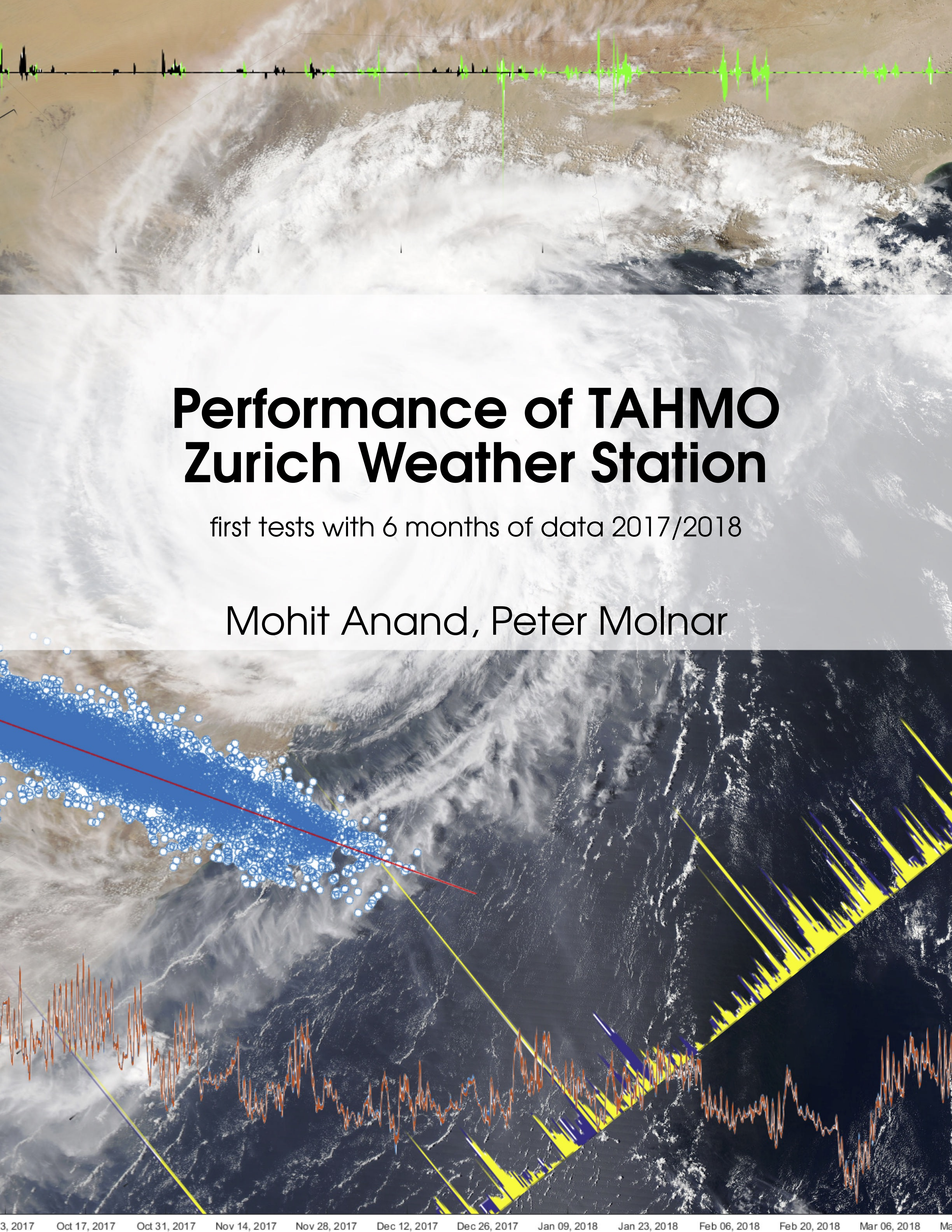

Performance of TAHMO Zurich Weather Station

first tests with 6 months of data 2017/2018

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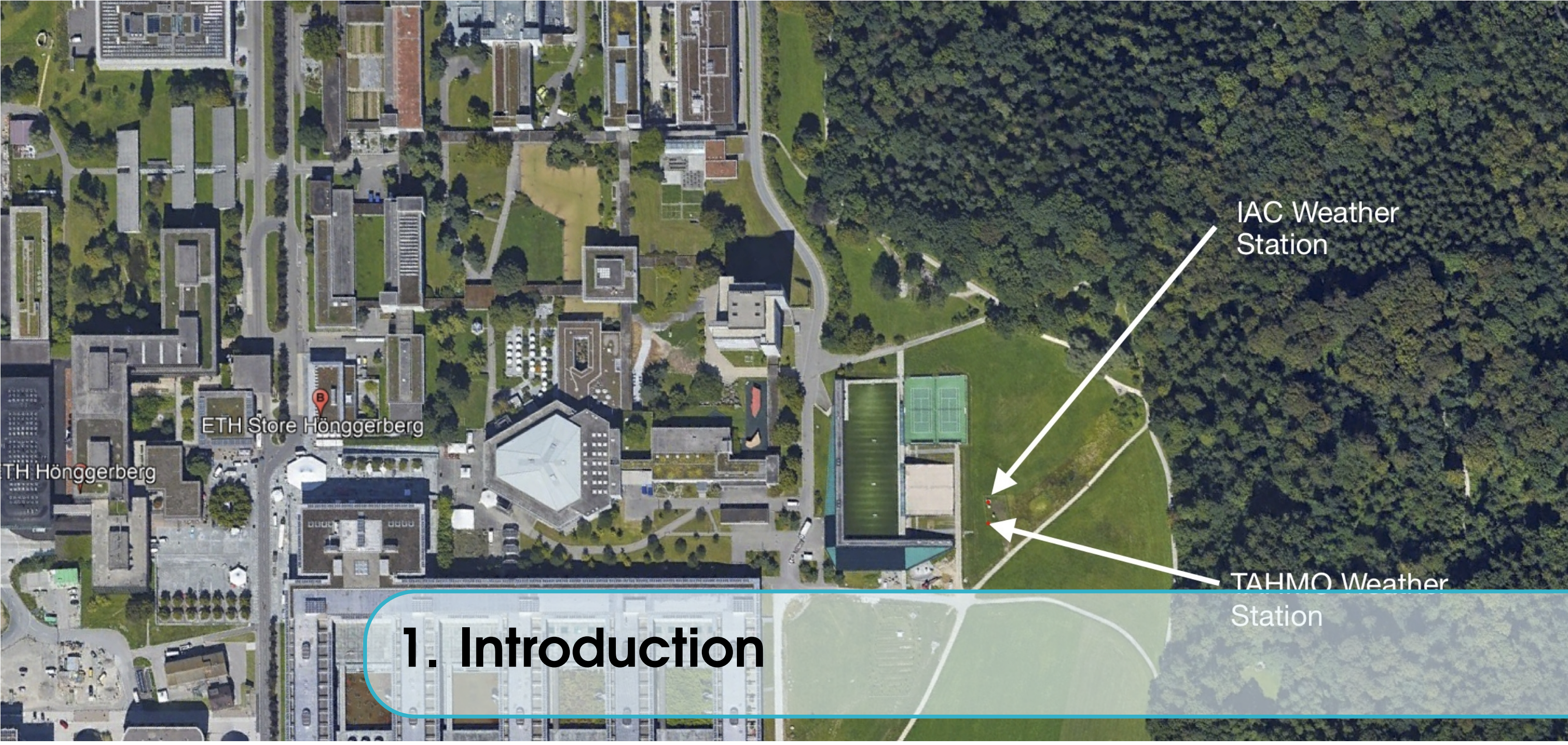

1. Introduction

1.1 Motivation

The Trans-African Hydro-Meteorological Observatory (TAHMO, `https://www.tahmo.org`) aims to install about 20,000 modern automatic weather stations across Africa. The TAHMO network is built with a new all-in-one weather station from METER called ATMOS 41 (`https://www.metergroup.com/environment/products/atmos-41-weather-station/`). The station has 12 embedded sensors with no moving parts, a solar powered logger, and a GSM module for data transmission. It is ideally suited for climate monitoring in remote locations in Africa and elsewhere.

