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Atmospheric Measurement Techniques Discussions

Interactive comment on "A comparison of rainfall measurements by multiple instruments" *by* X. C. Liu et al.

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This paper describes a comparison of the performance of six different rainfall sensors over a 10-month period. Three of these sensors were designed to measure rainfall amounts (rain gauges), two to measure drop size distributions (disdrometers), and one to detect present weather (present weather detector). Comparisons are presented for rainfall intensities, rainfall duration, and (in the case of the disdrometers) drop size distributions. The topic of the paper is certainly relevant. However, there are several issues that need to be addressed. The way in which the accuracy of the different instruments is actually assessed needs considerable improvement, and conclusions about the accuracy of the different instruments are missing. Specific comments on the paper are given below.

Response: Thanks for your constructive comments of our work, which enables us to further improve the quality of our manuscript.

Specific comments

1. In the introduction, I think the authors should discuss the results presented by Sieck, L. C., S. J. Burges, and M. Steiner (2007), Challenges in obtaining reliable measurements of point rainfall, Water Resour. Res., 43, W01420, doi: 10.1029/2005WR004519.

Response: Thank you for your comment. We have discussed the results presented by Sieck and added this reference (Sieck et al., 2007) in the revised manuscript.

2. On p. 522, line 17, the uncertainty for the tipping bucket rain gauge is given as "±0.2 mm under 250 mm h-1". It is not clear to me what this uncertainty means. Is this the uncertainty per tip? If so, this is an uncertainty of 100% ! I think the authors should make clear what this uncertainty means.

Response: The uncertainty here means the uncertainty of overall rain rate at rainfall intensities fewer than 250 mm h-1, not for one tip. According to the data sheet of RIMCO 7499, we have replaced the sentence by 'the accuracy is ± 1% at rainfall intensities up to 250 mm h-1, and ± 3% at rates up to 500 mm h-1'.

3. In Section 2.1, the authors should discuss how the time series of tips of the tipping-bucket rain gauge are converted to rainfall intensities. This is very important as it greatly influences the results presented in the remainder of the paper.

Response: one count of TBRG bucket tip corresponds to 0.2mm, the rainfall intensity (mm h-1) by tipping-bucket rain gauge was calculated by the TBRG total rainfall accumulation per minute, in which the TBRG total rainfall accumulation can be obtained by multiply TBRG total bucket tip count by 0.2mm.

4. In Section 2.1, could the authors note whether the gauges are heated?

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Response: According to the data sheet of RIMCO 7499 TBRG and WRG, the optional heater operates below -30°C; but the temperature of 27 rainfall events in this manuscript are not below -30°C, therefore the gauges are not heated. We have noted that in the revised manuscript.

5. In Section 2.2, the measurement principles of the present weather detector are not clear to me. I think an understanding of the measurement principle is very important for proper interpretation of the results, so please include a clear description of these measurement principles.

Response: Thank you for your comment. We have added a description of the measurement principles of the present weather detector in revised manuscript.

6. In Section 2.3, line 5, the authors state that "JWD's output is proportional to the size and fall velocity of the impacting drops". Although the output depends on both the size and fall velocity, it is not proportional to these. See Joss, J. and Waldvogel, A. (1977), Comments on "Some observations on the Joss-Waldvogel rainfall disdrometer", J. Appl. Meteorol., 16, 112-113 and Salles, C. and Creutin, J.-D. (2003), Instrumental uncertainties in Z-R relationships and raindrop fall velocities, J. Appl. Meteorol., 42, 279-290 for more information on this.

Response: We are sorry for the inaccurate description about JWD, "The disdrometer's output is proportional to the size and fall speed of the impacting drops" came from the reference: Tokay, A., Kruger, A., and Krajewski, W. F.: Comparison of drop size distribution measurements by impact and optical disdrometers, Journal of Applied Meteorology, 40, 2083-2097, 2001. We have corrected them in the revised manuscript.

7. In Section 2.3, line 17 of p.524, I think the authors should cite Salles, C. and Creutin, J.-D. (2003), Instrumental uncertainties in Z - R relationships and raindrop fall velocities, J. Appl. Meteorol., 42, 279-290 here.

Response: Thank you for your suggestion; we have added the citation in revised

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manuscript.

8. In Section 2, a discussion should be included on the effect of the installation in general and the wind specifically on the different instruments. An inspection of Figure 1 reveals that there is a great difference among the instruments in how they are installed. For example, the tipping bucket rain gauge is installed on the ground, whereas the weighing rain gauge is installed about 0.5 m above the ground, and has a wind screen to avoid wind effects.

Response: Thank you for your comment; the installations of instruments have different effect on their performances, whereas we assume that the instruments were installed at their optimum allocation in this manuscript. It is a very meaningful issue; we will discuss the effect of installation of different instruments on their performances in our next manuscript.

