Final answer for AMT-2018-179

Title: Evaluation of Windsond S1H2 performance in Kumasi during the 2016 DACCIWA field campaign

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We thank the anonymous referee for the helpful comments. We are responding to all the comments of the reviewers in this document and we have prepared a revised manuscripts where changes are marked and removed parts as follows: red correspond to reviewer #1 RC2, blue reviewer #1 RC3, green reviewer #2 RC4. In the following, comments of the reviewers are given in bold and italic with our responses are given in normal font. The final answer is structured as follow: 1) answer to reviewer #1 RC2 comment, 2) answer to reviewer #1 RC3 comment, 3) answer to reviewer #2 RC4 comments.

1. Answer to referee #1 RC2

Overall comments:

This paper describes progress towards developing a less expensive but reliable upper-air radiosonde. To evaluate their newly developed S1H2 sonde they compare its data to observations from high-quality Vaisala RS41-SG sondes. The observations were taken from 33 launches during the DACCIWA field campaign in Western Africa. Basically the authors conclude that the S1H2 sonde is a work in progress with the main issues being the poor performance of the GPS sensor leading to questionable winds and the slow response time of the temperature and humidity sensors. It's ironic that an instrument called a "windsond" would do such a poor job measuring winds. They conclude by offering some recommendations for future improvements. From the limited comparisons shown between RS41 and S1H2 observations, it is hard to properly judge the performance of the windsond. For example, only one intercomparison flight is made for data extending above the boundary layer. Figures 5-7 show data from this one flight. To get meaningful statistics to evaluate the windsond, data from 20 or more flights should be presented as in Jensen et al. (2016) and similar intercomparison studies. For soundings within the boundary layer, analyses are shown from (I believe) eleven flights (Figs. 8-9) and in a format that is difficult to interpret. I would recommend that analyses be presented in a more conventional format as biases and rms differences between the RS41 and windsond (see Fig. 8 of Jensen et al. 2016). While the paper has some major concerns in the way the analyses are presented, it is still of value in that it is introducing a new instrument with a promising upside that is in the early stages of development. Under major comments below I suggest several areas where paper could be improved.

Answer:

We agree that only one sounding over the boundary layer is not statistically sufficient to assess the S1H2 performances. A key point about the S1H2 is that its re-usable this particular sonde is of interest as as it illustrates the reusable capacity. Launches in which an S1H2 and RS92 are tapped together by default result in the loss of the sonde and so analysis of its re-use performance cannot be undertaken. Eleven RS41-SG have been launched simultaneously with two S1H2 during the re-use evaluation, so twenty-two S1H2 flights have been compared to eleven RS41-SG in the boundary layer. This method allowed us more data comparison and also less travel time to search the sondes as the two S1H2 launched simultaneously where landing in the same area.

Major comments:
While the windsond system is being marketed as a less expensive replacement to more conventional sondes, no where is the cost of the sonde system (laptop, antenna, etc.) and sondes mentioned in the paper. Please discuss this information.

Answer: We do not want to state the price of the sonde in the paper as the price is subject to evolution. This sondes requires a smaller ballon and and consequently less helium so saving are made on this side. The sonde is also re-usable so re-using the sonde up to 8 times can constitute a significant saving.

Line 24: The vertical resolution is also a function of the sampling rate.

Answer: True it has been added

Line 28-33: So the US sites are spending ~$237K per site per year. I would assume that the US sites are some of the more costly ones to maintain around the globe so I would guess your $440M is gross overestimate. You might want to state a range like from $237M to $440M. The statement referencing Martinez (2016) is confusing. It reads as if you saying that Greenland has 40 operational sites? I'm assuming you mean the Arctic has 40 sites. You may want to reword this statement. Also, is Martinez (2016) a valid reference?

Answer: A sentence to clarify that this estimate is only valid for the US has been added, the reference to Martinez has been removed as it was confusing and does not add essential information in this paper. Some corrections in the last few sentences of the introduction have been made to clarify that Windsond is a less expensive (in terms of initial set up and consumable costs) alternative for boundary layer radiosounding

With an operational ceiling of 6 km, it does not seem that the windsond system can be used to replace the sondes currently being used at operational sites which record data to 25 km and higher. With this mind what are the practical research applications of the windsond S1H2 as an upper-air system? Because of its limited range it seems best suited for use in boundary layer studies. However boundary layers are often characterizes with sharp gradients in potential temperature and moisture which the S1H2 has difficulty resolving because of its slow response time. Please discuss. Are there plans to use improved T and RH sensors with a better response time?

Answer: Windsond main objective is to enable boundary layer studies, so the Windsond has no upper-atmosphere application. The current response time limitation is the weakness of the system for boundary layer applications. In small scale, Sparv Embedded uses temperature and relative humidity sensors with a better response time, but currently, the cost is high in the context of radiosondes. Lowering the per-unit cost would take a sizeable investment in the production process to automate assembly and calibration. A key point is that the windsond system can be used in countries with limited resources to deploy a radiosounding network utilising the more accurate but more expensive sondes as well as field campaigns were multiple shallow sounding are required. An example of this application is the VORTEX-SE project, where Penn State University released 24 sondes at the same time to study winds around storm supercells and might release as many as 100 at a time in the next season. This is a unique feature of Windsond for dense measurements (http://windsond.com/swarmsonde-is-in-the-news/)

Line 56: Why is the operational ceiling at 8 km? Is this the burst altitude of the party balloon used with the sonde or are there some other considerations?

Answer: Supporting soundings higher than 8-10 km requires technology that more closely resembles traditional radiosondes, diminishing the advantages of Windsond. The sondes would be heavier and require a more expensive sensor suit to overcome the hasher measurement conditions in the upper atmosphere. Moreover, while not all users find it worthwhile to recover the sondes, at high altitude the sondes would drift too far for any recovery to be feasible. Windsond does not try to replace traditional sondes, but rather enable new low-altitude soundings.

Figure 4: It's difficult to see the ruler in this picture to get an idea of the length of the sonde.

Answer: The picture brightness has been fixed to see the ruler.

Line 104: Also mention that the RS41-SG pressure calculation uses the hypsometric equation.

Answer: This has been added line 104.

Line 123-124: Please clarify what it means "that the MW41 only produces the highest degree of signal processing". In other places you mentioned RS41 data before and after processing.

Answer: The predecessor of the MW41, the MW31 had a research mode and an operational mode. The research mode processes the data as little as possible only correcting solar radiation and pendulum effects, while the operational mode produces the highest degree of signal processing filtering raw data and interpolating discontinuous data. The MW41 has only the operational mode available, to obtain the equivalent of the MW31 research mode data (data before processing in the text) the flight have to be simulated from the flight archive with the minimum amount of data processing enabled

Line 126: Please clarify what corrections have been introduced. Have these corrections been implemented in the results from this study?

Answer: The sentence has been changed to: "During this experiment, the uncorrected data have been used, but the ground pressure altitude and temperature have been adjusted to the value measured by the ground-based instrumentation available on the Kumasi supersite."

Line 153: What is experiment 6?

Answer: The experiment 6 is the reproducibility experiment presented in section 6 this information has been added to the text

Line 167-168: This discrepancy between sensors at 2000 m is difficult to see in the manner that the data is displayed. Could the data be presented as a function of height or pressure to better show this?

Answer: We have chosen to directly compare each variable as the altitude error on the Windsond S1H2 would have superposed on each sensor error and not each sensor performance. Moreover, the Vaisala system does not have a pressure sensor and the pressure is calculated by the MW41 as detailed in section 3.3 while the Windsond has a pressure sensor so the profiles as a function of pressure would display data as a function of a calculated variable in one hand to a measured variable on the other hand. We could also display both sonde data as a function of the Vaisala altitude, but this will involve modifying the shape of the S1H2 profile to fit in the Vaisala altitude profile and consequently not display the actual profile obtained with the S1H2 system. We consequently think that displaying the data of the Vaiala sonde as the function of the Windsond data is the best way to assess the performance of each sensor without interference from other sensor errors.

Line 176: Please verify that Vaisala does not use GPS differential correction to compute winds as I thought they did. In fact this statement seems to contradict what is said earlier in lines 111-113. Did you mean the S1H2 does not do differential correction to compute winds.

Answer: Section 3.4 lines 110-118 have been rephrased for clarity as it was confusing the way it was presented.

The Vaisala sonde uses differential correction for latitude longitude and altitude positioning. However, the Vaisala system computes the wind speed independently from the position using the GPS signal without Differential correction.

The Windsond system does not have a differential correction on its GPS to compute latitude and longitude and uses pressure to compute altitude.

Line 176: It seems really puzzling why the Windsond winds are of such poor quality. For example the IMET sonde system does not use a differential wind correction and its winds compare quite favorable to the RS41 sonde. Can you give some explanation for the poor performance of the Windsond winds? Is some of this error due to the pendulum motion of the sonde swinging below the balloon which is filtered out in the RS41 processing but not filtered out by S1H2 system?

Answer: The poor agreement surprised Windsond as informal comparisons with Vaisala and Graw have shown good agreement in wind speed and direction. The pendulum is a possibility as the

Windsond has since increased the length of the tether line. During the performance flight, both Windsond and Vaisala were on the same tether line, while on the reproducibility flight the Windsond was on a shorter line compared to the Vaisala and there was no significant increase in the wind speed and direction error between the two experiments. This suggests that the pendulum correction does not have a significant impact on the wind speed and direction.

Wind gusts and local wind variation associated with the general slower response time of the Windsond system are more likely to explain this error.

Line 195: One sounding does not provide statistically significant evidence for this statement. See comments above.

Answer: We agree that one flight is not statistically significant for definitive conclusion. We have added that this has to be confirmed by more flights.

Section 5.2.2. So to clarify are you saying that the results shown for the S1H2 have no post processing and no corrections applied? Can you state what processing and corrections the MW41 performs. You mention smoothing in line 194. Is this smoothing of all fields? Is the balloon pendulum motion only taken out in the MW41 processed data?

Answer: The S1H2 has no post-processing applied especially no pendulum and radiation correction while the data processed by the MW41 have been filtered, pendulum and solar radiation effect have been corrected, and data gaps have been interpolated.

Figure 7: It appears that the surface or starting pressure used is different between the systems. Why is this?

Answer: The surface pressure is the same there is one point with the coordinate (0,0). However it is hard to see so the 2 zero lines have been added to figure 7 for clarity.

Line 207: Does the pressure difference between the two systems continue to increase with altitude?

Answer: A typo has been found and has been corrected in the manuscript. The altitude error increases with height while the pressure error remains stable.

Line 229: What is a .kml file? Does this need to be mentioned?

Answer: kml files or Keyhole Markup Language files are files used for expressing geographic annotation and visualization within Internet-based, two-dimensional maps and three-dimensional Earth browsers such as Google earth.

As this information is not essential the information have been deleted and replaced with: “the system automatically predicts and displays the expected landing point on a map view.”

Line 232: Are these flashes of light coming from the sonde? Please clarify.

Answer: Yes, the flashes of light are coming from inside the sonde we changed the sentence to “the contact between the sonde and the ground station was established, the sonde started immediately to emit loud beeps (about 15 seconds time interval) and flashes of light.”

Line 235: Have you considered if a 4m string is long enough to prevent balloon effects on the sonde observations? I believe the Vaisala system uses a much longer string (20-30m) to prevent any balloon impacts on the sonde data.

Answer: The 4 m string has been chosen following the constructor recommendation, however Windsond has since changed its recommendation for the sondes suggesting that balloon effects have been noticed.

