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Scientific note

An examination of the humidity correction by Vaisala RS80-A radiosondes for experiments and measurements at an inland Antarctic station

Naohiko Hirasawa[1], Masahiko Hayashi[2] and Takashi Yamanouchi[1]

[1] *National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515*
[2] *Fukuoka University, Jounan-ku, Fukuoka 814-0810*

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Abstract: The present paper examines the correction of humidity measurements by the Vaisala RS80-A radiosonde using data obtained at Dome Fuji Station, inland Antarctica. The correction method is based upon a procedure developed by L.M. Miloshevich *et al.* (J. Atmos. Oceanic Technol., **18**, 135, 2001). In the present study, experiments in a snow cave below ground, where a state of ice saturation is assumed, show that Miloshevich's coefficient is appropriate for temperatures warmer than −45℃ because the corrected humidity reflects the state of ice saturation. Below these temperatures a correction coefficient is needed. At −55℃, for example, a factor of 1.2 is needed. An examination using surface humidity data obtained from a routine aerological observation concluded that the correction coefficient is larger than Miloshevich's at temperatures colder than −50℃, so that the multiplication factor ($0.185968 \times \exp((-0.0339) \times T)$; T=temperature) is needed to apply Miloshevich's coefficient.

After the correction is performed, the relative humidity with respect to ice becomes 150% on average in the lower temperature range. Perpetual falling of ice crystals indicates at least an occurrence of ice saturation; this condition of high relative humidity is supported by downwelling of a large amount of water vapor in an intense temperature inversion layer and an extremely small number of ice nuclei, suggested by *in-situ* data. An improved correction applied to a vertical profile in the temperature inversion layer reveals that supersaturation with respect to ice appears at all levels. In the lowest layer, humidity increases with decreasing height, although observed data show steep dryness with decreasing height. This is considered a measurement error.

key words: correction of radiosonde humidity, Vaisala RS80-A, Antarctica, Dome Fuji Station, low temperature

1. Introduction

Humidity measurement at very low temperatures is one of the most difficult issues in aerological observation because of low accuracy and the increase in time constant at low temperatures. According to Miloshevich *et al.* (2001), the time constant is 7 s at −20℃, 27 s at −40℃ and 215 s at −70℃. Miloshevich derived a statistical temperature-dependent correction coefficient for temperatures warmer than −70℃, by comparing data between Vaisala RS80-A radiosondes and the NOAA cryogenic frostpoint hygrometer. The results provide a clue to radiosonde humidity analyses at temperatures colder than −40°C.

Recently developed cryogenic frostpoint hygrometers are useful in obtaining accurate humidity measurements (Voemel *et al.,* 1995; Oltmans and Hofmann, 1995; Fujiwara *et al.,* 2003; Voemel *et al.,* 2003). However, ordinary radiosondes will continue to be used for observational experiments, and it would be useful to correct data measured by routine observation throughout the world, especially to develop a correction for humidity measured by ordinary radiosondes.

In 1997, the 38th Japanese Antarctic Research Expedition (JARE-38) took quasi-routine aerological observations using the Vaisala RS80-A, one of the ordinary radiosondes at Dome Fuji Station on the main ridge of the east Antarctic ice sheet (Hirasawa *et al.,* 1999). The station had been opened for a deep ice-core drilling project (Watanabe *et al.,* 1999; Hondoh *et al.,* 1999). The elevation is about 3800 m a.s.l., and surface pressure is about 600 hPa. Annual mean air temperature is about −55°C, varying from −80°C in winter to −20°C in summer. A temperature inversion layer appears at the surface in winter, with an intensity of about 23°C and a thickness of approximately 400 m (Hirasawa *et al.,* 2002).

The present study examines Miloshevich's humidity correction using data measured both at the surface during the quasi-routine aerological observations, and during experiments in a snow cave at about 5-m-depth below the ground. The humidity in the cave may be considered stable and near ice saturation. Although it is generally difficult to obtain a true humidity reading in such low temperature conditions, these data are useful.