9. In Section 3, the time interval chosen for the analyses presented in this paper should be given (I believe it is 1 minute), and a brief discussion of the reason for this choice should be included.

Response: Yes, the time interval of all rainfall observation data is 1 minute, analyzing minute-by-minute spectra event-by-event we can obtain the details of different instruments performances. A brief discussion of the reason for this choice has been added in the revised manuscript.

10. All of the analyses of rainfall duration depend heavily on how the tips of the tipping-bucket rain gauge are converted to rainfall intensities and the chosen time interval. I assume that it is raining in a given time interval if the TBRG gives at least one tip, the WRG records a difference in weight, and the other instruments record at least one drop. Because the difference between a single drop on the one hand and a volume measurement on the other (a tip or a change in weight) can be large in very light rain, a comparison of rainfall duration based on these criteria does not seem very relevant to me.

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Response: The comparison of rain duration is one of the major problems discussed in this manuscript. There are many different instruments with different measurement principles for rain duration, rain rate, and DSDs at present, their performance varies with their principles, the comparison of various instruments in this manuscript are useful to the application of observation data of rainfall by different instruments. Some conclusions about different instruments' performance can be obtained from the comparison of rain duration, especially in a light rain. Limited by the measurement principle of TBRG, the rainfall duration can not be recorded by TBRG precisely, small change of rainfall might be neglected; whereas the optical instruments are much more sensitive to the light rain or small raindrops, small change of rainfall can be recorded. There are already many literatures that compared the disdrometers and rain gauges, the comparisons of rain duration in this manuscript are used to evaluate the rainfall timing accuracy of different instruments thoroughly, by which more conclusions can be obtained, therefore we believe that the comparison of rainfall duration by different instruments is necessary and of great significance.

11. On p.525, line 20, it is stated that "obvious discrepancies of observations are excluded". Please give a short description of how these discrepancies were detected and what caused them.

Response: Obvious discrepancies of observations are mainly due to the missing records by operational failures of instruments. For example, On March 1 2012, the records by 2DVD are missed from 19:14 to 24:00, while other instruments still recorded rainfall, therefore the rainfall event after 19:14 are excluded. It happened several times.

12. On p.526, line 5, it is stated that for the computation of the relative bias, "R1 is the bigger one". I don't think this is a good idea, because the result will always be positive. The information contained in the sign of ΔR on whether it is an under- or overestimation is then lost.

Response: Thank you for your comment. We have modified the computation in the

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revised manuscript, the comparisons (under- or overestimation) of instruments can be found in Table 2 and Table 3.

13. On p.526, the discussion of Fig.2 (p.541) on lines 10-17 implicitly suggests that TBRG is used as a reference. Although it is clear from p.528 that the authors do not intend this to be the case, I think it would be good to note this explicitly.

Response: Thank you for your comment; although the TBRG have large error for rainfall timing, the TBRG can record the rain amount accumulation precisely, we used the TBRG as a reference for the comparison of rain amount. We have noted this explicitly in the revised manuscript.

14. On p.527, lines 8, 9, and 11 (2x), the use of the word "bias" makes it sound like the differences are attributed to errors in the sensors. I suggest rephrasing, making use of words such as "difference". This also holds for p.530, line 21 (twice).

Response: Thank you for your suggestion, we have rephrased it.

15. On p.527, line 13, the errors in the TBRG are attributed to the tip resolution of 0.2 mm. However, with different conversion of the tip times to 1-minute rainfall intensities, these errors would be much less severe.

Response: Thank you for your comment. As suggested by another referee, We reran our comparisons with an average over 3 minutes, the evolution curve of rain rate are smoothed by the average over 3 minutes, and there is a slight improvement for rain rate comparisons, the errors are reduced to a certain extent, but limited by the inherent principle of TBRG, the error of rain rate and timing by TBRG in light rain is still obvious, which can not be ignored.

16. On p. 528, an algorithm is presented for generating a reference rainfall intensity based on a weighted average of measurements from five sensors. The weights are proportional to the rainfall intensity itself. This algorithm makes no sense to me. There is no reason to believe that the reference rainfall generated by this algorithm is any

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better than simply taking one of the sensors to be the reference or taking the average over all sensors. Because of the higher weight on larger intensities, this algorithm is likely to create a reference that is biased toward higher intensities. I strongly believe that simply choosing a single sensor to be the reference (or possibly two sensors; each one for a different intensity regime) based on known performance characteristics from literature is better.

