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A REFERENCE RADIOSONDE SYSTEM FOR IMPROVING WATER VAPOR MEASUREMENT IN IHOP_2002

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1. INTRODUCTION

One of the most important advances in the early history of weather forecasting was the development of the radiosonde in the late 1920s. Today, numerical weather prediction models rely on radiosonde data for their initialization because radiosondes provide the only operationally available upper-air data around the globe with an independent calibration. In recent years, radiosonde data has received increased attention in climate research because it provides the longest record (the last four or five decades) of upper-air temperature, humidity and wind, has a near-global coverage (best in the Northern Hemisphere), and has high vertical resolution.

Globally there are roughly 900 operational radiosonde stations and about fourteen different radiosonde types in use (Fig. 1). Frequent equipment and procedural changes have been made and continue to occur in this radiosonde network. All existing operational radiosondes have known observational errors. As a result, changes in instruments and/or data reporting practices among stations and with time have introduced spurious climate change signals. Currently, approximately fifty-one percent of radiosonde stations use radiosondes manufactured by Vaisala OY in Finland. A systematic and significant dry bias has been identified in Vaisala radiosonde humidity data collected during the Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA COARE) (Zipser and Johnson 1998; Wang et al. 2002). ATD collaborated with Vaisala developed physical models based on laboratory tests to correct the contamination dry bias along with other errors in Vaisala humidity measurements (Wang et al. 2002). However, even with physically-based, reproducible correction schemes, ATD found that correction methods using surface data as an independent **reference** work better than methods derived solely from laboratory tests. U.S. National Weather Service (NWS) used VIZ (Sippican) or similar radiosondes at all NWS stations before 1995, and started to introduce Vaisala RS80-H radiosondes to its stations in 1995. Currently, Vaisala radiosondes are used in 60 out of total 96 U.S. stations. Elliott et al. (2002) found detectable shifts in climate data record associated with changes from VIZ to Vaisala radiosondes. However, without **reference** data no simple adjustment to eliminate the artificial shift seems possible.

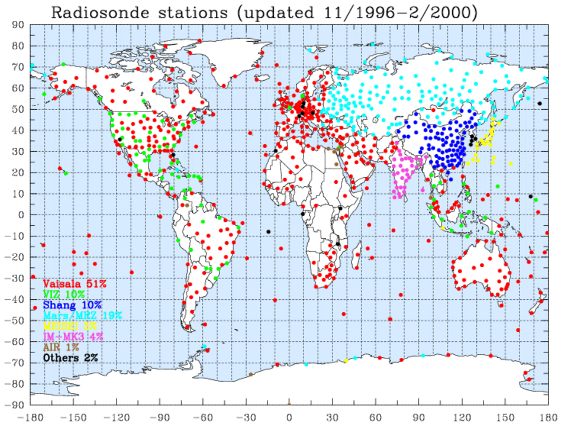

Fig. 1: Geographic distribution of global radiosonde stations (total 852) colored by radiosonde types. The percentage given in legend is the percentage of stations used by each type of radiosonde.

A fundamental requirement in the effort to reduce and eventually remove errors for various types of radiosondes, and to eliminate artificial spatial or temporal inhomogeneity, is to establish a reference device and/or a reference dataset for comparisons with radiosonde data. Development of a true reference radiosonde would provide an important tool to evaluate the absolute performance of particular radiosondes or specific sensors. If developed and deployed soon, while many of the primary radiosonde types and systems of the past 20 years remain in use, a reference radiosonde could help repair and improve homogeneity and continuity of radiosonde data records over time and space. Our goal is to develop a reference sonde system to serve as a transfer standard to compare and connect data from past, present and future sonde systems, as a calibration and quality-control tool for application in operational sounding systems and for comparison with many remote sensing systems, and also as a sensor test bed to facilitate the development of new sensors. Because the new sonde will produce reference-quality

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measurements, it will see frequent use as a research tool in a variety of weather and climate field programs.