During the performance flight, both sondes where tapped together under the 20 m meter string and the winds errors are a similar magnitude as during the reproducibility experiment so the balloon effect does not seem to have a significant impact on the sonde data.

Line 244: Please clarify what the “data alteration study” is.

Answer: The data alteration study is the study of the alteration of the sounding performance through sonde re-use. The text was changed to “data alteration from sonde re-use study”

Line 285: This is good suggestion and should be a standard practice for all flights (i.e.,proper surface base-lining of sondes)

Answer: Agreed

Table 3: Please mention the RH sensor response time.

Answer: The response time of the RH sensor was added

Listed below are some additional minor suggested changes the authors may want to consider.

Minor comments

All the suggested rewording have been applied to the manuscript

Line 48: suggested rewording, “because the LLC cover …”
Line 50: suggested rewording, “boundary layer sounding during …”
Line 69: “Figure 4 shows the Windsond …”
Line 74 “sensor is used in …”
Line 134 and elsewhere like Table 6: mention if time is GMT or LT.
Line 160: “all the assessed meteorological parameters …”
Line 168: “sudden warming …”
Line 171 and 172: change “reply” to “response”
Line 234: “When re-using the sonde …”
Line 256: “for locating soundings …”

Line 289: Seems like "different altitudes" should be "lower altitudes". This would be a good place to state the specific niche that the Windsond is trying to fill. Certainly in its current configuration it will never be used as an operational sounding.
Line 292: "longer response time …"

2. Answer to referee #1 RC3 for AMT-2018-179

Overall comments: The authors have offered adequate responses either by addressing my comments or revisions to the paper. However it should be clearly stated in the abstract that this Windsond is intended primarily for collecting boundary layer observations.

Answer: This information has been added on the first sentence of the abstract

Also note that boundary layers are typically 500 m over the tropical oceans but can be 5 km deep under summertime continental conditions. So in the first sentence of the conclusions where you state that it measures conditions at lower altitudes, lists an approximate height range where observations are considered good. For example,"... lower altitudes (up to 2 km)" or whatever altitude you trust your data.

Answer: This information has been added to the first line of conclusion

Finally, in your response you mention that you thought the balloon did not effect the winds. But there is also a concern during daylight flights that radiative effects off the balloon with a short 4m string could effect the T and RH measured by the sonde.

Answer: That is true, our answer was focussed on the wind speed error as the wind speed error was the largest. The balloon used under a 4 meter rope for the reproducibility experiment was smaller than the balloon used during the performance flight when the Windsond was taped to Vaisala sondes under the 20 meter string. The T and RH errors during the performance flight are a similar magnitude during the reproducibility experiment so the smaller ballon under a 4 m rope does not seem to have a similar impact on data compared to the larger balloon with a 20 m rope. However, we recognize that the use of a longer string with the smaller balloon would be an inexpensive way to reduce the radiative effects on the data collected by the Windsond system.

Suggested rewording:

All the suggested rewording have been applied to the manuscript

Line 30: This rough estimate varies regionally as the price of labor, helium and balloons is not the same around the globe. Yet operational costs are a significant investment in countries with limited resources.
Line 111-115: "... the Vaisala ground station has a GPS receiver ... However, wind speed and direction are determined independently from the GPS position using the GPS doppler frequency shifts.
Line 117: "Similar to the RS41-SG ..."
Line 206: "... performed. To be statically significant this result needs to be verified with additional performance ..."
Line 239: "During the descent after the sonde loses contact ..."

3. Answer to referee #2 RC4 for AMT-2018-179

This paper presents an evaluation of a relatively new low-cost radiosonde system against a well-established and widely used radiosonde based on measurements performed in June and July 2016 during a field campaign in Ghana - Western Africa. The low-cost radiosondes were recovered by the operators and reused up to 8 times, which allows the authors to analyse a relatively high number of ascends. It is shown that under "simple" atmospheric conditions temperature, humidity and pressure measured by both systems compare reasonably well, but as soon as larger vertical inhomogeneities occur the low-cost radiosonde suffers from slow sensor response and hysteresis. GPS-derived wind from the low-cost system is of very bad quality.

Unfortunately, the paper suffers from several weaknesses starting by the design of the measurements, missing technical information, lack of measurements under laboratory conditions and a very limited analysis of the data. The authors miss to cite and discuss relevant literature e.g . Legain et al. 2013 doi:10.5194/amtd-6-3339-2013 and Nash et al, 2010 WMO Report No. 107 Instruments and Observations. The weather situation is not sufficiently discussed and taken into account. Overall it seems to me that the paper is a kind of side product produced with minimal effort.
I think that the paper will not warrant publication as long as a mayor revision is done which addresses the following comments.

We would like to thank the reviewer for the references to the relevant literature we have missed and the their comments concerning the contextualisation of the work. This work was made in the context of the DACCIWA field campaign were the Windsond S1H2 was being integrated into a large scale scientific sounding programme for the first time. This sonde has never been used in this manner before hence we took the opportunity presented by the DACCIWA field campaign to compare the radiosonde with a proven system: providing benchmarking for the interpretation S1H2 sonde data obtained as part of DACCIWA. The experimental design was limited by the needs of the field campaign and the resources available but despite these limitations it did allow the identification of a number of issues with the Windsond S1H2 and to feed these back to the manufacturer to help the development of a reusable sonde system that is easier to use than the system presented by Legain et al., 2013.

The conclusion drawn in this paper is by no means a definitive conclusion on the Sparv Embedded system but a list of recommendation for development as well as recommendation for the future users of the DACCIWA field campaign data and as such is still usefull for the community.

Specific comments:2
Page 2 The first section is a marketing analysis which is mostly irrelevant if you want to discuss a reusable low cost sonde that is limited to 6000 m altitude. Sonde costs are fixed - price differences for launches in different regions depend on logistics and local labour.

Answer: Agreed, following reviewer #1 comments we have noticed that the first section is confusing so we added "This rough estimate varies regionally as the price of labour, helium and balloons and is not the same around the globe. Yet operational costs are a significant investment in countries with limited resources."

We have introduced Legain et al., 2013 system and discussed the limitations of the system for the development of an operational network using this sonde: "Re-usable sondes have been introduced for the first time by Legain, et al., 2013 which modified a Vaisala sonde to enclose it in a cage which is tied to a couple of balloon. The caged allowed the balloon to detached at a desired altitude and slowly descend before recovery. Despite this system has shown successful results in pressure temperature and humidity, and recovery rate it does not asses the effect of the cage and the two balloons on the obtained wind profile. The sonde modification required makes the use of this system more complex and can be an obstacle towards a global use of the system, this shows that re-usable sonde technologies are still a work in progress where manufacturers can develop their own solutions."

If the sounding program had the objective to evaluate the Windsond performance already from the beginning please explain the following: 1) Why is there only one tandem flight reaching higher altitudes performed 2) Why are all low altitude intercomparison flights performed only at 0600 and not distributed over day and night or at least over the launch times shown on figure 2. As the sondes were recovered no significant additional costs would have been created. 3) Why are the RS42 and Windsond not tied together for the low altitude intercomparison flights – the resulting spacial difference makes it impossible to separate instrument errors from atmospheric variability.

Answer: The goal of the DACCIWA ground field campaign was to provide a high-quality comprehensive dataset for processes studies, in particular interactions between low-level clouds (LLCs) and boundary layer conditions. The DACCIWA radio sounding program was then designed to complete these main objectives. The Vaisala RS42s were launched to provide synoptic observations during the campaign with complementary synoptic measurements during IOPs. The Windsond S1H2s were launched to provide more frequent boundary layer sounding during DACCIWA IOPs, to observe the evolution of the LLCs, and associated phenomena such as the Nocturnal Low-Level Jet (NLLJ) The frequent radiosounding program thus focussed on night-time measurements as detailed on figure 2.

As the S1H2 was never used in the context of a field campaign we had to control the quality of the S1H2 in order to facilitate the interpretation of the data recorded by the S1H2. This performance assessment had however to be done without impacting on the main objectives. We agree that only one sounding reaching higher altitudes is not statistically sufficient to assess the S1H2 performances. Launches in which an S1H2 and RS92 are tapped together by default result in the loss of the sonde and so would compromise the completion of the Windsond objectives. We were planning to perform more intercomparison flights toward the end of the campaign unfortunately, as quoted in section 6.2 the radio receiver has been damaged during the campaign preventing us from completing this final objective.

Due to limited human resources (5 scientists separated into 2 teams performing 12 hours shifts on-site to run the whole Kumasi supersite instrumentation), distributed flights over day and night were not possible, thus to comply with the DACCIWA objective the frequent radiosounding program focussed on night-time measurements as detailed on figure 2. It was advised by our Ghanaian partners to avoid going out of the supersite at night to avoid encounters with tropical wilderness and limit the robbery risk. For these reasons, sonde recovery took place after sunrise, thus, to limit the time between the launch of the sonde and the recovery, all the frequent radiosounding flights took place in the last part of the night and the intercomparison flights at 0600 UTC.

According to Sparv Embedded, the Windsond S1H2 system is reusable, requires a smaller balloon and less helium and can receive multiple sonde, for the first utilisation of the sonde these features have to be tested. The S1H2 sonde were launched using manufactuer recommendations to evaluate the performance of the sonde in regular use. At low wind speeds the signal-to-noise ratio in the wind speed measurement is worse, so reducing the ascent speed can adversely affect the wind speed accuracy. For these reasons the sonde were not tied together for the low-altitude comparison flights. We agree that this experimental design does not allow us to quantitatively asses the Windsond S1H2 performance, however, this design allows us to qualitatively asses the system where the wind speed and direction issues have been confirmed and evaluate an eventual data alteration trend through use.

Eleven RS41-SG have been launched simultaneously with two S1H2 during the re-use evaluation, so twenty-two S1H2 flights have been compared to eleven RS41-SG in the boundary layer. This method allowed us more data comparison and also less travel time to search the sondes as the two S1H2 launched simultaneously where landing in the same area.

Page 3 Please us UTC or LT but not AM / PM Is Fig. 2 really needed ? Please explain what you mean with simultaneous launched (see above). Please give more information about the calibration of the Windsond. Do sondes have individual factory calibrations stored on the sonde or does the manufacturer rely on the quality of its sensors only ? How is the multi sonde reception realized – please give details on the receiver technology. Please use Kelvin instead of _C for Accuracy and Resolution in Table 2

Answer: Following reviewer #1 recommendation all the times are now changed to UTC. Individual calibration is done by the sensor manufacturers, thus stored in the sensors, multi sonde reception is realized by time-division multiplexing. As requested temperatures are now expressed in Kelvin in Table 2.

Table 3-5 Anders Petersson is affiliated to the manufacturer of Windsond. You should be able to give detailed information about the sensors used in Windsond and their performance instead of "not available (to be assessed)". Is the given value for pressure accuracy valid for Vaisala or Windsond? Why is the Wind speed accuracy relative to the wind speed?

Answer: The cell alignment for the table 2 leads to a confusion for the pressure accuracy, the given accuracy value is only valid for Windsond, the Vasaila value is defined as combined uncertaincy and reproducibility. At low-speed the signal-to-noise ratio in the wind speed is worse, thus the dependency of wind speed accuracy relative to wind speed.

Page 5: Pressure sections: Please include in the discussion the results of the WMO radiosonde intercomparison 2010 about direct pressure measurements vs. derived pressure.

