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Performance of operational radiosonde humidity sensors in direct comparison with a chilled mirror dew-point hygrometer and its climate implication

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[1] This study evaluates performance of humidity sensors in two widely used operational radiosondes, Vaisala and Sippican (formally VIZ), in comparison with a research quality, and potentially more accurate, chilled mirror dew-point hygrometer named “Snow White”. A research radiosonde system carrying the Snow White (SW) hygrometer was deployed in the Oklahoma panhandle and at Dodge City, KS during the International H_2O Project (IHOP_2002). A total of sixteen sondes were launched with either Vaisala RS80 or Sippican VIZ-B2 radiosondes on the same balloons. Comparisons of humidity data from the SW with Vaisala and Sippican data show that (a) Vaisala RS80-H agrees with the SW very well in the middle and lower troposphere, but has dry biases in the upper troposphere (UT), (b) Sippican carbon hygristor (CH) has time-lag errors throughout the troposphere and fails to respond to humidity changes in the UT, sometimes even in the middle troposphere, and (c) the SW can detect cirrus clouds near the tropopause and possibly estimate their ice water content (IWC). The failure of CH in the UT results in significant and artificial humidity shifts in radiosonde climate records at stations where a transition from VIZ to Vaisala radiosondes has occurred. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1655 Global Change: Water cycles (1836); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques. **Citation:** Wang, J., D. J. Carlson, D. B. Parsons, T. F. Hock, D. Lauritsen, H. L. Cole, K. Beierle, and E. Chamberlain, Performance of operational radiosonde humidity sensors in direct comparison with a chilled mirror dew-point hygrometer and its climate implication, *Geophys. Res. Lett.*, *30*(16), 1860, doi:10.1029/2003GL016985, 2003.

1. Introduction

[2] Water vapor plays a crucial role in atmospheric radiation and in all phases of the hydrological cycle. Globally, most water vapor data come from radiosonde measurements. The radiosonde represents the only operational instrument that measure atmospheric temperature, humidity, and wind profiles from the surface to stratosphere (with high vertical resolution) under all weather conditions, and have been operating for more than five decades. Globally there are roughly 900 to 1000 operational radiosonde stations and about fourteen different radiosonde types in use. Currently, approximately fifty percent of operational radiosonde stations launch radiosondes manufactured by Vaisala OY in Finland. Vaisala RS80 radiosonde is the most frequently used radiosonde in the world, and has two types, RS80-A first introduced around 1980 and RS80-H introduced in 1992. Sippican radiosondes are used in 10% of global operational radiosonde stations. Note that the VIZ Manufacturing Co. became Sippican, Inc. in 1997. The U.S. National Weather Service (NWS) used VIZ or similar radiosondes at all stations before 1995 and started to introduce Vaisala RS80-H radiosondes to its stations in 1995. Currently, Vaisala radiosondes are used in 60 of the 96 U.S. stations. Because of known measurement errors in current radiosonde systems, and because of the historical changes in sondes used at many sites, a strong effort has focused on constructing a consistent global tropospheric temperature record from radiosonde data. In this paper, we investigate the quality of operational radiosonde humidity data.

[3] We evaluated the quality of Vaisala and Sippican humidity data by comparing with data collected by a more accurate chilled mirror dew-point hygrometer named Snow White (SW) and manufactured by Meteolabor AG, Switzerland. We summarize the performance of the SW hygrometer in Section 2. Instrumentation and data are described in Section 2. The main results from the comparisons between the SW and Vaisala RS80-H Humicap are presented in Section 3. Comparisons between the SW and Sippican CH are summarized in Section 4 along with the impacts of the results for understanding climate processes. The SW’s performance in detecting cirrus clouds and estimating cirrus IWC is evaluated in Section 5. Section 6 summarizes the primary finding.

2. Instrument and Data

[4] Most operational radiosondes use either a capacitive thin-film sensor or a resistive CH humidity sensor. Vaisala RS80 radiosondes use a “Humicap” capacitive thin-film humidity sensor that has two types, the “A” or “H”. Sippican radiosondes use a CH humidity sensor. Both capacitive sensors and CHs can show substantial errors and biases, in particular in the UT and in the stratosphere [e.g., *Kley et al.*, 2000; *Wang et al.*, 2002]. A third type of humidity sensor, a chilled mirror dew point hygrometer, is mainly used within research projects, and was used in this study to evaluate the performances of the capacitive and CH sensors and to assess its potential to improve humidity measurements in the UT. The chilled mirror hygrometer is widely accepted as a reference-quality humidity sensor

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among calibration laboratories around the world [e.g., *Tennermann*, 1999].

