Performance of the Meteolabor "Snow White" Chilled-Mirror Hygrometer in the Tropical Troposphere: Comparisons with the Vaisala RS80 A/H-Humicap Sensors

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ABSTRACT

The "Snow White" hygrometer is a low-cost, chilled-mirror hygrometer for radiosonde applications provided by a Swiss company, Meteolabor AG. A total of 54 Snow White soundings were conducted at five tropical stations in different seasons in 2000–01. All soundings were made with Vaisala RS80 radiosondes equipped either with the A-Humicap (22 soundings) or H-Humicap (32) relative humidity (RH) sensor. Comparisons of the RH with respect to liquid water between the Snow White and the different RS80 Humicap sensors are made. The Snow White measurements show reasonable agreement with the H-Humicap measurements from the surface up to ~12 km (above −50°C air temperature), the region where the H-Humicap sensor can be considered reliable. Above 12 km, the H-Humicap sensor tends to miss small vertical-scale structures in RH due to the time lag error, but on average both instruments show no significant difference up to 14 km (−65°C). The comparison between the Snow White and A-Humicap sensors shows the known A-Humicap dry bias error at low temperatures and second dry bias error in the wet lower troposphere. The latter error [(A-Humicap RH) ≃ 0.9 × (Snow White RH) above 50% RH] may be a common problem for the recent A-Humicap sensors. These intercomparisons confirm the validity of the Snow White measurements at least up to the tropical upper troposphere and above 3%–6% RH.

1. Introduction

Water vapor or humidity plays important roles in the troposphere and stratosphere, but accurate measurements that satisfy current scientific demands are still a challenge. This is in part due to the rapid decrease of approximately five orders of magnitude in vapor pressure from the surface to the tropopause, and due to its high variability in time and space. Most commercial relative humidity (RH) sensors on meteorological radiosondes are able to measure RH in the lower to middle troposphere. However, studies on the accuracy of these sensors are continuing at present (e.g., Elliott and Gaffen 1991; Kley et al. 1997; Miloshevich et al. 2001; Wang et al. 2002, and references therein). Above the middle troposphere, most RH sensors become too insensitive to measure the water vapor accurately. Some balloon-borne and aircraft-borne state-of-the-art sensors have been developed by researchers for this height region (Kley et al. 2000). However, these sensors are generally much more expensive than radiosondes and require special techniques for their operation, so that they are only used in some special campaigns. Although some ground-based and satellite-based remote sensing techniques are available for estimating the water vapor distribution, the accuracy and the spatial resolution of these measurements are sometimes insufficient for particular scientific issues.

Since 1996 Meteolabor AG of Switzerland has been providing a hygrometer named Snow White, which is a low-cost, dew/frost point hygrometer for radiosonde applications. This hygrometer is based on the well-known chilled-mirror physical principle to measure water vapor concentrations throughout the entire troposphere. It does not require additional infrastructure and utilizes facilities and techniques similar to those used for operational radiosonde or ozonesonde soundings. Some research groups have used this hygrometer as a

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potential reference instrument for RH sensors on radiosondes and as water vapor sensor in the upper troposphere.

The Soundings of Ozone and Water in the Equatorial Region/Pacific Mission (SOWER/Pacific) has been running since 1998 on a campaign basis to improve our understanding of the equtorial atmosphere by making balloon-borne measurements of ozone, water vapor, and meteorological parameters (Fujiwara et al. 2001; Vömel et al. 2002). For these two publications we used the cryogenic frost point hygrometer of the National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory (NOAA/CMDL, hereafter NOAA FPH). As a part of this mission, we have conducted a total of 54 soundings using the Snow White hygrometer at San Cristóbal in the Galápagos, at Christmas Island (Kiribati), and at three sites in Indonesia. These soundings cover different seasons between March 2000 and December 2001. The payloads consist of the Snow White hygrometer, electrochemical concentration cell (ECC) ozonesonde (in most cases), Vaisala RS80 radiosonde, and TMAX-C interface board. Thus, all soundings provide simultaneous water vapor measurements by the Snow White hygrometer and Vaisala RS80 Humicap sensor.

In this paper, we present the intercomparisons between the Snow White and RS80 A-Humicap/H-Humicap measurements and discuss the validity of the Snow White measurements in the tropical troposphere. The instrumentation and the observations are described in sections 2 and 3, respectively. The procedure of RH calculation from the Snow White dew/frost point temperature data is explained in section 4. Results and discussion are in section 5. Section 6 summarizes the findings. In the companion paper, Vömel et al. (2003, hereafter VOM) present the intercomparison between the Snow White and NOAA FPH measurements.