In Section 2 data correction in the cave will be examined, and surface humidity during the routine observations will be examined in Section 3. During the winter, an intense temperature inversion layer at the Dome Fuji Station occurs, and water vapor content increases steeply with height due to the temperature increment with height. The vertical mixing of the air creates a condition of supersaturation with respect to ice in the lower layer. Ice crystals (diamond dust) were almost continually falling, indicating the existence of a layer of ice saturation. A cryogenic frostpoint hygrometer, which had not worked continuously through the winter, often indicated that the frostpoint temperature was warmer than the air temperature. A vertical profile of humidity, corrected with the improved coefficient, is discussed in Section 4.

2. Experiments in a snow cave underground

Figure 1 shows the humidity measured in the cave (open circles) and the values corrected with Miloshevich's coefficient (solid circles) for all of the experiments. The experiments were conducted at a variety of temperatures, ranging between −35°C and −40°C, −45°C and −50°C, and around −55°C. The data for a temperature of −55°C, which is close to the annual mean air temperature at Dome Fuji Station, were measured 5 m below ground, the deepest location in the cave. The warmest temperature, approximately −35°C, was measured near the cave's ceiling, where a weak air flow is always observed; temperature varies several degrees C.

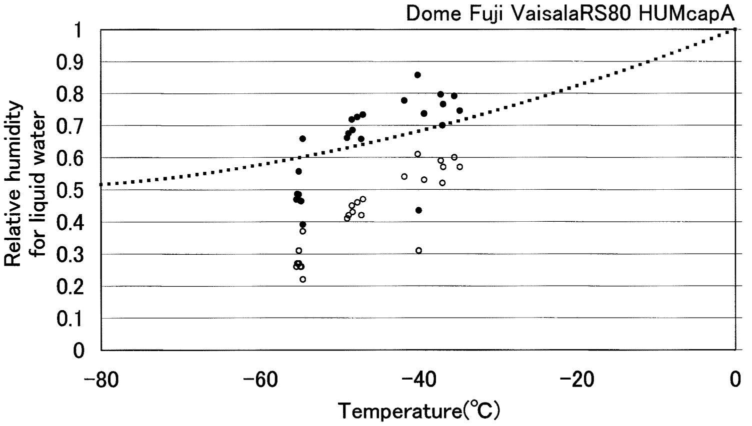

Fig. 1. Relative humidity with respect to water measured in a cave (open circles) and the values corrected with Miloshevich's coefficient (solid circles) vs. temperature. Dashed line indicates relative humidity at ice saturation with respect to water.

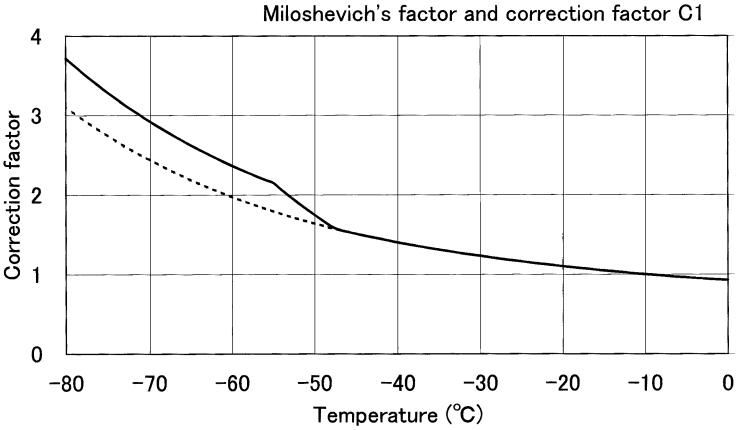

Fig. 2. Improved coefficient C1, described in eqs. (1.2) to (1.4), through experiments in the cave (solid line). C1 equals Miloshevich's coefficient (Mil(T)) in the temperature range warmer than −47.5℃. The dashed line indicates another part of the Mil (T).

The mean relative humidity for temperatures ranging between −35℃ and −40℃ is 73% with respect to water (106% with respect to ice), 69% (109%) between −45℃ and −50℃, and 50% (83%) around −55℃. From the corrected humidity indicating approximate ice saturation at temperatures between −35℃ and −40℃ and between −45℃ and −50℃, we may conclude that Miloshevich's coefficient works in these temperature ranges. However, as the corrected values at approximately −55℃ are still sub-saturation with ice, Miloshevich's coefficient must be increased so that humidity is brought up to the level of ice saturation. At −55℃, the factor is 1.2, although few experimental points are observed between −55℃ and −45℃. Information is not available for the temperature range colder than −55°C. Thus, as indicated in eqs. (1.1) to (1.4), the improved humidity factor is 1 at −47.5°C, and increases linearly to 1.2 at −55°C. At temperatures colder than −55°C, the factor is assumed to be a constant 1.2.