[5] The SW chilled mirror hygrometer is a low cost dew-point sensor designed for radiosonde application. The SW's accuracy of the dew-point temperature measurement is <0.1 K. The SW's response time is negligible at +20°C, 10 s at −30°C, and 80 s at −60°C. Several studies have defined the SW's performance characteristics and accuracy, and show that it can be used as one of candidates for reference humidity measurements in the troposphere [e.g., *Schmidlin*, 2001; *Fujiwara et al.*, 2003; *Vomel et al.*, 2003]. These studies also indicate some limitations of the SW sensors: a lower detection limit of 3 to 6% RH, inaccurate measurements above these very dry layers and their inability to measure true supersaturation in the presence of cloud particles. The data used in this study did not encounter these very dry layers. As discussed in Section 5, we take advantage of the SW's ability to measure oversaturation to detect clouds and possibly estimate their liquid or ice water content.

[6] A research radiosonde system was developed for and deployed during IHOP_2002. IHOP_2002 took place over the Southern Great Plains (SGP) of the United States from 13 May to 25 June 2002 (D. B. Parsons et al., Scientific overview document for the International H_2O Project (IHOP_2002), 2000, available from http://www.atd.ucar.edu/dir_off/projects/2002/IHOPdocs/sod_IHOPv2.1.pdf). The research radiosonde includes a Swiss SRS-C34 radiosonde, a Garmin GPS receiver and a 400 MHz telemetry transmitter. The C34 consists of a SW hygrometer, a CH manufactured by Sippican Inc., a copper-constantan thermocouple and a hypsometer. Sixteen research sondes were launched during IHOP on the same balloons with either Vaisala RS80 at the Homestead research site, Oklahoma (100.61°W 36.56°N) or Sippican VIZ-B2 radiosondes at Dodge City, Kansas (100.0°W 37.8°N). Each balloon sounding thus had coincident humidity profiles from three humidity sensors for inter-comparisons: the SW, the CH in the research sonde, and Vaisala RS80 Humicap or the CH in VIZ-B2.

3. Performance of Vaisala RS80-H

[7] Six research radiosondes were launched with Vaisala RS80-H during IHOP at the Homestead site. Mean relative humidity (RH) profiles measured by the SW, the CH inside the research sonde and Vaisala RS80-H are shown in Figure 1a. Note that all RHs used in this paper are RH with respect to water. The RS80-H agrees very well with the SW at temperatures warmer than ∼−15°C (or below ∼6 km) both in absolute RH values and in vertical variations, and then becomes consistently drier than the SW although it still captures RH vertical variations (Figure 1a). In four of the six soundings, the SW identified super-saturation layers around 10–13 km which could be cirrus cloud layers (see Section 5). The RS80-H reported much drier RHs in the 10–13 km layers although it did show increased RHs compared to adjacent vertical layers (see Figure 1a). The dry bias at cold temperatures increases with decreasing temperatures and is partially due to the time-lag and temperature-dependence (TD) errors [*Wang et al.*, 2002].

[8] An earlier collaborative project between NCAR ATD and Vaisala studied a sensor contamination dry bias in Vaisala RS80 humidity data, and found that the dry bias was due to the occupation of binding sites in the sensor polymer by non-water molecules emitted from the sonde packaging material [*Wang et al.*, 2002]. This cooperative study led Vaisala to introduce a new type of protective shield over the RS80 sensor boom in May 2000 to prevent contamination. The comparison shown in Figure 1a, especially at low altitudes, confirms that the new RS80-H with a sensor boom cover is free of contamination dry bias. We applied the TD correction presented in *Wang et al.* [2002] and the time-lag correction presented in *Miloshevich et al.* [2001] to one sounding with a super-saturation layer around 12 km. The corrected Vaisala sounding shows better agreement with the SW data although it is still drier and can not reach the ice saturation (not shown).