A part of the TAHMO initative is a school-to-school program which partners secondary schools in Africa with schools in North America and Europe. The program aims to give teachers and students of all levels the opportunity to connect the science curriculum with real weather data for both educational and research purposes. A contributor to this initiative at ETH Zurich is the SAS4SD project (Science Action in Schools for Sustainable Development, `http://www.sas4sd.ethz.ch/`) funded by swissuniversities. In this project teaching materials for high school science clubs are being developed for Ghana and Cameroun using TAHMO station data around the topics of agriculture (cocoa plantations, school gardens), rainfall and floods, sustainable waste management, and others.

One TAHMO station was set up at the Hoenggerberg Campus of ETH Zurich as part of SAS4SD. This report provides a first-order analysis of its performance in the first 6 months after installation when compared to a weather station of IAC (Institute of Atmospheric and Climate Science) of ETH Zurich which consists of traditional well-tested sensors typically used by meteorological services world-wide. The motivation was to quantify the differences between the ATMOS 41 and IAC gauges at a common sampling resolution $\Delta t = 10$ min, and to identify where and when the biggest differences occur. The aim is not to judge which of the two gauges is better, because we do not know the true value of the measured climatic variables.

We analysed air temperature, precipitation, wind speed and direction, relative humidity, atmospheric pressure, and solar radiation, because these are the main variables used in hydrological studies.

1.2 Data Remarks

R The comparison (testing) period is **20 September 2017 – 31 March 2018**. This is a period of **193 days**. The comparison is conducted at the sampling resolution of the IAC gauge which is $\Delta t = 10$ min. The testing period contained the entire winter period 2017/2018 in Zurich.

R The ATMOS 41 gauge (also called TAHMO station in this report) is recording all variables at a high sampling resolution and can record them at 1-min or coarser intervals, e.g. the TAHMO setting we use is $\Delta t = 5$ min. These values are averaged (or summed) to the 10-min resolution used in this comparison. The clock coherence of both instruments was checked.

R The IAC station data used for comparison actually consists of several independent sensors connected to a central logger in the meteo station field where also ATMOS 41 is installed. We do not list details of the IAC station sensors in this report. They are typical sensors used by meteorological services[1].

R For the solar radiation comparison we used the SwissMetNet station Reckenholz which is about 2.5 km straight-line distance from the meteo station field, where we have reliable measurements of incoming solar (short-wave) radiation at a $\Delta t = 10$ min resolution.

1.3 Comparison Metrics

For the statistical analysis of the data and differences between ATMOS 41 and the IAC gauge we use standard statistics (e.g. mean, standard deviation, etc.) and the average error, percent bias, mean absolute error, root mean square error, index of agreement, and the correlation coefficient.

- Mean: This is the arithmetic mean of the variables measured by both gauges.
- Maximum and Minimum: The maximum and minimum of a dataset during the testing period.
- Standard Deviation: Statistic used to quantify the amount of variation in a dataset. A low standard deviation indicates that the data points tend to be close to the mean, while a high standard deviation indicates that the data points are spread over a wider range of values.
- Coefficient of Variation: Standardized measure of dispersion defined as the ratio of the standard deviation to the mean.
- Average Error (AE): The average of the differences between the two gauges.
- Percent Bias (PB): The average error in percent of the IAC gauge measurement.
- Mean Absolute Error (MAE): The average of the absolute values of the differences between the two gauges. This is an absolute measure of the differences.
- Root Mean Square Error (RMSE): The root of the mean of the squared errors between the gauges, which gives more weight to larger departures between the two gauges.
- Index of Agreement (IoA): A standardized measure of the agreement between the gauges. A value of 1 indicates a perfect match and 0 indicates no agreement.
- Correlation Coefficient (CC): A measure of the strength and direction of the linear relationship between variables measured by the two gauges.

[1] https://www.meteoswiss.admin.ch/home/measurement-and-forecasting-systems/land-based-stations/automatisches-messnetz/measurement-instruments.html

2. Air Temperature

2.1 Gauge Description

ATMOS 41 consist of a small temperature sensor (thermistor) extending from the middle of four sonic transducers below the raingauge. Although it is not protected from radiation it sits at the bottom of the gauge, well ventilated and not in direct sunlight. It is however susceptible to solar heating of the instrument body. The manufacturer reports that the ATMOS 41 calculates the air temperature accurately because solar radiation and the wind speed are known. The resolution of the measurement is 0.1 °C and the accuracy is ±0.6 °C. Measurements are taken every 10 secs and averaged over the desired recording time interval.

2.2 Analysis and Discussion

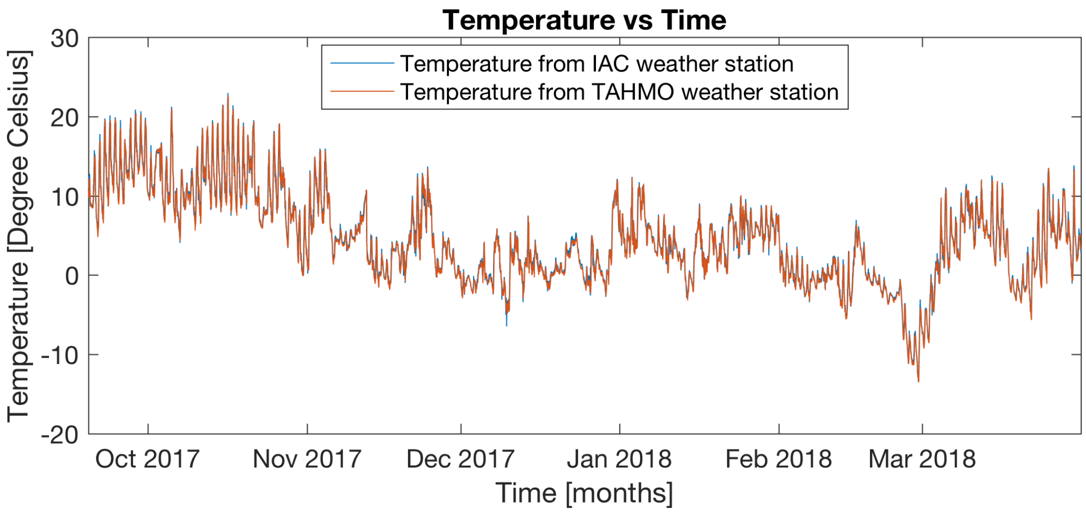

Figure 2.1: Air temperature timeseries of the two weather stations for the entire testing period.