$$RHc1(T)=C1(T)\times RH(T), \qquad (1.1)$$

$$C1(T)=Mil(T), \qquad (-47.5^\circ\mathrm{C}<T) \qquad (1.2)$$

$$C1(T)=Mil(T)\times\left(1+0.2\times\frac{-47.5-T}{7.5}\right), \qquad (-55^\circ\mathrm{C}\leqq T\leqq -47.5^\circ\mathrm{C}) \qquad (1.3)$$

$$C1(T)=Mil(T)\times 1.2, \qquad (T< -55^\circ\mathrm{C}) \qquad (1.4)$$

where T and RH are observed values of air temperature and relative humidity, respectively. $RHc1$ means humidity corrected with $C1$. Mil means the Miloshevich coefficient. Figure 2 shows Mil and $C1$ temperature-dependencies.

3. Correction of surface humidity data obtained during routine operation

Quasi-routine aerological observations conducted with a Vaisala RS80-A were taken from 15 February 1997 to 7 January 1998. To check operation of the transmitter and GPS system, each radiosonde was turned on for a few minutes at the launching site outside the building just before launch. During this time, the measured value of each sensor was stabilized. Using the humidity data derived from these measurements, the corrections described in eqs. (1.1) to (1.4) are examined.

Figure 3 shows the results of the correction, using coefficient C1. According to the results described in the previous section, the correction may be appropriately applied at temperatures warmer than −55°C. The corrected humidity is distributed around the

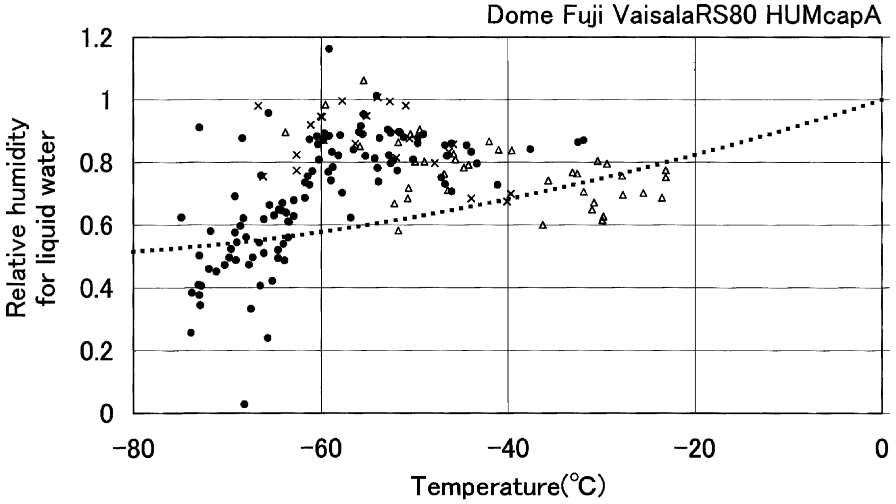

Fig. 3. Results of correction of surface humidity using C1. Each mark represents the following: February to April (×); May to September (●); and, October to January (△). The dashed line indicates a relative humidity at ice saturation with respect to water.

level of saturation with respect to ice at temperatures warmer than −40°C and is gradually increased with decreasing temperature between −40°C and −55°C (~150% with respect to ice saturation). In most of the observations below −40°C, a temperature inversion layer appeared (Hirasawa *et al.,* 1999); therefore, the excess above ice saturation results from a downward transport of water vapor. Moreover, at the station the number concentration of aerosols that have radii of more than 0.3μm, is a few hundred particles per 1 L, which corresponds to one hundredth of those observed in the tropics (Hayashi, 2001). The extremely small number of ice nuclei expected from the *in-situ* data above may contribute to supersaturation with respect to ice.

At temperatures below −60°C, humidity decreases steeply with decreasing temperature. There is no evidence of such a decrease in the relative humidity found in the meteorological features during such a colder spell. An inversion layer and the precipitation of ice crystals are also observed during the colder spells. Thus, the relative humidity with respect to ice is supposed to be 150%, which is the same as that at −55°C.