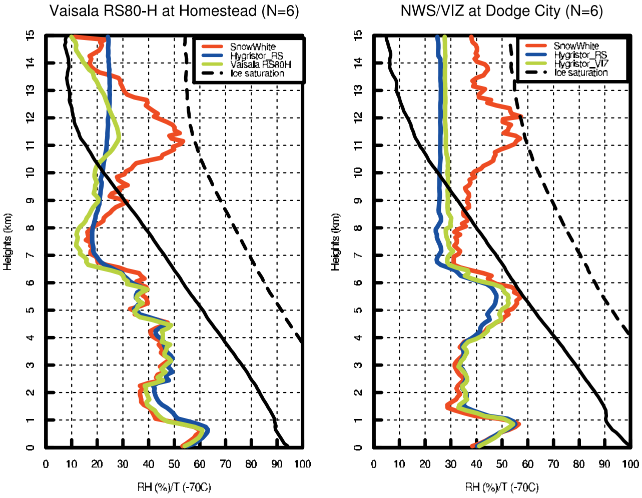

Figure 1. Mean RH profiles from six soundings launched at Homestead with Vaisala RS80-H (left panel, a) and six at Dodge City with NWS VIZ (right panel, b). Mean temperature profiles (solid black) measured by the research sonde are also shown in 0–100°C scale by adding 70°C to actual temperatures.

4. Performance of Sippican Radiosonde and Climate Implications

[9] For all six soundings launched at Dodge City with Sippican VIZ-B2 radiosondes, each sounding produced three simultaneous RH profiles from the SW and two CHs. Both CHs were manufactured by Sippican Inc. Figure 1b shows comparisons of mean RH profiles from the SW and two CHs and illustrates typical features of comparisons from all six soundings. Both CHs had slower responses than the SW, but the CH inside the research sonde was even slower than that in VIZ-B2 sondes (i.e., smaller RHs in the moist layers at ∼4–6 km in Figures 1b and 2b, and at ∼6–8 km in Figure 2a), even though the two sensors are essentially identical. The slower response of the CH in the research sonde was likely due to the fact that ventilation in the VIZ-B2 was better than in the research sonde because of its larger and shorter duct and larger air intake.

[10] The comparisons of six soundings show that both CHs stopped responding to humidity changes at colder temperatures (see an example in Figure 2a) or when RH changed dramatically over a short period of time (see an example in Figure 2b). Mean RH profiles in Figure 1b

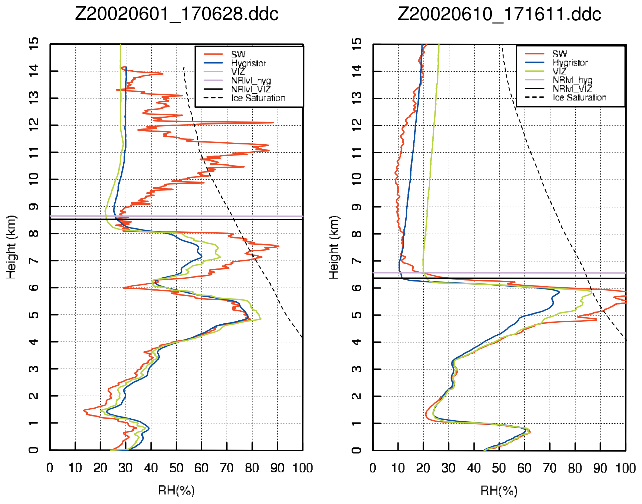

Figure 2. Comparison of RH profiles from the SW (red) and CHs in the research sonde (blue) and in NWS VIZ radiosonde (green) on June 1 (left panel, a) and 10 (right panel, b) at Dodge City. No-response levels are shown by black line for the research sonde and pink line for NWS VIZ.

show that both CHs lost sensitivity at temperatures colder than ∼−34°C (or above ∼8.5 km). For these cases, CH-measured RH stayed approximately constant during the rest of the flight and increased slightly as temperatures decreased (Figure 2). The variation of RH with altitude ($\partial RH/\partial z$) for all 22 CH RH profiles (16 by the CH in the research sonde and 6 by that in the VIZ-B2) is calculated to determine the level where the CHs stopped responding (“no-response” level); $|\partial RH/\partial z|$ is required to be less than 5%/km at and above the no-response level (see two examples in Figure 2). Temperatures at no-response levels range from −8°C to −55°C with a mean of −28°C. Our preliminary studies suggest that such insensitivity of the CH is partly due to its insufficient precision of voltage output. The CH measures voltage which is converted to resistance. In order to see 2% RH changes at RH < 20%, less than 2 mV voltage changes (<0.1% in relative values) are required to measure. In addition, the failure of CH in the UT is possibly due to the fact that the CH becomes frozen above a moist layer.

