important role in climate through the formation of clouds and precipitation, as a precursor for important chemical species (e.g., the OH radical) and as a tracer for stratosphere–troposphere exchange. Accurate observations are difficult to make because water vapor concentrations vary by five orders of magnitude with respect to both height and time. It has been found that biases in observed upper-air relative humidity in the Tropics leads to significant errors in estimations of radiative fluxes, atmospheric stability, and convective precipitation (Gutzler 1993; Guichard et al. 2000; Ciesielski et al. 2003). Improvements of the current routine radiosonde measurements are especially needed in the upper troposphere, where most humidity sensors become inaccurate. At many upper-air network stations the Vaisala Humicap sensors are used for humidity measurements. Since 1980 four types of humidity sensors have been introduced by Vaisala—the RS80A, RS80H, RS90, and, most recently, RS92. For the interpretation of the observations it is important to know the accuracy and reliability of these sensors in different circumstances. The performance of the different sensors has to be known in order to be able to produce homogenized datasets for process studies and climate research.

Several studies have been performed to assess the accuracy of these sensors and several schemes have been proposed to correct for the different types of errors. Miloshevich et al. (2001) and Wang et al. (2002) derived correction schemes for different errors of the RS80A and RS80H. Miloshevich et al. (2004) developed a method to correct for the slow response of the Humicap sensors and evaluated the correction scheme by comparing RS80H profiles with the National Oceanic and Atmospheric Administration/Climate Modeling and Diagnostics Laboratory (NOAA/CMDL) cryogenic hygrometer. In this study the effect of the time-lag correction on the RS80A, RS80H, and RS90 is evaluated by comparing the observations of the Humicap sensors with the chilled-mirror “Snow White” (“SW”) sensor from Meteolabor AG. Fujiwara et al. (2003) made a comparison of the RS80A/H with the Snow White sensor using data at five tropical stations, and found for the RS80A a dry bias in the wet lower troposphere and a reasonable agreement for the RS80H up to 12 km. In this study we compare the Snow White hygrometer results to Vaisala’s RS80 and RS90 sensors.

The observations we use for the comparison are the results of a sounding program in Paramaribo (5.8°N, 55.2°W), Suriname, near the northern coast of South

America. The objective of this program was to assess the properties of different water vapor sensors in a humid tropical environment. These observations were made between 1999 and 2005, and are part of a larger measurement program performed at this site, which includes weekly ozone soundings, total ozone column and UV measurements, and the observation of several other chemical components.

For this study 37 soundings were conducted with a payload of three sensors that simultaneously measured the water vapor profiles. Each sounding consisted of the Snow White hygrometer and two types of radiosondes from Vaisala (see Table 1). Details of the instrumentation are given in the next section, and the observations are compared in section 3. The effect of the time-lag error correction on the RS80 and RS90 results is presented in section 4. Finally, in section 5 the measured profiles are compared with European Centre for Medium-Range Weather Forecasts (ECMWF) model analyses and forecasts.

2. Instrumentation

a. The Vaisala RS80 and RS90 Humicap sensors

The Vaisala Humicap RH sensor is a thin-film capacitive sensor, using a highly porous polymer electrode, whose capacity depends on the amount of water vapor and the air temperature. Two different polymer materials are used in the sensors, the A-Humicap and the H-Humicap.

The Vaisala RS80A sondes contain the A-Humicap sensor and are widely used for routine soundings at many operational stations in the world. For example, the ozone soundings regularly made in Paramaribo contained this type of humidity sensor up to November 2003, after which time the RS80H (H-Humicap) sensor was used. Vaisala uses the H-Humicap polymer in both the RS80H and RS90 sondes. Moreover, the calibration procedure for these sensors is more accurate, as will be explained below under “error sources.” The RS90 radiosonde is equipped with two H-Humicap polymer sensors, each half the size of the older RS80 H-Humicap, which are alternately heated and used for measurement. The size reduction reduces the time lag and the dual-sensor design reduces the problems of icing and contamination of the polymer, improving the data quality.