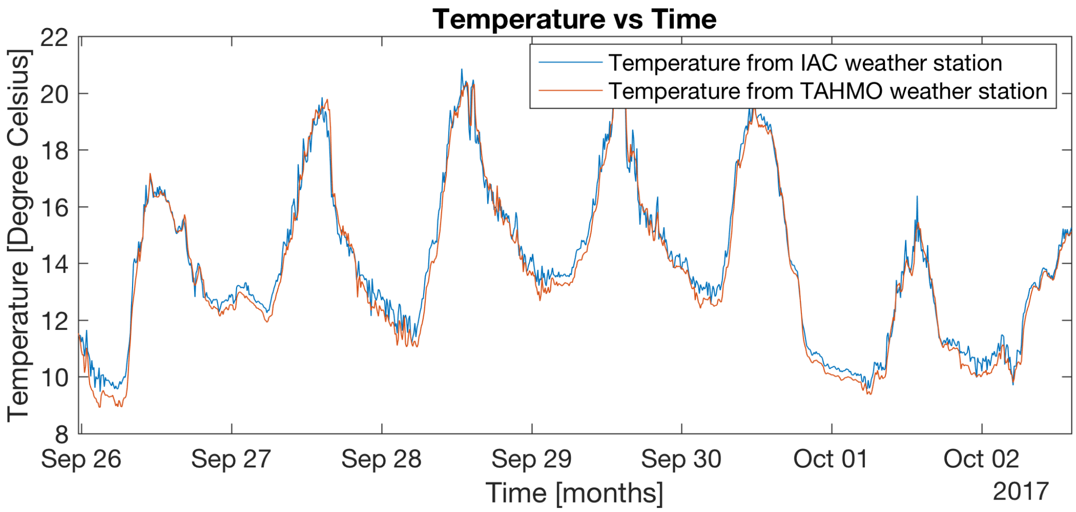

Figure 2.2: Daily variation of air temperature in the two weather stations for a shorter period 26 September to 2 October 2017.

The timeseries in Figs 2.1 and 2.2 show that there is very good agreement between the air temperature measured by both gauges. There is no evident long-term bias and the daily fluctuations are represented very well. The ATMOS 41 night-time lows are generally a little lower than the IAC gauge, which is likely caused by the ventilation of the IAC instrument. Notably, the day-time peaks are practically identical in magnitude and timing in both gauges.

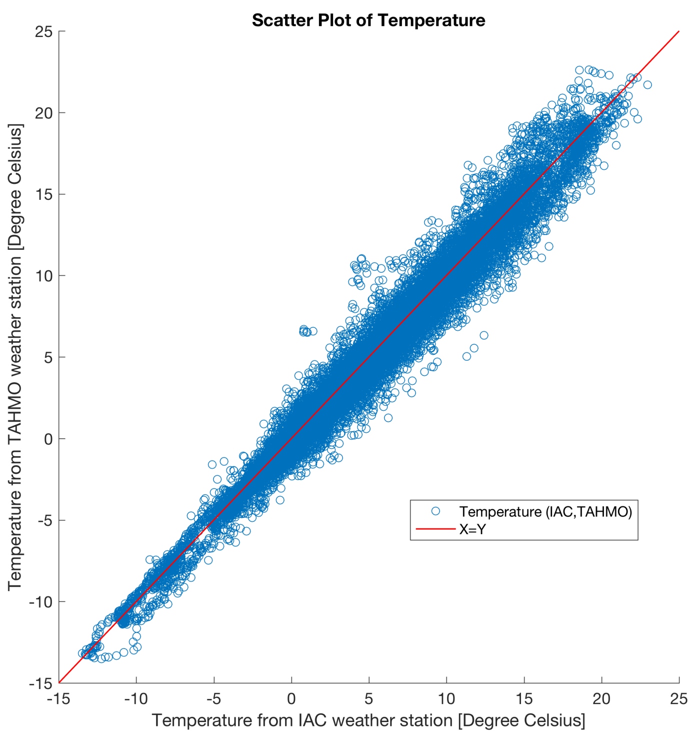

Figure 2.3: Scatterplot of air temperature from both gauges at the $\Delta t = 10$ min sampling resolution.

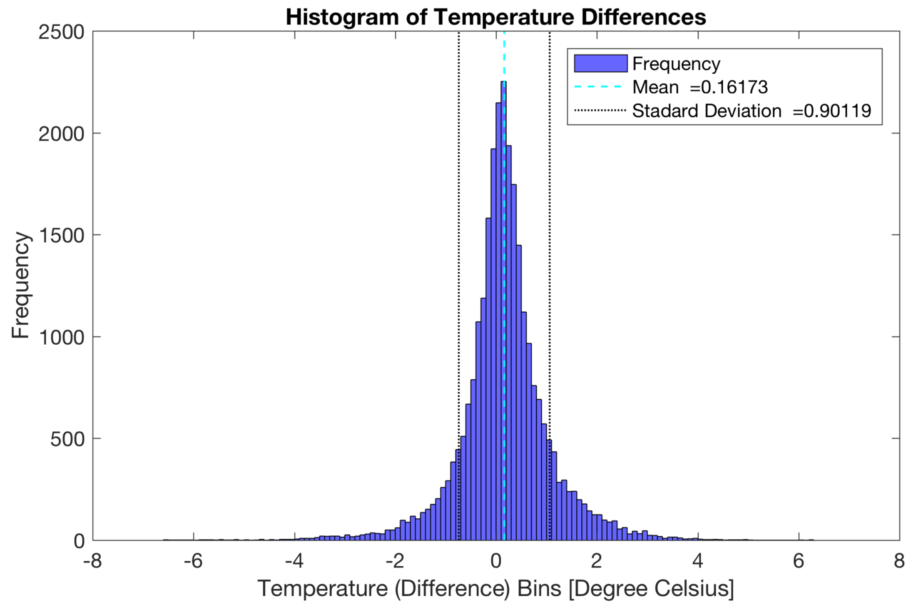

Figure 2.4: Histogram of the differences in the measurement of air temperature (IAC-ATMOS).

The scatterplot of air temperature at both gauges in Figure 2.3 confirms the agreement between the two gauges and the general lack of bias. The differences between the two gauges are summarized in the histogram in Figure 2.4 and the statistics of the differences are listed in Table 2.1.

The mean difference between the IAC and the ATMOS 41 gauge is only 0.16 °C (IAC is higher) with a standard deviation of 0.9 °C. The percent bias is 3.6% and the correlation coefficient is 0.99. The first indication is that the air temperature sensor of the ATMOS 41 gauge works very well and provides stable measurements for a wide range of temperatures (from 23 to -13 °C in our testing period). In Africa with higher temperatures overall and good ventilation during the day, the errors are likely to be even smaller. It still remains to be seen how the gauge performs for very high temperatures, e.g. above 30 °C, and how it is affected by wind still conditions.

