Impact of a New Temperature-Dependence Correction on Historical Meisei Radiosonde Humidity Data

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Abstract

A new temperature-dependence correction (T-D correction) for Meisei RS2-91, RS-01G, and RS-06G radiosonde relative humidity (RH) measurements has been developed recently to remove the artificial stepwise change of ~3% RH at 0°C associated with the present (original) correction. These radiosondes have been used at most of the Japanese upper-air stations since the 1990s. The historical radiosonde humidity records at Sapporo and Tateno stations on the 925, 700, and 500 hPa pressure levels show apparent large downward trends between 1999 and 2009. This is because the original T-D correction has only been applied since February 2003 after a moist bias was discovered. The new T-D correction is found to result in a much smaller downward RH trend at Sapporo and almost no trend at Tateno.

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1. Introduction

Atmospheric water vapor plays a critical role in the climate system because it acts as a greenhouse gas and a medium for heat exchange and transport, and because it is linked to the formation of clouds and precipitation. Thus, it is important to monitor and understand long-term variability in atmospheric water vapor. Water vapor variability has been assessed using radiosonde data (e.g., Dai et al. 2011), satellite data (e.g., Soden et al. 2005), and precipitable water (PW) data obtained from the Global Navigation Satellite System (GNSS) atmospheric delay measurements (e.g., Wang et al. 2013).

Routine radiosonde observations have been made globally since the 1940s and these data provide the longest record of upper air temperature, humidity, geopotential height, pressure, and horizontal winds. However, the original radiosonde record contains various errors and biases because of changes in instrumentation and observational practices, which cause non-climate-related changes or inhomogeneities (e.g., Seidel et al. 2009). For the case of Japan Meteorological Agency (JMA) stations, Fujiyoshi (2010) pointed out that the frequency of appearance of upper-level clouds estimated from radiosonde humidity data shows sudden changes when radiosonde instrumental changes occurred. Such inhomogeneities in the record have severely hampered the application of radiosonde humidity data in climate studies.

The radiosonde humidity data need to be homogenized to estimate long-term trends (e.g., Dai et al. 2011). The homogenization often involves first detecting stepwise change points in humidity time series statistically and then adjusting the time series to remove the discontinuities. Many homogenization methods have been developed to remove non-climatic changes without using metadata that describe the change points in instrumentation and bias information for each radiosonde type, because these metadata are often incomplete or not available. Such statistical homogenization methods can resolve many of the discontinuities in the historical radiosonde record. However, they may also remove some of the real climate signals (Sherwood 2007). If possible, homogenization should be performed with the metadata and bias information, rather than statistically.

We can understand the bias errors and sensor characteristics for each radiosonde type by conducting radiosonde intercomparisons for simultaneous flights (e.g., WMO 2011; Kobayashi et al. 2012; Sakota et al. 1999) and laboratory experiments using thermostatic chambers (e.g., Sugidachi and Fujiwara 2013). RH sensors on radiosondes have various bias errors such as manufacturer calibration error, solar radiation heating during daytime observations, contamination by cloud droplets, and slow sensor response at low temperatures (e.g., WMO 2011). Comparisons using flight tests can assess the net bias errors among different radiosondes during flights, but it is difficult to quantify each of the potential bias errors. Laboratory experiments cannot completely replicate the actual flight conditions such as solar radiation and ventilation around the RH sensor, but they are useful in quantifying radiosonde sensor characteristics such as the temperature dependence, response time, and individual differences.

The Meisei RS2-91 radiosonde was introduced in 1991, and its RH sensor was changed around June–July 1999 (Ishihara 2004; JMA Aerological Observatory 2012, personal communication). The same newer RH sensor has been used for the RS-01G (introduced in 2002) and RS-06G radiosondes (introduced in 2007). These radiosonde models have been used at most of the JMA and Japanese Self-Defense Force stations and some other Asian stations (Sugidachi and Fujiwara 2013). Sugidachi and Fujiwara (2013) pointed out that the RH measurements from these radiosondes show a stepwise change of ~3% RH at 0°C. This is due to a discontinuous correction factor in the processing software (introduced in February 2003) that compensates for the temperature dependence of the RH sensor, as follows:

$$\Delta RH = K_0 + K_1 T + K_2 T^2$$
$$RH_{corr} = RH_0 - \Delta RH$$
$$(-40°C \le T \le 0°C) \quad (1)$$