Response: This algorithm comes from the references as follows: “Boers, R., Haij, M. J. d., Wauben, W. M. F., and et al: Optimized fractional cloudiness determination from five groundâĂŘbased remote sensing techniques, Journal of Geophysics Research, 115, D24116, 2010.” and “Nash, J., Oakley, T., Vomel, H., and et al: WMO Intercomparison of High Quality Radiosonde Systems, World Meteorological Organization (WMO), Geneva2, Switzerland, 2011. Report No.107.”. This algorithm is designed to provide a reference when there’s no standard value or standard instrument. However this algorithm is likely to create a reference that is biased toward higher intensities, as you stated, we decide to take your advice, and we use the Weighing Rain Gauge (WRG) as the reference in the revised manuscript. However, compared the reference algorithm, the WRG and other instruments have worse correlation and larger standard deviation. Consider the different performance of different instruments at different intensity regime; we will discuss this issue in our next manuscript.

17. On p.529, Eq.(5), the second part (the sum) is incorrect. It should be something like where Nclass is the number of diameter classes and ΔDi is the diameter class width of class i.

Response: Thank you for your suggestion, we have corrected it in the revised manuscript.

18. On p.529, Eq.(6), expression for N0, explain that (m+4) is the gamma function with argument m + 4 (generally referred to as Γ(m + 4)).

Response: Thank you for your comment; we have modified it in the revised manuscript.

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19. On p.529, Eq.(6), note that these variables can be computed using any combination of three moments of the DSD. The choice of moment orders 3, 4, and 6 make sense as these are related to the highly relevant variables rainfall intensity (R) and radar reflectivity (Z).

Response: Yes, the moment orders 3, 4, and 6 are related to the highly relevant variables rainfall intensity (R) and radar reflectivity (Z).

20. On p.530, line 1, "where " is ambiguous (and even incorrect if interpreted according to mathematical conventions). It should be.....

Response: Thank you for your comment; we have corrected it in the revised manuscript.

21. On p. 530, line 7, I assume that by "drop numbers" the authors mean "number density (Nd).". If so, please put this in the axis label of Fig.6b (including correct units) as well.

Response: the "drop numbers" here means the total number of raindrops measured instead of "number density", the "drop number" is used to shows the measurement of raindrops.

22. On p.530, line 10, "Fig.3b" should be "Fig.4b".

Response: Thank you for your comment; we have corrected it in the revised manuscript.

23. On p.530, lines 18-19, I don't think you can conclude that the 2DVD "shows a better ability to measure large-size raindrops". It simply measures more of these raindrops (it is not necessarily better able to measure these).

Response: Thank you for your comment, it's not sufficient to conclude that conclusion, we have modified this sentence in the revised manuscript.

24. On p.530, line 25 and on p.531, lines 8-9 it is stated that the JWD measures more

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small-size drops than the 2DVD. Because there are simply much more small drops, this would mean that the JWD measures more drops than the 2DVD. This contradicts the results shown in Fig.6b, where the 2DVD consistently measures more drops than the JWD. I think this discrepancy should be thoroughly discussed.

Response: We have discussed this result thoroughly in the revised manuscript. Although the JWD can measure more small drops in a certain regime of raindrops' size, the 2DVD have a larger measurement range (spectral width), raindrops smaller than 0.3mm and larger than 4mm can be recorded, therefore 2DVD can measure more overall raindrops than JWD, the underestimation of overall raindrops by JWD shown in Fig.7e agreed well with the results shown in Fig.6b.

25. On p.531, lines 13-22 and Table 4, I don't think this is very relevant information.

Response: The raindrop size distribution (DSD) parameters are essential for applications in various disciplines. Take the remote sensing by weather radar for example, both radar measurements and rainfall are integral products of the DSD and a surface based disdrometer is often employed to derive Z-R relations for a climate region (Tokay, A., W. Petersen, P. Gatlin, and M. Wingo, 2013: Comparison of Raindrop Size Distribution Measurements by Collocated Disdrometers. J. Atmos. Oceanic Technol. doi:10.1175/JTECH-D-12-00163.1, in press), therefore the accurate measurement of DSD by disdrometers are very crucial. The comparison of DSD parameters by JWD and 2DVD in this sentence and Table 4 include M3(liquid water content), M4 (rain rate), M6(radar reflectivity), m, Λ, and Z, which are all important factors of DSDs and radar parameters, we believe that these discussions are meaningful and relevant to rainfall retrieval by radar, cloud modeling, and other applications.

26. Section 4 (Conclusions) just contains a summary of the paper, and no conclusions are drawn.

Response: Thank you for your comment; we have added relevant conclusions in the revised manuscript.

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27. In my view, the conclusions on p.532, line 26 through p.533, line 2 about the inaccuracy of the 2DVD cannot be drawn based on the results presented in this paper.

Response: Thank you for your comment; we have modified the relative conclusions in the revised manuscript. We found that small raindrops were underestimated by 2DVD when R > 15 mm h-1, the possible reason is that the small raindrops tend to be omitted in the more large raindrops due to the shadow effect of light. We believe that it is one problem or shortcoming of 2DVD; however, this issue should be discussed and examined thoroughly by using more measurements and comparisons.

Interactive comment on Atmos. Meas. Tech. Discuss., 6, 519, 2013.