Table 2.1: **Air Temperature Statistics and Differences (IAC-ATMOS)**

***Temperature* [°C]**	**Mean**	**Minimum**	**Maximum**	**Standard Deviation**	**Coefficient of Variation**
IAC	4.65	-13.49	22.97	5.59	1.20
TAHMO	4.49	-13.52	22.62	5.62	1.25
AE [°C]	**PB [%]**	**MAE [°C]**	**RMSE [°C]**	**IoA [-]**	**CC [-]**
0.16	3.60	0.62	0.92	0.97	0.99

3. Precipitation

3.1 Gauge Description

The ATMOS 41 contains a 9.31 cm diameter rain gauge (catch area 68 cm^2). During rain events, the draining mechanism forms the collected rain into drops that pass by the drip counter. The spring acts as a filter to keep out large particles (leaves and other debris) and insects, but still allows enough flow. Gold pins measure each drop of rain. Because the dripping mechanism forms a drop of a known size, the ATMOS 41 counts the drops and calculates the water volume. As the rain intensity increases, the drops become smaller, for which ATMOS 41 contains an algorithm to automatically compensate for drop size change as the rain intensity increases. The gauge is not heated and therefore accumulated snow needs to melt before it can be measured. The manufacturer reported range of measurement is 0–400 mm/h intensity, resolution is 0.017 mm, and accuracy is $\pm 5\%$ of measurement at intensities from 0 to 50 mm/h. Rainfall volume (depth) is accumulated at $\Delta t = 1$ min intervals and aggergated to the desired temporal resolution.

3.2 Analysis and Discussion

The direct comparison of precipitation between the IAC and ATMOS 41 gauges are complicated for a number of reasons. First, the manufacturer-reported resolution of the ATMOS 41 dripping gauge is 0.017 mm, while that of the IAC station tipping-bucket instrument is 0.1 mm. Second, the ATMOS 41 is not heated, while the IAC rain gauge has a heating mechanism which melts solid precipitation so that it can be recorded.

We first investigated the cumulative precipitation amounts measured at both gauges in Figure 3.1. Over the testing period ATMOS 41 showed a total precipitation of 467.3 mm, while the IAC gauge recorded 508.1 mm. The difference of about 40 mm (8.7%) is remarkably low considering that the 6-month testing period contained practically a whole winter season 2017/2018. The periods of freezing conditions are marked in the figure with lighter color.

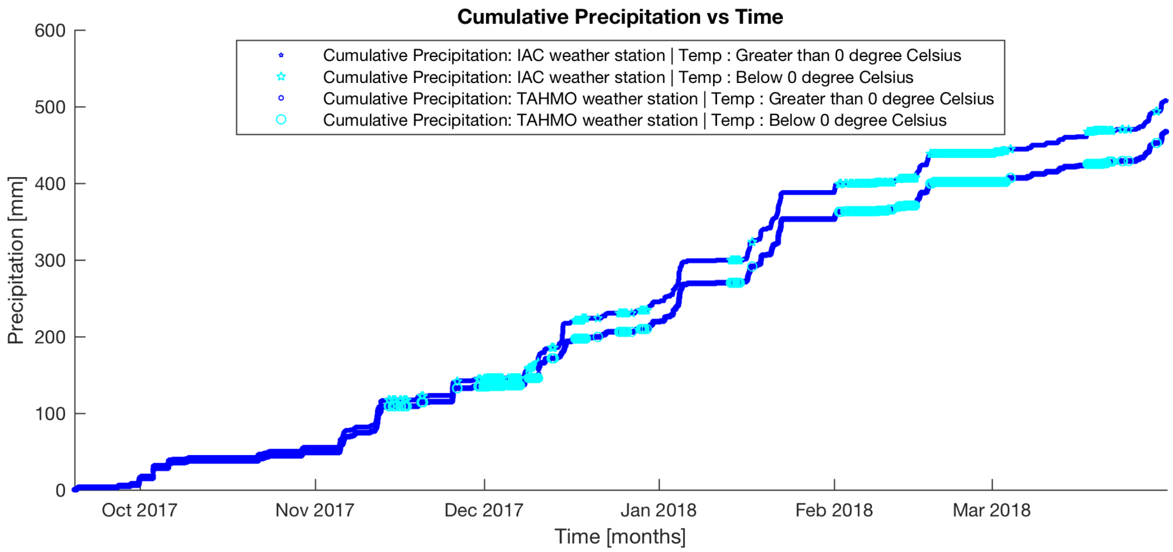

Figure 3.1: Cumulative precipitation of the two weather stations with highlighted periods of below-zero air temperatures.

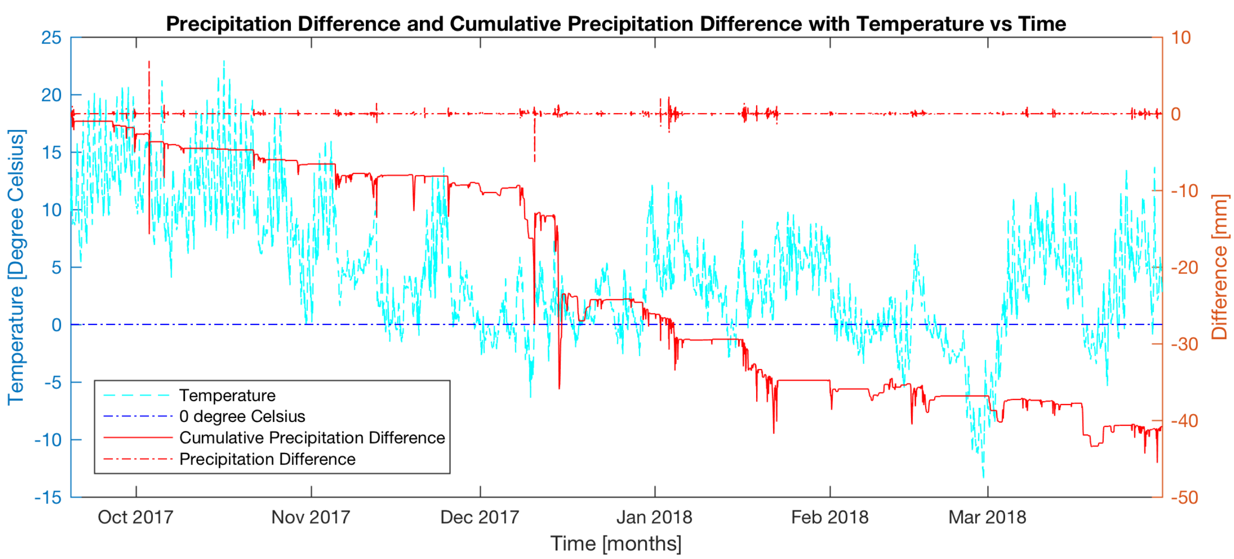

Figure 3.2: Air temperature on the left y-axis and the instantaneous and cumulative precipitation differences TAHMO-IAC on the right axis.

To further understand where the differences in the gauge readings come from and what is the role of snow, we plotted the instantaneous and cumulative differences along with the air temperature in Figure 3.2. Two interesting observations can be made here. First, although generally the ATMOS 41 gauge measures slightly lower precipitation accumulations than the IAC gauge, the biggest differences come during snowfall (which occurs between 0–2 °C), when the ATMOS 41 gauge does not measure any precipitation. Second, after the end of the snowfall, when air temperatures rise, the accumulated snow in the ATMOS 41 gauge melts and is measured as precipitation when the IAC gauge shows none. This melting rate is always less than the water content of the accumulated snow as it is likely that some of the snow is blown out of the shallow and unprotected ATMOS 41 gauge by wind. A good example of this is the snow event in mid-December.