where ΔRH (%) is the correction, T (°C) is air temperature uncorrected for solar heating, RH_0 (%) is uncorrected RH, RH_{corr} (%) is corrected RH, and K_i is a set of constants (K_0 = 2.86, $K_1 = -1.68 \times 10^{-1}$, $K_2 = -2.02 \times 10^{-3}$). Corrected RH values below 1% are set to 1%. Note that at 0°C, $\Delta RH = K_0 \neq 0$% RH. This correction, hereafter referred to as the original T-D correction, compensates moist biases below the freezing point, and has been applied at all JMA stations using Meisei RS2-91, RS-01G or RS-06G, usually since February 2003. Based on laboratory experiments, Sugidachi and Fujiwara (2013) proposed extending the range of the original T-D correction to +14.5°C to resolve the artificial stepwise change at 0°C (referred to as the new T-D correction hereafter). The new T-D correction has not been applied yet to operational radiosonde data.

In this study, we investigate the impact of the original and new T-D corrections on the long-term radiosonde humidity record at two JMA stations: Sapporo (WMO station 47412, 43°04'N, 141°20'E; surface level 26 m until 30 November 2009, 18 m starting 1 December 2009) and Tateno (WMO station 47646, 36°03'N, 140°08'E, surface level 31 m before 30 November 2009, 26 m after 1 December 2009). Elevation changes at these stations on 1 December 2009 were not launch site relocations, but the definition of the radiosonde surface data level (which determines the re-

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ported surface pressure) was changed from the station barometer elevation (inside the meteorological office) to the actual launch elevation (1 meter above the surface by the balloon inflation building).

2. Data and method

The Integrated Global Radiosonde Archive (IGRA; http://www.ncdc.noaa.gov/oa/climate/igra/) provides daily radiosonde data at more than 1500 stations for the period from 1938 to the present. The archive contains information extracted from each transmitted sounding and is expressed in common units, including limited metadata (WMO station ID, year, month, day, UTC hour, and launch time), and each reported standard and significant level (pressure, geopotential height, temperature, dew point depression [DPD, temperature minus dew point], wind direction, and wind speed [m s^{-1}]). As specified by WMO code formats, each station converts the original radiosonde RH values to DPD.

The JMA uses the following equation to convert RH values to DPD values (JMA 1995):

$$\mathrm{DPD} = \frac{(T+243.5)^2 \ln\left(\frac{\mathrm{RH}}{100}\right)}{(T+243.5)\ln\left(\frac{\mathrm{RH}}{100}\right) - 4303.4} \tag{2}$$

where T is air temperature (°C). In this study, we recover the RH value from T and DPD using Eq. (2). We also convert RH to specific humidity (SH) to understand the variability of water vapor alone by using the following equation (Bolton 1980):

$$e = 6.112\exp\left(\frac{17.67T_d}{T_d+243.5}\right)$$
$$s = \frac{\varepsilon e}{P-(1-\varepsilon)e} \tag{3}$$

where e is water vapor pressure (hPa), T_d is dew point (°C), s is SH (kg kg^{-1}), P is air pressure (hPa), and $\varepsilon = 0.622$ is the ratio of the molecular weight of water vapor and dry air.

Radiosonde instrument information, reported in the 31313 section of soundings by JMA stations since 1995, is not included in IGRA. However, reported instrument codes only indicate basic models such as Meisei RS2-91 (code 47) or RS-01G (code 55), so information from original soundings is still insufficient for this analysis. For example, the exact dates when the RS2-91 RH sensor changed and when the T-D correction was introduced at the JMA stations are not given. Therefore, we obtained the information directly from the JMA Sapporo District Meteorological Observatory for the Sapporo station and from the JMA Aerological Observatory for the Tateno station. According to this information, the RS2-91 radiosonde was introduced on 7 February 1993 at Sapporo and on 1 October 1992 at Tateno, and the new RH sensor was introduced for the RS2-91 on 24 June 1999 at Sapporo and on 13 July 1999 at Tateno. The original T-D correction was introduced on 1 February 2003 at both stations.

