Referee #2

Summary:

The manuscript by Lee et al. studies the solar radiation influence on temperature measurements by the Vaisala RS41 radiosonde using the Korean KRISS Upper Air Simulator environmental chamber.

The authors characterize the radiation error of this radiosonde as function of pressure, temperature, ventilation speed, and sensor orientation and tilt. They discuss the uncertainties of their measurements and show a rough comparison with the operational correction of this effect built into the Vaisala sounding system software.

The setup of their chamber and the measurements done as part of this study are excellent. However, the interpretation requires significant refinement, especially since they are providing a quantitative analysis of their measurements, which should eventually become applicable to sounding operations.

I would recommend publication of this manuscript only after major revisions, for which I provide detailed comments and suggestions below.

→ We thank the Reviewer for valuable comments. We have revised the manuscript to comply with the Reviewer's comment as below.

Major comments:

I will start from the end, since this is where this study potentially may have the most important significance.

A) Application to real atmospheric observations and comparison to the Vaisala radiation correction table

The largest weakness of this manuscript is that the measurements as such cannot be easily applied to sounding operations, since a substantial amount of interpretation of the measurements is missing. This is best demonstrated by the comparison with the Vaisala operational radiation correction table, which is presented, but discussed in only one sentence.

The Vaisala radiation correction table is applied in a significant fraction of soundings globally. The study here has the potential to support or improve this table. Unfortunately, this is not done and the reader is unable to decide, whether any of the measurements that were presented are in contradiction or support of the Vaisala table, or what factors need to be considered to make such a comparison. To be able to do so, some elements of the comparison have to be clarified. First, the solar angle used by Vaisala is not the same as the incident angle used by the authors. This needs to be clarified. Using their measurements, it should be possible to create a table similar to that by Vaisala. This requires describing the tilt of the sensor boom on the radiosonde in operational use and making some assumptions about the pendulum and rotation movement of the sonde and applying their measurements to those. Second, the solar flux requires much more discussion. The radiation correction depends on the total flux, not just the direct solar flux. Some discussion about albedo and cloud cover is essential before a comparison can be done. It may not be possible to provide a direct validation of the Vaisala table, but at least the factors that contribute must be described in much more detail. The authors very briefly mention an effective solar flux and should expand this discussion greatly.

→ First of all, the users of RS41 cannot apply the radiation correction obtained by any method including this work, because the manufacturer does not provide raw temperature without correction. This work primarily intends to present the capability of the UAS to obtain a radiation correction of any radiosonde. RS41 is used as an example.

The tilting experiment in this work is to show that the radiation correction of RS41 is proportional to the effective irradiance (S_{eff}) to the sensor boom, not to the direct irradiance (S_0). The maximum tilting angle is 27 ° due to the small space in the test chamber. (We agree that larger tilting angles are needed to better imitate the actual effective irradiance to the sensor at different solar angles.) Nevertheless, the final radiation correction formula is provided based on the effective irradiance in Eq. (11).

We think that the calculation of the effective irradiance to the sensor and the application of the correction formula to actual soundings are the share of users because the situation is not identical globally. Nevertheless, an approach to the calculation of effective irradiance by averaging over the rotation is added in Fig. 8. Then, a graphical comparison of radiation corrections by the manufacturer and the UAS which includes the albedo effect is added in Fig. 9.

Before: The radiation correction of RS41 by the UAS is based on Eqs. (13) and (14) for different pressure ranges. Although the conditions for the UAS correction are different from those considered by the manufacturer, a rough comparison of the radiation corrections is presented in Table 11. For the UAS correction, the solar irradiance is assumed to be $S = 1360\ \mathrm{W \cdot m^{-2}}$ at all pressure values. Depending on the effective irradiance (S_{eff}), the UAS correction value should be revised in a proportional manner using Eqs. (13) and (14).