There have been several studies reported in literature on measurement errors associated with the Vaisala sensors, and various bias corrections have been suggested (e.g., Leiterer et al. 1997; Miloshevich et al. 2001; Wang et al. 2002; Fujiwara et al. 2003). A number of error sources have been identified, namely,

TABLE 1. Details of the payloads of the sondes launched in Paramaribo. Data resolution is 0.1% RH except (*), which is 1% RH (Vaisala DigiCORA). Sondes were launched either at around 0330 (M: morning) or around 2000 (E: evening) LT.

Sounding No.	Launch date M/E	Snow White	RS90 (production month)	RS80A/H (production month)
1	16 Oct 2002 E	X	X (Nov 2001)	A (Jan 2000)
2	17 Oct 2002 E	X	X (Nov 2001)	A (Jan 2000)
3	18 Oct 2002 E	X	X (Nov 2001)	H (May 2001)
4	22 Oct 2002 E	X	X (Nov 2001)	A (Oct 2001)
5	23 Oct 2002 E	X	X (Nov 2001)	A (Oct 2001)
6	29 Jan 2003 E	X	X (Nov 2001)	A (Feb 2001)
7	28 Feb 2003 E	X	X (Nov 2001)	A (Feb 2000)
8	31 Mar 2003 E	X	X (Nov 2001)	A (Feb 2001)
9	30 Apr 2003 E	X	X (Nov 2001)	A (Feb 2001)
10	30 May 2003 E	X	X (Nov 2001)	A (Feb 2001)
11	30 Jun 2003 E	X	X (Nov 2001)	A (Feb 2001)
12	11 Feb 2004 E	X	X (Nov 2001)	H (Aug 2003)
13	18 Feb 2004 E	X	X (Nov 2001)	H (Oct 2003)
14	25 Feb 2004 E	X		H (Oct 2003) + A (Jun 2001)*
15	10 Mar 2004 E	X		H (Oct 2003) + A (Dec 2002)*
16	17 Mar 2004 E	X		H (Oct 2003) + A (Dec 2002)*
17	15 Oct 2004 M	X		H (Nov 2003)* + A (Dec 2002)
18	21 Oct 2004 M	X		H (Jun 2004)* + A (Dec 2002)
19	27 Oct 2004 M	X		H (Jun 2004)* + H (Jun 2004)
20	31 Oct 2004 M	X		H (Jun 2004)* + H (Jun 2004)
21	3 Nov 2004 M	X		H (Nov 2003)* + H (Nov 2003)
22	6 Nov 2004 M	X	X (Nov 2001)	A (Sep 2002)
23	9 Nov 2004 M	X		H (Nov 2003)* + H (Nov 2003)
24	10 Nov 2004 M	X	X (Nov 2001)	H (Nov 2003)
25	12 Nov 2004 M	X	X (Nov 2001)	H (Jun 2004)
26	15 Nov 2004 M	X	X (Nov 2001)	H (Jun 2004)
27	16 Nov 2004 M	X		H (Nov 2003)* + A (Oct 2001)
28	22 Nov 2004 M	X		A (Dec 2002)* + A (Dec 2002)
29	22 Feb 2005 E	X	X (Nov 2001)	H (Dec 2002)
30	26 Feb 2005 M	X		H (Dec 2002) + H (Dec 2004)*
31	27 Feb 2005 E	X		H (Dec 2002) + H (Dec 2004)*
32	1 Mar 2005 E	X		H (Dec 2002)
33	4 Mar 2005 M	X	X (Nov 2001)	H (Dec 2002)
34	7 Mar 2005 M	X		H (Dec 2002) + H (Dec 2004)*
35	8 Mar 2005 E	X		H (Dec 2002) + H (Dec 2004)*
36	10 Mar 2005 E	X		H (Dec 2002) + H (Dec 2004)*
37	13 Mar 2005 M	X		H (Dec 2002) + H (Dec 2004)*

1) Sensor contamination: This causes a dry bias, whose magnitude depends on the sensor polymer, age, storage temperature, and the RH itself, with the H-Humicap being more sensitive to contamination than the A-Humicap. Wang et al. (2002) found for the 2-yr-old RS80A (A-Humicap) and RS80H (H-Humicap) sensors a dry bias resulting from contamination of 2% and 10% RH, respectively, near saturation at a temperature of 20°C. Vaisala solved this problem by packing the RS80 sensor arm in a special low-outgassing plastic cover with a desiccant material inside. This cover is placed on all sondes produced after June 2000. Because of the different construction material of the RS90 it is expected that the contamination error for this sensor is negligible.