In this paper, we describe our first version of the reference radiosonde system developed for the International H_2O Project (IHOP_2002) (Parsons et al. 2000) and present main results from analysis of the IHOP reference radiosonde data. IHOP_2002 took place over the Southern Great Plains (SGP) of the United States from 13 May to 25 June 2002. The main goal of IHOP_2002 is improved characterization of the four-dimensional distribution of water vapor and its application to improving the understanding and prediction of convection. The main goals of the IHOP deployment of the reference radiosonde were to perform intercomparisons among different radiosonde humidity sensors and to compare the reference radiosonde data with other remote sensors to obtain a measure of the accuracy of the wide variety of water vapor remote sensors deployed during IHOP. The instrumentation and data are described in Section 2. Main results from comparisons between SW and Vaisala RS80 are presented in Section 3. Comparisons between SW and carbon hygristors in the reference sonde (RS) and in NWS VIZ radiosonde are summarized in Section 4 along with climate impacts of the results. SW's performance on detecting cirrus clouds and estimating their IWC is evaluated in Section 5. Section 6 summarizes main results and presents planned future work.

2. INTRUMENTATION AND DATA

The main components of the first version of reference radiosonde are a Swiss SRS-C34 radiosonde manufactured by Meteolabor AG, Switzerland (Hoegger et al. 1999) to measure temperature, humidity and pressure, a Garmin GPS receiver to measure wind, a dropsonde 400 MHz telemetry transmitter to transmit data from multiple sensors to the ground (Hock and Franklin 1999), and a wood or plastic boom for carrying the RS at one end and another radiosonde at the other end. The C34 consists of a Snow White (SW) chilled-mirror dew-point hygrometer and a carbon hygristor manufactured by Sippican Inc. for humidity measurements, a small copper-constantan thermocouple (0.05 mm diameter) for temperature and a full range hypsometer for the pressure. The SW hygrometer is used as our reference humidity sensor, and is based on the physically well-known 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. The mirror temperature is equivalent to the dew-point temperature of the air. The SW uses a 3 mm X 3 mm copper-constantan thermocouple directly mounted on the cold side of the Peltier cooler as a mirror and a temperature sensor at the same time. The accuracy of the mirror temperature measurement is < 0.1 K. The SW response time is negligible at $+20^0$C, 10 s at -30^0C, and 80 s at -60^0C. The SW needs no individual calibration and can be used again without recalibration if recovered after flight. Several studies have been done to define SW's characteristics and accuracy, and show that it can be used as the reference humidity measurement in the troposphere and possibly in the lower stratosphere (Fujiwara et al. 2002; Vomel et al. 2002).

A Suburban van was used for balloon inflation and sonde preparation, and as a mobile sounding station and a chase vehicle. A Garmin GPS receiver was mounted at the top of the van to provide the van location. The RS was launched with either Vaisala RS80 at Homestead site or NWS Sippican (VIZ) radiosondes at Dodge City on the same balloon. During IHOP sixteen reference radiosondes were launched and summarized in the Table 1. After releasing the sonde, the operators drove the van to chase and eventually recover the sonde. We recovered fourteen sondes. Each sounding has humidity data from three humidity sensors for intercomparisons, SW, carbon hygristor inside RS, and Vaisala RS80 Humicap or carbon hygristor inside NWS/VIZ. The data from all 16 soundings have been quality controlled individually through Atmospheric Sounding Processing Environment (ASPEN) software, visually checked, corrected individually for some bad points and averaged to 2 s data. Note that all relative humidity (RH) presented below is RH with respect to water.

