The Behavior of the Snow White Chilled-Mirror Hygrometer in Extremely Dry Conditions

H. VÖMEL

Cooperative Institute for Research in Environmental Sciences, University of Colorado, and NOAA/Climate Monitoring and Diagnostics Laboratory, Boulder, Colorado

M. FUJIWARA AND M. SHIOTANI

Kyoto University, Kyoto, Japan

F. HASEBE

Hokkaido University, Sapporo, Japan

S. J. OLTMANS AND J. E. BARNES

NOAA/Climate Monitoring and Diagnostics Laboratory, Boulder, Colorado

(Manuscript received 21 February 2003, in final form 7 April 2003)

ABSTRACT

The Snow White hygrometer, made by Meteolabor AG, Switzerland, is a new chilled-mirror instrument using a thermoelectric Peltier cooler to measure atmospheric water vapor. Its performance under dry conditions is evaluated in simultaneous measurements using the NOAA/CMDL frost-point hygrometer at Boulder, Colorado; San Cristóbal, Galápagos Islands, Ecuador; Watukosek, Indonesia; and Mauna Loa Observatory, Hawaii.

The Snow White exhibits a lower detection limit of about 3%–6% relative humidity, depending on the sensor configuration. This detection limit is determined by the temperature depression attainable by the thermoelectric cooler. In some cases, loss of frost-point control within layers with relative humidity below this detection limit caused inaccurate measurements above these dry layers, where the relative humidity was within the detection range of the instrument.

The sensor does not operate in the stratosphere because of the large frost-point depression and the large potential for outgassing of water from the instrument box and the sensor housing. The instrument has some capabilities in the tropical tropopause region; however, the results are somewhat mixed.

1. Introduction

In situ water vapor measurements in the upper troposphere and lower stratosphere have recently gained significant attention. Still, the available data are sparse, mainly because of the technical difficulties measuring low amounts of water vapor. Most radiosonde humidity sensors are limited to altitudes well below the tropical tropopause and do not respond to water vapor in the stratosphere. There have been significant efforts to correct known problems in leading radiosonde humidity sensors, that is, dry bias in the Vaisala Humicap-A (Miloshevich et al. 2001), contamination in the Vaisala Humicap-H (Wang et al. 2002), and time lag in the Vaisala Humicap-H (Miloshevich et al. 2002). Nevertheless, the need for sensors that accurately measure water vapor in the upper troposphere and lower stratosphere remains. The Snow White chilled-mirror hygrometer, which will be described in detail in the instrumentation section, is a new commercial instrument made by Meteolabor AG, Switzerland, that has recently gained attention and is used at a number of sites for process studies. This instrument may potentially bridge the gap left by other sensors; however, its behavior is not yet well characterized and the response under a variety of conditions is not well documented.

A statistical evaluation using simultaneous Vaisala radiosonde data as reference is presented by Fujiwara et al. (2003). This study shows that in the tropical lower and middle troposphere, where Vaisala Humicap-H sensors are considered reliable, the Snow White in general produces accurate data. Furthermore, this study also identifies two different dry biases of the Vaisala Humicap-A sensor, one of which has been identified previ-

Corresponding author address: Holger Vömel, NOAA/CMDL, 325 Broadway, Boulder, CO 80303.
E-mail: holger.voemel@noaa.gov

ously using the National Oceanic and Atmospheric Administration (NOAA)/Climate Monitoring and Diagnostics Laboratory (CMDL) frost-point hygrometer (Miloshevich et al. 2001). However, due to the various issues of the Vaisala Humicap-A and Vaisala Humicap-H sensors in the tropical upper troposphere, this study could not investigate the behavior of the Snow White in the uppermost troposphere or in extremely dry layers.

The NOAA/CMDL frost-point hygrometer is currently the only lightweight balloon-borne instrument, bridging the gap for humidity measurements between the middle troposphere and the middle stratosphere. It has been flown monthly at Boulder, Colorado, since 1981 and campaign based at numerous other sites. While it may be considered a reference instrument for water vapor measurements in the upper troposphere and lower stratosphere, its price tag limits its use to special applications, where upper-tropospheric and stratospheric water vapor measurements are the focus. Here we present simultaneous measurements of water vapor by the Snow White and the NOAA/CMDL frost-point hygrometers and discuss the limitations of the Snow White hygrometer under very dry conditions as well as its behavior in the stratosphere and the upper troposphere.