2. Instrumentation

a. Meteolabor Snow White hygrometer

The Snow White hygrometer continuously measures the dewpoint or frost point temperature during a ballon flight, using a 3 mm × 3 mm mirror attached on the cold side of a Peltier element. The hot side of the Peltier element is cooled by the air with an aluminium radiator. The thickness of the condensate (either dew or frost) on the mirror is monitored with a lamp, optical fiber, and phototransistor, and the electric feedback circuit automatically controls the power of the Peltier cooler so as to maintain a constant condensate layer on the mirror, in other words, to maintain the mirror temperature at the dew/frost point temperature of the environment. The Snow White mirror is made of two thin metals (copper, and constantan plated with gold) and is a part of a thermocouple, so that the mirror acts as a thermometer at the same time. Thus, the heat capacity of the mirror–cooler system is minimized, allowing stable measurements in the whole tropospheric temperature range without any artificial oscillation. The mirror, lamp, and optical fiber are situated in a separated 3 cm × 1 cm × 5 cm metallic sensor housing, which has a slit opening for air intake. This sensor housing is also equipped with a heater that operates in cloud layers to avoid icing of the sensor and to make total water measurements. The Snow White hygrometer works with two dry cell batteries, one for the Peltier cooler and the sensor-housing heater and the other for the lamp and control circuit. This instrument does not require any prelaunch calibration. It should be noted that, similar to other chilled-mirror sensors, the Snow White hygrometer requires sufficient airflow on the mirror surface, which is provided by the balloon ascent rate of $\sim$5 m s^{-1}.

The manufacturer estimates that the accuracy of the mirror temperature measurement is $<$0.1 K, that the response time, which is largely determined by the time constant for the vapor–water or vapor–ice equilibrium, is negligible at +20°C, is 10 s at −30°C, and 80 s at −60°C, and lastly that the maximum temperature depression that the Peltier element can produce is 50 K at +20°C ($\sim$2% RH if the Peltier hot-side temperature equals the air temperature), 32 K at −30°C ($\sim$2% RH), and 22 K at −80°C ($\sim$1% RH). In the present study we used two models of Snow White, ASW33 and ASW35. The latter has a larger aluminium radiator to cool the hot side of the Peltier element, but the essential parts are identical between the two. The limitations of the measurements will be discussed later.

There are two types of Snow White, a ''day'' type and a ''night'' type. In the day type the sensor housing and radiator are enclosed in a styrofoam housing with a duct, whose surface is covered with a waterproof material to prevent solar light contamination to the optical measurement. In the night type, on the other hand, the sensor housing and radiator are exposed to minimize potential water vapor contamination and outgassing problems and to maximize the cooling efficiency of the radiator. This type should be launched at night. Furthermore, for most of the soundings we monitored the following three housekeeping data: 1) the phototransistor output voltage to monitor the thickness of the condensate on the mirror (i.e., mirror reflectivity); 2) the current passing through the Peltier element to monitor the power of the cooler; and 3) the Peltier hot-side temperature to study the cooling efficiency of the radiator.

The payloads consist of the Snow White hygrometer, ECC ozonesonde (which can be omitted), Vaisala RS80 radiosonde with the A-Humicap or H-Humicap sensor, and TMAX-C interface board. The ground receiving system consists of an antenna, 403-MHz receiver, modem, and computer. The software to receive, process, and display the telemetry data in real time was developed at NOAA/CMDL.[1] The sampling interval of 7–8

[1] This software is available for any researcher in the science community. Contact Holger Vömel of NOAA/CMDL.

s is determined by the interface board. In most cases TOTEX TX2000-type rubber balloons were used in order to reach a typical altitude of ~35 km with a typical ascending rate of ~5 m s^{-1}.

b. Vaisala Humicap sensors

The Vaisala Humicap RH sensors are thin-film capacitive sensors using a highly porous polymer electrode, whose capacitance depends on the amount of water vapor and on the air temperature. There are currently three models of Vaisala Humicap sensor. The A-Humicap sensor is the original humidity sensor on RS80 radiosondes and has been widely used at operational stations since the early 1980s. The H-Humicap sensor was introduced for RS80 radiosondes in the early 1990s and has been used in some research programs and at some operational stations. These two sensors use different polymer materials and different algorithms in the data processing and have different accuracies. (Recently, Vaisala released a new radiosonde, RS90, which is equipped with two H-Humicap sensors.) Measurements are always reported as RH with respect to liquid water even below 0°C air temperature. We will follow this convention also for values calculated from the Snow White measurements and report them as RH with respect to liquid water (see section 4).

The manufacturer notes that the accuracy of Humicap sensors is <3% RH. A-Humicap RH (RH_A) measurements are typically limited to air temperatures above −30°C or altitudes below 10 km in the Tropics, while H-Humicap RH (RH_H) measurements may be extended to −50°C or 12 km in the Tropics. The limitations and possible correction schemes for these sensors have been discussed by Kley et al. (1997), Miloshevich et al. (2001), Wang et al. (2002), and others.

In our sounding system, we did not perform the ground check correction for RS80 pressure, temperature, and humidity measurements. The radiation correction for the temperature measurement is applied in our software.