Meisei RS2-91 was replaced by Vaisala RS92 on 1 December 2009 at both stations. Vaisala RS92 has been found to have a substantial daytime dry bias due to solar heating of the RH sensor, which is not protected by a reflective cap due to its design, although the bias and some other errors are considered to be corrected by DigiCORA version 3.64 (Kobayashi et al. 2012; Wang et al. 2013). This software version was not installed at Sapporo and Tateno stations. Analysis of Vaisala RH errors is beyond the scope of this paper. Vaisala RS92 was replaced with Meisei RS-11G at Sapporo starting 1 September 2013 and at Tateno starting 2 July 2013.

Figure 1 shows the time series of temperature and RH at 500 hPa at Sapporo and Tateno, using the original data obtained from the IGRA. We see that the instrumental change points correspond to the discontinuities in the RH time series. In this study, we focus on the period with the new RH sensor; that is, from 24 June 1999 to 30 November 2009 at Sapporo and from 13 July 1999 to 30 November 2009 at Tateno. We apply the new T-D correction proposed by Sugidachi and Fujiwara (2013) to the original data over these periods, and evaluate its impact on the humidity record. Figure 1 also shows the difference between the daytime (9:00 JST, or 0:00 UTC) and nighttime (21:00 JST, or 12:00 UTC) measurements. This difference is probably due to the dry bias from solar radiation heating (e.g., WMO 2011), in addition to the real atmospheric diurnal variability. The relative daytime dryness is about the same in the entire Meisei RS2-91 period as in the Vaisala RS92 period at both stations, suggesting that daytime heating of the RH sensor is similar with Meisei RS2-91 (under a rain-protective cap) and Vaisala RS92 (with no cap). The Meisei RS2-80 carbon RH sensor in a duct was only slightly drier in daytime, but it registered neither very dry nor very moist conditions. Since the Meisei RS2-91 correction formula does not account for possible solar heating, the following discussion considers only nighttime data to avoid complications.

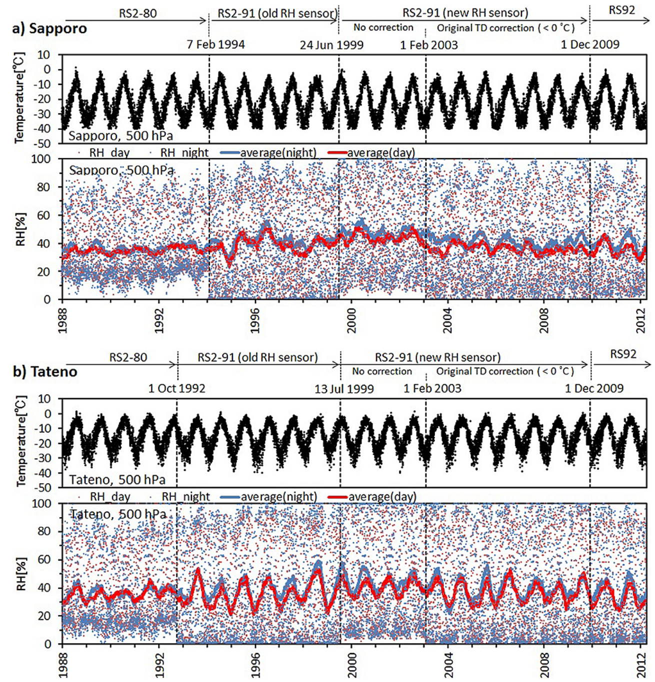

Fig. 1. Time series of temperature (top panels, black) and relative humidity (RH) (bottom panels, red and blue) at 500 hPa at Sapporo (a) and Tateno (b), using the original IGRA data. Dots represent the 12-hourly daily RH data and solid lines represent 4-month running averages, to improve the presentation, for the daytime (red) and nighttime (blue) measurements.

3. Results and discussion

Figure 2 shows the deseasonalized time series and their linear fits for RH at 925, 700, and 500 hPa at Sapporo and Tateno. Lines in color are daily anomalies from daily means based on the Meisei RS2-91 period at each station, smoothed by averaging anomalies for 31 days centered on each day, with the annual mean RH added to each smoothed anomaly value. In the top panels, the input RH values and corresponding means are based on the original data obtained from IGRA, where the T-D correction (Eq. 1) is applied only below 0 °C and only starting February 2003. In the bottom panels, anomalies are computed and smoothed in the same way, but the input data for means and anomalies is corrected by applying the T-D correction where it was not applied originally, below +14.5°C through January 2003 and between 0 and +14.5°C starting February 2003. The corrected linear fits show smaller