2. Instrumentation

a. The NOAA/CMDL hygrometer

The NOAA/CMDL hygrometer is based on an instrument originally developed by Mastenbrook and Dinger (1960). It uses the chilled-mirror principle, in which a layer of condensate on a mirror is maintained at a constant reflectivity by continuously adjusting the temperature of the mirror, so that condensate neither grows nor shrinks. Under this condition the mirror temperature is equivalent to the dewpoint or frost-point temperature of the air above the mirror, depending on the phase of the condensate. The current instrument was designed in the late 1970s (Oltmans 1985) and has been used with only minor modifications since then (Vömel et al. 1995).

A cryogen cools the mirror and a powerful heater is used against this cold sink to control the mirror temperature, allowing fast cooling and heating as well as a fast response time throughout the entire measurement range. Cryogenic cooling is essential for stratospheric measurements, where the frost-point depression can reach in excess of 100 K, which is unattainable by most other means of cooling.

The data of the NOAA/CMDL hygrometer, the Snow White hygrometer, an additional ozone sonde, and the Vaisala radiosonde are digitized on board the payload using a Tmax interface board and transmitted in a digital format to the ground station using the Vaisala radiosonde transmitter. In the ground station, the data are processed in real time using STRATO, the NOAA/CMDL sounding software.

The measurement uncertainty of this instrument is largely determined by the ability of the instrument controller to maintain a constant frost layer. Minor factors are mirror calibration and digitizing errors, among others. The overall uncertainty is typically better than 0.5°C in frost-point temperature (Vömel et al. 1995). Including a 0.2°C uncertainty in the air temperature measurement, this translates to an uncertainty in relative humidity (RH) of 6% of the %RH value in the lower troposphere to better than 10% of the %RH value near the tropopause and in the stratosphere. For example, in the tropopause region the uncertainty at saturation (100% RH) would be 10% RH, but only 2% RH under dry conditions of 20% RH.

Intercomparisons with other instruments have taken place, in particular for stratospheric measurements (Kley et al. 2000), and have shown the reliability of the NOAA/CMDL frost-point hygrometer. It is currently the only lightweight balloon instrument that can accurately measure water vapor from the lower troposphere to the middle stratosphere and is generally accepted as reference instrument for this altitude region.

b. The Snow White hygrometer

The Snow White instrument is a new chilled-mirror hygrometer that uses the same physical principle as the NOAA/CMDL hygrometer. This instrument utilizes a single-stage thermoelectric Peltier device to cool the mirror, which under no load can produce a temperature differential of up to 40 K. Dewpoint or frost-point depressions of this magnitude are theoretically possible, but in reality will be somewhat smaller, since the Peltier hot side will be above ambient temperature and since heat transport across the Peltier cooler reduces the attainable temperature differential. Furthermore, the efficiency of the Peltier device is highly temperature dependent. A 3 mm × 3 mm copper–constantan thermocouple is directly mounted on the cold side of the Peltier cooler and acts as mirror and temperature sensor at the same time.

The uncertainty for the mirror temperature measurement is better than 0.1°C; combined with the 0.2°C uncertainty in air temperature measurement, this translates to an uncertainty in RH of about 2% of the %RH value. For example, in the upper troposphere at saturation (100% RH) the uncertainty would be 2% RH and at dry conditions of 20% RH the uncertainty would be 0.4% RH. If we consider the uncertainty due to the controller stability, this uncertainty may become slightly larger.

The models flown here are the ASW32 introduced in 1997 and the ASW35 introduced in 2000. The later model includes some improvements over the earlier model; however, for most of the discussions here, the model number does not play a significant role. Beginning with the ASW35 model, there are two different versions of this instrument. In the daytime version, the sensor and the cooling fins attached to the Peltier hot

TABLE 1. Listing of all soundings used in this evaluation.

Year	Location	Snow White model	Soundings
1998/99	Boulder, CO	ASW32 (day)	2
1998	San Cristóbal, Ecuador	ASW32 (day)	2
2000	San Cristóbal, Ecuador	ASW35 (night)	5
2001	Watukosek, Indonesia	ASW35 (night)	4
2002	Mauna Loa Observatory, HI	ASW35 (day)	1
2002	San Cristóbal, Ecuador	ASW35 (day)	2

side are mounted inside the instrument Styrofoam box. This arrangement protects the detector from stray light and the cooling fins from solar heating. It also allows a shielding of the sensor from rain. In the nighttime version, the sensor is almost completely exposed and mounted either on top or on the side of the instrument. The cooling surfaces are exposed as well and painted black to increase radiative cooling. This arrangement improves cooling of the Peltier hot side and minimizes contamination issues caused by outgassing of water vapor from the instrument box. However, due to the exposure of the sensor, this instrument can only be flown at night and in nonprecipitating conditions.