3. Observations

Table 1 lists the campaigns between March 2000 and December 2001. We used five stations: San Cristóbal Island (0.90°S, 89.62°W, 8 m) in the Galápagos Islands, Ecuador; Christmas (Kiritimati) Island (at the Mini Hotel) (1.52°N, 157.20°W, ~0 m), Kiribati; Bandung (6.9°S, 107.6°E, 740 m), West Java, Indonesia; Bukittinggi [at the dormitory of the Indonesian Meteorological and Geophysical Agency (BMG)] (0.25°S, 100.38°E, 895 m), Sumatra, Indonesia; and Watukosek (7.5°S, 112.6°E, 50 m), East Java, Indonesia. We conducted a total of 22 simultaneous soundings with the A-Humicap sensor and a total of 32 simultaneous soundings with the H-Humicap sensor. There were five cases of malfunction in the RS80 radiosonde (the sensors or transmitter) and two cases of malfunction in the Snow White hygrometer. These soundings are excluded in the following analyses.

TABLE 1. Snow White sounding campaigns.

Period	Station*		RS80 Humicap
Mar 2000	San Cristóbal Island	(6)	A
	Christmas Island	(6)	A
Sep 2000	San Cristóbal Island	(3)	A
	Bandung, Indonesia	(3)	A
Nov–Dec 2000	San Cristóbal Island	(6)	H
	Christmas Island	(7)	H
	Bukittinggi, Indonesia	(7)	A (4), H (3)
Jul 2001	Bandung, Indonesia	(4)	H
Sep 2001	San Cristóbol Island	(3)	H
Nov–Dec 2001	Watukosek, Indonesia	(5)	H
	Christmas Island	(4)	H

* The number of soundings is in parentheses.

During the March 2000 campaigns, we used the day-type Snow White hygrometers, which were launched either during the day or at night after conversion to night type by exposing the sensor housing and radiator. However, we did not see any difference in the performance of these different types. Since September 2000, we have monitored the three housekeeping data of the Snow White hygrometer and conducted all the soundings at night using a night type. Other changes included the installation of a larger radiator in November 2000 (i.e., the model change from ASW33 to ASW35) and the application of a temperature-dependent phototransistor output gain in July 2001. The latter shortened the response time of the sensor especially at very low temperatures and somewhat improved the performance in the tropopause region. However, the essential parts of the Snow White hygrometer, all the elements in the sensor housing, for example, remained identical throughout 2000–01, and we did not see any change in the performance below the tropopause region during this period.

RS80 radiosondes used in the campaigns were typically less than 1 yr old, with the exception of the San Cristóbal November–December 2000 campaign where we used the H-Humicap radiosondes manufactured in 1996–97. All RS80 radiosondes provided after August 2000 were shipped with a new airtight cap on the sensor boom, which reduces the chemical contamination problem during storage.

4. Calculation of relative humidity from the Snow White data

For the comparison between the Snow White and Humicap measurements, we calculate the Snow White RH with respect to liquid water, RH_{SW}, from the Snow White dew/frost point temperature data and the RS80 air temperature data. We use the Goff–Gratch formulations [Goff and Gratch 1946; see also Eqs. (1) and (2)

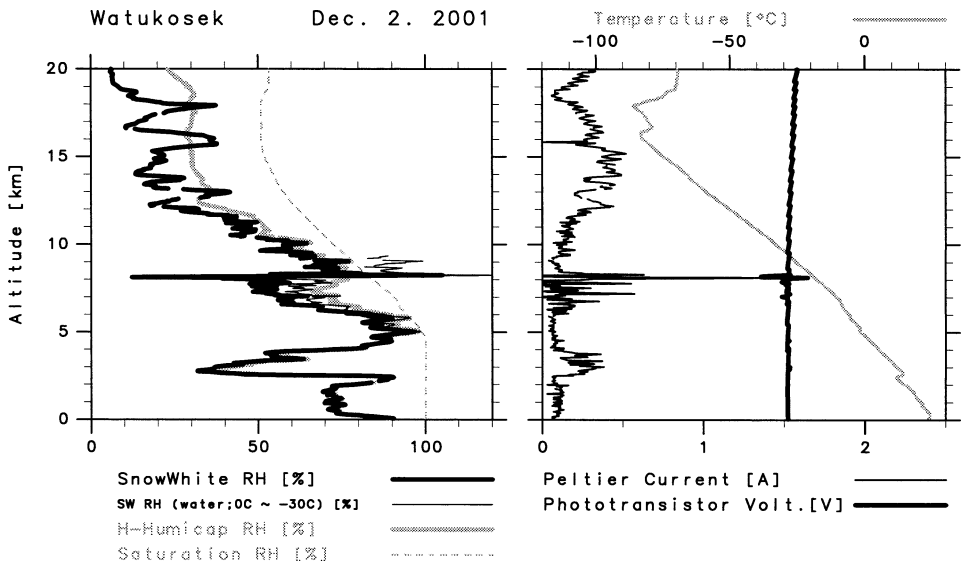

FIG. 1. Sounding at Watukosek, Indonesia, on 2 Dec 2001. (left) RH_{SW} (ice is assumed on the mirror at $T_m < 0°C$) (thick black), RH_{SW} ($-30°C < T_m < 0°C$; liquid water is assumed on the mirror) (thin black), RH_H (thick gray), and SRH (dashed gray). (right) Air temperature (gray), Peltier current (thin black), and phototransistor voltage (thick black).