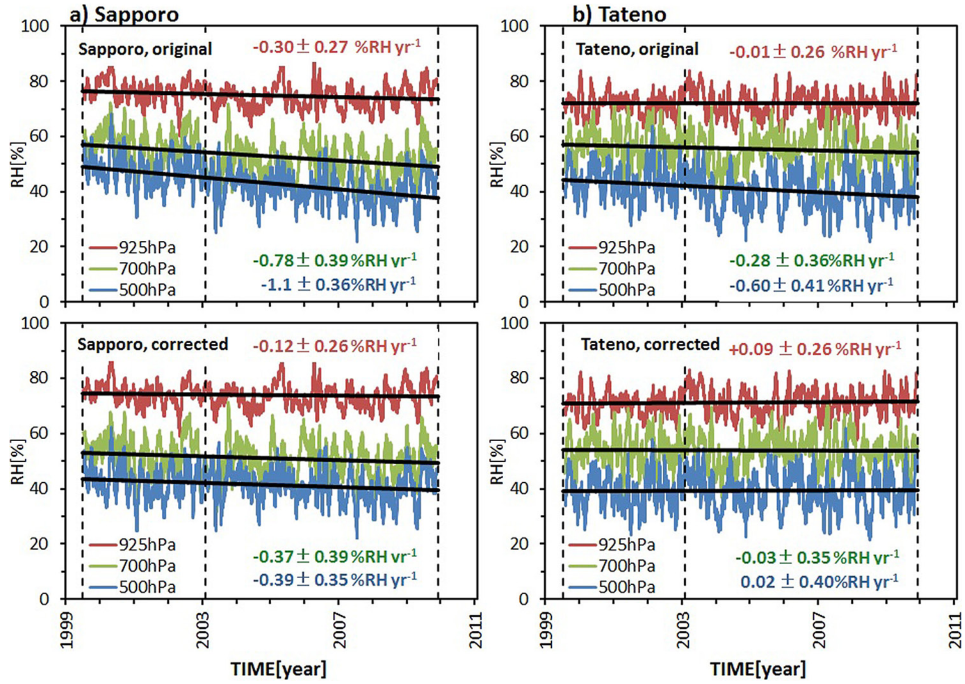

Fig. 2. Time series of deseasonalized and averaged RH for 31 days at 500 hPa (blue), 700 hPa (green), and 925 hPa (red) at Sapporo (a) and Tateno (b). Linear fits for the period from 24 June 1999 to 1 November 2009 for Sapporo, and from 13 July 2009 to 1 November 2009 for Tateno are shown as black lines. The values of the regression and 95% confidence interval for each time series are also shown. Top panels show the original IGRA time series; bottom panels show the corrected time series using the new T-D correction proposed by Sugidachi and Fujiwara (2013).