Equation (1.3), defined above, is replaced here. The improved coefficient $C2$ in the lower temperature range is statistically defined by the least squares method under conditions of $C2(T)=1.2\times Mil(T)$ at $T=-55$°C and $C2(T)=1\times Mil(T)$ at $T=T_0$ which is between −45°C and −55°C. The results follow:

$$RHc2(T)=C2(T)\times RH(T), \qquad (2.1)$$

$$C2(T)=Mil(T), \qquad (T_0<T) \qquad (2.2)$$

$$C2(T)=Mil(T)\times 0.185968\times \exp((-0.0339)\times T), \quad (T\leqq T_0) \qquad (2.3)$$

$$T_0=\frac{\log 0.185968}{0.0339}\sim -50^\circ\mathrm{C}, \qquad (2.4)$$

where $RHc2$ is the corrected humidity with $C2$.

The correction coefficient, $C2$, functions are shown together with those of Miloshevich in Fig. 4. The humidity levels corrected with $C2$ are shown in Fig. 5.

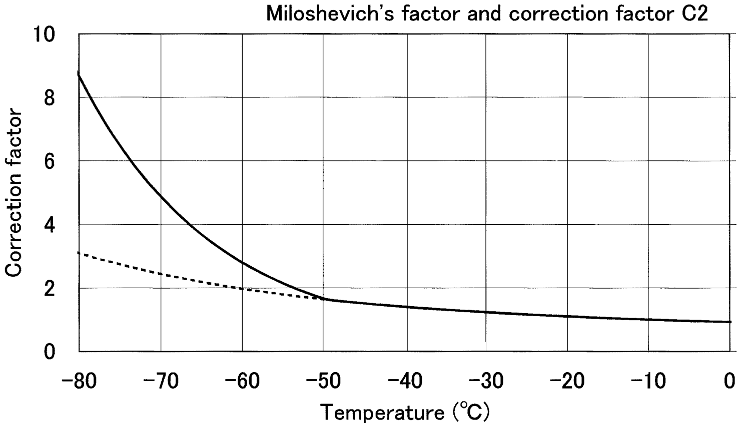

Fig. 4. Improved coefficient C2, described in eqs. (2.2) to (2.4), through the examination of surface data of the quasi-routine observations (solid line). C2 equals the Miloshevich coefficient (Mil(T)) in the temperature range above −50°C. The dashed line shows another part of the Mil (T).

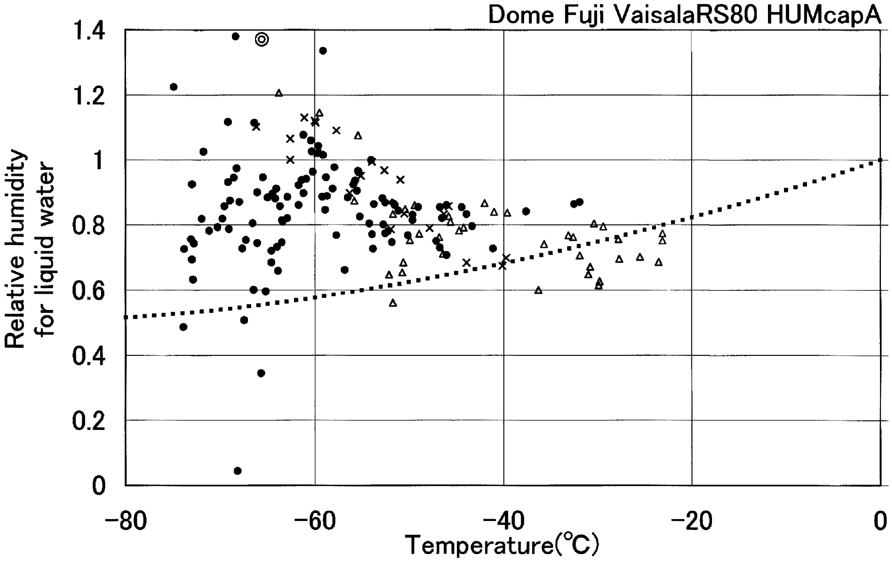

Fig. 5. Same as description for Fig. 3, but using C2. The plot of 13 September is indicated by ◎, as the date when the vertical profile was analyzed in Fig. 6.