of Murray (1967), e.g.] for the relation between temperature, T, and water vapor pressure, e [$e_{liq}(T)$ for water vapor in equilibrium with liquid water, and $e_{ice}(T)$ for water vapor in equilibrium with ice]. [For a comparison of the various formulations, see Elliott and Gaffen (1991) and Marti and Mauersberger (1993).] If the condensate on the Snow White mirror is liquid water (dew),

$$RH_{SW} = [e_{liq}(T_m)/e_{liq}(T_a)]100\%, \quad (1)$$

where T_m is the Snow White mirror temperature, and T_a is the air temperature measured by the radiosonde. If the condensate on the mirror is ice (frost),

$$RH_{SW} = [e_{ice}(T_m)/e_{liq}(T_a)]100\%. \quad (2)$$

The saturation relative humidity, SRH, is 100% when $T_a \geq 0°C$. When $T_a < 0°C$, the ice saturation is calculated as

$$SRH = [e_{ice}(T_a)/e_{liq}(T_a)]100\%. \quad (3)$$

SRH is always equal to or less than 100%. If $RH_{SW} >$ SRH, the air is supersaturated and/or cloud particles or droplets are present. The Snow White hygrometer measures close to the total water content in cloud layers and cannot distinguish between supersaturated air and the presence of cloud particles.

When $T_m > 0°C$, it is certain that the condensate on the mirror is liquid water. However, for $T_m \leq 0°C$, the condensate on the mirror may not be ice but supercooled liquid water. Our tropical soundings indicate that the condensate on the Snow White mirror is often liquid water down to $-20°$ to $-30°C$ mirror temperatures. Based on the housekeeping data as well as the mirror temperature data itself, we can determine a single level for each sounding where the condensate on the mirror was converted from liquid phase to ice. Following common practice (e.g., Elliott and Gaffen 1991), we use the Goff–Gratch water formulation also for $T < 0°C$, although in their original paper (Goff and Gratch 1946), this formulation is only defined at $T \geq 0°C$.

Figure 1 shows a sounding result at Watukosek on 2 December 2001. Around 8 km, RH_{SW}, phototransistor voltage, and Peltier current all show spiky noise. Below this level, the RH_{SW} assuming liquid condensate on the mirror (thin black curve) agrees better with RH_H (gray solid curve), whereas above this level, the RH_{SW} assuming ice condensate (thick black curve) agrees better with RH_H. This indicates that, in this case, supercooled water existed on the mirror up to 8 km ($T_m \sim -21°C$) and then froze. (Note that the small discontinuities in the phototransistor voltage data above the conversion level are only due to an insufficient digit number of the saved data in the software.)

With plots similar to Fig. 1, we determined the conversion level for each sounding. The assumptions and criteria for the determination are as follows.

1) There is only a single conversion level in a sounding, with liquid condensate below and ice condensate above this level.
2) At the conversion level, spiky noise is often observed in RH_{SW}, phototransistor voltage, and the Peltier current. The housekeeping data are very informative, but the conversion level can also be determined from the comparison with Humicap measurements alone.
3) After the determination of the conversion level, the relationship between RH_{SW} and RH_A/RH_H is consistent with other soundings.

It often took 30–70 s for the Snow White measure-

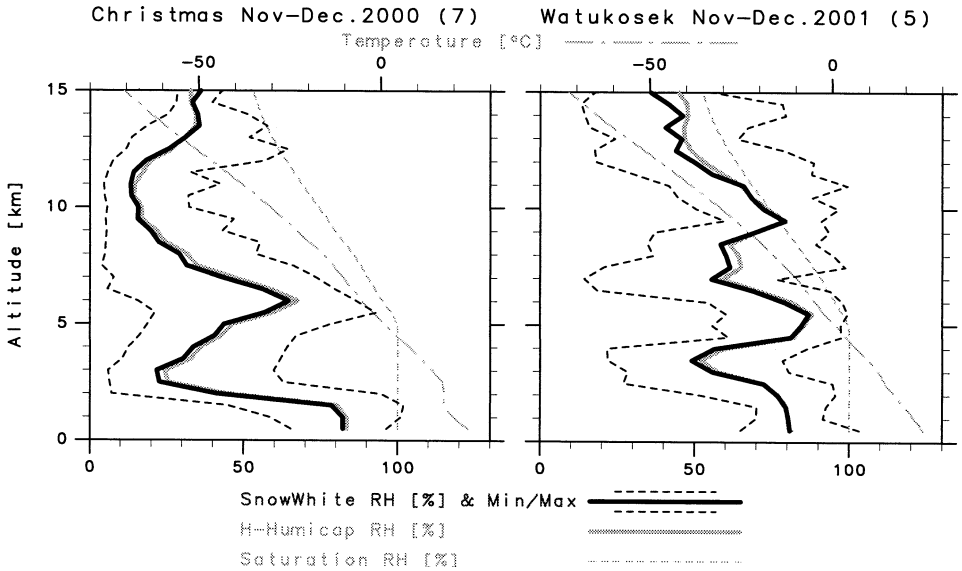

FIG. 2. Average profiles of RH_{SW} (thick black), RH_H (thick gray), SRH (dashed gray), and air temperature (dash–dot gray) from (left) seven soundings at Christmas Island in Nov–Dec 2000 and from (right) five soundings at Watukosek in Nov–Dec 2001. The averages are taken for every 500 m, and the maximum and minimum RH_{SW} in each bin are shown by dotted black curves.

ments to be stabilized again after the conversion. The data in this short period were excluded for the following analyses. We also excluded data where the Peltier current was close to its maximum (above ~1.4 A), which indicated that the air was too dry for the instrument to operate properly. In these regions condensate on the mirror is partially or completely lost. These extremely dry layers were observed in some soundings in the middle troposphere at San Cristóbal and Christmas Island. The limitation of the Snow White measurements in extremely dry conditions (<3%–6% RH) is discussed by VOM.