2) The sensor aging error: This is caused by the long-

term instability of the sensor material, causing a dry bias. This error is larger for A-Humicap sensors (RS80A) than for H-Humicap sensors (RS80H and RS90). Wang et al. (2002) estimated for the RS80A a dry bias of -5% at saturation after 2-yr storage time, increasing with 0.5% RH per year thereafter. The error can partially be eliminated by performing a ground check of the sensor at 100% RH in addition to the 0% RH ground check that is standard procedure for the Vaisala sensors prior to launch (Leiterer et al. 1997).

3) The calibration method: The relative humidity is derived from the measured sensor capacitance of the Humicap. This capacitance of the polymer sensor is both dependent on the RH and on the temperature. At low RH the temperature dependence of the sen-

sor response is linear, but near ice saturation and at low temperatures the response is highly nonlinear. The standard data processing algorithm calculates RH by scaling between two curves, which are the linear approximations for the temperature dependence at 0% RH and at ice saturation. The approximation of the temperature-dependent response of the sensor at ice saturation at low temperatures (below -25°C) is especially inaccurate. The error involved is referred to as the temperature-dependence (TD) error. Miloshevich et al. (2001) derived corrections for this error by comparing simultaneous observations of the RS80A sensor with the cryogenic frost-point hygrometer from NOAA. Correction factors for the RS80A range from close to 1.0 at temperatures warmer than -25°C to 1.1 at -30°C (~ 10 km height) and more than 1.4 below -50°C (12 km). Below -40°C the TD error dominates all other errors. The TD correction factors for RS80H and RS90 are much lower because Vaisala uses a polynomial expression for the temperature dependence of these sensors, which is more accurate (Wang et al. 2002; Miloshevich et al. 2004).

- 4) Instrument response time: The response time increases with decreasing temperature, and when it is long, compared to the time scale of humidity variations, it will give rise to time-lag (TL) errors. The temperature dependence of the response time τ is determined in the laboratory and polynomial fits are derived by Miloshevich et al. (2001, 2004) for the RS80A and -H and the RS90 sensors. In section 4 the TL error will be discussed in more detail.

b. Meteolabor AG Snow White hygrometer

The Swiss company Meteolabor AG produces the SW hygrometer. This instrument continuously measures the dew-/frost-point temperature during a balloon flight, using a $3\text{ m} \times 3\text{ m}$ mirror attached to the cold side of a Peltier element. The hot side of the Peltier element is connected to an aluminum radiator, which is cooled by the air. During a flight a layer of condensate (dew or frost) is maintained on the mirror by cooling it down to the dew-/frost-point temperature. The thickness of the condensate is monitored using a lamp, an optical fiber, and a phototransistor. The electric feedback circuit automatically controls the power of the Peltier cooler to maintain a constant layer of condensate on the mirror. The mirror temperature (the dew-/frost-point temperature) is measured because the Snow White mirror is also a thermocouple. The sensor housing is equipped with a heater, which operates in cloud layers to avoid sensor icing and to make total water measurements (Wang et al. 2003).

In this study all soundings were equipped with the so-called “night”-type Snow White, that is, an ASW35 sensor without the Styrofoam cover of the sensor housing, in order to avoid the outgassing and improve the cooling of the radiator. Additional housekeeping data related to the hygrometer (Peltier current, temperature of the hot side of the Peltier element, and phototransistor voltage) are also collected during the flight in order to monitor the behavior of the instrument and assess the dew-to-frost conversion level. The lower detection limit of the night-type SW is about 3% relative humidity (Vömel et al. 2003). Saturation vapor pressure over water and ice are calculated with the expressions given in Hyland and Wexler (1983) consistent with the processing used by Vaisala. For additional technical details of the SW hygrometer and the calculation of the relative humidity from the SW data the reader is referred to Fujiwara et al. (2003).

c. Ground station

The Snow White is connected with the Vaisala radiosonde using a TMAX-C interface board (available from TMAX, 990 Toedtl Dr., Boulder, CO 80305), which allows eight analog channels to be transmitted in addition to the normal Vaisala channels. The ground receiving system consists of an antenna and 403-MHz receiver. The software used to receive and process the data in real time was developed at NOAA/CMDL (more information about this software can be found online at <http://cires.colorado.edu/~voemel/strato/strato.html>). The sampling interval was 7–8 s (determined by the TMAX interface), and the typical ascent rate was $\sim 5\text{ m s}^{-1}$. The data of the Vaisala sensor are stored with a resolution of 0.1% RH.