After (Line 397-413): In order to apply the correction formula to actual soundings, the effective irradiance to the sensor should be known. However, radiosondes constantly change positions with respect to the solar irradiation through rotation and pendulum motion, the calculation of effective irradiance resorts on the mean of effective irradiance over the motion of radiosondes. Figure 8(a) shows a schematic diagram of a radiosonde with parameters that affect the effective irradiance S_{eff} on the sensor. Then, the effective irradiance to the sensor can be calculated as follows:

$$S_{\mathrm{eff}} = S_{\mathrm{dir}} \cdot \left| \cos\alpha \cos \Theta \cos\varphi - \sin\Theta \sin\alpha) \right| , \tag{18}$$

S_{dir} is solar direct irradiance, θ is boom tilting angle, α is solar elevation angle and φ is azimuthal angle. The effective irradiation area (A_{eff}/A_0) on the sensor boom is averaged over rotation (φ) with a fixed tilting angle $\theta = 45$ ° and plotted as a function of the solar elevation angle as shown in Fig. 8(b). Using this effective irradiance, the radiation correction by the UAS is obtained and compared with that of the manufacturer at two different α (45 ° and 90 °) as shown in Fig. 9. For the UAS correction, the solar direct irradiance is assumed to be 1360 $W \cdot m^{-2}$ at all pressure values. To simulate the albedo effect, the radiation correction with additional irradiance of 400 $W \cdot m^{-2}$ is also calculated. Consequently, the radiation correction of the UAS is smaller than the Vaisala by about 0.5−0.7 °C at −70 °C and 5 hPa when only the solar direct irradiance (1360 $W \cdot m^{-2}$) is considered with the solar elevation angle $\alpha = 45-90$ °. When the albedo effect is additionally included (400 $W \cdot m^{-2}$), the gap between the two corrections is reduced to 0.04−0.4 °C at −70 °C and 5 hPa with $\alpha = 45-90$ °. The radiation corrections of the manufacturer and the UAS at some representative conditions are summarized in **Table 11**.

Modified Table (Table 11): Table 11 is modified to include the radiation correction of the UAS obtained by the above method.

B) Uncertainties and their interpretation

The uncertainty discussion is very important, but can be much improved. Table 4 is just an overview of the measurement ranges and a little confusing here. It could be deleted without loss. The discussion of the uncertainty in pressure and temperature measurement can be deleted as well. As Table 9 shows, this uncertainty does not contribute to the final result, which is immediately obvious given the weak dependence of the radiation error as function of pressure and temperature.

→ As mentioned in the above comment, this work aims at presenting the capability of the UAS to obtain a radiation correction of any radiosonde using RS41 as an example. The uncertainty of temperature and pressure should be presented in this perspective. The weak dependence of T and P in Table 9 also provides information to readers.

The uncertainty in the ventilation speed requires more discussion. The table lists a stability, but does not define to what it refers. It also lists a spatial gradient without specifying over which distance it applies. Most importantly, some discussion about the flow regime would be very useful. For laminar flows such as are more likely at low pressures, there should be significant velocity gradients from the walls inward. This is not discussed. If present, such gradients could explain the tilt results shown in Figure 6.

The uncertainty in irradiance lists the spatial gradient as the largest source. Again, gradient over what distance is meant here? It could be mentioned that the uncertainty of the radiation source is a negligible contribution compared to the lack of knowledge of the radiation field in true atmospheric soundings. This could be contrasted. In their conclusion, the authors indicate that they are working on a two-thermistor measurement with different emissivities. This discussion should be expanded and reference to the multi-thermistor work done by Schmidlin and others could be provided for reference.

→ Description on the measurement by the laser Doppler velocimetry (LDV) inside the test chamber is added. The central region around the sensor (35 mm x 35 mm) in the test chamber was measured by the LDV and thus the gradient from the wall was not measured.

The work by Schmidlin is mentioned with the dual-thermistor measurement in **Conclusions.**

Added sentence (Line 103-104): Thus, the reference value and SI traceability of the ventilation speed are obtained by using the sonic nozzles in the UAS.

Before: The generated air flow is measured through laser Doppler velocimetry to investigate the spatial gradient in the test chamber.

After (Line 108-111): The generated air flow is measured through laser Doppler velocimetry (LDV) (Dantec, Model: BSA F60) to investigate the spatial gradient in the test chamber. Ar-ion laser (3W) having a wavelength of 514.5 nm is used with a focal length of 400.1 mm and nominal beam spacing of 33 mm.

Before: The spatial gradient of the ventilation speed in the test chamber is measured through laser Doppler velocimetry at KRISS.