The error in RH_{SW} is estimated with the method by Elliott and Gaffen (1991) (see their appendix). If we assume the measurement accuracy (one-standard-deviation error) for the Snow White dew/frost point temperature and RS80 air temperature as ±0.1 and ±0.2 K, respectively, the resultant error in RH_{SW} becomes ~2% RH at saturation under the tropical tropospheric conditions. This is a lower limit of the actual measurement uncertainty because the accuracy of 0.1 K refers to the mirror temperature measurement, not the dew/frost point temperature measurement, and neglects the uncertainty introduced by the control circuit, which will greatly contribute to the total uncertainty of the Snow White measurements. Also, the accuracy of the formulations for water vapor pressure calculation would contribute to the total uncertainty. For example, Miloshevich et al. (2001, appendix B) mentioned that a different formulation gives different RH values from the Goff–Gratch formulation by 0.9% RH (with respect to ice) at −50°C to 5.2% RH at −80°C. Therefore, the total uncertainty might be much greater, but we cannot estimate it quantitatively at this moment. The estimated error has little influence on the main results and discussion in the next section.

5. Results and discussion

a. Snow White versus H-Humicap

Figure 2 shows the average RH profiles for the Snow White and H-Humicap measurements at Christmas Island in November–December 2000 and at Watukosek in November–December 2001. The former is an example for a relatively dry environment, and the latter for a very wet environment. Both sensors show reasonable agreement within the measurement uncertainty from the surface up to around 11–12 km. Above 12 km, the time lag error of the H-Humicap sensor (e.g., Miloshevich et al. 2001) becomes noticeable (see Fig. 1). In this region the H-Humicap measurements tend to miss small vertical-scale structures that the Snow White measurements still capture, but the average profiles do not differ significantly up to around 14 km.

Figure 3 shows the scatterplot of RH_H versus RH_{SW} from 28 soundings between the surface and 12 km (~−50°C air temperature). [Note that the data points with RH < 3%–6% were excluded by the Peltier current consideration (section 4).] Except for some outliers, the data points are generally distributed around the $y = x$ line, with a small difference of 1%–2% below ~50% RH.

Figure 4 shows the ratio of RH_H to RH_{SW} as a function of air temperature. The data points are centered around unity down to −40° to −50°C (Fig. 4, top panel). Most

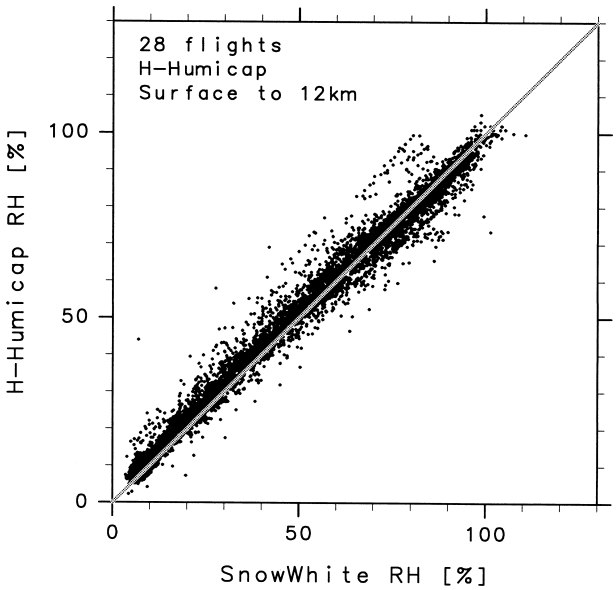

FIG. 3. Comparison of RH_{SW} and RH_H below 12 km (above $\sim -50°C$ air temperature) from 28 tropical soundings.