Answer: We have added: "The WMO radiosonde intercomparison experiment 2010 showed that pressure measurement derived from geopotential heights and radiosonde measurements of temperature and relative humidity profile were very reproducible and suitable for all radiosounding operations for system where GPS system are set up correctly which includes the Vaisala system. This shows that the Vaisala derived pressure is a reliable reference to assess the Windsond pressure sensor, and the Windsond cost can be lowered by removing the pressure sensor in future version of the Windsond system depending on its GPS system accuracy."

Page 6: Please explain uncorrected data vs data correction for all parameters for the Windsond. What was the procedure to "adjust" ground pressure altitude and temperature? Wow large were these "adjustments" and why was this not done for humidity? I am still astonished that only one tandem flight to higher altitudes was performed! A larger number of such flights under different weather situations as well as during day and night would have improved the evaluation significantly. The flight was in 2016 and not 2006. Since all flights were performed during night or early morning radiative effects cannot be evaluated. Experimental design needs to be explained in more detail.

What was the length of the line connecting the sondes to the balloon? How did you tape the sondes together? Is it excluded that waste heat of one sonde influenced the other? Why did you set the Windsond acquisition to 3 seconds - according to table 1 the measurement cycle is 1s for both sondes. Please give details about the weather situation.

Answer: As mentioned in section 4 the Windsond S1H2 firmware has a single operational mode and produces uncorrected data, the only correction applied was to simply differentiate the ground value from the ground-based instrumentation and apply this difference to the profile. The altitude correction was in the [-10; +10] m range, pressure correction was [-2;+2] hPa, and temperature [-2;+2] range. In the stable nocturnal boundary layer, surrounding vegetation is expected to affect the local humidity values while having a limited effect on the temperature, for this reason humidity correction were not performed.

We agree that a larger number of flights would have improved the evaluation, however, the goal of this evaluation was to assess the quality of the Windsond data in context of the DACCIWA data analysis framework and also to address limitations of the Windsond system in the tested configuration. The radiative effect could not be be evaluated but needs to be evaluated for future use of the system. The flight was in 2016 we have corrected the typo.

The line connecting the sonde to the balloon was 20 m and the sonde were taped together making sure that the temperature and humidity sensors of each sonde were not interfering or influenced each other. At the time of the test, 1 s sampling rate was not compatible with the version of the firmware tested this is now available in the new version.

5.1.2 Should be renamed to Signal processing for low altitudes – Boundary layer higght was not detected - I would expect a boundary layer height around 100 m at the launch time of the sonde rising up to 1500 m during the day in this region during the monsoon period.

Answer: Agreed the title has been modified

Page 7: Can you explain why you have chosen different ascent rates and non-attached sondes for evaluating the reproducibility? I can't see any sense in this procedure since natural atmospheric variation will be at least in the same range as the instrument error. Profile comparison – It would be nice to have a profile plot if you do profile comparisons! Instead of showing scatter plots it would make much more sense to plot vertical profiles of PTH as well as wind for both sondes with an additional profile showing the vertical profile of the difference (Vaisala – Windsond) for each parameter together with the accuracy as stated by the manufacturer's datasheet. This would allow a meteorological interpretation. How do you measure cloud top temperature above the cloud top – The RS41-SG sensors are detecting the cloud top temperature and humidity before the S1H2 : : :..????

Answer: As mentioned in our answer concerning the page 2 comment we have chosen a different ascent rate in order to test the accuracy of the sonde by following constructor recommendation, test the multisonde reception and recovery system, and to increase the number of sonde tested.

We have chosen to directly compare each variable as the altitude error on the Windsond S1H2 would have superposed on each sensor error and not each sensor performance. Moreover, the Vaisala system does not have a pressure sensor and the pressure is calculated by the MW41 as detailed in section 3.3 while the Windsond has a pressure sensor so the profiles as a function of pressure would display data as a function of a calculated variable in one hand to a measured variable on the other hand. As discussed in the WMO intercomparison, basic raw data are to diagnose problems with a radiosonde during evaluation. We could also display both sonde data as a function of the Vaisala altitude, but this will involve modifying the shape of the S1H2 profile to fit in the Vaisala altitude profile and consequently not display the actual profile obtained with the S1H2 system. We consequently think that displaying the data of the Vaiala sonde as the function of the Windsond data is the best way to assess the performance of each sensor without interference from other sensor errors.

The structure of this sentence was confusing and has been changed to: "For both temperature and relative humidity, the RS41-SG sensors are detecting the sudden temperature and humidity changes consecutive of the top of a cloud before the S1H2 sensors"

Page 8: Change reply time to response time
The atmosphere is characterized by vertical inhomogeneities, inversions and clouds – radiosondes therefore have to have sensors with low response time and neglectable

hysteresis – if this is not the case the sonde is simply not suitable as radiosonde – or only for nice weather well mixed cloud free boundary layer.

Answer: Following reviewer #1 comments answer time has been replaced by response time.

The current response time limitation is the weakness of the system for boundary layer applications. In small-scale, Sparv Embedded uses temperature and relative humidity sensors with a better response time, but currently, the cost is high in the context of radiosondes. Lowering the per-unit cost would take a sizeable investment in the production process to automate assembly and calibration.

Page 9: More recent versions of the Windsond firmware certainly correct the altitude bias - have you checked this? Is it possible to reprocess the measurements to verify? To me it is not shown that newer firmware versions correct the altitude bias. The conclusions are too favourable – Windsond cannot handle inhomogeneities due to the high response time of the sensors, GPS derived wind error is far above the 5% error given by the manufacturer and to my opinion useless. It is not shown that at least the altitude correction in the latest versions of Windsond improve the systematic altitude error. As the WMO intercomparison results and the Vaisala sonde show pressure sensors are not needed any more for radiosondes – the "robust performance" of the pressure sensor us unfortunately only of minor importance.

Answer: We agree the word certainly was too favourable for something we have not tested, this has been corrected to probably. We have added the statement in the conclusion : "These limitations make the deployment of an operational network using this system under the tested configuration impossible."

The WMO intercomparison shows that pressure sensor are not needed anymore for radiosondes in situation where GPS radiosondes are set up correctly which is not the case of the Windsond. Thus the evaluation of the pressure sensor is important to assess the use of the Windsond S1H2 data in a meteorological context such as tephigrams.

Page 10:

The experimental design shows several weaknesses – as already addressed the fact that the sondes were not tied together during the ascends makes it nearly impossible to separate instrument error and atmospheric variance. I would recommend to test each sonde prior nest launch instead of a simple visual inspection.

Answer: In the morning stable boundary layer horizontal variations are small so the instrument error would still be significant compared to the atmospheric variance. We agree, however, that atmospheric variance will add some noise to the error recorded between sondes. Despite these weakness this design allows us to show that there is no clear trend in data alteration consecutive with sonde re-use during the experiment.

We agree that testing sonde prior the next launch should be the standard, however limitated ressources made a detailed inspection impossible. This standard is unfortunately not always respected as Legain et al,. 2013 also relaunched a large number of sonde immediately after recovery.

I would strongly recommend to perform additional measurements with a larger number of sondes under laboratory conditions to determine sensor accuracy and inertia over a wide range of temperature and humidity and to compare the results to the sondes datasheets first. Reproducibility can also better be tested in a combination of repeated tandem flights and climate chamber measurements – this would allow the separation of sensor degradation and atmospheric influence in real atmospheric conditions.

Answer: These are interesting comments, but these go beyond the scope of this paper, here we test the performance of the sonde during a field campaign which is similar to Legain et al., 2013 where the system was tested during 2 field campaigns. The sonde recovery system cannot be tested in an atmospheric chamber as well as the different natural hazard encountered in a rough environment such as West Africa. Despite the different limitations of the experimental design we have been able to identify some limitations of the system especially for the GPS system which are worth publishing to provide indication to Sparv Embedded and future users of the system.

Table 6 is unreadable – it extends 4 pages – please consider a condensed way of presentation.

Answer: Agreed, we have substituted table 6 with figure 8 that condenses all the information of table 6

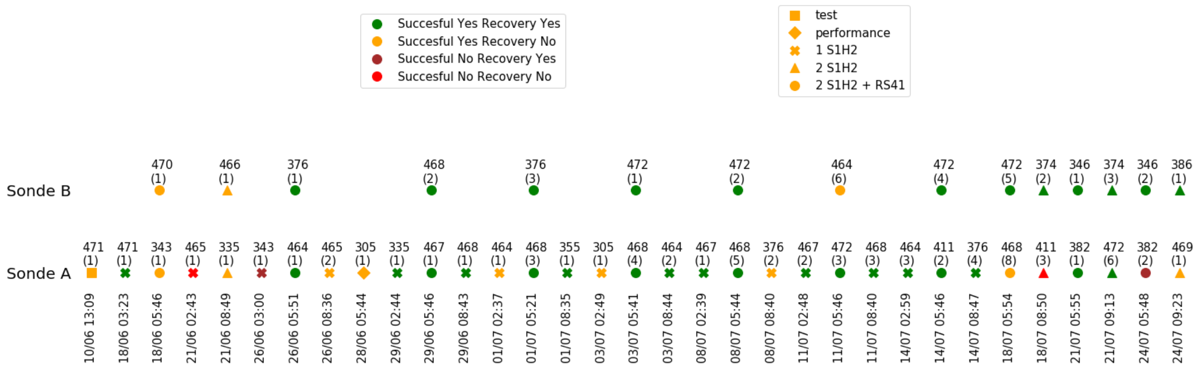

Figure 1 Timeline listing sounding time in UTC, the shapes indicate the corresponding number of radiosonde S1H2 launched (test denotes the test sonde, performance denotes the S1H2 launched taped to an RS41-SG, +RS41 denotes simultaneous launched with the Kumasi Agromet supersite), the sonde id with the number of time the sonde has been used under brackets, the colors indicates flight result and the recovery result.

Page 11:

Please give the percentage of unsuccessful flights and flights with sondes that did not cut off. Is the number of data from sondes that did not cut off large enough to do a representative evaluation for altitudes between 650 and 1000 m?

It is nearly impossible to separate the different markers in Fig. 8. Maybe separated figures would help.

Answer: Only 3 flights with failed cut-off were launched simultaneously with an RS41 so an evaluation between 650 and 1000 m would not lead to a statistically representative evaluation of the Windsond system. This evaluation would also be beyond the scope of this evaluation which focusses on how well the low-level cloud and low-level jets are represented in this study.

We agree that on figure 8 the markers are nearly impossible to separate, but separated figure would increase the number of figures without leading to more interesting conclusions.

As you have a large number of flights over several days available I would recommend to do not only a statistical analysis based on scatter plots and regressions but also a more meteorological where you create classes of different weather situations e.g. with and without low level clouds and analyse the behaviour of the sondes along the vertical profile.

Answer: During the DACCIWA field campaign the low-level cloud was a recurrent feature and only one IOP night was identified without a low-level cloud so a meteorological climatology based analysis would not be relevant.

Fig. 9 – why do you use lines to connect the markers?

Answer: We decided to use lines to connect the marker to help the reader to see that there is no real trend between sonde usage and data alteration.

Page 12: A check of the sonde sensors before reusing it should be the standard procedure – see my comment to page 10.

Answer: Agreed this should be a standard but field campaign constraints can limit the time on the sonde check to avoid the radiosonding program to compromise other instruments objectives.

A system for low altitude rapid soundings using high quality radiosondes was already introduced and tested by Legain et al. 2013. The questions to me is if a low cost and unfortunately low-quality system like the Windsond really makes sense with all the weaknesses we have seen in your evaluation especially - considering the fact that higher quality sondes can also be recovered and reused so that the cost difference between the sondes gets even less important. Please discuss!