There are some other periods of noisy data. For example, in the month of October where a large difference in precipitation was found even when the temperature was about 10–15 °C. This could be due to clogging of the funnel in ATMOS 41 with debris and subsequent removal of the debris, or some other effect.

The fact that both gauges have a differently resolved samling volume is also potentially relevant. To compare this effect, we simulated the ATMOS 41 data as if it were a tipping-bucket gauge with a 0.1 mm accuracy like the IAC gauge at the $\Delta t = 10$ min resolution, and we conducted the analysis on storms events separated by dry periods, rather than individual 10-min intervals. An example of a single snow storm event resampled to the 0.1 mm volume accuracy is shown in Figure 3.3. Here it is evident that at the beginning of the storm snow is collected in the ATMOS 41 gauge and melted away only later.

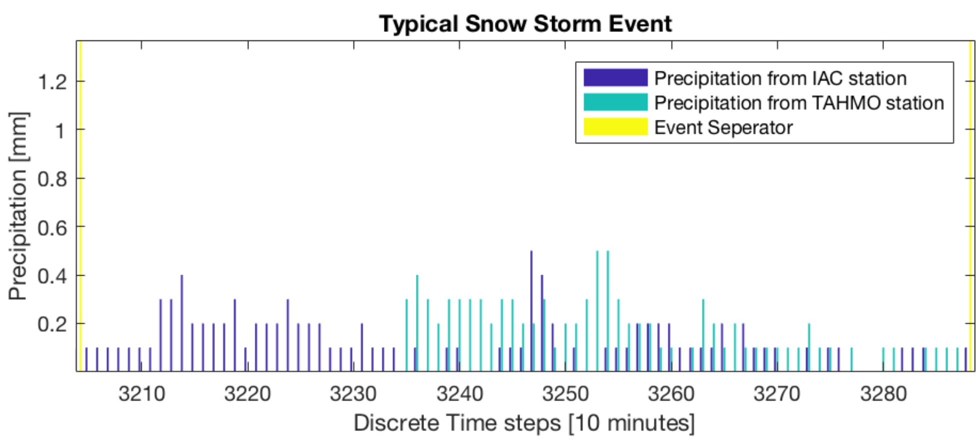

Figure 3.3: Example of an event resampled with 0.1 mm accuracy to the 10-min resolution from ATMOS 41 (TAHMO) and the IAC gauge.

Precipitation statistics recorded at the $\Delta t = 10$ min intervals are listed in Table 3.1 for both gauges and resampled (simulated) ATMOS 41 and in Table 3.2 for the events. At the event scale it is very clear that the gauges agree reasonably well in terms of precipitation amounts in each storm (1.9 mm per event in IAC and 1.74 mm per event in ATMOS 41). The histogram of the precipitation differences at the $\Delta t = 10$ min intervals in Figure 3.4 shows that the individual 10-min intervals can indeed show bigger differences, due to snow and the issues discussed above. This is also supported by the statistics of the differences in Table 3.3. The results clearly show that an event-based analysis is more suitable to quantify the coherence between the two precipitation gauges. The correlation coefficients are 0.66 at $\Delta t = 10$ min scale and 0.95 at the event scale. Future analysis should also focus on the measurement of extreme rain rates, which appear to be similar (maximum 6.9 mm/10-min in IAC gauge versus 6.4 mm/10-min in ATMOS 41), to verify if the ATMOS 41 gauge does not lose accuracy in these conditions. This will be important for Africa and heavy torrential downpours.

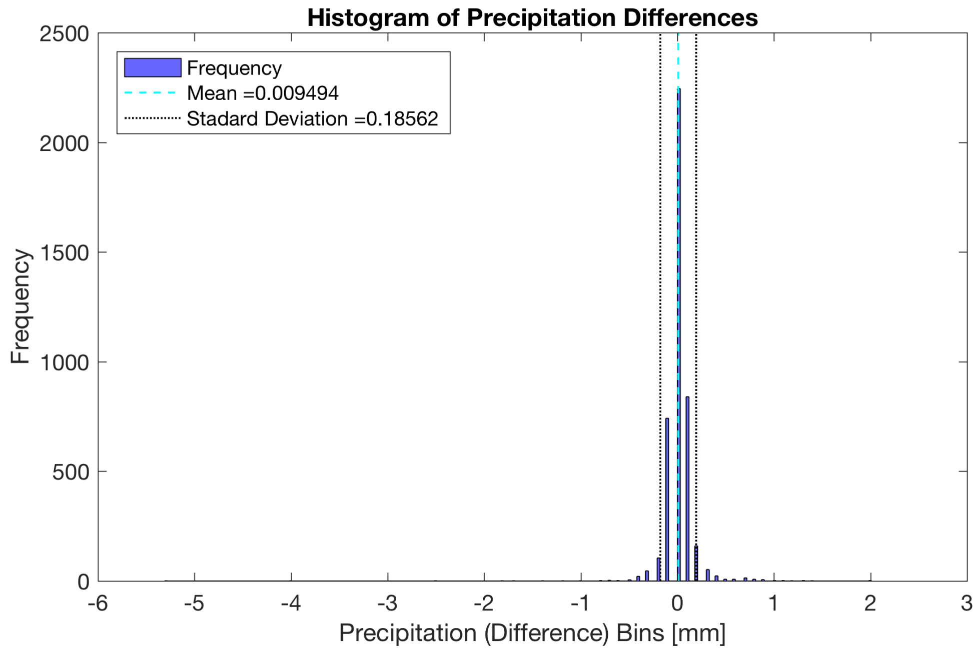

Figure 3.4: Histogram of the differences in the measurement of precipitation from both gauges (IAC-ATMOS).

Table 3.1: **Precipitation Statistics: 10-min intervals (TAHMO-O original and TAHMO-S simulated)**

Precipitation [mm/10min]	**Mean**	**Minimum**	**Maximum**	**Standard Deviation**	**Coefficient of Variation**
IAC	0.12	0	6.9	0.22	1.84
TAHMO-O	0.11	0	6.35	0.23	2.12
TAHMO-S	0.11	0	6.4	0.23	2.14

Table 3.2: **Precipitation Statistics: event-based**

Precipitation [mm/event]	**Mean**	**Minimum**	**Maximum**	**Standard Deviation**	**Coefficient of Variation**
IAC	1.90	0	32.6	4.55	2.40
TAHMO	1.74	0	33.1	4.33	2.48

Table 3.3: **Precipitation Differences (IAC-ATMOS): comparison**

Precipitation [mm]	**AE [mm]**	**PB [%]**	**MAE [mm]**	**RMS [mm]**	**IoA [-]**	**CC [-]**
10-min data	0.009	8.75	0.07	0.18	0.36	0.66
events	0.15	8.74	0.50	1.46	0.89	0.95

4. Wind Speed and Direction

4.1 Gauge Description

Wind speed in ATMOS 41 is measured by ultrasonic signals emitted from four transducer arranged at right angles at the bottom of the raingauge. Wind speed is calculated by measuring differences in the time it takes for sound to travel back and forth between the sensors. The gauge also estimates the wind direction from the perpendciularly arranged sensors. The manufacturer reported range of wind speed measurement is 0–30 m/s, measurement resolution is 0.01 m/s and accuracy is the greater of 0.3 m/s or 3% of measurement. Wind direction resolution is $1^\circ$and accuracy is $\pm 5^\circ$. Wind speed and direction are recorded at 10 sec frequency and the average is reported at the desired time resolution.