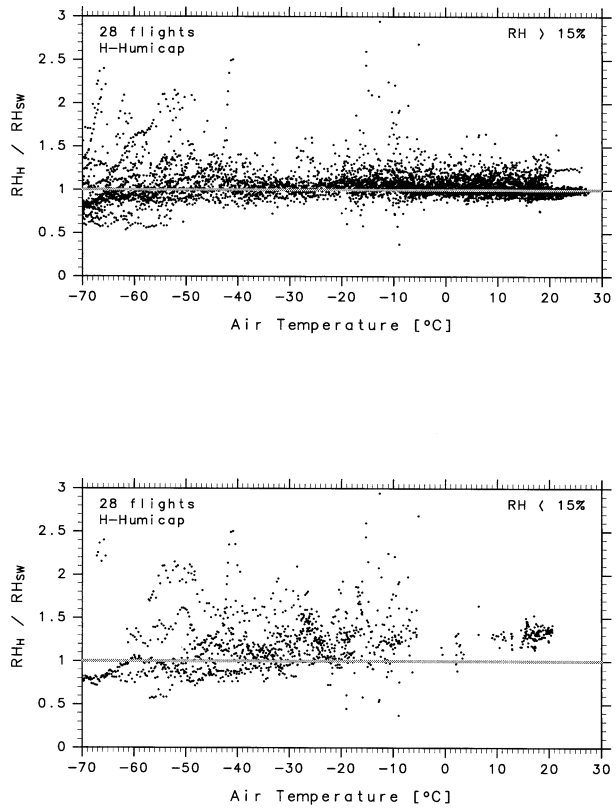

FIG. 4. Ratio of RH_H to RH_{SW} as a function of air temperature from 28 tropical soundings for (top) RH > 15% and (bottom) RH < 15%.

of the outliers above unity between $-10°$ and $-50°C$ correspond to low RH values (6% < RH < 15%), where small discrepancies are enlarged in the ratio (Fig. 4, bottom panel). Some outliers above unity at $T > -20°C$ correspond to steep vertical gradients in RH often observed in the lower to middle troposphere (see sudden RH drop at 2.5 km in Fig. 1). These outliers are due to the different response times of the two sensors, which become noticeable at sudden RH changes. Below $-50°C$, the outliers are due to the significantly slower response of the H-Humicap sensor (i.e., the time lag error), but on average, there is no significant bias down to $\sim -65°C$. Miloshevich et al. (2001) noted that RH sensors, in general, cannot measure ice supersaturation and will report ice saturation instead in such a case. However, some of our tropical H-Humicap measurements did show layers of ice supersaturation. In Fig. 4, most of the supersaturation data are distributed below $-20°C$ and slightly below unity (0.9 to 1).

In summary, the Snow White and H-Humicap measurements show reasonable agreement between the surface and 12 km in the Tropics (down to $-50°C$ air temperature), and we could not recognize any significant bias between the two sensors in this region. Above 12 km (below $-50°C$), the time lag error of the H-Humicap sensor smooths out small vertical-scale structures in RH. However, on average, the sensors do not differ significantly up to around 14 km (down to $-65°C$).

b. Snow White versus A-Humicap

Figure 5 shows the average RH profiles for the Snow White and A-Humicap measurements at San Cristóbal Island in March 2000 and at Bukittinggi in November–December 2000. Again, these are examples for a relatively dry and a very wet environment. Unlike the comparison with the H-Humicap sensor, the comparison with the A-Humicap sensor shows large discrepancies in the wet lower troposphere (below 5–6 km) as well as in the upper troposphere (above 10 km). The two measurements are comparable only in the middle troposphere where the RH values are intermediate.

Figure 6 shows the scatterplot of RH_A versus RH_{SW} from 19 soundings between the surface and 10 km ($\sim -30°C$ air temperature). This altitude region corresponds to the region where the A-Humicap measurements are thought to be valid (e.g., Kley et al. 2000). Below 40% RH, mostly in the middle troposphere, the data points are generally distributed around the $y = x$ line. However, above 50% RH, mostly in the lower troposphere, the A-Humicap measurements tend to become drier than the Snow White measurements as the RH value becomes larger. When the Snow White sensor indicates 90% RH, the A-Humicap sensor indicates $\sim$80% RH on average, that is, $RH_A \simeq 0.9 \times RH_{SW}$ above 50% RH. (If we apply the least squares method to all the data points in Fig. 6, we obtain $RH_A = 0.88 \times RH_{SW} + 1.8$.)

Because Snow White and H-Humicap measurements show reasonable agreement in the lower troposphere (section 5a) and because the essential parts of the Snow

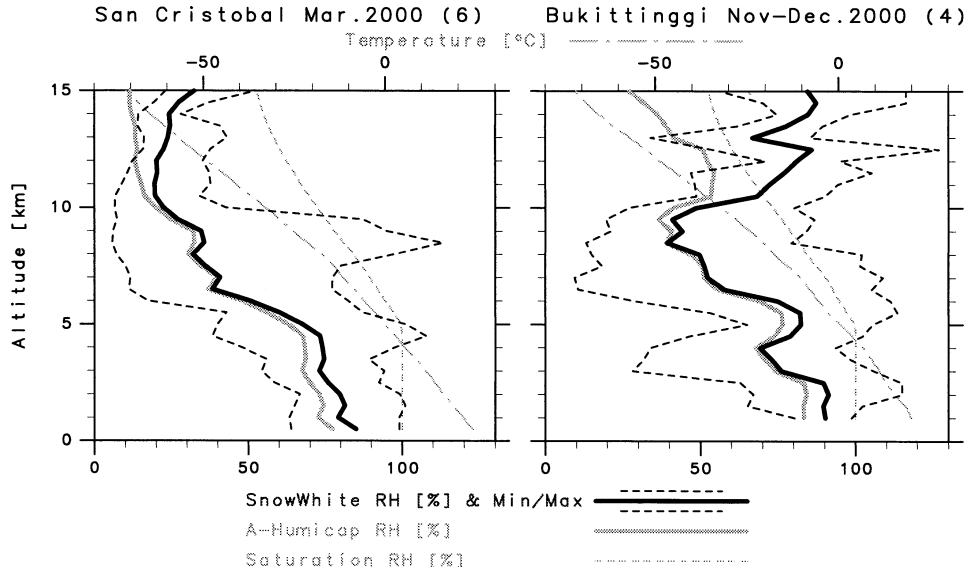

FIG. 5. Same as Fig. 2 but for RH_A (thick gray) and from (left) six soundings at San Cristóbal in Mar 2000 and (right) from four soundings at Bukittinggi in Nov–Dec 2000.