Answer: As remarked by the referee #1 our conclusions shows that the Windsond S1H2 is a work in progress and the result presented in this manuscript are introducing a new instrument in the early stage of its development. The system presented by Legain et al 2013 does not asses the consequences of the drag generated by the protection cage on the measured wind profile. Moreover, the modification applied to the sonde system required qualified personal and can limit the generalised used of this sonde.

A key point is the Windsond system does not requires any modification or complex balloon system so if that system become accurate enough it will provide a easy to use solution in countries with limited to deploy a radiosounding network utilising the more accurate but more expensive sondes. The multi sonde capability is also another key point for field campaigns were multiple shallow sounding are required. An example of this application is the VORTEX-SE project, where Penn State University released 24 sondes at the same time to study winds around storm supercells and might release as many as 100 at a time in the next season. This is a unique feature of Windsond for dense measurements (http://windsond.com/swarmsonde-is-in-the-news/).

Please change longer answer time to response time!
Change from answer time to response time have been made following remarks from reviewer #1.

It would be nice to know if newer Windsond firmware really has corrected the problems with GPS derived wind and pressure. I therefore strongly encourage you to perform the further performance evaluations and include their results into a revised version of your manuscript.

Answer: We agree that it would be interesting but this analysis would go beyond the scope of this paper and would require more time and capabilities to perform this study.

Evaluation of Windsond S1H2 performance in Kumasi during the 2016 DACCIWA field campaign

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Abstract. Sparv Embedded, Sweden (http://windsond.com) has answered the call for less expensive but accurate reusable radiosondes by producing a reusable sonde primarily intended for boundary-layer observations collection: the Windsond S1H2. To evaluate the performance of the S1H2, in-flight comparisons between the Vaisala RS41-SG and Windsond S1H2 were performed during the Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa (DACCIWA) project (FP7/2007-2013) ground campaign at the Kumasi Agromet supersite (6°40'45.76''N, 1°33'36.50''W) inside the Kwame Nkrumah University of Science and Technology (KNUST), Ghana campus. The results suggest a good correlation between the RS41-SG and S1H2 data, the main difference lying in the GPS signal processing and the humidity response time at a cloud top. Reproducibility tests show that there is no major performance degradation arising from S1H2 sonde re-use.

1 Introduction

Accurate in-situ measurements of tropospheric temperature, pressure, water vapour and wind profiles provide critical input for numerical weather forecasting and climate models, in the quantification of atmospheric thermodynamic stability, for the development and application of remote-sensing retrievals, and as an important constraint for atmospheric process studies. Since the 1930s such measurements have been made by small instrument packages attached to balloons (Jensen et al., 2016) known as radiosondes; the vertical resolution of the profile being determined by the ascent rate of the balloon (Martin et al., 2011). The many changes in instrumentation, sounding practices and data processing are discussed at length by many authors including Haimberger 2007; Vömel et al., 2007; Haimberger et al., 2008; Rowe et al., 2008; Sherwood et al., 2008; McCarthy et al., 2009; Miloshevich et al., 2009; Seidel et al., 2009; Dai et al., 2011; Hurst et al., 2011; Thorne et al., 2011; Moradi et al., 2013; Wang et al., 2013; Dirksen et al., 2014; Yu et al., 2015; Bodeker et al., 2016; Jensen et al., 2016.

The operational cost of launching a radiosonde is high: according to B. Blackmore 2012, personal communication, as cited by Gonzalez et al., 2012, the National Weather Service (NWS) Weather Forecasting Offices (WFO) estimates that the cost per unit launch of a radiosonde in the US is US$ 325 (Price includes radiosonde, balloon and labour) and a total of $21,827,000 a year if 2 launches are made at 92 sites. This rough estimate varies regionally as the price of labour, helium and balloons and is not the same around the globe. Yet operational costs are a significant investment in countries with limited resources.

For many years the provision of radiosounding technology has been dominated by the likes of Vaisala and Graw but over the last decade there has been an increase in the call for less expensive but accurate devices (Douglas, et al., 2012; Martinez 2016; Krauchi and Philipona 2016). The development of a cheaper re-usable radiosounding system could contribute to the development of a denser operational network in regions in the world with limited financial resources, as well as being useful for field campaigns where multiple shallow soundings are needed.

Re-usable sondes have been introduced for the first time by Legain, et al., 2013 which modified a Vaisala sonde to enclose it in a cage which is tied to a couple of balloon. The caged allowed the balloon to detached at a desired altitude and slowly descend before recovery. Despite this system has shown successful results in pressure temperature and humidity, and recovery rate it does not asses the effect of the cage and the two balloons on the obtained wind profile. The sonde modification required makes the use of this system more complex and can be an obstacle towards a global use of the system, this that re-usable sonde technologies are still a work in progress where manufacturers can develop their own solutions.

The Windsond S1H2 from Sparv Embedded, Sweden (http://windsond.com) aims to reduce the cost of boundary-layer sounding through its re-use and multi-sonde reception features, while remaining a compact and relatively simple to use system. This paper presents the results of the first field campaign utilisation of the Windsond S1H2 during the Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa (DACCIWA) project (FP7/2007-2013) ground campaign at the Kumasi Agromet supersite. Here the performance of this radiosonde are compared with that of established Vaisala RS41 in order to prepare the future interpretation the nocturnal boundary layer observations recorded, as well as an assessment of the system overall robustness.

2 The field site

The instrument comparison took place within the framework of the DACCIWA ground campaign at the Kumasi Agromet supersite (6°40’45.76’’N, 1°33’36.50’’W) inside the Kwame Nkrumah University of Science and Technology (KNUST), Ghana campus: figure 1 shows the location of the field site with respect to the West African Region, Ghana and Kumasi.

The DACCIWA ground campaign has been designed to allow the identification of the controlling processes and factors for low-level clouds LLCs formation and to investigate the low-level clouds (LLCs) effects on the convective boundary layer (CBL). The sounding programme consisted of synoptic sounding at 0600 UTC using a Vaisala (RS41-SG or RS92) radiosonde launched at the Agromet supersite. This time was selected because ~~then~~ the LLC cover was expected to be most intense. In addition to the daily soundings, frequent radiosondes were launched at regular intervals during Intensive Operation Periods (IOPs). The sounding programme had three objectives: 1) to provide the daily statistic of atmospheric conditions 2) to provide more frequent boundary layer ~~radio~~sounding during DACCIWA IOPs to observe the evolution of the LLCs and associated phenomena such as the Nocturnal Low-Level Jet (NLLJ) and 3) evaluate the Windsond performance. Figure 2 shows the sounding rationale during DACCIWA IOPs: a single S1H2 launched at 0300 UTC ~~3 AM~~, two at ~~6 AM~~ 0600 UTC simultaneously with an RS41-SG launch and a final single S1H2 at 0900 UTC ~~9 AM~~.

The performance comparison between the two systems consisted of: 1) a comparison of the Windsond S1H2 and Vaisala RS41-SG sondes and 2) an assessment of the reproducibility of the S1H2 during the DACCIWA field campaign.

3 The S1H2 Windsond

The Windsond S1H2 is a lightweight (12g) sonde manufactured by Sparv Embedded of Sweden with an operational ceiling of 8 km. Being lightweight the size of the balloon is substantially smaller, a 19-inch “party balloon” being recommended, and hence requires less helium. Like any sounding system, there is a radio receiver. For the Windsond the RR1-250 Radio Receiver is used and this is connected directly to the host laptop via USB: the arrangement is shown in figure 3. The system has an operational frequency configurable in the range 400 MHz to 480 MHz.

The Windsond launch procedure requires no pre-flight calibration and the firmware in use (v1) allowed up to 4 sondes to be active at any one time. In September 2016, version 2 of the firmware was launched allowing 8 sondes to be active simultaneous while the latest version allows 16.

The operational software provides a "cutdown" feature: when activated the cord attaching the sonde to the balloon is cut. This in conjunction with the integrated instrument retrieval system and prediction of landing site makes the retrieval and reuse of the sonde viable. The S1H2 uses a 1.9g 75mAh rechargeable lithium-ion battery (separate battery): the separated battery allows the sonde to be reused quickly after recovery.

Figure 4 shows the Windsond S1H2 and it can be seen that it is based in a styrofome cup: all key features are shown.

Table 1 summarises some of the key physical characteristics of the Windsond S1H2 and the Vaisala RS41, the sonde used for sensor comparison test.

3.1 Temperature

Table 2-5 show, on a parameter by parameter scale, a comparison of sensor characteristics. The RS41-SG uses a platinum temperature resistor while a band-gap temperature sensor is used in the Windsond S1H2. The silicon band-gap temperature sensor is a type of thermometer or temperature detector commonly employed in electronic devices. It has good stability in extreme environmental conditions due to the integral stability of crystalline silicon. Silicon band-gap temperature sensors operate on the principle that the forward voltage of a silicon diode is temperature dependent. Band-gap technology has the advantage of being low cost, accurate and reliable, provide highly consistent measurements, have a positive temperature coefficient with a very low drift over time (Burlet et al. 2015).

Both sensors have the same resolution but the S1H2 has a smaller operational range. The platinum wire temperature sensor of the RS41-SG is both more accurate and has a faster response time than the band-gap sensor (Table 2. Vaisala, 2014 and Windsond Catalogue, 2016).

3.2 Humidity

Both sondes use a thin film capacitor to make humidity measurements. These sensors provide a high accuracy, excellent long-term stability and negligible hysteresis. They are insensitive to contamination by particulate matter, are not permanently damaged by liquids and are resistant to most chemicals. A capacitive humidity sensor works like a plate capacitor. The lower electrode is deposited on a carrier substrate, often a ceramic material. A thin polymer hygroscopic layer acts as the dielectric, and on top of this is the upper plate, which acts as the second electrode but which also allows water vapour to pass through it, into the polymer. The water vapour molecules enter or leave the hygroscopic polymer until the water vapour content is in equilibrium with the ambient air or gas. The dielectric strength of the polymer is proportional to the water vapour content. In turn, the dielectric strength affects the capacitance, which is measured and processed to give a relative humidity measurement.

The RS41-SG humidity sensor integrates humidity and temperature sensing elements. Pre-flight automatic reconditioning of the humidity sensor effectively removes chemical contaminants in order to improve humidity measurement accuracy. The integrated temperature sensor is used to compensate the effects of solar radiation in real time. The sensor heating function enables an active de-icing method in freezing conditions during the flight. (Table 3 from Vaisala, 2014 and Windsond Catalogue, 2016).

3.3 Pressure

The RS41-SG has a number of variants and particular importance here is the RS41-SG and RS41-SGP. Although both sonde types provide pressure, temperature, humidity and wind measurements it is in the manner in which pressure is derived that the difference arises. The SGP variant has the same pressure sensor as in the RS92 sonde but with revised electronics and calibration while the SG has no pressure sensor at all. In the latter case, the values of atmospheric pressure are calculated from satellite ranging codes, combined with differential corrections from the MW41 ground station. Pressure calculation also uses temperature and humidity from the radiosonde and the hypsomeric equation.

The S1H2 measures the pressure with a Microelectromechanical (MEMS) piezoresistor pressure sensor. This technology etches a diaphragm into a silicone substrate. Micro piezoresistors measure the deformation of the diaphragm due to changing pressure.