[11] The failure of CHs to detect moisture in the UT evident in these intercomparisons has major impact on long-term climate records. As mentioned in Section 1, U.S. radiosonde stations have been undergoing the transition from VIZ to Vaisala radiosondes since 1995. *Elliott et al.* [2002] show that the largest change in RH associated with this transition at all stations occurs at 100 hPa with a decrease of 10–20% RH, which is most likely due to the failure of the CHs at 100 hPa as observed in our study. Figure 3 shows monthly mean RH profiles from April to August in 1994, 1995, 1996, 1999, 2000, and 2001 at Topeka derived from 6 s high-resolution and twice-a-day NWS radiosonde data. RHs in the UT drop significantly and exhibit seasonal variations from 1999 to 2001 when Vaisala radiosondes were used, but show no variations with height or season from 1994 to 1996 when VIZ radiosondes were used (Figure 3). It is well known that U.S. radiosonde stations started to report RH below 20% and at temperatures below −40°C in October 1993 and changed the coefficients used for RH < 20% in June 1997 [*Elliott et al.*, 2002]. All these changes were expected to improve VIZ RH data in the UT. However, our results show that CHs still fail to measure humidity at temperatures as warm as −8°C. We have to question whether efforts made in the last ten years to improve the UT humidity measurements using the CH is worth because of the incapability of the CH in the UT. As concluded by the Stratospheric Processes And their Role in Climate (SPARC) assessment [*Kley et al.*, 2000], among many different operational radiosonde humidity sensors, only the thin film capacitor sensors are capable of measuring in the UT. As shown in Section 3, the Vaisala RS80 sondes also exhibit significant errors in the UT. However, since the sensors do not lose their response the possibility remains that some of the errors induced in the climate record by these systems may be corrected.

5. Detecting Cirrus Clouds Using the SW

[12] It has always been a challenge to measure cirrus clouds and their physical and optical properties because of their cold temperatures, complicated microphysics, and occasional sub-visible (optically thin) nature. The SW is capable of measuring dew point temperatures higher than the dry-bulb temperature (i.e., RH > 100%) from the surface to the tropopause if the sensor flies through clouds containing liquid water or ice crystals. The SW’s heated sensor housing evaporates water droplets and small ice crystals in the air sample, resulting in an apparent super-saturation. Note that the SW cannot distinguish between supersaturated air and the presence of cloud particles. By assuming that the ambient air reaches ice saturation, the total cloud liquid/ice water content can be calculated from the SW RH profiles, although one cannot distinguish the presence of liquid water from ice cloud particles. In ten out of the 16 IHOP soundings, the SW showed saturated or supersaturated layers near or right below the tropopause, indicating the presence of cirrus clouds.

[13] To quantitatively determine cirrus cloud boundaries (top/base), the cloud-boundary determination scheme developed by *Wang and Rossow* [1995] was applied to the SW data using a 96% RH threshold to indicate clouds. Cirrus cloud IWC profiles were also calculated. Figure 4 shows two examples. On May 30, the SW identified a cloud layer between 10.68 and 12.62 km with a mean IWC of 6.4 mg/m^3. This cirrus cloud layer was not evident on satellite images

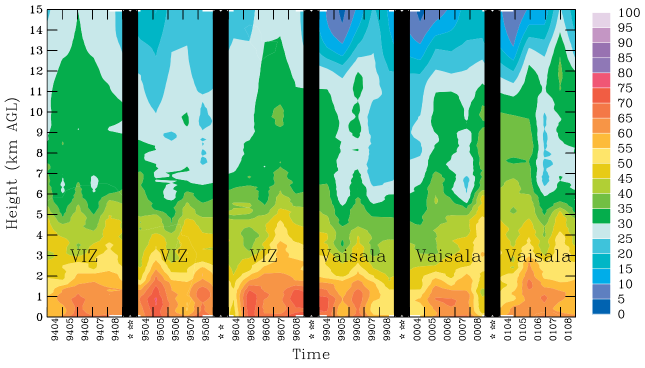

Figure 3. Monthly mean RH profiles from April to August in 1994, 1995, 1996, 1999, 2000, and 2001 at Topeka.