White sensor remained identical throughout 2000–2001, we suggest that the discrepancy is due to a bias error of the A-Humicap sensor. Since the discrepancy is noticeable below 5 km (above 0°C), it is not related to the ambiguity of the condensate phase on the Snow White mirror. Although we did not perform the ground check correction (0% RH adjustment) to the Humicap sensors, this does not account for the RH dependence of the observed bias, with larger discrepancy at larger RH values. Furthermore, the results show reasonable agreement at lower RH values.

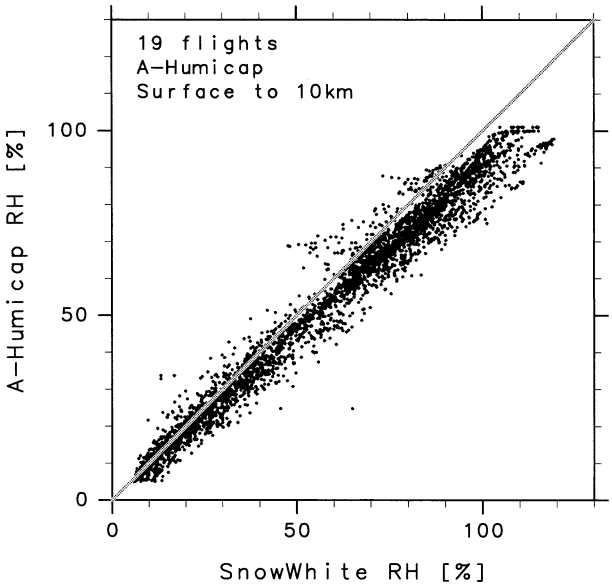

FIG. 6. Comparison of RH_{SW} and RH_A below 10 km (above ~−30°C air temperature) from 19 tropical soundings.

A possible cause is the bias error due to chemical contamination and aging, but note that the A-Humicap sensors that we used were all manufactured within a year. The National Center for Atmospheric Research Atmospheric Technology Division (NCAR ATD) and Vaisala recently established a correction scheme for chemical contamination of the Humicap measurements (Wang et al. 2002), which is based on the age of the sensor and measured RH. However, the maximum correction at a sensor age of 1 year is only ~2% at 100% RH. Therefore, the NCAR/ATD–Vaisala correction for chemical contamination cannot explain our results quantitatively. In 2000, the Meteorological Research Institute of the Japan Meteorological Agency conducted simultaneous soundings of the Vaisala RS80-15G radiosonde (A-Humicap) and Meisei RS2-91 radiosonde (equipped with an independent thin-film capacitive sensor) at Tsukuba, near Tokyo, Japan, and found a dry bias in the A-Humicap measurements similar to our results (Hajime Nakamura 2002, personal communication). They further investigated the RH dependence of this dry bias using a chamber RH calibrator and a reference chilled-mirror hygrometer at room temperatures (16°–24°C), and confirmed that the Meisei sensors basically agree with the reference hygrometer and that the A-Humicap sensors have a dry bias with a linear RH dependence whose magnitude becomes larger at larger RH values. At 90% RH measured by the reference hygrometer, the A-Humicap sensors indicated ~75% RH. Therefore, it is highly plausible that the dry bias that we observed in the tropical lower troposphere is a common problem, at least for the A-Humicap sensors manufactured in 2000–01, and that this problem has not yet been well recognized.

Figure 7 shows the ratio of RH_A to RH_{SW} as a function

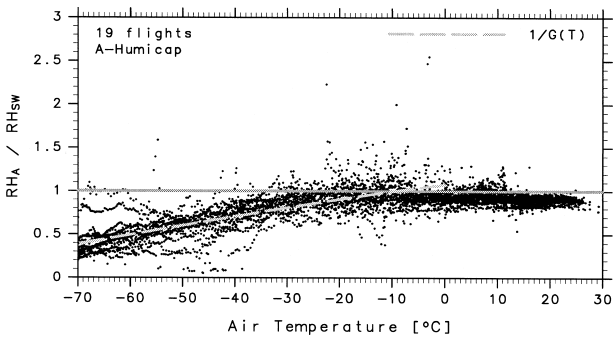

FIG. 7. Ratio of RH_A to RH_{SW} as a function of air temperature from 19 tropical soundings. The dashed gray slanted curve is from Miloshevich et al. (2001) and shows the $1/G(T)$ relation between the A-Humicap and NOAA FPH sensors.