The difference in performance characteristics (table 4) between the two sondes arise from the S1H2 making direct pressure measurements while those of the RS41-SG are derived indirectly. The WMO radiosonde intercomparison experiment 2010 (Nash et al., 2011) showed that pressure measurement derived from geopotential heights and radiosonde measurements of temperature and relative humidity profile were very reproducible and suitable for all radiosounding operations for system where GPS system are set up correctly which includes the Vaisala system. This shows that the Vaisala derived pressure is a reliable reference to assess the Windsond pressure sensor, and the Windsond cost can be lowered by removing the pressure sensor in future version of the Windsond system depending on its GPS system accuracy.

3.4 Position and winds

The Vaisala system measures latitude, longitude and height using onboard GPS receiver pseudorange and applies a differential correction: the Vaisala ground station has a GPS receiver. Use of differential GPS techniques in principle improves the accuracy and resolution of measurements. However, wind speed and direction are determined independently from the GPS position using the GPS doppler frequency shifts.

The Windsond GPS ground station is not a GPS receiver, therefore latitude and longitude are determined using onboard GPS receiver pseudorange without differential correction. Similar~~ly~~ to the RS41-SG, the S1H2 wind speed and direction are determined independently from latitude and longitude using the GPS signal without differential correction explaining the two systems similar performance characteristics as seen on table 5.

The Vaisala system determines height using the GPS pseudorange with differential correction while the Windsond uses sonde pressure. The Windsond altitude algorithm tested here does not include hypsometric correction and is corrected in later versions.

4 Signal Processing

The Vaisala sounding system MW41 has a single operational mode, unlike the older MW31 which features an operational and a research mode, producing different degrees of signal processing. The MW31 research mode processes the data as little as possible only correcting solar radiation and pendulum effects, while both MW41 and MW31 operational modes produce the highest degree of signal processing in which raw data are filtered and discontinuous data are interpolated. The non-processed data described in the previous section were produced by simulating the flight with the archived data and leaving as little post-processing as possible similarly as the MW31 research mode.

The Windsond S1H2 firmware has a single operational mode and produces uncorrected data. Later versions of Windsond has since introduced data correction of all parameters. During this experiment, the uncorrected data have been used, but the ground pressure altitude and temperature have been adjusted to the value measured by the ground-based instrumentation available on the Kumasi supersite.

5. Windsond S1H2 v Vaisala RS41-SG Performance Comparison.

5.1 Experimental design

5.1.1 Profile comparison

The performance of the S1H2 Windsond was assessed by taping S1H2 Windsond and RS41-SG radiosonde together on the same flight at the Kumasi Agromet supersite for the DACCIWA synoptic flight on the 28th of June 2006 launching at 05:44 UTC. Despite the Windsond S1H2 acquision cycle is one second (Table 1) the firmware was only supporting three second acquision and was set accordingly while the Vaisala RS41-SG to one second. Vaisala RS41-SG data have been reduced to three-second data by selecting measurements taken at the same time as the Windsond S1H2 and only measurements below 6000 m a.g.l have been considered because of the S1H2 recommended operational ceiling. A statistical comparison including linear regression and correlation coefficient between temperature, relative humidity, altitude, wind speed, meridional wind, zonal wind recorded by both sondes was performed. The Windsond S1H2 produces wind speed and wind direction only, the 2-π periodicity of wind direction makes linear regression irrelevant, so it has been converted to zonal and meridional winds.

5.1.2 Signal processing effects for low altitudes

To analyse the signal processing effect, the same procedure as in 5.1.1 has been performed on the data recorded by the S1H2, the RS41-SG and the RS41-SG after processing from the MW41. The scope has been reduced to data up to 1000 m a.g.l, allowing to see in greater details the difference between the datasets. It also allows direct comparison with the reproducibility experiment where flights never exceeded 1000 m a.g.l.

5.1.3 Pressure comparison

The RS41-SG does not provide raw pressure data so the performance evaluation of the S1H2 pressure sensor is completed by comparing it to the pressure calculated by the MW41 from the RS41-SG data following the procedure described in 5.1.2.

Moreover, the S1H2 altitude measurement uses the pressure sensor data. To assess the influence of the pressure sensor error on the altitude error, the pressure difference between S1H2 pressure and the processed RS41-SG pressure is compared to the difference between the S1H2 and RS41-SG altitude.

During the reproducibility experiment presented in section 6, sondes are not attached together and are flying at different ascent rate. To assess the reproducibility of the S1H2, each reproducibility flight data have to be re-aligned to similar vertical level. The comparison between the pressure and altitude error is used to assess the best vertical level boxes to use in the reproducibility experiment data analysis.

5.2 Results

5.2.1 Profile comparison

The scatter plot on figure 5 compares respectively temperature, relative humidity, altitude, wind speed, meridional wind, zonal wind recorded by both sondes, with colours indicating the corresponding altitude according to the RS41-SG. The red line indicates the linear regression between both datasets. For all the assessed meteorological parameters the linear regression parameters are in the range [0.83:1.01] with a correlation coefficient over 0.6 indicating a relatively good agreement between both sondes. However, some discrepancies between parameters or due to sudden atmospheric changes have been identified.

The relative humidity and temperature regression line coefficients on figure 5 (a, b) are within 10^{-2} to 1 with correlation coefficient over 0.9, meaning that both sondes are in general agreement over the whole flight. At 2000 m (dark green on figure 5 (a, b)) occurs a sudden temperature increase and relative humidity decrease, and shows discrepancies between sensors. The relative humidity below 2000 m is around 100% indicating the presence of clouds. The sudden warming associated with a sudden drying consequently corresponds to the top of a cloud. For both temperature and relative humidity, the RS41-SG sensors are detecting the sudden temperature and humidity changes consecutive of the top of a cloud before the S1H2 sensors. The faster response time of the RS41-SG platinum temperature resistor compared to the S1H2 band-gap temperature sensor explains the faster RS41-SG reply to temperature change, while the heating system on the RS41-SG humidity sensor evaporating the cloud water explains the faster RS41-SG reply to relative humidity change.

Wind speed and horizontal wind components, on figure 5 (d, e, f) have the lowest correlation coefficient of all parameters and points are noisy so a smoothing can potentially partially resolve the wind speed and wind component bias. However, the linear regression coefficient below 1 indicates that the S1H2 regularly underestimates the winds. This underestimation can be explained by difference in GPS sensor or the antenna as the Vasaila system does not use differential correction to measure winds.

The correlation between both sensor altitude on figure 5 (c) is the highest of all parameters, while the large root mean square error over 100 and the linear regression coefficient below 1 indicates that the S1H2 regularly underestimate the sonde ascent compared to the RS41. This underestimation can be explained by the absence of hypsometric correction in the S1H2 altitude determination algorithm or/and errors due to the pressure sensor. The influence of the pressure sensor error on altitude error is assessed in section 5.2.3.

5.2.2 Signal processing effects in the boundary layer

The scatter plot on figure 6 compares respectively temperature, relative humidity, altitude, wind speed, meridional wind, zonal wind recorded by the S1H2, the RS41-SG and the RS41-SG after processing from the MW41, with colours indicating the corresponding altitude according to the S1H2 with a maximum altitude set to 1000 m. The red line indicates the linear regression between the S1H2 and the RS41-SG data while the blue line indicates the linear regression between the S1H2 and the RS41-SG data after processing from the MW41. A comparison between figure 5 and figure 6, shows that in the boundary layer the correlation between S1H2 and raw RS41-SG is smaller than for the whole profile, this is certainly due to the smaller amount of points considered putting greater emphasis on errors. The comparison of the linear regression coefficient for each parameter on figure 6 shows that the processed RS41-SG data are closer to a 1 for 1 ratio with the S1H2 and the correlation between processed RS41-SG and S1H2 is greater than between the raw RS41-SG and the S1H2. This feature is certainly due to the smoothing operated by the MW41 on the RS41-SG and the adjustment of the maximum relative humidity to 100%. This result shows that the inexpensive Windsond system can reach a level of performance close to the expensive Vaisala system in the boundary layer. However, due to a limited number of sonde available only one performance flight has been performed. To be statistically significant this result needs to be verified with more performance comparison flights.

5.2.3 Pressure comparison

The scatter plot on figure 7 (a) compares the pressure recorded by the S1H2 and calculated by the MW41 after processing from the RS41, with colours indicating the corresponding altitude according to the S1H2 with a maximum altitude set to 1000 m and the blue line indicates the linear regression between both measured and calculated pressures. The ratio between the pressure measured by the S1H2 and calculated by the MW41 is close to 1 for 1, with an almost perfect correlation and an error below 3 hPa. Comparison of the altitude difference measured by the 2 sondes and the pressure difference between the calculated and measured pressure shows that over 200 m the pressure difference remains between 2 and 3 hPa while the altitude difference is regularly increasing with height. This shows that the S1H2 pressure sensor error influence on the S1H2 altitude underestimation is small. More recent versions of the Windsond firmware, including hypsometric correction is probably correcting the altitude bias. The pressure difference consistently remaining between 2 and 3 hPa, thus vertical level boxes of 1hPa are chosen to re-align the sondes during the reproducibility experiment.

5.3 Windsond S1H2 vs Vaisala RS41-SG Performance comparison conclusions

The performance comparison between the Windsond S1H2 and the Vaisala RS41-SG shows the potential of the Windsond system which is able to closely match the temperature, pressure and humidity of the Vaisala RS41-SG even after processing by the MW41. However, when a sudden temperature and humidity change happen the slower response time of the Windsond system leads to temporary bias in the profile. The main weakness of the Windsond S1H2 lies into its GPS sensor and antenna which leads to a systematical error in wind speed and components which complicates the observation of phenomenon such as the NLLJ. A more advanced signal processing, can improve the GPS sensor performances. The robust performance of the pressure sensor associated to the altitude systematic error show that corrections in the altitude retrieval algorithm implemented in the latest versions of the Windsond firmware can improve the altitude measurement. The consistent pressure measurements, is leading to use pressure level as the vertical reference to compare the Windsond S1H2 and the Vaisala RS41-SG during the reproducibility experiment.

6. S1H2 Windsond Reproducibility Experiment

6.1 Experimental design

The assessment of a sonde reproducibility is essential to guarantee the reliability of the sounding data during the data analysis: alterations of the sonde performance under different atmospheric conditions have to be taken into account for a complete understanding of the data. The re-use feature of the S1H2 requires an evaluation of the data alteration due to the sonde re-use in addition to the reproducibility evaluation using new sondes under different atmospheric conditions.

To complete both assessments, sondes have been launched and retrieved until they got lost. To ensure, according to the authors, the best compromise between ensuring a satisfying recovery rate and a full LLC coverage, the cut-off was set at an altitude of 650 m AGL. At the preset cut-off altitude, two heating coils are activated and the string connecting the sonde to the balloon burnt through. During the sonde descent, after the sonde loses contact with the ground station at approximatively 100 m AGL, the system automatically predicts and displays the expected landing point on a map view.~~During the sonde descent, until the sonde loses contact with the ground station at approximatively 100 m AGL, the system automatically backs up the trajectory and the predicted landing point in a file.~~

The ground station was carried to the predicted location, on getting closer, approximately within 50 meters, the contact between the sonde and the ground station was established , the sonde started immediately to emit loud beeps (about 15 seconds time interval) and flashes of light. Signal strength increased when approaching the sonde and the vice versa. Once retrieved the sonde was switched off.