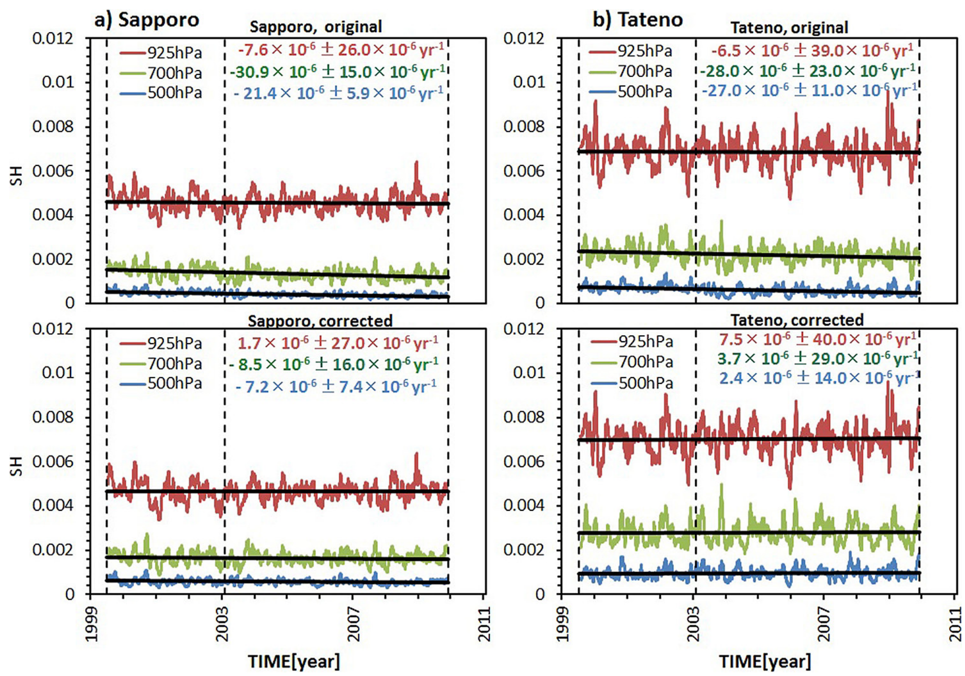

Fig. 3. As for Fig. 2, but for specific humidity.

downward trend values than the original linear fits. The new T-D correction is found to result in much smaller downward trend values at 500 hPa at Sapporo and almost no trend at Tateno. In this paper, the likelihood of RH (SH) trends is based on the results of statistical significance testing (T-testing) performed at confidence levels of 95% (JMA 2012). For the effective degrees of freedom, the number of data is divided by the effective decorrelation time (i.e. 31 for the averaged data for 31 days). It should be noted that the uncertainty estimation of these linear fit values does not consider the measurement uncertainty.

Figure 3 shows the original and corrected SH time series. The corrected SH values are derived from dew point values calculated from the RH values with the new T-D correction shown in the bottom panel of Fig. 2. We see that the original SH linear fits show spurious large downward trends, especially at 500 and 700 hPa, at both stations. The corrected SH linear fits show no significant trends at Sapporo and Tateno.

Previous observational studies (e.g., Soden et al. 2005; Trenberth et al. 2005) show that tropospheric water vapor is globally increasing under the assumption of near-constant RH, although there is strong interannual variability. The corrected results at Tateno are consistent with the near-constant RH hypothesis, but the results at Sapporo are not, and show downward RH trends at 500 in the 2000s. This is probably in part because the period in this study is too short to detect RH trends with the warming climate. To extend our analysis over longer periods, we need to investigate the biases between the RS2-91 and the older radiosonde models such as the Meisei RS2-80 and RS2-91 with the old RH sensor, which had been used in the 1980s and the 1990s at JMA stations. In addition, the RS2-91 RH corrected by the new T-D correction still contains a small bias error depending on temperature and RH, which is up to about +5 ± 4% RH (the confidence interval represents the expanded uncertainty with the coverage factor k = 2) around −10°C (Sugidachi and Fujiwara 2013). Because such a bias error has a large impact on the uncertainty estimation of RH linear trends, further efforts are needed to reduce the measurement uncertainty by making more simultaneous flights and detailed laboratory experiments. Where possible, we will make laboratory experiments and in-flight comparisons with reference instruments such as chilled-mirror hygrometers to quantify the errors in radiosondes used in the past.

4. Conclusions

The original and new T-D corrections on the RH measurements from the Meisei RS2-91, RS-01G and RS-06G radiosondes not only correct the bias error of individual soundings, but also influence the analysis of long-term humidity variability in the upper air. For these radiosonde RH measurements, the new T-D correction proposed by Sugidachi and Fujiwara (2013) should be applied to the historical RH record. However, information on the exact dates of updating of the sensor in the RS2-91 and the introduction of the original T-D correction was not available publicly (e.g., in the IGRA). Thus, we obtained the information directly from the Sapporo and Tateno stations to investigate the impact of the T-D corrections. We hope that in the near future, complete metadata will be made available by the operational agencies, as these metadata are critical for climate studies.

The corrected linear fits show smaller downward trend values than the original linear fits. These results show that the humidity variability in the 2000s at stations using the Meisei RS2-91, RS-01G, and RS-06G radiosondes strongly depends on whether or not the new T-D correction is applied. However, this correction does not consider the solar radiation heating during daytime observations, contamination by cloud droplets, or slow sensor response at low temperatures. Also, the humidity values corrected by the new T-D correction may still include small wet biases during nighttime observations (Sugidachi and Fujiwara 2013). To further reduce uncertainties in humidity trends, we need more laboratory experiments and in-flight comparisons with reference instruments.

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