of air temperature. The large discrepancy below −30°C is due to the ''temperature-dependence error'' or ''calibration error'' of the A-Humicap sensor (Miloshevich et al. 2001; Wang et al. 2002), which is caused by an inaccurate data processing algorithm. The superimposed curve shows the statistical ratio of the A-Humicap measurements to the NOAA FPH measurements as a function of air temperature derived from 95 soundings at Boulder, Colorado (Miloshevich et al. 2001). This curve is only defined between 0° and −70°C and does not capture the behavior above 0°C. The Snow White data agree well with this curve, suggesting that the Snow White measurements are not significantly different from the NOAA FPH measurements at least over this temperature range. Note again that above 0°C with RH values mostly above 50%, we find that $RH_A/RH_{SW} \simeq 0.9$.

Thus, the Snow White and A-Humicap measurements agree only in the middle troposphere, where RH values are intermediate or low. Above 10 km (below −30°C air temperature), the A-Humicap measurements exhibit the documented dry bias error. In the wet lower troposphere, where RH values are often larger than 50%, the A-Humicap measurements also exhibit a dry bias error, with $RH_A \simeq 0.9 \times RH_{SW}$ above 50% RH. This error may be a common problem at least for A-Humicap sensors manufactured in 2000–01.

6. Summary

We presented the results of 54 soundings using the Snow White chilled-mirror hygrometer at five tropical stations during different seasons in 2000–01. All soundings used Vaisala RS80 radiosondes equipped either with an A-Humicap RH sensor or H-Humicap sensor as the data transmitter and pressure–temperature–humidity sensors. We monitored three housekeeping data of the Snow White hygrometer for most of the soundings. It has been shown that supercooled liquid water is present on the Snow White mirror down to −20° to −30°C mirror temperatures, and that a single conversion level where the condensate on the mirror freezes can be determined for each flight. Relative humidity with respect to liquid water is then calculated from the Snow White dew/frost point temperature and is compared with RH from H-Humicap and A-Humicap sensors.

A total of 28 tropical Snow White and H-Humicap soundings showed reasonable agreement between the surface and 12 km (above −50°C air temperature). This result demonstrates the generally good performance of the Snow White hygrometer, although in extremely dry conditions below 3%–6% RH it did not work properly (see the intercomparison between the Snow White hygrometer and NOAA FPH in the Tropics by VOM). Due to the time lag error, the H-Humicap sensor tended to miss small vertical-scale structures in RH above 12 km (below −50°C), which the Snow White sensor did measure and resolve. On average, however, both instruments did not differ significantly up to around 14 km (down to −65°C).

A total of 19 Snow White and A-Humicap soundings showed reasonable agreement only in the middle troposphere, where the RH values are intermediate or low. Above 10 km (below −30°C air temperature), the A-Humicap sensor showed the temperature-dependence dry bias error, which has already been well characterized. In the wet lower troposphere, where the RH values are often larger than 50%, the A-Humicap sensor also showed a dry bias error, with $RH_A \simeq 0.9 \times RH_{SW}$ above 50% RH. The NCAR ATD–Vaisala correction for chemical contamination is too small to account for this error. This could be a new type of dry bias error of the A-Humicap sensors, which has not yet been documented.

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REFERENCES

Elliott, W. P., and D. J. Gaffen, 1991: On the utility of radiosonde humidity archives for climate studies. *Bull. Amer. Meteor. Soc.*, **72,** 1507–1520.

Fujiwara, M., F. Hasebe, M. Shiotani, N. Nishi, H. Vömel, and S. J. Oltmans, 2001: Water vapor control at the tropopause by equa-

torial Kelvin waves observed over the Galápagos. *Geophys. Res. Lett.,* **28,** 3143–3146.

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

Kley, D., and Coauthors, 1997: Tropospheric water-vapor and ozone cross-sections in a zonal plane over the central equatorial Pacific Ocean. *Quart. J. Roy. Meteor. Soc.,* **123,** 2009–2040.

——, J. M. Russell III, and C. Phillips, Eds.,2000: SPARC assessment of upper tropospheric and stratospheric water vapour. SPARC Rep. No. 2, WCRP 113, WMO/TD No. 1043, 312 pp. [Available online from http://www.aero.jussieu.fr/~sparc/.]

Marti, J., and K. Mauersberger, 1993: A survey and new measurements of ice vapor pressure at temperatures between 170 and 250 K. *Geophys. Res. Lett.,* **20,** 363–366.

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.

Murray, F. W., 1967: On the computation of saturation vapor pressure. *J. Appl. Meteor.,* **6,** 203–204.

Vömel, H., and Coauthors, 2002: Balloon-borne observations of water vapor and ozone in the tropical upper troposphere and lower stratosphere. *J. Geophys. Res.,* **107,** 4210, doi:10.1029/2001JD00707.

——, M. Fujiwara, M. Shiotani, F. Hasebe, S. J. Oltmans, and J. E. Barnes, 2003: The behavior of the Snow White chilled-mirror hygrometer in extremely dry conditions. *J. Atmos. Oceanic Technol.,* **20,** 1560–1567.

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.