All soundings use a Vaisala RS80-H radiosonde and a Tmax interface board, which allows eight analog channels to be transmitted in addition to the normal Vaisala channels. The early ASW32 model was highly susceptible to radio frequency interference (RFI), which could confuse the controller. Therefore, these soundings had to be launched with the radio transmitter separated from the main payload by about 50 cm. This problem was rectified in the later model; however, as a precaution the transmitter is still separated from the main payload. In the ASW35 the sensitivity for condensate detection has been improved, which should help the frost-point control in the upper troposphere.

The Snow White instruments flown in 2000 and 2001 monitored the mirror reflectivity as a proxy for the frost coverage on the mirror, the Peltier current, and the Peltier hot-side temperature, providing additional information about the behavior of the instrument.

3. Observations and discussion

The observations presented here are simultaneous balloon-borne measurements of water vapor by the Snow White hygrometer, the NOAA/CMDL frost-point hygrometer, and the Vaisala Humicap-H sensor, which allow a direct evaluation of the performance of the Snow White sensor. The soundings analyzed here are listed in Table 1.

The generally good agreement of the Snow White and the Vaisala Humicap sensor in the tropical lower and midtroposphere has been shown by Fujiwara et al. (2003). Therefore, we will focus on the low humidity limit and on the behavior in the upper troposphere and lower stratosphere.

Soundings using the early ASW32 model had occasionally shown a limited battery life for the 1.5-V battery running the Peltier cooler. Extended operation at the surface and in the cold temperatures in the upper troposphere may limit the capacity of this battery and influence the observations in the upper troposphere. This behavior was observed in only one profile using an early ASW32 model and could be suspected in two other soundings. In the later ASW35 model a larger D-cell battery was installed and the battery lifetime was found to be sufficient even for soundings in excess of 3 h. Thus, with normal operations on the ground before launch, the battery duration does not pose a limiting factor in the current Snow White model and is not considered a problem in the following discussions.

a. Low humidity limit

Figure 1 shows a sounding at San Cristóbal, Galápagos Islands, Ecuador, on 29 November 2000, which is marked by an extremely dry layer between 6 and 10 km. In this region the NOAA/CMDL hygrometer and the Vaisala Humicap-H show less than 10% RH, with a minimum of 1.4% at 6 km. The Snow White and Vaisala Humicap-H agree well below 6 km, but within the dry layer and above, there is a strong disagreement between the Snow White and the other two sensors (Fig. 1a). The frost-point depression measured by the NOAA/CMDL hygrometer at 6 km is 42°C, whereas the Snow White frost-point depression does not exceed 36°C. The Snow White mirror reflectivity, which should stay approximately constant, is elevated, indicating that the Snow White lost frost coverage on the mirror (Fig. 1b). Under this condition the measured temperature no longer corresponds to the frost-point temperature. At the same time the Peltier current is at its maximum, which shows that the instrument is responding properly, but unable to reach the frost-point temperature. Frost-point temperatures out of reach for the Snow White are observed for 4 min between 6.0 and 7.2 km, during which the Snow White mirror lost most frost coverage. Between 7.2 and 9.0 km, the Snow White mirror temperature is below the frost point, but control was not regained. Formation of the frost layer on the mirror is a function of the available water vapor as well as of the temperature difference between the mirror and the ambient frost point. Apparently, under these dry conditions the time required to recreate the frost layer to the levels detected by the Snow White is too long and the addi-