4.2 Analysis and Discussion

Wind analysis was divided into two parts: wind speed and wind direction. Figure 4.1 shows the timeseries of the wind speed measurement from the two weather stations, while in Figure 4.2 a shorter segment of data is shown. In general, the conclusion is that although the wind speed peaks are sometimes matching, in general the IAC gauge under-reported wind speed compared to ATMOS 41. The overall correlation coefficient at the $\Delta t = 10$ min resolution was 0.82. Especially when wind speeds were low, the propellers of the IAC anemometer often stopped rotating. The scatterplot of the two gauge measurements in Figure 4.3 shows the spread between the data.

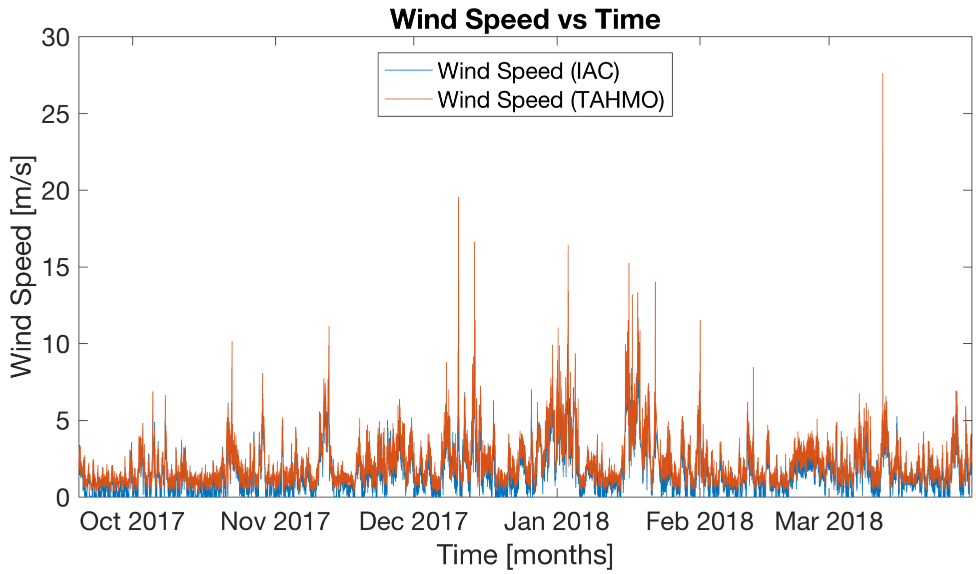

Figure 4.1: Wind speed timeseries measured by the two weather gauges for the entire testing period.

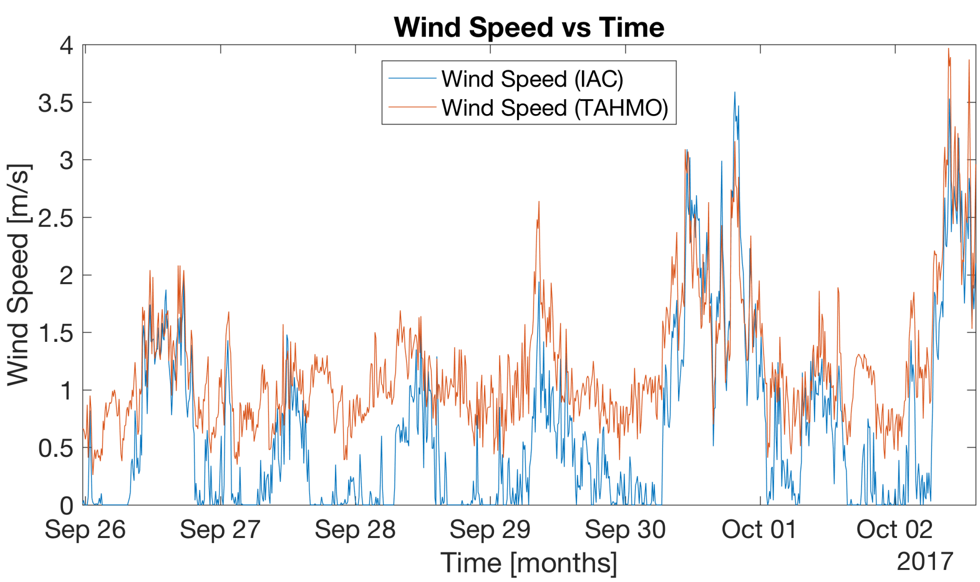

Figure 4.2: Daily variation of wind speed in the two weather stations for a shorter period 26 September to 2 October 2017.

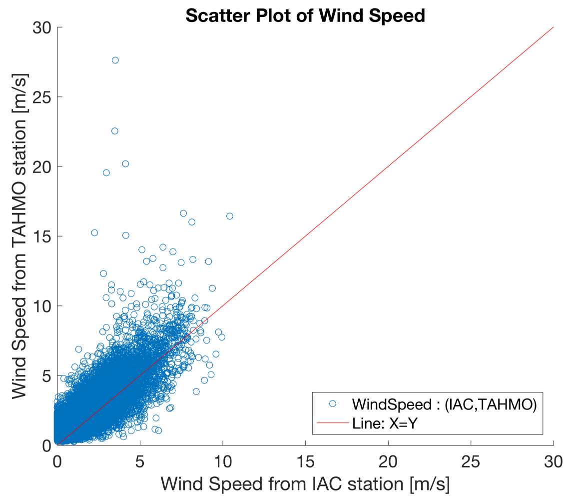

Figure 4.3: Scatterplot of wind speed from the two weather stations at the $\Delta t = 10$ min sampling resolution.

The analysis of the wind direction gives some additional insight into the differences between the gauges. Figure 4.4 gives the direction of average wind speed for ATMOS 41 and the direction of peak wind speed for IAC station (the direction of average wind speed was not available). The time resolution was 10 minutes and hence these two quantities were assumed to be comparable in such short duration. The directions were binned in 10 degree bins. It is noticeable that the IAC station showed high values in the cardinal directions (0°-10°, 90°-100°, 180°-190°, 270°-280°), which may be an artifact of the two-propeller fixed system of the anemometer which does not allow for plan rotation.

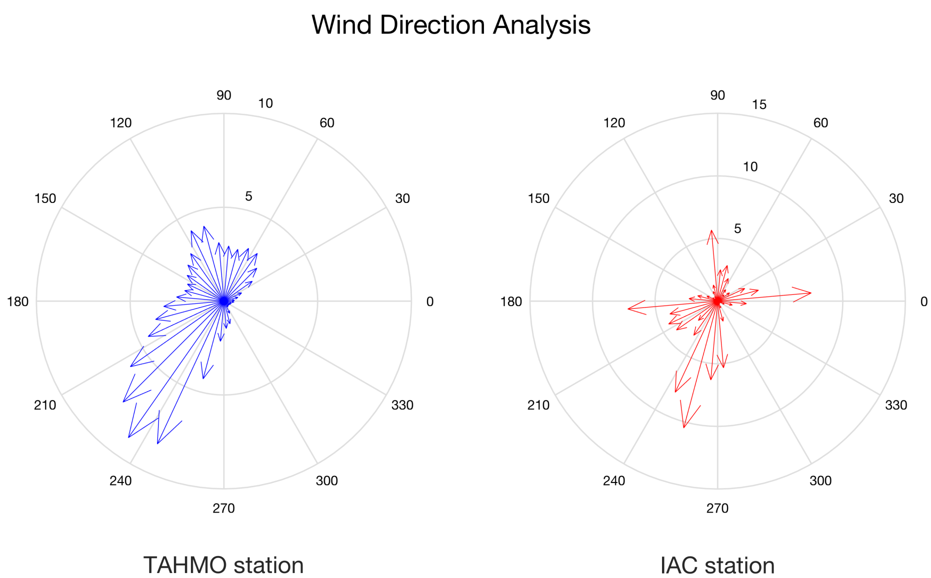

Figure 4.4: The arrow shows the direction of average wind speed for the ATMOS 41 (TAHMO) station and the direction of peak wind speed for the IAC station. The magnitude of vector shows the frequency of occurrence in percentage. 0 degree denotes North and 90 degrees denotes East.