After (Line 327-332): The spatial gradient of the ventilation speed in the test chamber is measured through the LDV at KRISS. The measurement dimension using the LDV was 35 mm x 35 mm around the sensor (central) location with 5 mm interval (49 points) in the test chamber (50 mm x 50 mm). The measurement was performed at the condition of $v = 4.67\ \mathrm{m \cdot s^{-1}}$ (reference value), $P = 550$ hPa, and room temperature. The LDV value averaged over the measurement area (35 mm x 35 mm) was $4.63\ \mathrm{m \cdot s^{-1}}$. The difference between the reference and the measurement average is assumed to have a rectangular probability distribution for the calculation of the uncertainty of spatial gradient.

Added Statement (Line 341-342): The uncertainty of the solar simulator will be negligible compared to that of the actual radiation field in atmospheric soundings due to the lack of knowledge.

Before: The temperature difference in the two sensors of the radiosonde is used to measure solar irradiance in situ.

After (Line 435-439): The temperature difference in the two sensors of the radiosonde is recorded with varying environmental parameters in the UAS to be reversely used to measure solar irradiance in situ during sounding. In this sense, the approach based on dual sensors is different from previous works that estimate the air temperature using several other temperatures measured by sensors with different emissivity (Schmidlin et al., 1986).

The uncertainty due to sensor rotation seems to be larger than the measured signal, which questions the uncertainty derivation; in particular since there clearly is a signal present.

→ The uncertainty is corrected to be the half of the previous value.

Before: the corresponding standard uncertainty ($k = 1$) is obtained considering the maximum value (0.06 °C) divided by $\sqrt{3}$. Consequently, the uncertainty due to sensor rotation is 0.035 °C ($k = 1$).

After (Line 352-354): the corresponding standard uncertainty ($k = 1$) is obtained considering the half-maximum value (0.03 °C) divided by $\sqrt{3}$. Consequently, the uncertainty due to sensor rotation is 0.017 °C ($k = 1$).

The final uncertainty (Section 4.10) is most likely pressure dependent, but no such pressure dependence is given. Whether or not there should be a pressure dependence would certainly require some more explanation.

→ The pressure and other conditions for the final uncertainty in **Table 10** are presented in **Table 9**. The uncertainty will be similar for other pressures and temperatures due to the weak dependency.

C) Rotation and tilt discussion

The discussion of rotation and tilt is rather sparse and could provide much more detail. The authors do not mentioned that the sensor boom of the Vaisala radiosonde is tilted from the vertical in operational use, which justifies their tilt measurements. I assume the 27 deg tilt used refers to the tilt of the sensor boom in operational use, but this has not been said. The tilt in real world soundings also depends on the pendulum motion of the radiosonde such as described by Dirksen et al. (2014). Thus, the sensor tilt is a little more complicated.

→ As mentioned in the above comment, the tilting experiment in this work is to show that the radiation correction of RS41 is proportional to the effective irradiance (S_{eff}) to the sensor boom, not to the direct irradiance (S_0). The maximum tilting angle is 27 ° due to the small space in the test chamber. An approach to the calculation of effective irradiance by averaging over the rotation is added in Fig. 8.

It is also important to point out, that the sensing element of the Vaisala radiosonde is a lengthy device, where tilt and rotation are likely to play an important role. Other radiosondes using spherical bead thermistors would be much less affected by tilt and rotation.

→ The difference depending on the sensor geometry is mentioned as suggested.

Added Statement (Line 131-133): The geometry of the temperature sensor of the Vaisala RS41 is a rod shape and thus the rotation and tilt affect the effective irradiance and the direction of air ventilation. Other radiosondes using spherical bead thermistors would be less affected by the rotation and tilt.

Measuring the temperature variation during rotation at 5 s is questionable, when the resolution of the data system is at best 1 s. Could it be that the minimal change at this speed is due to the inability to resolve the variations in time?

→ The ($T_{\mathrm{on\_max}} - T_{\mathrm{on\_min}}$) for 5 s duration is (0.01–0.02 °C) which is around the measurement resolution of RS41 (0.01 °C).

Before: The difference between the peaks ($T_{\mathrm{on\_max}} - T_{\mathrm{on\_min}}$) increases with the rotation period.