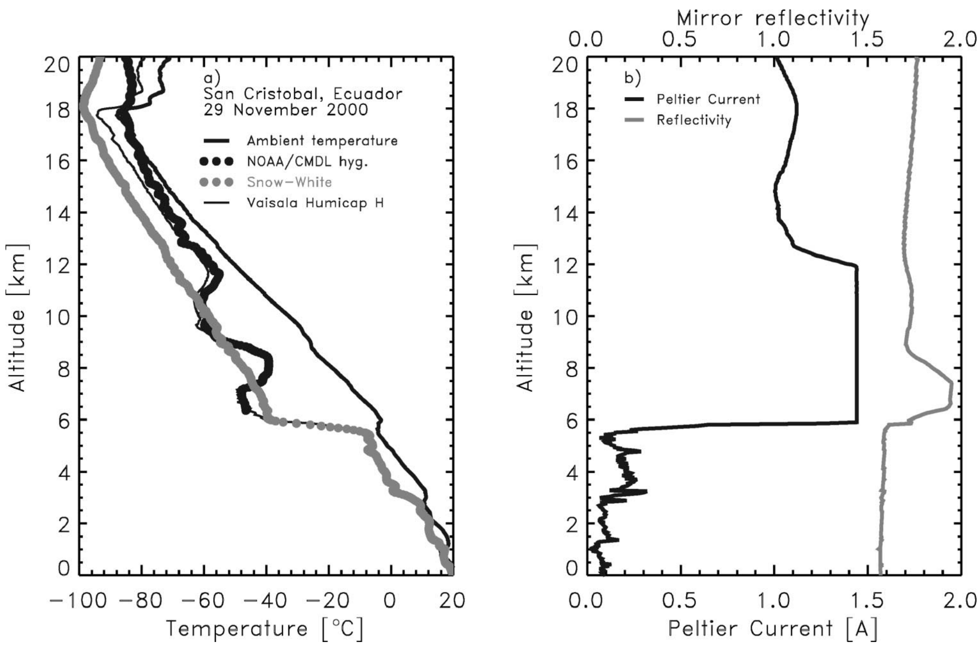

FIG. 1. (a) Frost-point sounding at San Cristóbal, Galápagos Islands, Ecuador, using the NOAA/CMDL frost-point hygrometer, the Snow White hygrometer, and the Vaisala Humicap. (b) Mirror reflectivity and Peltier current of the Snow White hygrometer for this sounding.

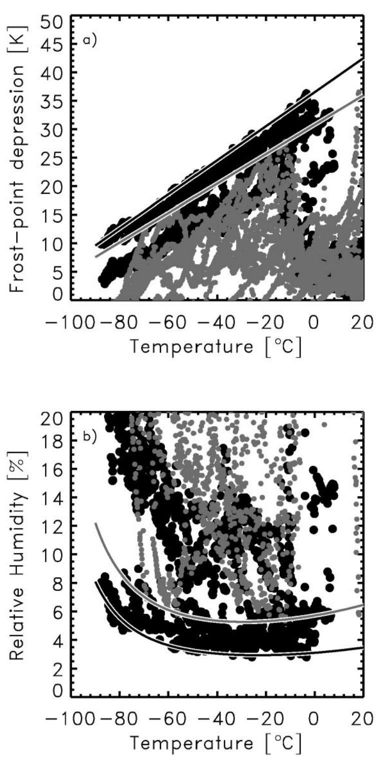

FIG. 2. (a) Temperature depression of the Snow White mirror for the night version (black points) and the day version (gray points). The fitted lines give a limit for 95% of the data points, where the sonde had lost frost coverage. (b) The same data expressed in relative humidity. The fitted lines are the linear fits in (a) also expressed as relative humidity.

tional cooling below the frost-point temperature is insufficient to fully restore the frost coverage on the mirror. Between 10 km and the tropopause, the mirror temperature remains well below the ambient frost point, but the frost coverage is insufficient for proper control of the frost-point temperature. This condition was observed in all of the five soundings launched in November/December 2000 at San Cristóbal, and a complete loss of control, as shown in Fig. 1, was observed in three of five soundings. The same behavior was seen in shallow layers in soundings launched at Boulder and at Mauna Loa Observatory, Hawaii.

These soundings establish a lower bound for the humidity that can be detected with the Snow White sensor under realistic atmospheric sounding conditions. Figure 2a shows the difference between mirror temperature and ambient temperature for these soundings. Black points correspond to night version data, and gray points correspond to day version data. The largest values correspond to mirror temperature depressions, when the mirror had fully or partially lost the frost coverage, and represent the maximum frost-point depressions that the instrument can detect. The fit for the night version, which covers 95% of all mirror temperatures under this condition, is 36.5 K at 0°C, 27.5 K at −30°C, and 12.6 K at −80°C. Over most of the temperature range this translates to a lower limit for the detectable relative humidity of about 3%, increasing at the low temperature level to 5% at −80°C (Fig. 2b). The limit for the day version is slightly worse with a lower limit for the relative humidity of around 6%, increasing to more than 9% at −80°C.

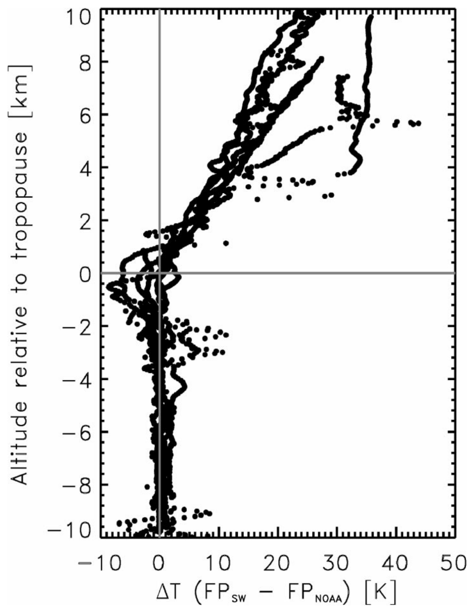

FIG. 3. Frost-point difference between the Snow White and the NOAA/CMDL hygrometer for eight soundings at various locations. Generally there is good agreement in the troposphere and no agreement in the stratosphere.