Table 1: Summary of reference radiosondes launched during IHOP

2nd Sonde	Number of soundings	Locations	Time of launches
Vaisala RS80-H	7	Homestead, OK (100.606ºW 36.559ºN)	all 18Z except one at 11Z (6 am CST) and one at 3Z (10 pm CST)
Vaisala RS80-A	2	Homestead, OK (100.606ºW 36.559ºN)	15Z and 19Z
NWS VIZ B-2	7	Dodge City, KS (100.0ºW 37.8ºN)	18Z

3. COMPARISON BETWEEN SW AND VAISALA RS80

The RH profile at 18 Z on June 18, 2002 at Homestead was measured by SW, RS carbon hygristor and Vaisala RS80-H Humicap and is shown in Fig. 2 along with temperature profiles measured by the RS (thermocouple) and RS80-H radiosondes. The RS80-H agrees very well with the SW below ~6 km (~-15°C) both in absolute RH values and in vertical variations of

RHs, and then becomes consistently drier than SW above 6 km although it still captures RH vertical variations (Fig. 2). The SW identifies a supersaturation layer within 11.4-12.7 km which could be a cirrus cloud layer (see Section 5), while the RS80-H measures RHs below 30% in this layer although it shows the increase of RHs comparing to adjacent layers (Fig. 2). Six other soundings flown with RS80-H show similar features. Fig. 3 shows the scatter plot of comparisons of RHs from RS80-H Humicap and SW, and temperatures from RS80-H F-thermocap and RS thermocouple derived from all 7 soundings flown with RS80-H. Vaisala RS80-H agrees very well with SW at T > ~-5°C (< 1% RH difference on average), and then shows increasing dry biases as temperatures get colder (Fig. 3). The dry bias of Vaisala RS80-H at cold temperatures is most likely due to time-lag errors, but a temperature-dependence error may also contribute to a small degree (Wang et al. 2002). The comparisons in Fig. 2 and 3 confirm that the new RS80-H with a sensor boom cover, which is an improvement made after the collaborative work between Vaisala and ATD described in Section 1 and Wang et al. (2002), is free of contamination dry bias. The temperature from RS (thermocouple) is consistently warmer than that from RS80-H by about 0.65°C (Fig. 3). This difference is still under investigation.

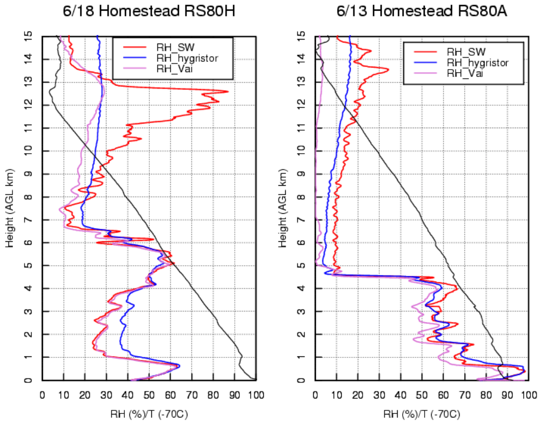

Fig. 2: Comparison of RH profiles from SW (red), carbon hygristor (blue) in RS and Vaisala RS80 (pink) on June 18 (with RS80-H) and on June 13 (with RS80-A) at Homestead. Temperature profile (black) measured by thermocouple in RS is also shown in 0-100°C scale by adding 70°C to actual temperatures.

Two ~10-year-old RS80-A sondes (manufactured in 1992) were launched with the RS at Homestead on June 13 and 23 (June 13 case shown in Fig. 2). RHs measured by RS80-A are consistently drier than that from SW (Fig. 2), which is due to known contamination dry bias in RS80-A (Wang et al. 2002). The scatter plot of comparisons for data below 5 km (minimizing other errors above 5 km) in Fig. 3 shows that the dry bias increases with RH, reaches a maximum (~14%) at ~85% RH, then shows a small decrease. Such dependence of dry bias on RH is consistent with that shown by lab tests described in Wang et al. (2002), but the dry bias shown here has much larger magnitude than that produced by our correction schemes. The contamination dry bias is expected for these old RS80-A sondes because the sonde packaging material gradually outgases nonwater molecules which reduce the ability of the polymer to absorb water molecules (Wang et al. 2002). However, Fujiwara et al. (2002) found that RS80-A sondes manufactured in 2000-2001 with the new protective shield over the sensor boom also has a dry bias of ~10% at RH > 50%. As shown in Section 3, the new RS80-H with the sensor boom cover is free of contamination dry bias. More studies need to be done to understand still-existing dry bias in RS80-A sondes.