The corrected humidity values are distributed around 150% of ice saturation in the lower temperature range, although the variance in the corrected humidity is larger at lower temperatures, which may represent difficulty in performing the measurements.

4. Application to a vertical profile

Figure 6a shows the vertical profiles of relative humidity measured on 13 September 1997 (*RH*obs), one corrected (*RH*mil) with the Miloshevich coefficient and the other (*RHc*2) with coefficient *C*2. Figure 6b shows the specific humidity that was calculated. This case is shown in Fig. 5, with ◎ at a temperature of −65.6℃ and the corrected humidity of 137%. The profile of relative humidity at ice saturation with respect to water is also shown.

The data were obtained by tethered (between the surface and an approximate height of 100 m) and free lifted radiosondes. The accuracy of temperature and humidity measurements obtained by free lifted radiosonde in the intense inversion layer is not high because the sensor humidity at the extremely low temperature took a long time to measure. Although the height of the top of the inversion layer was approximately 4100 m (Fig. 7), the temperature difference (18.9℃) at the lowest 100 m from the surface accounted for nearly 95% of the total amount (19.8℃).

A similar feature is also found in the humidity field. As the data are obtained by tethered radiosonde at lower levels, the temperature and humidity fields may have relatively better accuracies. As seen in Fig. 6a, *RH*obs is in the state of sub-saturation with respect to ice, so that ice crystals are not being found, and *RH*obs decreases steeply with decreasing height in the lowest layer (~20 m height). In contrast, both *RH*mil and

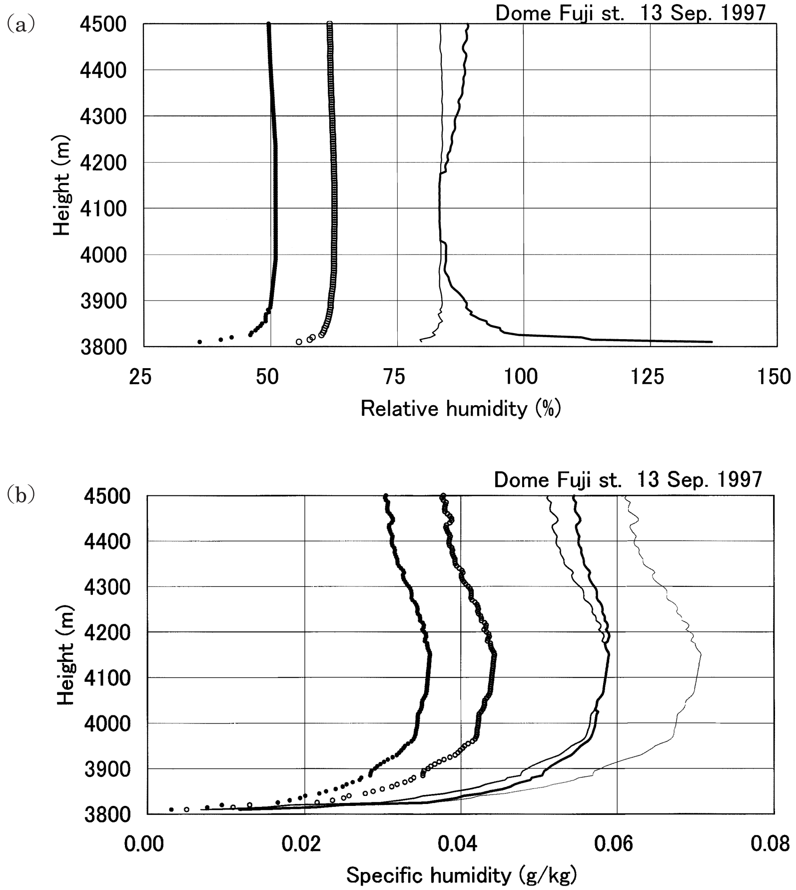

Fig. 6. (a) Vertical profiles of relative humidity measured (RHobs, a chain of solid circles), corrected with Miloshevich's coefficient (RHmil, a solid line) and with C2 (RHc2, a thick solid line). The profile of relative humidity at ice saturation with respect to water is shown with a chain of open circles. The data are obtained by tethered (between the surface and approximately 100 m in height) and free-lifted radiosondes. (b) Same as (a) but for specific humidity. The state of water saturation is shown with a thin line.