It should be pointed out that the temperature depression reached by the Snow White is not identical to the temperature gradient across the Peltier cooler. The temperature depression that can be attained below ambient temperature depends on the cooling of the hot side of the Peltier cooler, which in the troposphere is always above ambient temperature. Convective cooling of the Peltier hot side with attached cooling fins is most efficient in the lower troposphere but decreases in the upper troposphere. Solar heating further reduces the cooling efficiency, explaining the slightly higher limit for the day version.

b. Stratospheric behavior

Figure 3 shows the difference between the frost-point temperature measured by the Snow White and by the NOAA/CMDL frost-point hygrometer for the soundings at Boulder, San Cristóbal, and Mauna Loa Observatory, which are not affected by the low humidity limit. While there is a reasonable agreement between the two sensors throughout most of the troposphere, in the stratosphere all soundings show a strong increase in the frost-point temperature measured by the Snow White. The most important reason is the limited cooling capacity of the Peltier cooler, since the frost-point depression rapidly increases in the stratosphere. Over Boulder about 50% of all soundings using the NOAA/CMDL frost-point hygrometer since 1981 show frost-point temperatures unattainable by the Snow White Peltier cooler (using the tropospheric limits established above) at an altitude of 500 m above the local tropopause. In tropical regions the same level of frost-point depression is reached at about 2 km above the local tropopause. However, the available data show that this is an upper limit and that for observations close to a cold tropopause smaller attainable frost-point depressions can be expected.

Outgassing of water vapor from the instrument package and the balloon is known to be a serious issue since the early days of balloon-borne stratospheric water vapor measurements (Mastenbrook 1966). In the day version of the Snow White the sensor is inside the Styrofoam box, which has a significant potential to contaminate measurements in the stratosphere. In the night version, where mirror and optics are housed inside a small aluminum enclosure above the main package, contamination is expected to be less. It has not been determined where the influence of contamination becomes relevant, but previous soundings with the NOAA/CMDL frost-point hygrometer have shown that contamination can influence stratospheric measurements beginning at the tropopause. With the limitations of the Peltier cooler and the materials of the instrument package, stratospheric measurements using the Snow White need to be considered inaccurate.

c. Upper-tropospheric behavior

The behavior in the tropopause region below the tropopause is more complicated, and the soundings obtained so far do not allow for a clear characterization. Figure 4 shows four profiles with good agreement between the Snow White and the NOAA/CMDL hygrometer up to the tropopause. Figure 4d shows a sounding that encountered a dry layer up to 7.5 km, but the Snow White was able to recover at 9 km and to provide acceptable data in the upper troposphere. A sounding 2 days later (not shown) encountered dry layers in the same altitude region, but the Snow White did not recover fully and provided only poor data in the upper troposphere. All soundings in Fig. 4 show good data up to the tropopause, but not much above.

Figure 5 shows four soundings, where the upper-tropospheric Snow White measurements do not agree with the NOAA/CMDL data. In these soundings, the Snow White relative humidity disagrees with the NOAA/CMDL hygrometer in some region below the tropopause using the uncertainties defined above and shown in Fig. 5a. The sounding at Boulder on 15 February 1999 (Fig. 5a) used a day version and encountered a shallow layer of low humidity at 7.5 km. Between this layer and the tropopause at 10.8 km the Snow White shows significantly lower values. A sounding at San Cristóbal on 6 September 1998 (Fig. 5b) also encountered a shallow layer of low humidity at 7.4 km; however, above this altitude the Snow White RH is significantly above the NOAA/CMDL RH, and between 14 km and the tropopause at 16.4 km significantly above ice saturation. In both cases a loss of frost coverage could be the cause for the misbehavior;