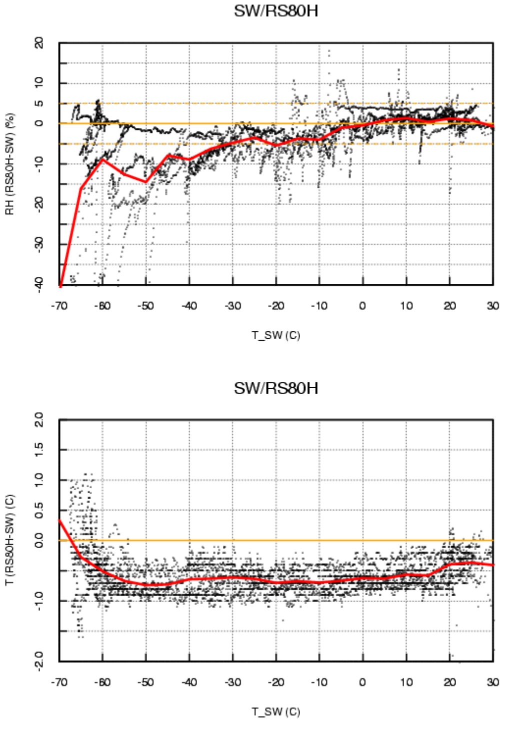

Fig. 3: Scatter plot of RH difference between RS80-H and SW and temperature difference between RS80-H and thermocouple in RS as a function of temperatures measured by thermocouple in RS. Red lines are averaged differences in 5°C bin.

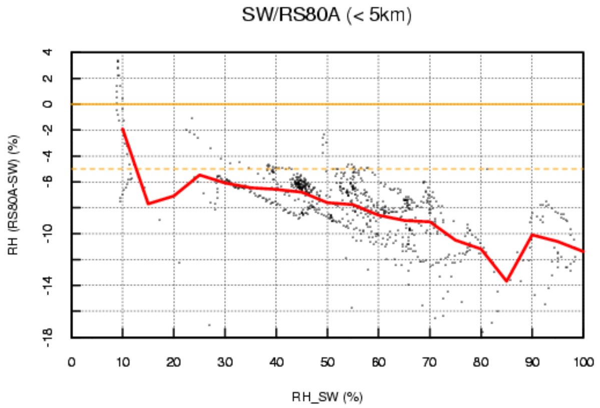

Fig. 4: Scatter plot of RH difference between RS80-A and SW as a function of RHs measured by SW. The red line is averaged difference in 5% RH bin.

4. COMPARISONS BETWEEN SW AND CARBON HYGRISTOR AND IMPLICATIONS ON CLIMATE IMPACTS

For all seven soundings launched at Dodge City, each sounding produces three simultaneous RH profiles from SW and two carbon hygristors, one inside RS (i.e., inside Swiss SRS C34) and one inside NWS VIZ radiosonde. Both carbon hygristors are manufactured by Sippican, Inc. and exactly same humidity sensors. Fig. 5 shows comparisons of RH profiles from SW and two carbon hygristors on June 1 and June 20, and represents typical features of comparisons from all seven soundings with both hygristors and other nine soundings with the RS hygristor (see examples shown in Fig. 2).

The comparisons of all soundings show that both hygristors have slower response time than the SW, but the hygristor in the RS is even slower than that in NWS/VIZ sondes, such as inside the moist layers in 6-8 km on June 1 and in 4-6 km on June 10 (Fig. 5 and 2), even though the two sensors are the same. The latter feature is likely due to the fact that the ventilation in NWS/VIZ is better than the RS, i.e., larger and shorter duct and larger air intake, and that we added the GPS receiver on the top of the C34 and protected it with a Styrofoam block which interferes with the air flow into the duct (Fig. 6).