When re-using the sonde the cup and lid were checked for any physical damage. The lid of the cup was then opened to confirm if there are no physical damages to any part (i.e. the heating coils or the printed circuit board PCB). A 4 m polyester string (sewing thread) was wound around a cardboard (4×2×0.3 cm) cut-out with the ends left free: one to attach to the balloon the other to tie to the heating coil.

The sonde renewal strategy has been based on the sonde damage or loss. If a sonde has been lost or any physical damages were not amendable for the next routine flight a new sonde has been introduced. This strategy has been chosen to fully evaluate the degradation of the sonde, in terms of both retrieval and data quality but reduced the number of reproducibility flights with new sondes. The number of times each sonde has been flying as well as the sonde recovery success are detailed in Figure 8. The results will be analysed and associated with the different reasons for a sonde loss.

Flights, where an S1H2 has been launched simultaneously with another RS41-SG, have been selected for the reproducibility and data alteration from sonde re-use study. During the simultaneous flights, the RS41-SG and S1H2 were attached to different balloons and consequently not climbing at the exact same ascent rate. The comparison of each pair requires the data to be aligned at the same vertical level and the systematic underestimation of the altitude by the S1H2 associated to the robust performances of the S1H2 pressure sensor led to the use of 1 hPa pressure ranges. For each pair, temperature, relative humidity, total, zonal and meridional winds have been boxed in the pressure ranges. The pairs have been then sorted by the number of time the S1H2 have been used and the median value for each range and S1H2 number of use have been computed before a similar statistical comparison is performed on the median values.

6.2 Results

Figure 8 details the sonde flight number, the flight success and the sonde recovery for each flight. More than 70% of the sonde launches have been recovered with the sonde 468 being used 8 times. The recovery rate could have been improved with more experience using the system and if the receptor had not been damaged due to the difficulties of carrying a laptop with an antenna in the tropical rainforest and different hazards such as tropical animals. The radio receiver RR2 with Bluetooth connection seems promising for soundings in a difficult or harsh environment to overcome these difficulties. Only 5 flights have been identified as unsuccessful showing the overall robustness of the S1H2 radio antenna through the experiment.

The scatter plot on figure 9 compares respectively temperature, relative humidity, altitude, wind speed, meridional wind, zonal wind recorded by the S1H2, and the RS41, boxed in 1 hPa range and sorted according to the number of soundings of the S1H2 as indicated by the different markers, with colours indicating the corresponding altitude according to the RS41-SG with a maximum altitude set to 1000 m AGL. The presence of data over 650 m AGL is explained by some failure of the cut-off system leading to the loss of the sonde but supplementary data for the comparison. For every parameter, the different markers are superposed randomly indicating the absence of performance degradation over time with the use of the S1H2 system. However, the sonde S1H2 464 used for the 6^{th} time systematically underestimates relative humidity and overestimates meridional wind but the sonde 468 used for the 8^{th} time does not show a particular anomaly suggesting a contamination of the 464 sonde relative humidity sensor. Temperature and relative humidity of sonde 468 during its 8^{th} flight at 800 m AGL (yellow) show the presence of a cloud top where the lag in the S1H2 answer is identified as in the performance flight.

Figure 10 shows the linear regression coefficient and the correlation between the boxed S1H2 and the RS41-SG data for each number of use. For temperature and altitude, the markers are superposed while for the other parameters markers are more spread but no clear trend can be identified. The sonde 464 used for the 6^{th} time low correlation and linear regression coefficient for relative humidity and large meridional speed linear regression coefficient confirms the contamination damaged on the sonde identified in figure 8. The relative humidity low correlation of the sonde 468 used for the 8^{th} can be explained by the cloud top found in figure 8. The low or negative linear regression coefficient values for speed confirms the lack of accuracy met in the performance flight and underline a need for improvement in the wind speed calculation from the GPS data.

6.3 S1H2 Windsond Reproducibility experiment conclusions

The reproducibility experiment showed the robustness of the recovery system as well as the sensors. No clear performance degradation have been identified through the flights and the sondes have been recovered up to 7 times. Similar performance weaknesses have been identified such as the GPS sensor correction and the sensitivity abrupt temperature and humidity changes.

However, the maximum altitude has been limited to 650 m AGL to ensure a satisfactory recovery rate which limits the use of the sonde recovery feature, and a sonde at its 6^{th} use showed sign of contamination. A check of the sonde sensors values with ground instrumentation is consequently necessary before reusing the sonde to increase the confidence in the measurement.

7 Summary and conclusions

The Windsond S1H2 has been developed with the goal of providing an immediate view of local conditions at lower altitudes (up to 6000 m AGL) with a focus on portability and low operating costs to simplify a frequent use in the field.

In order to characterise the performances of the Windsond, an intercomparison flight has been undertaken at the Agronet supersite in Kumasi, Ghana on the 28th of June 2016. The results show that most of the data recorded below 6000m are in agreement. However, abrupt changes in temperature and humidity show that the Windsond needs a longer ~~answer~~ response time for these changes. Wind speed and components relatively low performance shows that the GPS sensor and its antenna is a weakness of the current system. These limitations make the deployment of an operational network using this system under the tested configuration impossible.

In the boundary layer, the RS41-SG data processing increase the agreement with the S1H2 data showing that the expensive Vaisala system performance can be approached by the low-cost S1H2 system. The pressure calculated by the MW41 from the RS41-SG data are in good agreement with the MEMS pressure senor from the S1H2. The robust performance of the S1H2 pressure sensor shows that error on the altitude estimation is mainly due to the absence of hypsometric correction in the retrieval algorithm that current version of the firmware should have corrected. It is therefore recommended that further performance evaluation of the sonde with a more recent version of the firmware to be conducted.

A reproducibility experiment has been undertaken to assess both the performance of the sonde performance under different atmospheric conditions and the data degradation due to the sonde re-use. Some of the simultaneous flights were performed with sondes used several times. The results show that there is no real causality between correlation or ratio between the sonde changes and re-use of a sonde showing there is a minor degradation in the data accuracy for re-used sondes. However, one sonde showed contamination signs on the relative humidity sensor. The authors recommend to compare the sonde performance with ground instrumentation before re-using the sonde.

The capacity of using the same sonde up to 8 times in such a mixed environment as Kumasi constitutes a success for the Windsond recovery system. However, the author would have wished a louder beep to help recovery in a noisy environment and also a vibrating system to help the sonde to fall off trees when the sonde, unfortunately, is stuck on it. The overall success of this experiment shows the potential of this new technology. It is therefore recommended that further experiments assess quantitatively the reproducibility of the sonde to be conducted in a different environment.

Author contribution

Geoffrey E.Q. Bessardon and Kwabena Fosu-Amankwah designed the experiments and carried them out under the supervision and advice of Barbara J. Brooks. Geoffrey E.Q. Bessardon performed the data analysis. Anders Peterson provided valuable Windsond system information to perform the analysis. Geoffrey E.Q. Bessardon prepared the manuscript with contributions from all co-authors.

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Competing interests

The authors declare that they have no conflict of interest.

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Sonde Characteristics	RS41-SG radiosondes	S1H2 Windsond
Weight	109g	13 g
Dimensions	272 x 63 x 46 mm	90 x 75 x 75 mm
Battery type	Lithium, nominal 3 V (integrated)	Rechargeable lithium-ion (separate battery)
Battery capacity	> 240 min	> 60 min sounding and two days in recovery mode
Transmitter power	Min. 60 mW	max 100 mW
Telemetry range	350 km	60 km
Measurement cycle	1 s	1 s

Table 1 Summary of key physical characteristics of the RS41 and the Windsond S1H2 (based on Table 5 from Vaisala, 2014 and Windsond Catalogue, 2016)

Sonde Characteristics	RS41-SG radiosonde	S1H2 Windsond
Temperature		
Sensor type	Platinum resistor	Band gap
Measurement range	+60 °C to -90 °C	+80 °C to -40 °C
Accuracy repeatability in calibration	0.1 °C	0.3 °C
Resolution	0.01 °C	0.01 °C
Response time (63.2%, 6 m/s flow, 1000 hPa)	0.5 s	5 s

Table 2 Sondes temperature sensor manufacturer specifications (based on Table 1 from Vaisala, 2014 and Windsond Catalogue, 2016)

Sonde Characteristics	RS41-SG radiosondes	S1H2 Windsond
Humidity		
Sensor type	Thin-film capacitor, integrated T sensor and heating functionality	Capacitive
Measurement Range	0-100% RH	0-100% RH
Accuracy repeatability in calibration	2.0% RH	2.0 % RH
Resolution	0.1 % RH	0.05 % RH
Combined uncertainty in sounding	4% RH	Not Available (to be assessed)
Reproducibility in sounding	2% RH	Not Available (to be assessed)
Response time (63.2%, 6 m/s flow, 1000 hPa)	Heated sensor: <0.3 s Cold sensor < 10 s	5 s

Table 3 Humidity sensor manufacturer specifications (based on Table 2 from Vaisala, 2014 and Windsond Catalogue, 2016)

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Sonde Characteristics	RS41-SG radiosondes	S1H2 Windsond
Pressure		
Sensor type	GPS-derived	MEMS pressure sensor
Range	Surface to 3hPa	1100 - 300 hPa
Accuracy	Defined as combined uncertainty and reproducibility	1.0 hPa
Resolution	0.01 hPa	0.02 hPa
Combined uncertainty in sounding	1.0>100 hPa 0.3<100 hPa 0.04<10 hPa	Not Available (to be assessed)
Reproducibility in sounding	0.5>100 hPa 0.2<100 hPa 0.04<10 hPa	Not Available (to be assessed)

Table 4 Pressure sensor manufacturer specifications (based on Table 3 from Vaisala, 2014 and Windsond Catalogue, 2016)

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Sonde Characteristics	RS41-SG radiosondes	S1H2 Windsond
Wind		
Wind speed range	0-160 m/s	0-150 m/s
Wind speed accuracy	0.15 m/s	ca 5%
Wind speed resolution	0.1 m/s	0.1 m/s
Wind direction range	0-360 degree	0-360 degree
Wind direction accuracy	2 degrees	Depends on GPS conditions
Wind direction resolution	0.1 degree	0.1 degree
Wind velocity uncertainty	0.15 m/s	Not Available (to be assessed)
Wind direction uncertainty	2 degree	Not Available (to be assessed)

Table 5 Sondes wind measurement characteristics (based on Table 7 from Vaisala, 2014 and Windsond Catalogue, 2016)