In addition to the RS80–TMAX-C combination described above, a second Vaisala radiosonde (RS90 in most cases; see Table 1) is connected to the Snow White flight box, and its data are collected using a separate receiver, the DigiCORA II. The sampling interval of this second Vaisala sensor is $\sim 2\text{ s}$ and the data resolution is 1% RH (in Table 1 the second Vaisala sensor on each payload is labeled with a “*”). To compare the observations of the three sensors, the data are all interpolated to the Snow White levels. The soundings typically reached an altitude of between 30 and 35 km, but for the comparison we do not use data above 16-km height. Only data collected during the ascent are used in our analysis.

3. Comparison of the sensors

In total 37 sondes were launched at irregular time intervals (Table 1) during several measurement cam-

FIG. 1. (left) Comparison of the Snow White sensor with the RS80A observations and (right) ratio of $RH_{RS80A}/RH_{SnowWhite}$ as a function of air temperature below 12-km altitude and based on 19 simultaneous soundings. The gray dashed line in the right panel represents $RH_{RS}/RH_{RS,c}$, where the subscript c refers to the value after the temperature-dependent correction from Miloshevich et al. (2001), based on a comparison with the cryogenic frost-point hygrometer from NOAA. Snow White observations of RH below 15% are indicated in gray.

paings. All soundings took place in the evening around 2000 local time (LT; 2300 UTC) or at night around 0330 LT (0630 UTC) in nonprecipitating conditions. All data presented are without a 0% and 100% RH ground check because this was not part of the standard procedure prior to all launches. The effect of other bias corrections will be discussed in this section and in section 4. Snow White observations in extremely dry conditions, where the capacity of the Peltier cooler was not sufficient to reach the frost- or dewpoint, were left out of the comparison. This occurred at approximately 3% of the data points below 16-km altitude.

To rule out the effect of icing of both sensors on the statistics, a subset was made by discarding observations in or above clouds in the full dataset. Based on the relative humidity measured by the Snow White sensor, around nearly 40% of the data points between 10 and 15 km were rejected for this subset (around 20% of all points). In the comparison the full dataset (including clouds) is used, unless stated otherwise.

a. RS80A versus Snow White

Figure 1 shows the individual data points of the RS80A versus the Snow White based on 19 soundings. In Fig. 2, the mean and standard deviation within 1-km vertical bins were calculated for each sounding, and subsequently averaged over all soundings. A clear, dry bias from approximately -4% to -8% in relative humidity is found for the RS80A between the surface and 4 km (0°C). In the midtroposphere (4–8 km) the dry bias is reduced to less than 3%, and it rapidly increases

above 10 km. The dry bias of the RS80A (significance level $>99\%$) at high relative humidity in the lower troposphere has been reported before (e.g., Leiterer et al. 1997; Fujiwara et al. 2003; Nakamura et al. 2004), and is also found in the subset consisting of only cloud-free data. The least squares fit in our observations is $RH_{RS80A} = -0.24 + 0.90 RH_{SW} (\%)$, similar to that found by Fujiwara et al. (2003).

Two errors may have caused the large dry bias of the RS80A, that is, sensor aging and sensor contamination. The RS80A sensors used in this study were, on average, ~ 2 yr old (see Table 1), which would explain a dry bias resulting from sensor aging of approximately -5% RH at saturation (Wang et al. 2002). Nearly all RS80A sensors were produced with the special plastic cover designed to avoid contamination. The two sensors without this cover (soundings 1 and 2) showed relatively small dry biases near the surface of -2% and -4% RH, respectively. It is therefore unlikely that sensor contamination is responsible for the large dry bias that was found.