Both hygristors stopped responding to humidity changes at colder temperatures or when RH changes dramatically over a short period of time. For example, two soundings in Fig. 5 show that both hygristors lose sensitivity above 8.5 km on June 1 and above ~6.5 km on June 10. For these cases, hygristor-measured RH stays approximately constant during the rest of the flight and increases slightly as temperatures are decreasing (Fig. 5 and 2). The variation of RH with altitude (FRH/Fz) is calculated for all 21 hygristor_measured RH profiles, and is used to determine the level where the hygristor stops responding (called a no-response level). |FRH/Fz| is required to be less than 5%/km at and above the no-response level. Temperatures at no-response levels are displayed in Fig. 7 for all 21 hygristor_measured RH profiles, are below 0°C for all profiles, but can vary a lot from sounding to sounding and are -28°C on average. Preliminary studies suggest that such insensitivity of carbon hygristor in the upper troposphere (sometimes in the middle troposphere) is partly due to characteristics of variations of RH with resistance and insufficient precision of voltage output for carbon hygristor. The carbon hygristor 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.

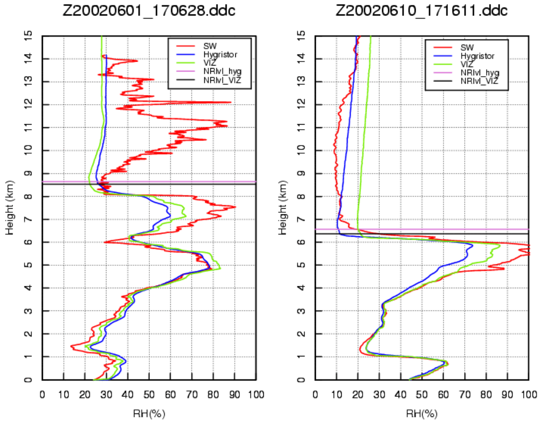

Fig. 5: Comparison of RH profiles from SW (red) and carbon hygristors in RS (blue) and in NWS VIZ radiosonde (green) on June 1 and on June 10 at Dodge City. No-response levels determined by hygristor_measured RH profiles are shown by black line for RS and pink line for NWS VIZ.

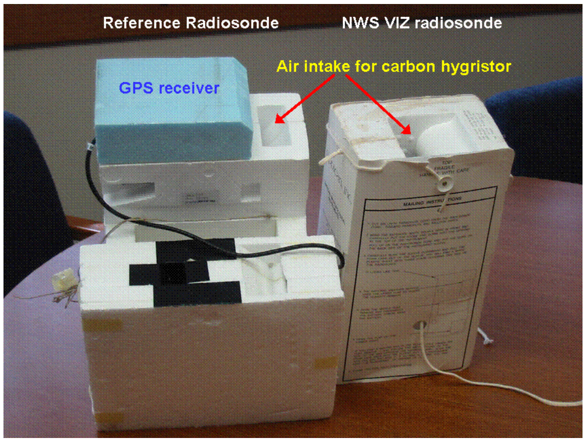

Fig. 6: A picture of reference radiosonde and NWS VIZ radiosonde showing air intakes for carbon hygristors.

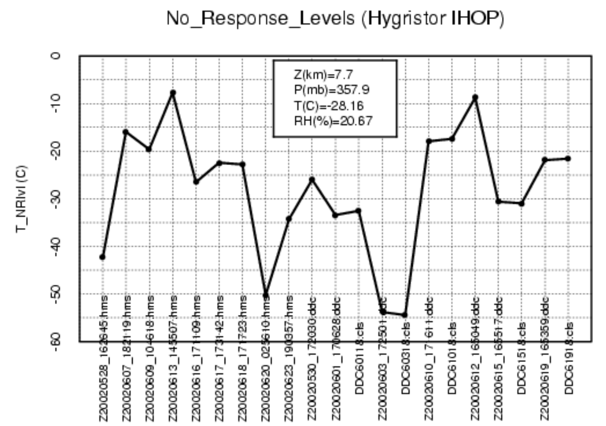

Fig. 7: Temperatures at no-response levels derived from 21 RH profiles measured by carbon hygristors in RS (16 with file names in x- axis started with Z) and in NWS/VIZ (5 with file names in x-axis started with DDC).