After (Line 267-268): The difference between the peaks ($T_{\mathrm{on\_max}} - T_{\mathrm{on\_min}}$) for 5 s duration is (0.01–0.02 °C) which is around the measurement resolution of RS41 (0.01 °C) but is increased with the rotation period.

The authors speculate that mostly conduction from the sensor boom is responsible for the temperature variations during rotation. This is a reasonable assumption, but may require some more explanation and possibly an additional figure showing the geometry during rotation. Since the actual temperature sensor is in parallel with the axis of rotation, no change in surface area is expected here. However, the exposed surface area of the sensor boom changes significantly, which justifies the assumption. This should be shown explicitly. The temperature increase due to conduction appears to be small compared to the temperature increase due to direct irradiation of the sensor. This could be expanded as well.

→ The rotation axis is the temperature sensor itself, not the center of the boom. Therefore, the temperature sensor only spins on the spot and thus the distance between the sensor and the light source does not change at all during the rotation. This implies that the irradiance to the sensor is constant whereas the light incident angle (effective irradiance) to the sensor boom changes with rotation. This explains why the maximum temperature peak appears twice during a full cycle.

Based on the observation, the contribution of the conduction to ΔT_{rad} compared to that by the direct irradiation of the sensor is mentioned as suggested.

Added Statement (Line 263-265): The rotation axis is the temperature sensor itself, not the centre of the boom in this work. Therefore, the temperature sensor only spins on the spot and thus the distance between the sensor and the solar simulator does not change during the rotation.

Added Statement (Line 280-282): The relatively small ($T_{\mathrm{on\_max}} - T_{\mathrm{on\_min}}$) with respect to ΔT_{rad} observed in this work suggests that the contribution of the thermal conduction to ΔT_{rad} is small compared to that by the direct irradiation of the sensor.

D) Underlying physical model

All fit equations have the form shown in Figure 1. Is there a physical model that justifies this equation? If not, then this fit equation may be not be the most suitable, since it forces a split of the measurements into two pressure regimes. Using a single 5th order (or even 3rd order) polynomial of delta T over LOG P could provide a single fit over the entire pressure range from 5 to 500 hPa with similar results.

In addition, the fit equation provides a constant radiation error between 500 and 1000 hPa, which is somewhat surprising and in contrast to the model underlying the Vaisala table. A polynomial fit could improve here.

The polynomial fit would retain the temperature dependence at low pressures, which is an interesting result of their study.

→ Exponential fittings are replaced by polynomial fittings with $\log_{10} P$ to provide a single fit over entire pressure range of 5−500 hPa as suggested. Consequently, residuals by polynomial fittings (±0.03 °C) are smaller than those by exponential fittings (±0.04 °C) as shown in Fig. 2(b). Therefore, polynomial fittings are newly used to obtain radiation correction formula throughout the revised manuscript.

Modified Figure (Figure 2): Figure 2(a) is replotted by using parabola fittings of $\log_{10} P$ and the residual in Fig. 2(b) is newly obtained accordingly.

Modified Equation (Equation 1, 9, 10 & 11): The backbone of the Equations is changed to $\Delta T_{\mathrm{rad}} = A_0(T) + B_0(T)\cdot\log(P) + C_0(T)\cdot[\log(P)]^2$

Modified Table (Table 1): The original **Table 1** is removed and **Table 2** is relabeled to **Table 1. Table 1** is modified to include information on new coefficients of $A_0(T)$, $B_0(T)$, and $C_0(T)$.

Minor comments:

The authors could also make a statement how they expect the radiation correction to behave at speeds lower than 4 m/s. Some research groups fly radiosondes at lower ascent speeds to gain higher vertical resolution and would be interested in seeing the effect of the slower ascent.

→ The validity of the effect of the ventilation speed is limited to 4−7 $\mathrm{m\cdot s^{-1}}$ in this work. When v is higher than 7 $\mathrm{m\cdot s^{-1}}$ or lower than 4 $\mathrm{m\cdot s^{-1}}$, the formula underestimates the correction value. This point is described in the revised manuscript.

Added Statement (Line 249-250): The linear relationship between the ventilation speed and the radiation correction in Eq. (9) is only valid in the range of 4−7 $\mathrm{m\cdot s^{-1}}$. When v is higher than 7 $\mathrm{m\cdot s^{-1}}$ or lower than 4 $\mathrm{m\cdot s^{-1}}$, the formula underestimates the correction value.