In both Figs. 1 and 2 it is apparent that there is also a dry bias in the upper troposphere below approximately -15°C . This is because in the normal data processing, the temperature-dependent response of the sensor to water vapor is represented by a linear expression, which is not very accurate at low temperatures. We applied the correction derived by Miloshevich et al. (2001) for this TD error, which is based on calibration chamber measurements performed by Vaisala. As can be seen in the average profile (Fig. 2) the correction rectifies most of the mean difference that is found be-

FIG. 2. Average profile of (left) RH and (right) std dev observed by the Snow White hygrometer (thick black line) and Vaisala RS80A (dotted line), based on 19 soundings and vertical bins of 1 km. Dashed lines represent RS80A profiles corrected for the TD error (Miloshevich et al. 2001) and the thin black lines represent RS80A profiles corrected for the TD error and TL error (Miloshevich et al. 2001, 2004).

tween the RS80A and the Snow White in the upper troposphere (>8 km; $<-20^{\circ}\text{C}$).

The average standard deviation (Fig. 2, right panel) is a measure of the ability of the sensor to detect small-scale variations in the vertical humidity profile. For each sounding it is calculated from the individual observations within the 1-km bins and then averaged over all soundings. Each 1-km bin contained approximately 25–30 data points for each sensor. The variability of RH measured by the RS80A decreases at colder temperatures because of the longer response time of the sensor at low temperatures, that is, resulting from the time-lag error. Individual profiles (with and without TD correction) indicate that the RS80A sensor is not able to detect any variation in relative humidity above 12 km that is observed by the Snow White hygrometer. The TD error correction does not correct for the lack of variability in the upper troposphere. Corrections for the TL error are discussed further in the next section.

b. RS80H versus Snow White

There were 25 soundings made with the RS80H sensor. Because some payloads consisted of two RS80H sensors, we obtained in total 35 RS80H profiles. Scatterplots of the RS80H versus Snow White are given in

Fig. 3. The agreement with the Snow White observations is better than that which is found for the RS80A. Figure 4 shows that in the lowest 3 km no significant bias is found. Between 3 and 7 km there is a wet bias of $\sim 2\%$ RH, increasing to 5% at 10 km and above (significance level $>99\%$). The RH averaged over all simultaneous Snow White and RS80H soundings was lower than the RH averaged over all simultaneous Snow White and RS80A soundings. The large variability of $\text{RH}_{\text{RS80H}}/\text{RH}_{\text{Snow White}}$ in Fig. 3 (right panel) is mainly caused by the low-humidity points measured by the Snow White in combination with the wet bias of the RS80H. Figure 3 also shows the ratio $\text{RH}_{\text{RS}}/\text{RH}_{\text{RS}_c}$, where RH_{RS_c} represents the relative humidity after the correction from Wang et al. (2002) for the temperature-dependence error for 10% and 90% RH. However, applying these corrections would yield an even larger mean bias above 10 km. The same comparison with only the cloud-free data yields a similar wet bias. This suggests that icing problems of the Humicap sensors and/or possible sublimating ice coverage of the Snow White housing are not causing the bias, which thus remains unexplained.

FIG. 3. (left) Comparison of the Snow White sensor with the RS80H observations and (right) ratio of $RH_{RS80H}/RH_{SnowWhite}$ as a function of air temperature below 12-km altitude and based on 35 simultaneous soundings. The gray lines in the right panel indicate the ratio $RH_{RS}/RH_{RS,c}$, where $RH_{RS,c}$ represents the RH after the correction from Wang et al. (2002) for the TD error for 10% (dashed) and 90% (full) RH. Snow White observations of RH below 15% are indicated in gray.

The variations of the relative humidity observed by the RS80H within 1-km vertical bins are similar to what is measured by the Snow White up to a height of 8 km. The variability decreases rapidly above this height be-

cause of the longer response time of the sensor at temperatures below -20°C (see the next section).

Six soundings were made with two RS80H sensors of different ages (soundings 30, 31, and 34–37). In Fig. 5

FIG. 4. Average profiles of (left) RH and (right) std dev observed by the Snow White hygrometer (thick black line) and Vaisala RS80H (dotted line), based on 35 soundings and vertical bins of 1 km. The thin black lines represent RS80H profiles corrected for the TL error (Miloshevich et al. 2004).