The failure of carbon hygristor in the upper troposphere described above would have great climatic impacts. 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)[3] show that the largest change in RH associated with this transition at all stations occurs at 100 mb with a decrease of 10-20% RH, which is most likely due to the failure of the carbon hygristor at 100 mb found here. Fig. 8 shows monthly mean RH profiles from April to August in 1994, 1995, 1996, 1999 and 2000 at Dodge City and Topeka derived from 6s high-resolution and twice-a-day NWS radiosonde data. It shows that RHs in the upper troposphere at Topeka drop significantly in 1999 and 2000 when Vaisala radiosondes were used and exhibit seasonal variations, but show no variations with both height and seasons from 1994 to 1996 when VIZ radiosondes were used. The no-response level defined above is also calculated from Topeka data for 1994-1996 period and 1999-2000 period (Fig. 9). The temperature at no-response levels for VIZ data has a wide distribution from -15ºC below with a peak probability in -55ºC to -60ºC bin, while Vaisala soundings show insignificant variations with heights at temperatures below -50ºC. It is well known that U.S. radiosonde stations in October 1993 started to report and calculate RH below 20% using “1b” coefficients for VIZ radiosondes instead of reporting as 19% before, and to report RHs at temperatures below -40ºC instead of reporting them as “missing”. Since June 1997, VIZ RH data have been calculated using “1a” coefficients for RH < 20%. All these changes are expected to improve VIZ RH data in the upper troposphere. However, our results show that the carbon hygristor (used as VIZ humidity sensor) still fails to measure humidity at temperatures as warm as -5ºC. The questions that need to be answered are whether any improvements have been made in VIZ RH measurements in the upper troposphere in the last ten years and whether the failure is due to incapability of the sensor or human factors.

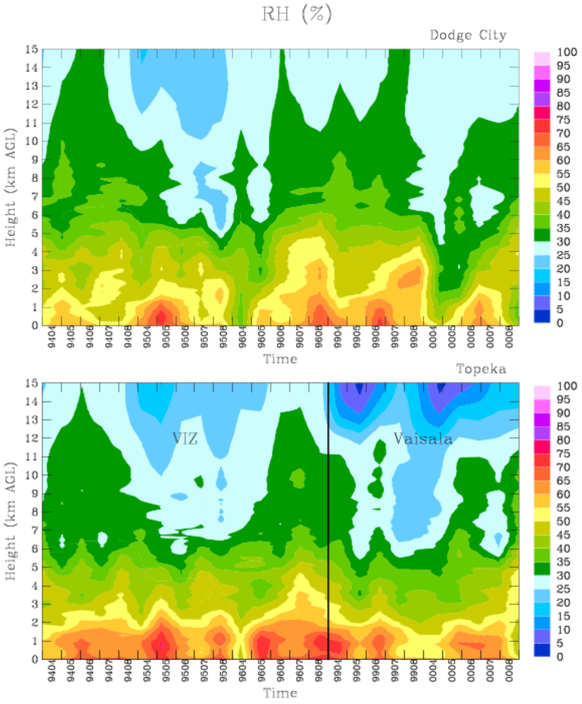

Fig. 8: Monthly mean RH profiles from April to August in 1994, 1995, 1996, 1999 and 2000 at Dodge City and Topeka (see text for details).

5. DETECTING CIRRUS CLOUDS USING SW

It has always been a challenge to measure cirrus clouds and their physical and optical properties because of their cold temperature, complicated microphysics and their occasional subvisibility (optically thin). Snow White is capable of measuring dewpoint temperature higher than the ambient temperature (i.e., RH > 100%) from surface to tropopause if it 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 super-saturation. Note that SW cannot distinguish between supersaturated air and the presence of cloud particles. Total cloud liquid/ice water content can be calculated from SW_measured RH profiles by using ice saturation RH profile although it cannot identify whether it is liquid or ice cloud. In ten out of all 16 soundings, SW shows saturated or supersaturated layers near or right below the tropopause, indicating the presence of cirrus clouds.