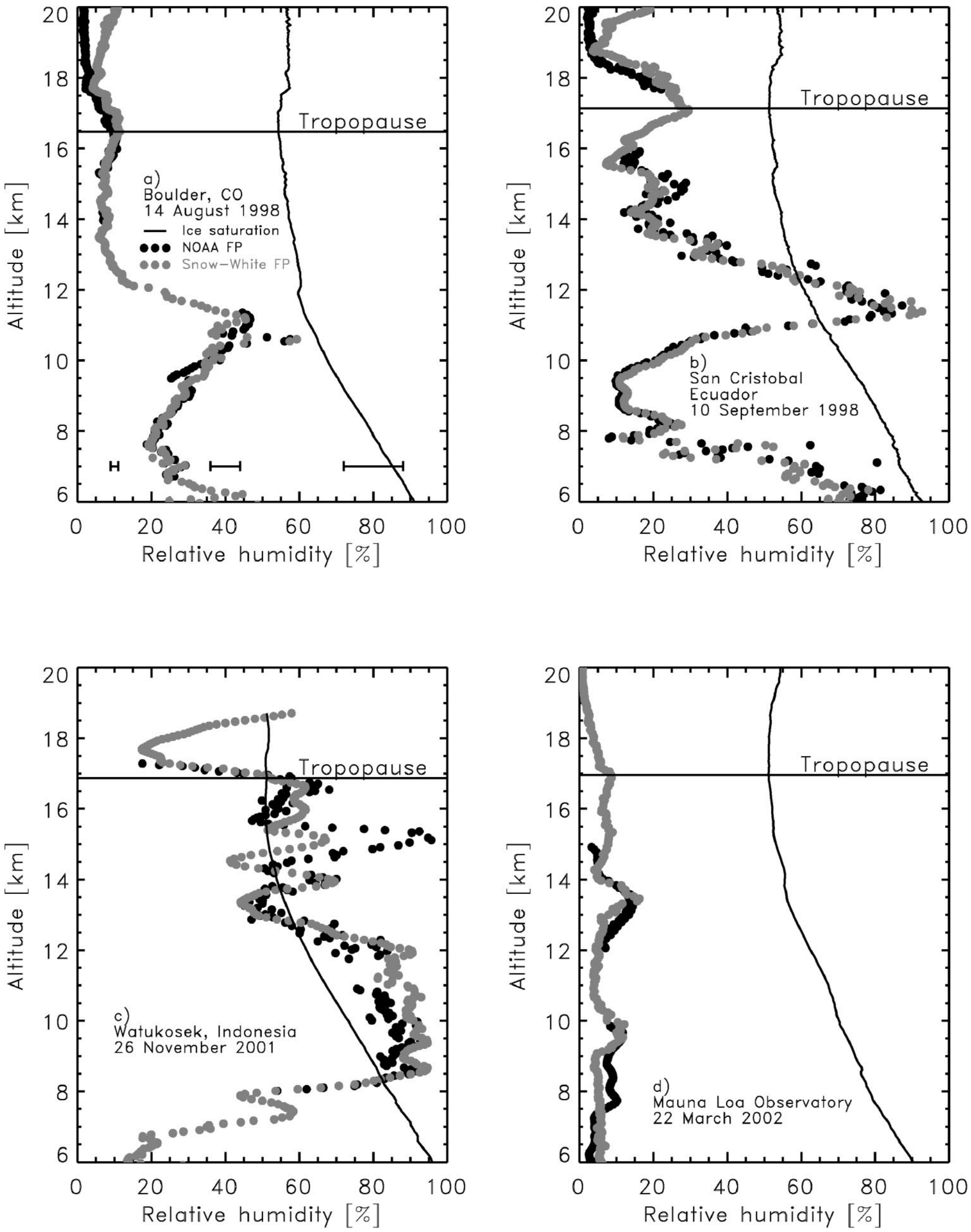

FIG. 4. Four soundings showing good agreement between the Snow White and the NOAA/CMDL hygrometer in the upper troposphere. The error bars shown in (a) apply at 10%, 40%, and 80% RH.

however, the behavior in Fig. 5b is not fully explained by a loss of frost coverage.

In Figs. 5c and 5d, the Snow White measurements are outside the uncertainty range of the NOAA/CMDL RH values above around 15 km, with a tropopause near 16.5 km. In both soundings, structures in the NOAA/CMDL RH profile are reproduced by the Snow White up to 1 km above the tropopause, although with large and varying offsets. The Snow White values are too high in Fig. 5c and too low in Fig. 5d. While the disagreement in Fig. 5c may be explained by insufficient cooling capacity of the Peltier cooler, the cooling capacity in the sounding in Fig. 5d is clearly sufficient. This sounding shows an overshoot of the Snow White frost-coverage controller during the RH change at around 15.2 km. The disagreements in these two soundings could therefore be explained as well by problems in the control circuit at very cold frost-point temperatures below −75°C. Since these soundings did not have the additional monitors, we do not have information about the frost coverage during these soundings.