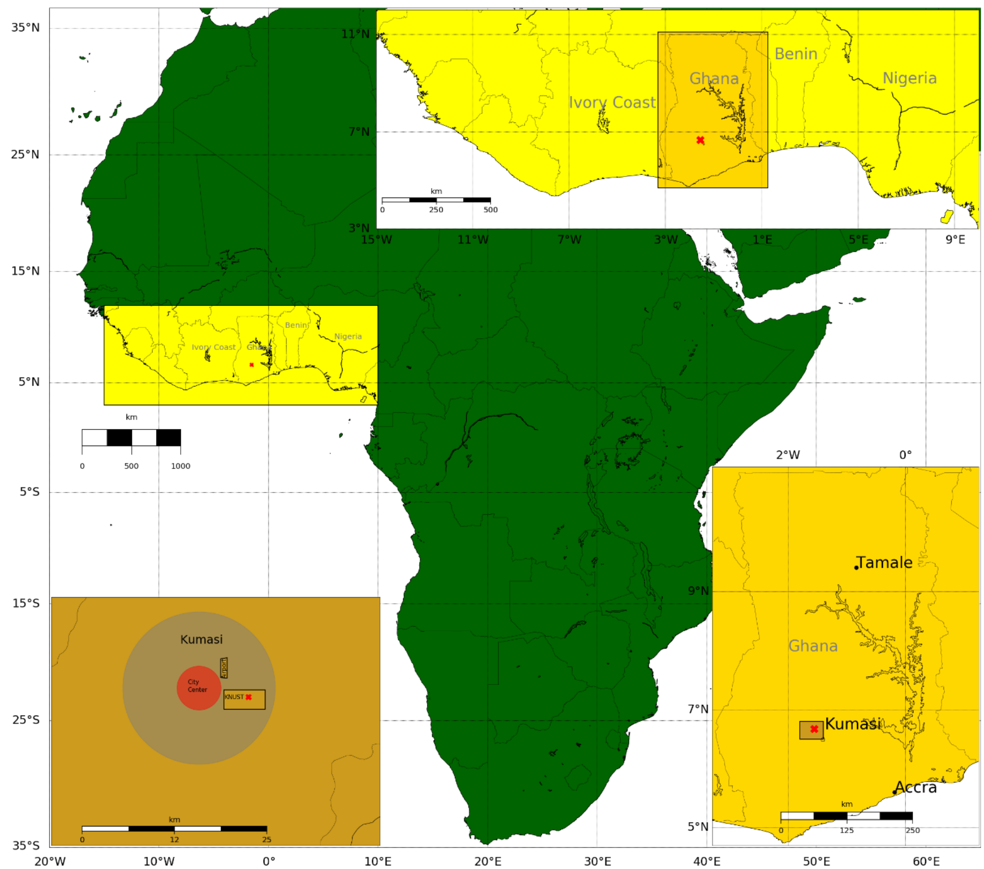

Figure 1 Location of the field site with respect to Africa, the West African Region, Ghana and Kumasi

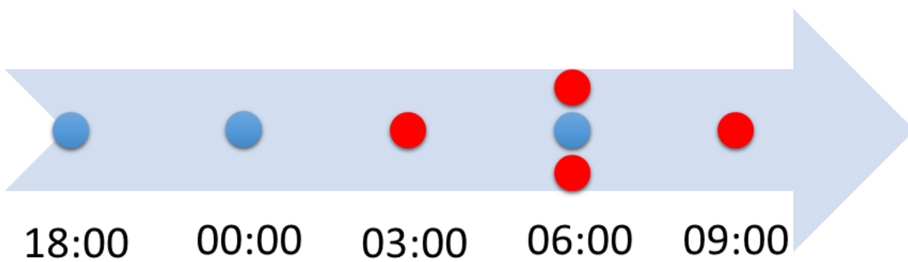

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Figure 2 Scheme representing the sonde routine strategy during DACCIWA IOPs, with RS41-SG (blue) and Windsonde S1H2-R (red) time is UTC

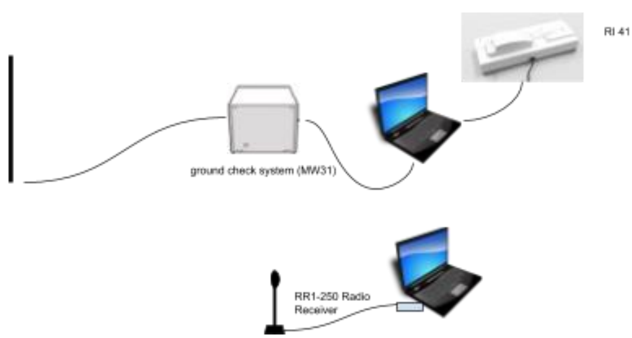
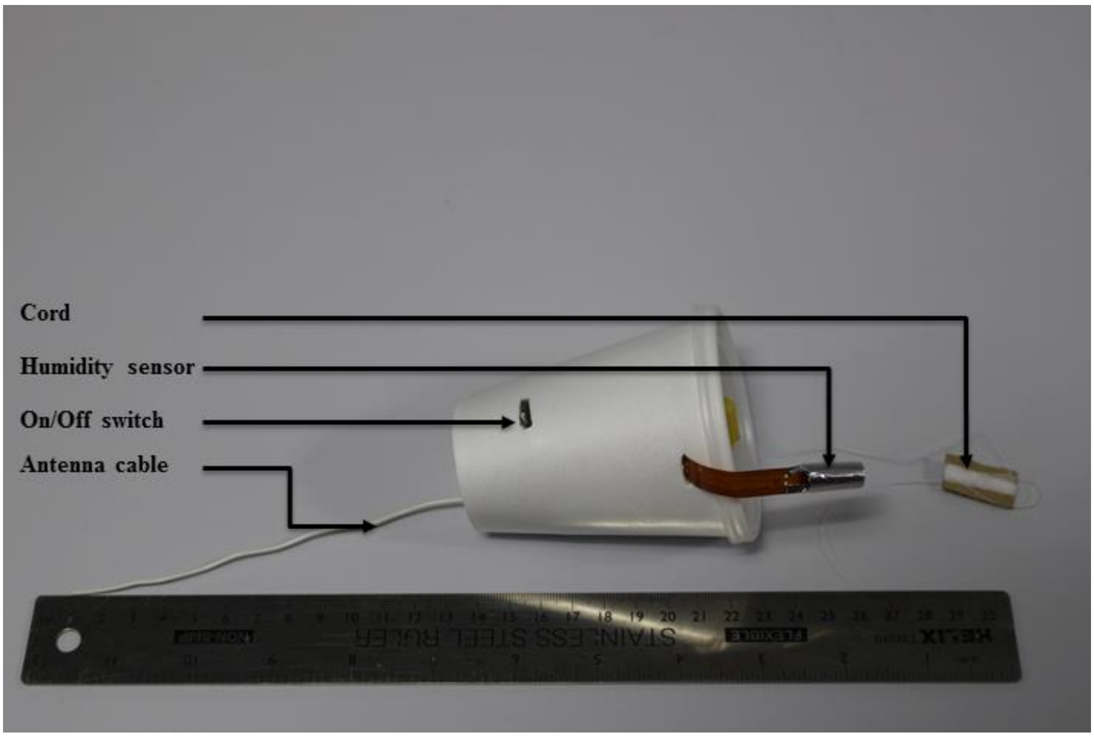


Figure 3 Experimental system setup: antennae, sounding system, and ground check system (MW41)



Cord
Humidity sensor
On/Off switch
Antenna cable

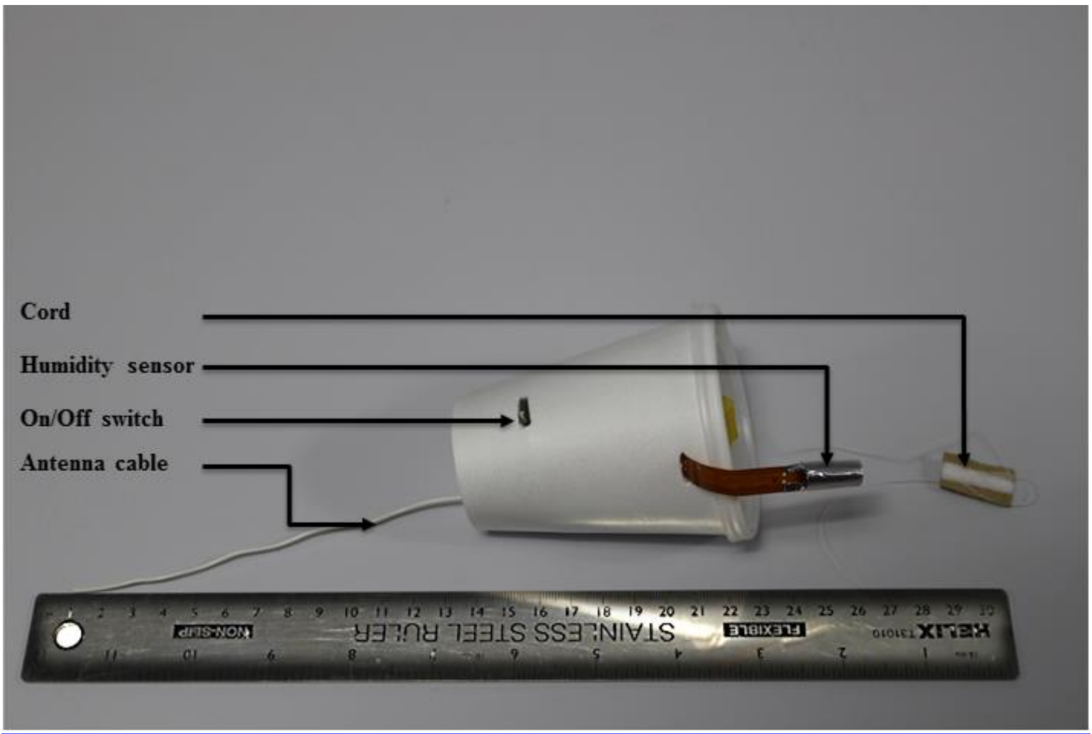


Figure 4 External shot of the S1H2

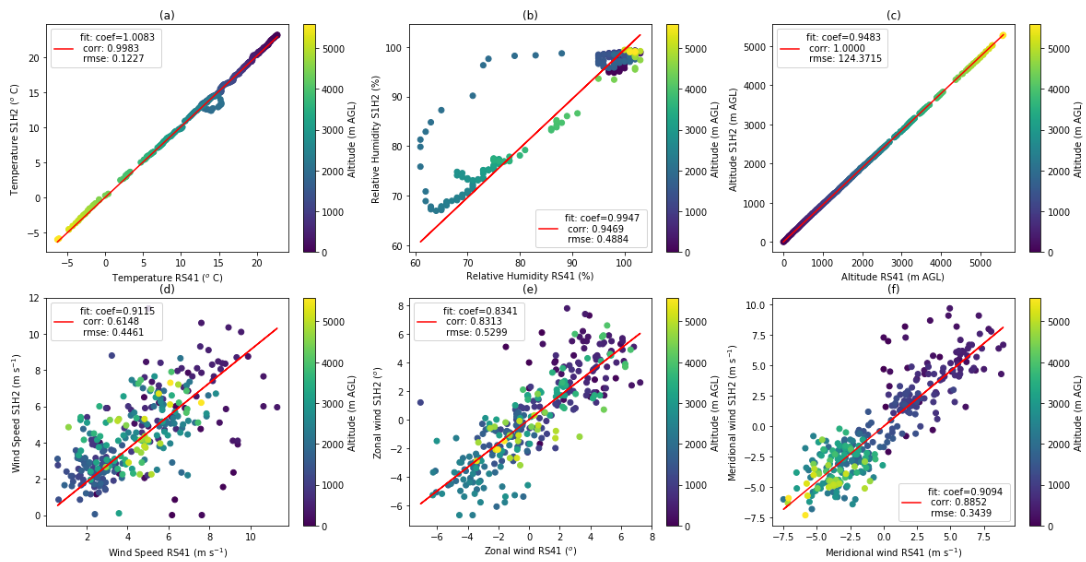


Figure 5 Comparison of temperature (a), relative humidity (b), altitude (c), wind speed (d), zonal winds (e) and meridional winds (f) recorded by the Windsond S1H2 and the Vasaila RS41-SG during the flight of the 28/06/2016 05:44 UTC in Kumasi. The colors are based on the Vaisaila RS41-SG measured altitude with the maximum altitude set to 6000 m. The red lines indicate the linear regression of each parameter.