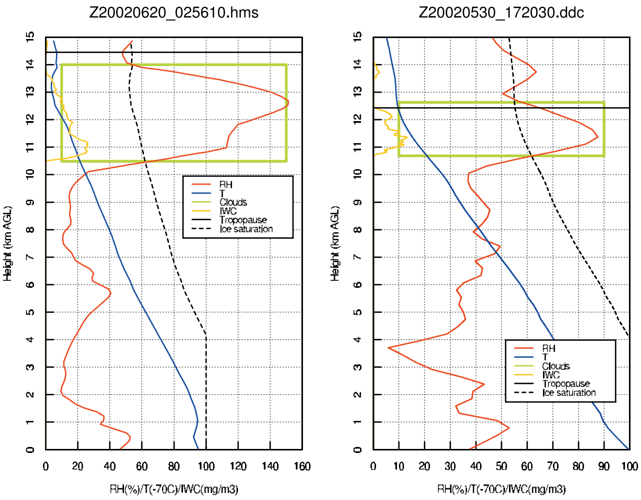

Figure 4. Smoothed SW RH (red) and temperature (blue, in 0–100°C scale by adding 70°C) profiles from the research sonde on June 20 at Homestead (left panel) and on May 30 at Dodge City (right panel). Cloud boundaries are labeled as green boxes. Orange lines are cloud IWC profiles, and black lines give the tropopause locations.

probably because the cloud was optically thin, but it was visible in the aerosol depolarization data collected by NASA's scanning Raman lidar (SRL), and corresponded qualitatively well with SRL data in cloud top and base heights. The SW RH profile at 0256 UTC on June 20 indicated a thick cirrus cloud layer between 10.5 and 14 km (232–132 hPa), and showed the expected decrease of IWC with decreasing temperature (increasing height). The GOES-8 satellite data at 0246 UTC on June 20 showed cloud tops above 200 hPa in the Homestead area; the surface observer also reported the appearance of a cirrus anvil. Cirrus clouds determined from ten super-saturated soundings had a mean top height of 12.27 km and base height of 10.72 km, a mean thickness of 1.55 km, a mean ice water path (IWP) of 6.43 g/m^2, and a mean distance from cloud top to tropopause of 0.63 km. These mean values qualitatively agree with data derived from cloud radar data in the summer of 1997 in SGP by *Mace et al.* [2001], which are 12.1 km (top height), 10.3 (base height), 2 km (thickness), 8.1 g/m^2 IWP and 1.8 km from cloud top to tropopause, respectively. Larger IWP and larger distance of the layer top from the tropopause shown by cloud radar data are probably due to some sub-visible clouds missed by cloud radar.

6. Concluding Remarks

[14] Sixteen dual soundings of research radiosondes with either Vaisala RS80 (at the Homestead site, OK) or with Sippican VIZ-B2 (at Dodge City, KS) radiosondes were made during IHOP_2002. Each sounding provides coincident RH profiles measured by the SW, a CH in the research sonde, and either Vaisala RS80 Humicap or a CH in Sippican VIZ-B2 radiosonde. Comparisons of RH profiles from different humidity sensors yield the following main results. (1) The comparisons of humidity data from the SW with that from Vaisala RS80-H with the new sensor boom cover for preventing contamination show that Vaisala RS80-H radiosonde has good performance in measuring humidity in the lower and middle troposphere but has time lag errors in the UT. (2) CHs in both the research sonde and the Sippican VIZ-B2 showed time-lag errors throughout the troposphere. The slower response for the CH in the research sonde than that in the Sippican VIZ-B2 was likely due to poor ventilation in the research sonde, suggesting that, in addition to improving sensor accuracy, special attention should also be paid to other factors affecting the quality of radiosonde data. (3) Both CHs failed to respond to humidity changes in the UT, sometimes even in the middle troposphere. This lack of response has produced significant and artificial humidity changes in the UT at stations where a transition from VIZ to Vaisala radiosondes occurred. The absence of significant humidity response by CHs in the UT precludes adjustments or transfer functions, so any artificial shifts in climate moisture records associated with CHs probably cannot be removed. (4) The SW data reveal SW's ability to detect cloud layers and possibly estimate cloud LWC and/or IWC, especially for high/cold cirrus clouds which are often difficult to measure. SW-estimated cirrus cloud properties agree qualitatively with data from other instruments.

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