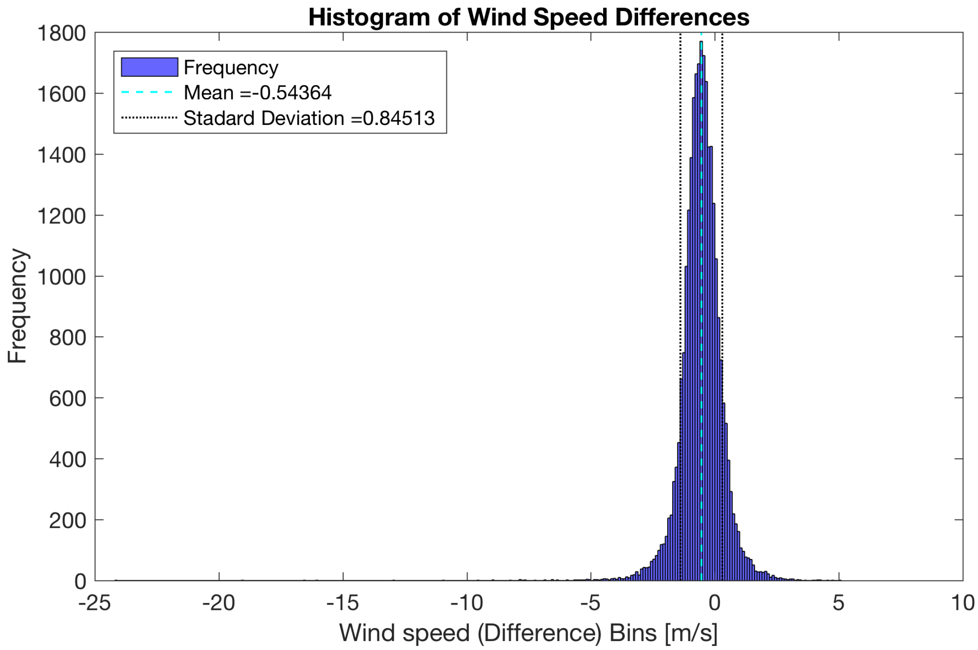

Figure 4.5: Histogram of differences in wind speed from the two stations (IAC-ATMOS).

The statistics of the wind speeds and the differences between the gauges (IAC-ATMOS) are reported in Table 4.1. The histogram of wind speed differences are shown in Figure 4.5. The mean difference was -0.54 m/s (standard deviation 0.85 m/s) and it is evident that the ATMOS 41 gauge produces about 25% higher wind speeds than the IAC gauge. In this particular case it is possible that the ATMOS 41 gauge is in fact closer to the truth for wind gusts, but the fact that wind speed is practically never zero in the ATMOS 41 gauge is possibly due to the nature of the ultrasonic measurement. This should be followed up with more analyses.

Table 4.1: **Wind Speed Statistics and Differences (IAC-ATMOS)**

***Wind Speed* [m/s]**	**Mean**	**Minimum**	**Maximum**	**Standard Deviation**	**Coefficient of Variation**
IAC	1.59	0	10.43	1.37	0.86
TAHMO	2.13	0.24	27.61	1.46	0.69
AE [m/s]	**PB [%]**	**MAE [m/s]**	**RMSE [m/s]**	**IoA [-]**	**CC [-]**
-0.54	-25.5	0.75	1.005	0.53	0.82

5. Relative Humidity

5.1 Gauge Description

The sensor in ATMOS 41 measures relative humidity and air temperature, and computes vapor pressure as the saturation vapor pressure at sensor temperature multiplied by the relative humidity. The resolution of the sensor is 0.1% and accuracy varies with temperature and humidity and is ±3%. Relative humidity is recorded at high frequency and the average is reported at the desired time resolution.

5.2 Analysis and Discussion

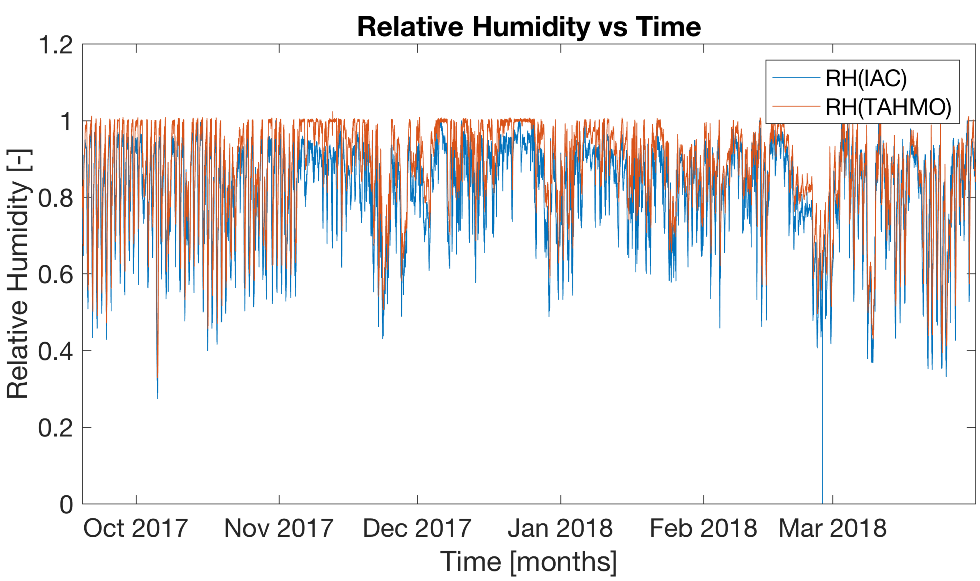

Figure 5.1: Relative humidity timeseries for the two weather stations for the entire testing period.