*RHc*2 show larger values than the ice saturation, indicating that the inversion layer is suitable for the formation of ice crystals.

The improved coefficient *C*2 is larger in a colder temperature range, that is, in the lower layer. Consequently, *RHc*2 increases steeply in the lowest layer although *RH*mil decreases in that layer, like *RH*obs. The generally dominant downwelling over inland Antarctica (White and Bryson, 1967) is supposed to transport water vapor downward from the warmer upper layer to the colder lower layer. As the temperature decreases with decreasing height, the relative humidity in *RHc*2 is consistently larger in the lower layer of the downwelling. Moreover, the decrease in specific humidity with decreasing height (Fig. 6b) suggests that water vapor is not only transported from the upper layer to the lower layer, but also changes in phase from water vapor to ice crystals (that is, it

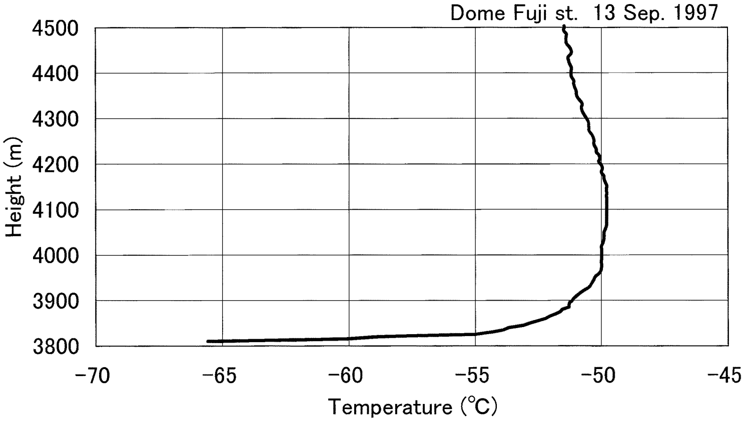

Fig. 7. Same as Fig. 6 but for temperature.

sublimes).

5. Summary

The present paper reports a correction to humidity measurements collected by the Vaisala RS80-A radiosonde using data obtained at Dome Fuji Station, inland Antarctica. The correction is based upon Miloshevich *et al.* (2001). First, humidity data were measured in a snow cave below ground and analyzed. The temperature profile of the cave is stable within a temperature range between −35°C and −55°C. The humidity in the cave is considered to be almost at ice saturation.

At temperatures warmer than −45°C, the data are corrected to ice saturation using Miloshevich's coefficient, indicating that it is appropriate. In contrast, the humidity corrected using Miloshevich's coefficient indicates levels below ice saturation at approximately −55°C. When it is multiplied by 1.2, the humidity is corrected to approximately ice saturation. We let the factor C1 increase linearly from 1.0 at −47.5°C to 1.2 at −55°C; be constant in the temperature range colder than −55°C.

Corrections with $C1$ are examined using surface humidity data obtained from the routine aerological observations. The corrected humidity at −55°C indicates an ice saturation of approximately 150%, which is still sub-saturation with respect to water. The intense temperature inversion layer with the downwelling, the perpetually falling ice crystals, and the extremely small number of aerosols support such calculations of high relative humidity.

At temperatures colder than −55°C, the corrected humidity is less than the ice saturation despite similar atmospheric conditions to those at −55°C. Thus, an additional improved coefficient function was derived in the low temperature range to allow the corrected relative humidity with respect to ice to reach 150%. Eventually, the correction coefficient $C2$ was tuned consistently using the results of $C1$, consisting of a two-part temperature range, above and below −50°C.

When the correction using $C2$ is applied to the vertical profile of the temperature inversion layer as observed on 13 September 1997, the humidity is calibrated to be larger over ice saturation at all levels. It is increased with decreasing height in the lowest layer, while the observed data show steep dryness with decreasing height. The corrected profile is consistent with downward transport of water vapor and formation of ice crystals through sublimation in the whole layer.

The present paper does not provide correction for either data reported from an ascending radiosonde or data observed in the stratosphere where the temperature is also extremely cold. Moreover, variances in the corrected humidity due to instrumental error should be estimated. The investigation of these issues remains in the future.

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