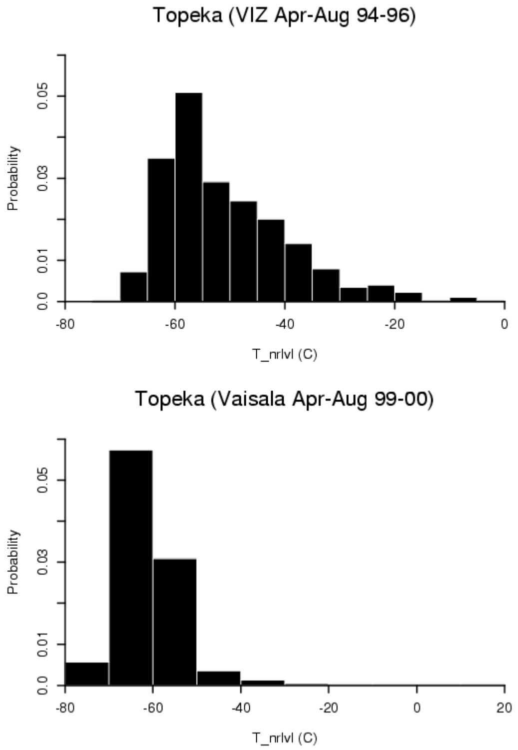

Fig. 9: Histograms of temperatures at no-response levels at Topeka for data from 1994 to 1996 and in 1999-2000.

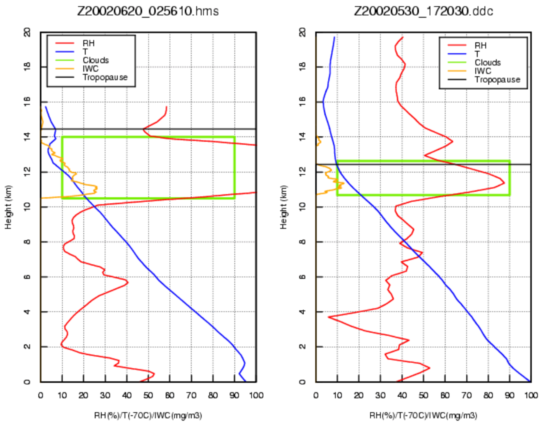

Fig. 10: Smoothed RH profiles (red lines) and temperature profiles (blue lines) from thermocouple on June 20 at Homestead and on May 30 at Dodge City. Cloud boundaries determined by SW RH profiles are labeled as green boxes. Orange lines are cloud IWC profiles, and black lines give the tropopause locations.

To quantitatively determine cirrus cloud boundaries (top/base), the cloud-boundary determination scheme developed by Wang and Rossow (1995) is applied to the SW data by using 96% RH threshold inside clouds. Cirrus cloud ice water content (IWC) profiles are also calculated. Fig. 10 shows two examples. The conventional lapse-rate tropopause is also determined using temperature profiles and is shown in Fig. 10. On May 30, SW identifies a cloud layer in 10.68-12.62 km with a mean IWC of 6.4 mg/m^3 (Fig. 10). This cirrus cloud layer did not show up on satellite images probably because it was optically thin, but was visible in the aerosol deposition data collected by NASA's scanning Raman lidar (SRL), and corresponds qualitatively well with SRL data in cloud top and base heights. The SW RH profile at 0256 UTC on June 20 indicates a thick cirrus cloud layer in 10.5-14 km (232-132 mb) with a mean IWC of 11.75 mg/m^3, and shows the expected decrease in IWC with decreasing temperature (increasing height) (Fig. 10). GOES-8 satellite data at 0246 UTC on June 20 show cloud tops above 200 mb in the Homestead area; the surface observer also reported the appearance of a cirrus anvil. Cirrus cloud locations, physical thickness, mean IWC and tropopause heights for all ten cirrus-cloud soundings are displayed in Fig. 11. After excluding the data on June 3 which has anomalous high RHs from 8 km to the top of the profile, SW-detected cirrus clouds have 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 that 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 of subvisible clouds missed by cloud radar.