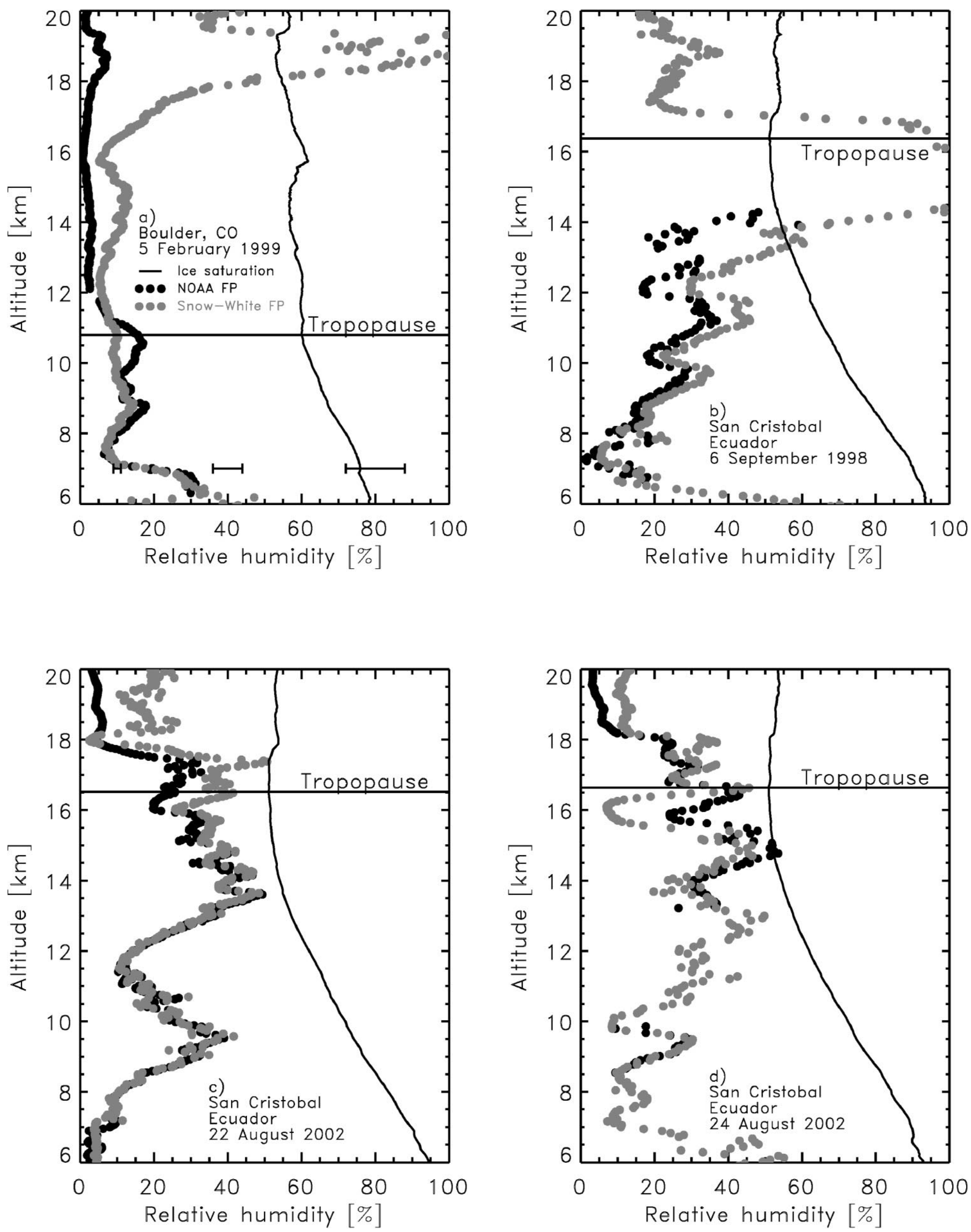

FIG. 5. Four soundings showing poor agreement between the Snow White and the NOAA/CMDL hygrometer below the tropopause. The error bars shown in (a) apply at 10%, 40%, and 80% RH.

d. Relevance of the dry humidity limit

Very shallow layers may only cause a short disturbance in the profile, if the frost coverage on the mirror is immediately regained. In these cases the humidity only within the dry layer will not be measured accurately. In more extensive dry layers, or in dry layers at higher altitudes, the loss of frost coverage may cause erroneous measurements after the encounter and exit of the dry layer. In these cases a certain amount of time is required to rebuild the frost coverage, which may influence parts (see, e.g., Fig. 4d, between 7.5 and 9.5 km) or all of the profile (see Fig. 1) above the dry layer.