FIG. 5. Comparison of observations with the RS80H sensors of different age, based on six simultaneous soundings.

the results of the 24-month-old sensors are plotted versus the results of simultaneous measurements made with 3-month-old sensors. No significant effect of aging or contamination is found, which indicates that the plastic cover to prevent contamination of the sensor introduced by Vaisala in June 2000 is effective.

c. RS90 versus Snow White

In total, 19 soundings were made with the RS90 in combination with the Snow White hygrometer. Figure 6 indicates a better agreement between both sensors be-

low 12 km compared to the RS80–Snow White combinations. Figure 7 shows a small wet bias of 2%–3% below 7 km (significance level >99%). The variance profiles are similar for both sensors up to about 12 km. The increasing sensor-response time affects the humidity variance of the RS90 at 12 km and above, which is at a considerably higher altitude than that in the case of the RS80.

In Fig. 8 the profiles of the average correlation coefficient of the three Vaisala sensors with the Snow White observations are shown. It clearly illustrates the improved behavior of the RS90 in the upper troposphere. Moreover, the rapid deterioration of the performance of the RS80A and RS80H above ~11 km altitude can also be seen. The correlation coefficient profile of the RS80A did not significantly change after the TD and the TL corrections were applied.

4. The time-lag error

From the observational data presented in the previous section it is clear that in the upper troposphere the performance of the Humicap sensors is hindered by the slow response. The time the sensors need to adjust to the environment depends on the design of the sensor and on temperature. Time-lag errors occur when the response time is large compared to the time scale of the humidity variations during the ascent. The temperature dependence of the response time has been determined in the laboratory by Vaisala for the RS80 and RS90 sensors. They used seven sensors of each type, and the response was measured at six temperatures between -60° and $+25^{\circ}\text{C}$. A polynomial fit to the measurements of the response time of each sensor type for in-

FIG. 6. (left) Comparison of the Snow White sensor with the RS90 observations and (right) ratio of $\text{RH}_{\text{RS90}}/\text{RH}_{\text{Snow White}}$ as a function of air temperature below 12-km altitude and based on 19 simultaneous soundings. Snow White observations of RH below 15% are indicated in gray.

FIG. 7. Average profile of (left) RH and (right) std dev observed by the Snow White hygrometer (thick black line) and Vaisala RS90 (dotted line), based on 19 soundings and vertical bins of 1 km. The thin black lines represent RS90 profiles corrected for the TL error (Miloshevich et al. 2004).

creasing as well as decreasing humidity is made by Miloshevich et al. (2004). The RS80H sensor is significantly slower than the RS80A and the RS90 at all temperatures. A response time of over 10 s is found for the RS80A below approximately -35°C (above ~ 10 km height), for the RS80H below -25°C (above ~ 9 km height), and for the RS90 below -40°C (above ~ 11 km height).

Miloshevich et al. (2004) developed a procedure to correct for the time-lag error of the Humicap sensor, which will be briefly summarized below. In the correction procedure the assumption is made that the sensor responds exponentially to a change of relative humidity as described by

$$\frac{dU_m}{dt} = \frac{U_a - U_m}{\tau}, \quad (1)$$

where U_m is the instantaneous measured humidity, U_a is the ambient humidity, and τ is the response time of the sensor derived from the Vaisala laboratory tests (Miloshevich et al. 2004). If the ambient humidity U_a is treated as a constant during the time between two measurements, the measured humidity at the end of the time step can be written as

$$U_m(t + \Delta t) = U_a - [U_a - U_m(t)]e^{-\Delta t/\tau}. \quad (2)$$

Equation (2) can be rearranged to get an expression for the ambient humidity estimated from the measured humidity at two subsequent times [$U_m(t)$ and $U_m(t + \Delta t)$], that is, the corrected humidity U_c ,

$$U_c = \frac{U_m(t + \Delta t) - U_m(t)X}{1 - X}, \quad \text{where } X \equiv e^{-\Delta t/\tau}. \quad (3)$$

At cold temperatures, when the sensor responds slowly to the ambient relative humidity, X will be close to one and the corrected profile becomes extremely sensitive to the measured humidity fluctuations. This poses a problem when data are stored with a resolution of only 1% RH (see Table 1). In the upper troposphere the “staircase” representation of the ambient humidity profile with the 1% RH steps results in extreme fluctuations in the corrected profiles. This problem is avoided by applying the smoothing procedure that is described in detail by Miloshevich et al. (2004). This smoothing algorithm minimizes the third derivative of the relative humidity in a few iterations, allowing for changes to the original data point between -0.5% and 0.5% RH.