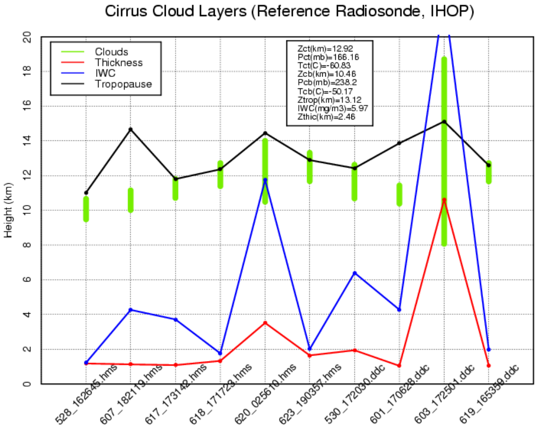

Fig. 11: Summary of cirrus cloud properties estimated by SW for ten cloudy soundings, including cloud locations (green bars), thickness (red lines), and average IWC (blue lines) along with tropopause heights (black lines). Mean cloud top/base heights, pressures, and temperatures (Zct, Zcb, Pct, Pcb, Tct, Tcb), mean cloud thickness (Zthic) and IWC, and mean tropopause heights (Ztrop) are given in the legend.

6. SUMMARY AND FUTURE PLANS

A reference radiosonde system was developed and deployed during IHOP_2002, and was launched sixteen times on the same balloon either with Vaisala RS80 radiosondes at Homestead or with NWS VIZ radiosondes at Dodge City. Each sounding provides coincident RH profiles measured by the reference humidity sensor (Snow White (SW) chilled-mirror dewpoint hygrometer), VIZ carbon hygristor in RS and either Vaisala RS80 Humicap or carbon hygristor in NWS VIZ radiosonde. Main results are summarized here. (1) Intercomparisons of humidity data from new Vaisala RS80-H with the sensor boom cover for preventing contamination with SW show that Vaisala RS80-H radiosonde has good performance in the middle and lower troposphere but has time lag errors in the upper troposphere. (2) Carbon hygristor in both RS and NWS VIZ radiosonde bears time-lag errors, but the one in RS has even slower response than the one in NWS VIZ sonde although two sensors are exactly the same. It is likely due to poor ventilation of carbon hygristor in RS, suggesting that, in addition to improve sensor accuracy, special attention should also be paid to external factors affecting the quality of radiosonde data. (3) Both carbon hygristors fail to respond to humidity changes in the upper troposphere, sometimes even in the middle troposphere, resulting in significant humidity changes in the upper troposphere (UT) at stations where the transition from VIZ to Vaisala radiosondes occurred. Carbon hygristor data are unable to show any seasonal and vertical RH variations in the upper troposphere. Such failure of the carbon hygristor in UT is not correctable, so the artificial shift in climate record associated with it 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-measured cirrus cloud properties agree qualitatively with data from other instruments.

The development of this version of reference radiosonde was our first attempt. The design of RS (both hardware and software) needs some major modification (maybe a completely new design) to reduce its cost, size, weight and improve its ease of operation. Both our study and similar studies by others convince us that SW can be used as the reference humidity sensor. The SW's ability to detect cloud layers and measure their LWC/IWC needs to be validated by flying with other cloud instruments, and some improvements will be made to SW for better cloud measurements. The focus of this paper is on humidity measurement since it is the most difficult parameter to measure accurately. In the future, the reference temperature, pressure, wind and height sensors will also be selected and evaluated. The future reference radiosonde will have a flexible infrastructure to allow it to be easily adapted to many types of sensors and many modes of deployment.

7. ACKNOWLEDGMENTS

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