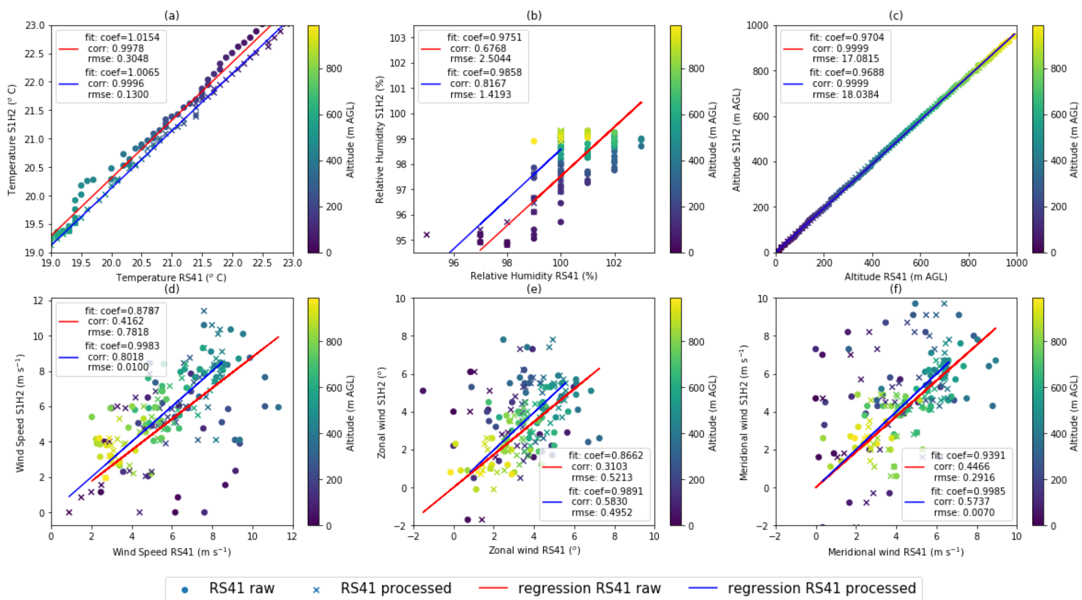


Figure 6 Comparison of temperature (a), relative humidity (b), altitude (c), wind speed (d), zonal winds (e) and meridional winds (f) recorded by the Windsond S1H2 and the Vasaila RS41-SG before and after processing during the flight of the 28/06/2016 05:44 UTC in Kumasi. The colors are based on the Vaisaila RS41-SG measured altitude with the maximum altitude set to 1000 m.

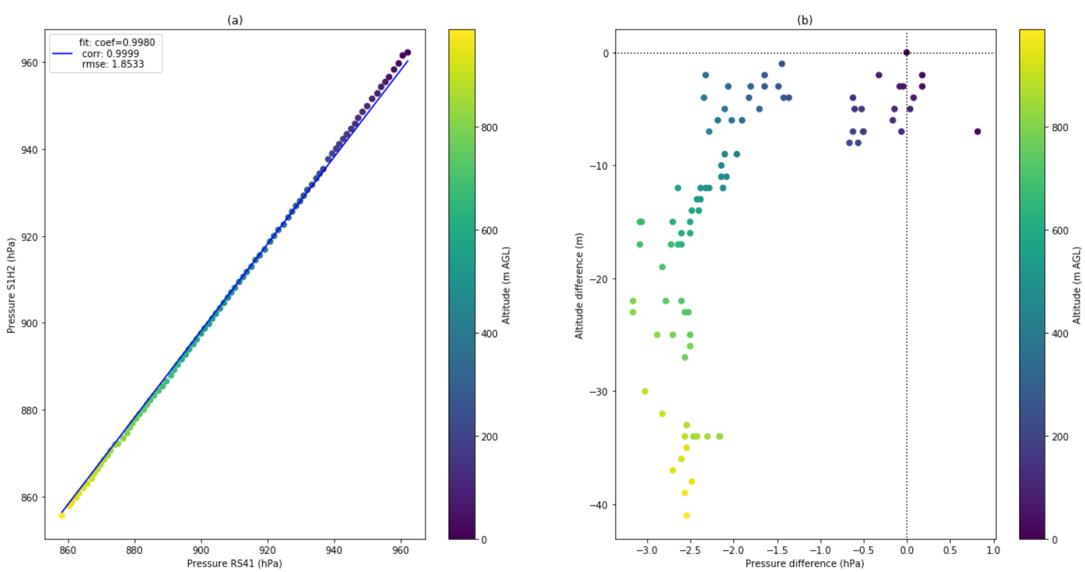


Figure 7 Comparison of pressure recorded by the Windsond S1H2 and calculated by the Vasaila MW41 (a), the pressure difference between the recorded Windsond S1H2 and the Vaisala MW41 and the altitude difference between the Windsond S1H2 and the Vaisaila RS41-SG (b) during the flight of the 28/06/2016 05:44 in Kumasi. The colors are based on the Vaisaila RS41-SG measured altitude with the maximum altitude set to 1000 m.

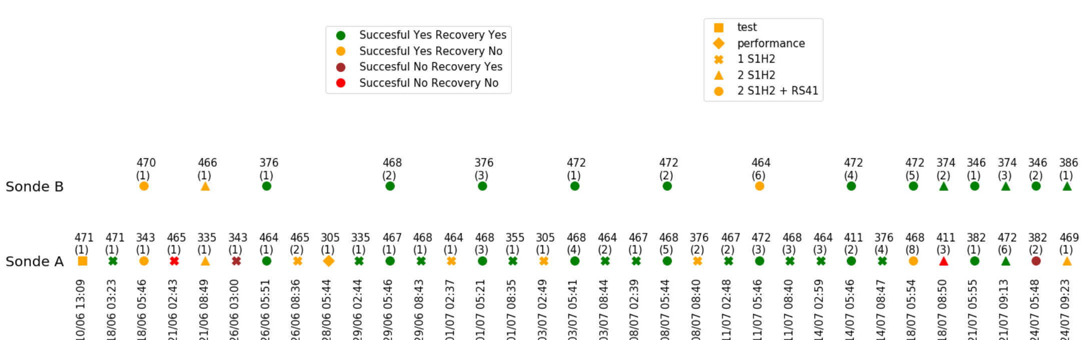


Figure 8 Timeline listing sounding time in UTC, the shapes indicate the corresponding number of radiosonde S1H2 launched (test denotes the test sonde, performance denotes the S1H2 launched taped to an RS41-SG, +RS41 denotes simultaneous launched with the Kumasi Agromet supersite), the sonde id with the number of time the sonde has been used under brackets, the colors indicates flight result and the recovery result.

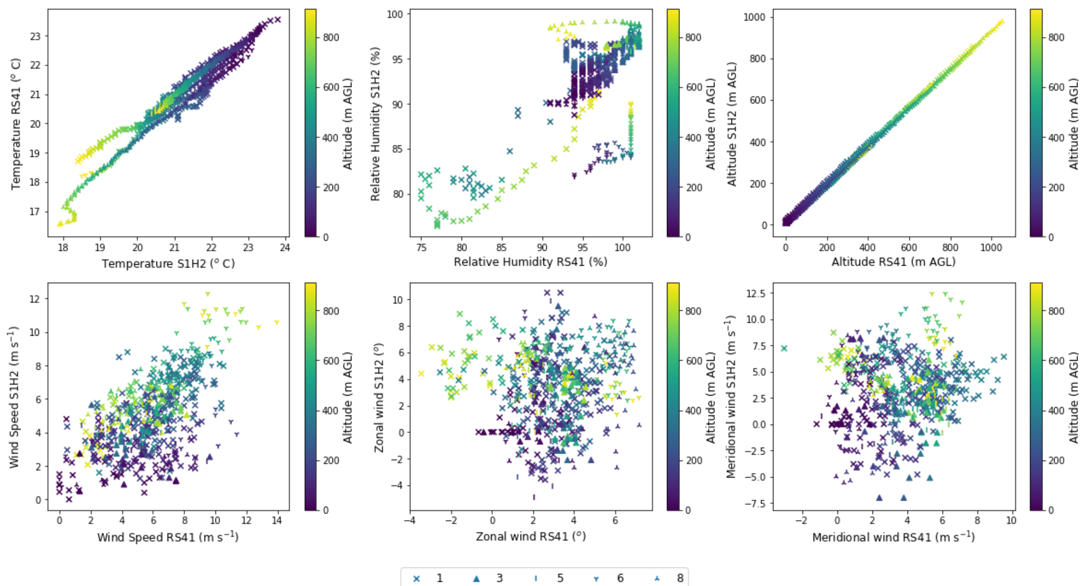
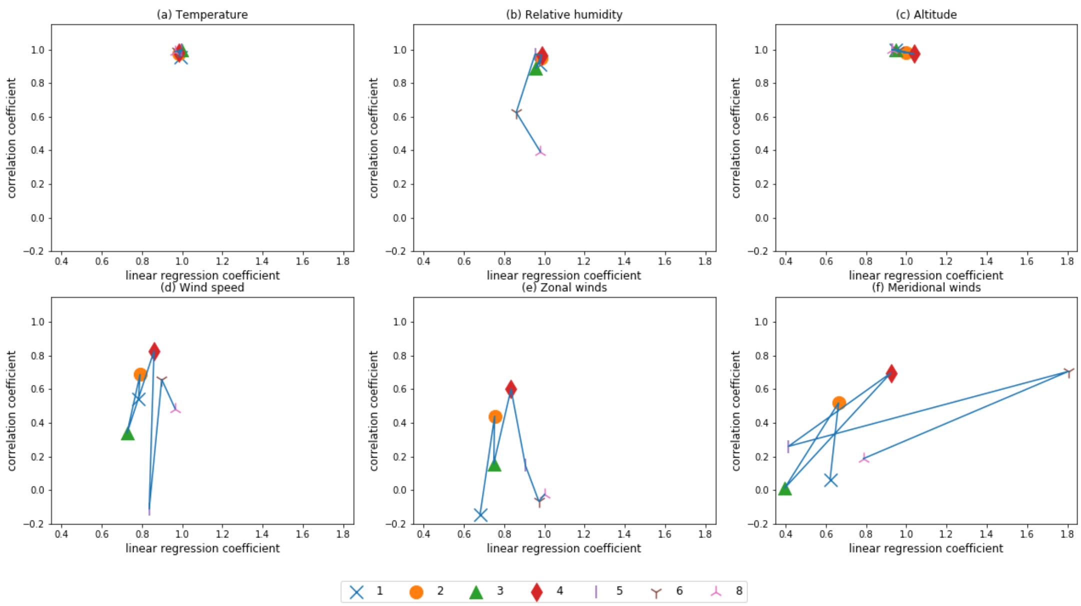


Figure 9 Comparison of temperature (a), relative humidity (b), altitude (c), wind speed (d), zonal winds (e) and meridional winds (f) recorded by the Windsond S1H2 and the Vasaila during the DACCIWA field camapign in Kumasi. Each marker corresponds to the median value over 1hPa range for all the flights where the S1H2 was used respectively for the 1st, 2nd, 3rd, 4th, 5th, 6th and 8th time. The colors are based on the Vaisaila RS41-SG measured altitude with the maximum altitude set to 1000 m.



485 **Figure 10 : Comparison of the correlation coefficient and the linear regression coefficients between the S1H2 and the RS41-SG temperature (a), relative humidity (b), altitude (c), wind speed (d), zonal winds (e) and meridional winds (f) for all the flights where the S1H2 was used respectively for the 1st, 2nd, 3rd, 4th, 5th, 6th and 8th time.**