Whether the dry humidity limit is relevant for routine observations, which typically do not include a reference instrument, depends on the frequency with which dry layers that cannot be properly measured by the Snow White are encountered. The frequency of these events depends on the geographical region and is evaluated using routine radio soundings with the Vaisala Humicap-H sensor. Here, soundings that encounter dry layers with a relative humidity below 5% of at least 500-m thickness at any altitude below 10 km are considered as problematic soundings for the Snow White.

At Boulder about 10% of all radiosoundings exhibit layers of less than 5% RH, with a seasonal maximum in October, when about 20% of soundings may show these dry layers. At Hawaii, dry layers are encountered in 60% of all soundings, with no seasonal dependence. At San Cristóbal, dry layers are observed in 45% of all soundings and in 65% of the soundings during October–November–December. At Watukosek, Indonesia, dry layers are observed in 25% of all soundings and in 50% during June–July–August.

4. Conclusions

While the generally good performance of the new Snow White chilled-mirror hygrometer in the troposphere has been demonstrated by Fujiwara et al. (2003), some important limitations remain. The most important limitation is the cooling efficiency of the Peltier cooler. While this device is capable of achieving large temperature differences, the temperature depression below ambient temperature depends on the cooling of the hot side and thermal losses in the sensor head. The limited cooling power of the Peltier element is sufficient for a large number of observations, but where measurements past this limit are important, it may only be overcome with a stronger cooling device, a cryogenic system such as that used in the NOAA/CMDL hygrometer, or a hybrid between Peltier and cryogenic cooling. The clear advantage would be an important expansion of the measurement range, with the disadvantage of a more complicated system. This development is currently undertaken at Meteolabor AG.

Other improvements may focus on the sensitivity of frost-layer detection. This issue becomes extremely important in the uppermost troposphere under very cold conditions, when the water vapor concentration becomes very small. Improvements of the sensor may extend the measurement range consistently up to the tropical tropopause.

Routine soundings with the current system may not always have a reference instrument, which would allow the identification of dry layers, where the Snow White might loose control. Thus, monitoring the mirror reflectivity and the Peltier current is recommended for routine observations. These instrument signals provide a strong indication of the proper functioning of the Snow White.

The night version of the Snow White is preferred for observations where the best altitude range is expected. However, stratospheric measurements cannot be considered accurate for Snow White models ASW35 or earlier.

Acknowledgments. The authors would like to thank Paul Ruppert for very helpful discussions and the changes introduced into the Snow White prior to this study. The authors also would like to acknowledge Mario Agama, Jaime Cornejo, and Francisco Paredes at the San Cristóbal Observatory of the Ecuadorian National Institute for Meteorology and Hydrology (INAMHI), and Slamet Saraspriya, Ninong Komala, and Agus Suripto of the Indonesian National Institute of Aeronautics and Space (LAPAN) for the extensive support during the field campaigns at Watukosek. This research has been funded in parts by the Grant-in-Aid for Scientific Research of Priority Areas (B), Grant 11219202, MEXT, Japan.

REFERENCES

Fujiwara, M., M. Shiotani, F. Hasebe, H. Vömel, S. J. Oltmans, P. W. Ruppert, T. Horinouchi, and T. Tsuda, 2003: Performance of the Meteolabor ''Snow White'' chilled mirror hygrometer in the tropical troposphere: Comparisons with the Vaisala RS80 A/H-Humicap sensors. *J. Atmos. Oceanic Technol.,* **20,** 1534–1542.

Kley, D., J. M. Russell III, and C. Philips, Eds., 2000: SPARC assessment of upper tropospheric and stratospheric water vapour. SPARC Report No. 2 WCRP 133, WMO/TD No. 1043, 312 pp.

Mastenbrook, H. J., 1966: A control system for ascent-descent balloon soundings of the atmosphere. *J. Appl. Meteor.,* **5,** 737–740.

——, and J. E. Dinger, 1960: The measurement of water vapor distribution in the stratosphere. Naval Research Laboratory Tech. Rep. NRL 5551, Washington, DC, 35 pp.

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, 2002: Impact of Vaisala radiosonde humidity corrections on ARM IOP data. *Proc. 12th ARM Science Team Meeting,* St. Petersburg, Florida, Atmospheric Radiation Measurement Science Team, 1–9.

Oltmans, S. J., 1985: Measurements of water vapor in the stratosphere with a frost point hygrometer. *Proc. 1985 Int. Symp. on Moisture and Humidity,* Washington, DC, Instrument Society of America, 251–258.

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.

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.