FIG. 8. Profiles of the correlation between various Vaisala Humicap sensors and the Snow White hygrometer.

Figure 9 illustrates the effect of the TD and TL corrections on some Humicap profiles. Figure 2 shows that the TD correction (Miloshevich et al. 2001) significantly improves the agreement with the Snow White observations above 9 km, although a dry bias remains throughout most of the profile. The TL correction (Miloshevich et al. 2004) is applied after the TD correction (which is applied only to the RS80A profiles). In the examples of Fig. 9a the effect of the latter correction is noticeable above ~ 11 km (below -40°C), where the response time of the RS80A becomes larger than 20 s. The humidity maxima and minima are more pronounced and shifted to a lower altitude, improving the agreement with the Snow White profile, especially between 10- and 14-km height. Figure 2 (right panel) shows the standard deviation of the relative humidity within 1-km vertical bins, averaged over all RS80A soundings. Here it can be seen that there is a clear increase of variability between 10- and 14-km altitudes resulting from the TL correction, but it is still smaller than that observed by the Snow White sensor. The effect of the TL correction on the correlation coefficient (R) of the Snow White and RS80A observations is negligible for the full dataset as well as for the cloud-free subset.

Two examples of the effect of the TL correction on the RS80H profiles are given in Figs. 9b and 9c. The impact of the correction becomes noticeable at a height of approximately 10 km, which is at a lower altitude than for the RS80A, caused by the slower response of the RS80H sensor. The variability of the relative hu-

midity profile is on average increased above 9 km, and becomes similar to the variability observed by the Snow White sensor up to a height of 13 km (Fig. 4, right panel). The effect of the TL correction on R is limited, and R remains still considerably lower than that which was found for the RS80A. When only the cloud-free data are used the profile of R above 13 km is significantly improved (Fig. 8), which suggests that icing of the RS80H sensor is a serious problem in the upper troposphere. Applying the TL correction to the RS80H data does not change the average wet bias in the upper troposphere, as can be seen in the average profiles in Fig. 4 and the example profiles in Figs. 9b and 9c.

The smaller RS90 sensor has a shorter response time and therefore the TL correction becomes noticeable at a higher altitude (>12 km) than in the profiles of both RS80 sensors (Fig. 9d). The variability is increased above 11 km and is in reasonable agreement with the Snow White observations up to 14 km (Fig. 7). The application of the TL correction and the selection of only cloud-free data do not have a serious effect on the correlation between the RS90 and the Snow White observations. Because icing of the RS90 is avoided by the dual, pulse-heated sensor design, this result also suggests that the Snow White was not seriously affected by icing of the sensor housing.

On average, the agreement between individual profiles measured by the Vaisala sensors and those measured by the Snow White increases when the TL correction of Miloshevich et al. (2004) is applied. However, above approximately 13-km height the effect of the ambient humidity on the sensor signal becomes negligible. At these heights the correction algorithm mainly amplifies the noise of the Vaisala signal, and the correlation with the Snow White observations is lost.

5. Comparison of Snow White observations with ECMWF model data

The 37 profiles that have been measured by the Snow White sensor are compared with the model profiles calculated by ECMWF. For the comparison we averaged each Snow White profile up to 16 km to the ECMWF model resolution. The effective horizontal resolution of the operational ECMWF model is approximately 40 km, and the vertical resolution in the midtroposphere is roughly 500 m. The Paramaribo observations were not available for assimilation in the ECMWF forecast system. The nearest station that provides sounding data that are operationally assimilated by ECMWF is Cayenne in French Guyana, which is approximately 400 km to the east of Paramaribo.