In the introduction, the authors should also mention that the first approach to reducing the solar heating effect is applying highly reflective coatings. This is particularly relevant, since they later refer to thermistors with different emissivities.

→ The use of highly reflective coatings in previous works is mentioned in the Introduction.

Before: To minimize the effect of radiative heating of radiosonde temperature sensors, the size of sensors has been reduced.

After (Line 47-48): To minimize the effect of radiative heating of radiosonde temperature sensors, the size of sensors has been reduced (De Podesta et al., 2018) and highly reflective coatings are used (Luers and Eskridge, 1995; Schmidlin et al., 1986).

The authors could provide a discussion about the homogeneity of the temperature in their system, in particular the wall temperatures versus the air temperature, given that they have a very strong heat source.

→ The true radiation correction is the temperature difference between the sensor and air ($T_{\mathrm{on}} - T_{\mathrm{air}}$). However, the air temperature measured in the current chamber system does not represent that in free atmosphere since the air is heated by irradiation for a short time while passing through the test section. The test section is also slightly heated by the irradiation and thus affects the sensor for the air temperature measurement in the chamber. In this work, the radiation correction (ΔT_{rad}) is obtained by the difference in the temperatures with irradiation (T_{on}) and without irradiation (T_{off}); $\Delta T_{\mathrm{rad}} = T_{\mathrm{on}} - T_{\mathrm{off}}$.

Added Statement (Line 143-146): The true radiation correction is the temperature difference between the sensor with irradiation and air ($T_{\mathrm{on}} - T_{\mathrm{air}}$). However, the air temperature measured in the current chamber system does not represent that in free atmosphere since the air is heated by irradiation for a short time while passing through the test section. The test section is also slightly heated by the irradiation and thus may affect the sensor installed for the air temperature measurement.

In Section 3.5, it is not perfectly clear, whether the authors varied the radiative flux or not. I assume that they did not, but rather do make the argument that the results should scale with the flux. This is reasonable, but could be made a little clearer.

→ The irradiance is fixed at $S_0 = 980\ \mathrm{W \cdot m^{-2}}$ throughout this work. A sentence is added to argue that the result should be scaled with the flux.

Added Sentence (Line 259): The radiation correction (ΔT_{rad}) is then scaled with the actual irradiance (S) by the factor of S/S_0.

The use of the factor SQRT(3) is mentioned repeatedly, but never justified. A reference to GUM would be useful with a brief explanation of what this factor does. This should be done only once at the beginning of the uncertainty section and other repetitions could be deleted.

→ The factor SQRT(3) is explained with the GUM as a reference

Added Sentence (Line 332-333): Then, the standard uncertainty of this estimate is the half-width of the distribution divided by $\sqrt{3}$ (Iso, 2008).

Added Reference: GUM is added as a reference.

The arrows in Figures 1a and 1b should be a lighter color to make them better visible. The photo in Figure 1a could be brightened. The direction of the airflow should be indicated.

→ The color of the arrows in Figure 1 is changed. The direction of the air flow is indicated in Fig. 1(b).

In the legend of Figures 2 through 4, for simplification, the symbols and dashed lines should be combined (e.g.: --o--). The caption could then explain that the dashed lines show the fit and the symbols the actual measurements.

→ Combining the legend using (e.g.: --o--) is impossible because the symbols and fitting lines are generated separately using the Origin software.

Figure 2: If a 5th order polynomial was used, then panels a) and b) could be combined to show the results over the entire pressure range using a logarithmic pressure axis.

→ Exponential fittings are replaced by polynomial fittings with $\log_{10} P$ to provide a single fit over entire pressure range of 5−500 hPa as suggested.

Figure 4: The indications of the different slopes should be removed from the actual Figure and the values could be added in a brief discussion either in the caption or in the main text.

→ The indications of the different slopes are removed from the Figure since they are already described in the manuscript.

Figure 6: The fat arrows should be removed. What they are supposed to indicate could be explained in the caption.

→ The fat arrows are removed from the Figure.

The language could be checked by a native speaker for more unusual expressions used by the authors.

→ The original manuscript was checked by a professional language editor before submission.