Figure 10 shows plots of the ECMWF and Snow

FIG. 9. Examples of RH profiles measured by the Snow White and RS80A/H and RS90 sensors with and without corrections (TD error correction from Miloshevich et al. 2001; TL correction from Miloshevich et al. 2004). Dotted lines indicate ice saturation in terms of the RH over water.

White relative humidity, averaged over all 37 soundings, as well as the standard deviations (std dev). There is good agreement between the average modeled and observed profiles throughout most of the troposphere. However, the observations show a slightly higher variability than the model profiles, which can be explained by the fact that the model data represent a grid box,

while the observed profile consists of point values, averaged only in the vertical direction. Figure 11 shows corresponding scatterplots of the ECMWF model values and the observed values between 200 and 800 hPa, indicating that individual measured profiles can be considerably different from those modeled. Correlation coefficients for the Paramaribo profile are 0.77 and 0.66

FIG. 10. Profiles of the average (thick lines) and std dev (thin lines) of RH observed from the Snow White hygrometer and from analyses and ECMWF forecasts. For the morning launches (see Table 1) 42-h forecasts were used, valid for 0600 UTC (0300 LT), and for the evening launches 36-h forecasts were used, valid for 0000 UTC (2100 LT). The averages and std devs are based on 37 individual profiles.

for the analyses and the ~ 36 h forecast, respectively (see note on the forecast period in the caption of Fig. 10).

6. Conclusions

We have performed relative humidity soundings with several sensors at the tropical station Paramaribo in

Suriname (5.8°N , 55.2°W). The sounding payloads consisted of a chilled-mirror hygrometer from Meteolabor AG, called “Snow White,” and two capacitive sensors from Vaisala. The behavior of the Snow White has been studied by both Vömel et al. (2003) and Fujiwara et al. (2003), who have found a good performance up to at least 16-km height and above 3%–6% RH. In this study we used the Snow White sensor as the reference and compared it with data from the RS80A, RS80H, and RS90 sensors, which are currently used at many routine sounding stations around the world.

The RS80A observations show a dry bias in the lower troposphere between -4% and -8% RH, similar to what was found by Fujiwara et al. (2003). Sensor aging, as suggested by Wang et al. (2002), could have caused this bias because the sensors were, on average, ~ 2 yr old at launch. The dry bias of the RS80A in the upper troposphere could be almost entirely corrected by the temperature-dependence error correction scheme provided by Miloshevich et al. (2001). A significant wet bias in RH from $+2\%$ to $+5\%$ was found in the RS80H profiles in the upper troposphere, which, to the authors’ knowledge, has not been reported before in literature. The temperature-dependent error correction given by Wang et al. (2002) would further increase this discrepancy between the RS80H and Snow White. We did not find a significant effect of either aging or contamination of the sensors that increases with time. Selecting a subset of data using only cloud-free observations did not eliminate or significantly reduce the wet bias. Therefore, we were not able to provide an explanation for this observed bias. The RS90 sensor showed a small but significant wet bias of 2%–3% below 7-km altitude

FIG. 11. Comparison of the (left) Snow White observations with ECMWF analyses and (right) forecasts between 200 and 800 hPa. Launch times and forecast periods the same as Fig. 10.

compared to the Snow White, but the correlation coefficient with the Snow White remained higher than 0.9 up to heights of about 14 km.

The time-lag correction procedure of Miloshevich et al. (2004) increases the variability of the Humicap sensors in the upper troposphere. Because of the slow response time the variability of the uncorrected data was too low compared to the Snow White observations. This improvement is most clearly seen in the RS80H profiles, with the locations of the relative maxima and minima being shifted downward compared to the more smooth uncorrected profile. The variability of the three sensor types after the correction is in better agreement with the Snow White variability. Selecting only cloud-free data clearly indicated that the performance of the RS80H is affected by icing in cloud layers.

We did not find a severe bias between the average Snow White profile and the model profile from the European Centre for Medium-Range Weather Forecasts. Between 200 and 800 hPa the model analysis profiles showed a correlation coefficient of 0.77 and the forecast (which was a combination of 36- and 42-h model prediction) showed a correlation of 0.66.

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