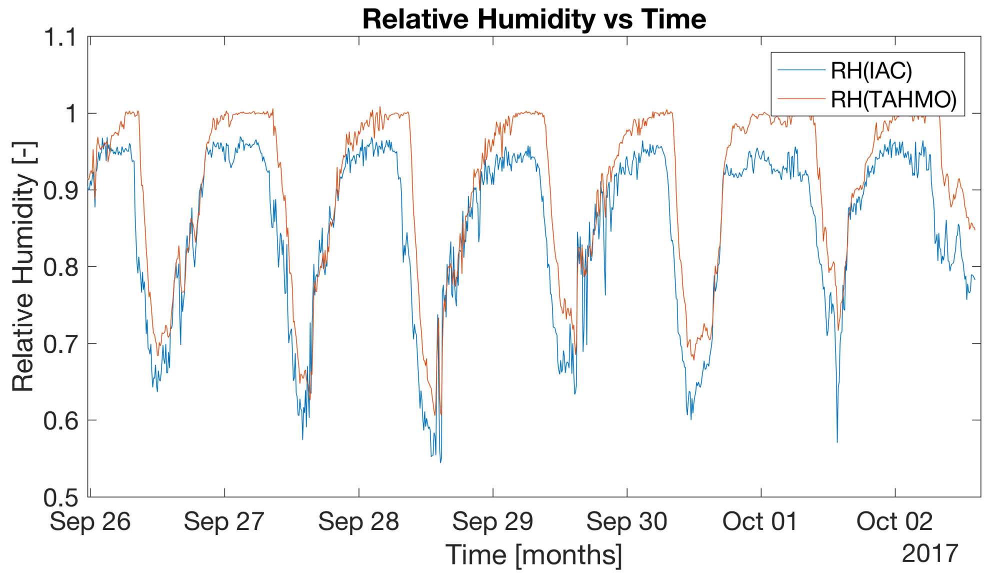

Figure 5.2: Daily variation of relative humidity in the two weather stations for a shorter period 26 September to 2 October 2017.

Figures 5.1 and 5.2 show the timeseries of relative humidity (RH) for the testing period and a shorter 1-week period in more detail for the two gauges. The tendency is for ATMOS 41 to produce slightly higher values than the IAC station, and saturate at 100% relative humidity at night-time more often. The IAC gauge reaches 100% relative humidity much less frequently.

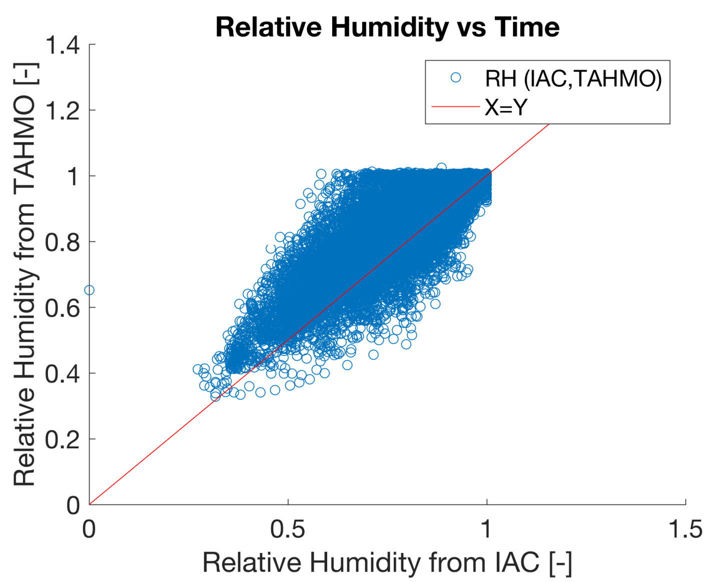

Figure 5.3: Scatterplot of relative humidity from the two weather stations at the $\Delta t = 10$ min sampling resolution.

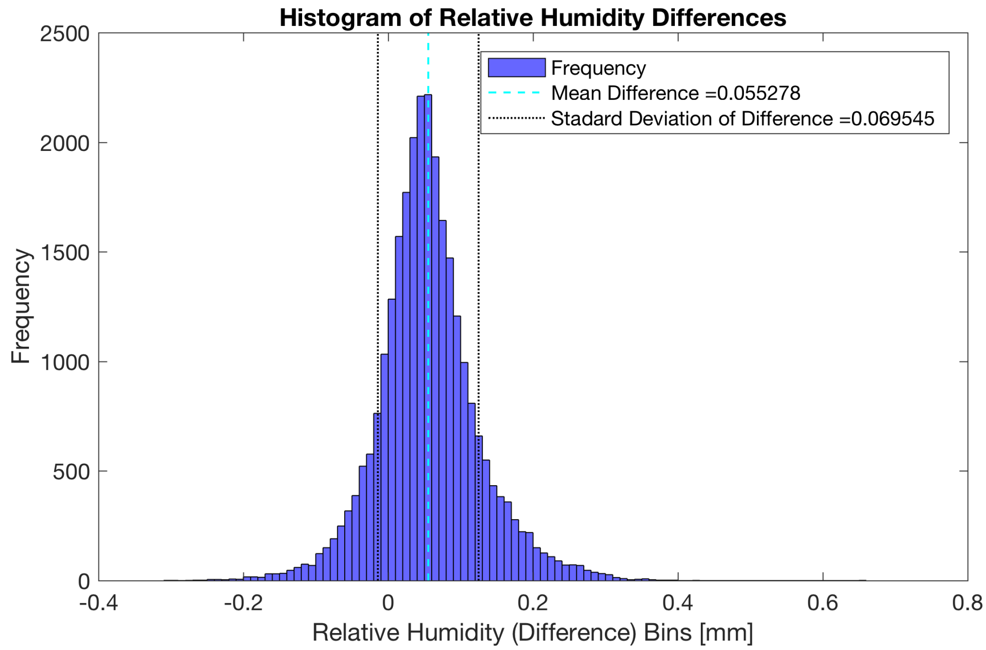

Figure 5.4: Histogram of the difference of relative humidity from the two weather stations (ATMOS-IAC).

The scatterplot in Figure 5.3 also indicates that the bias towards higher values in ATMOS 41 comes mainly during conditions of higher atmospheric moisture. Figure 5.4 shows the histogram of differences and the statistics are reported in Table 5.1 as the difference IAC-ATMOS. The percent bias between the gauges is 6.4%.

Relative humidity is a complex measurement, in ATMOS made by a permeable Teflon screen below the raingauge, protected from direct solar radiation. Relative humidity is dependent on air temperature, so there are two variables to control: the liquid vapour content and air temperature. Considering this, the differences between the two gauges are not very high. In addition, for hydrological studies it is vapor pressure (product of RH and saturation vapor pressure computed by an empirical equation) that is a more relevant measure of water content in the atmosphere, e.g. for evapotranspiration potential, etc. The frequent saturation at 100% relative humidity in ATMOS 41 could be verified with more measurements.

Table 5.1: **Relative Humidity Statistics and Differences (ATMOS-IAC)**

***Relative Humidity* [-]**	**Mean**	**Minimum**	**Maximum**	**Standard Deviation**	**Coefficient of Variation**
IAC	0.81	0.0005	1	0.13	0.16
TAHMO	0.87	0.33	1.02	0.12	0.14
AE [-]	**PB [%]**	**MAE [-]**	**RMSE [-]**	**IoA [-]**	**CC [-]**
0.06	6.36	0.07	0.09	0.46	0.84

6. Atmospheric Pressure

6.1 Gauge Description

The barometric pressure sensor measures the atmospheric pressure of the environment in which the ATMOS 41 is placed. With a range from 50 to 101 kPa, it is suitable for measurement across a wide range of elevations. The sensor output will depend mainly on the installation altitude with smaller changes caused by weather. The resolution of the sensor is 0.01 kPa and the accuracy is ± 0.1 kPa. Pressure is recorded at high frequency and the average is reported at the desired time resolution.

6.2 Analysis and Discussion

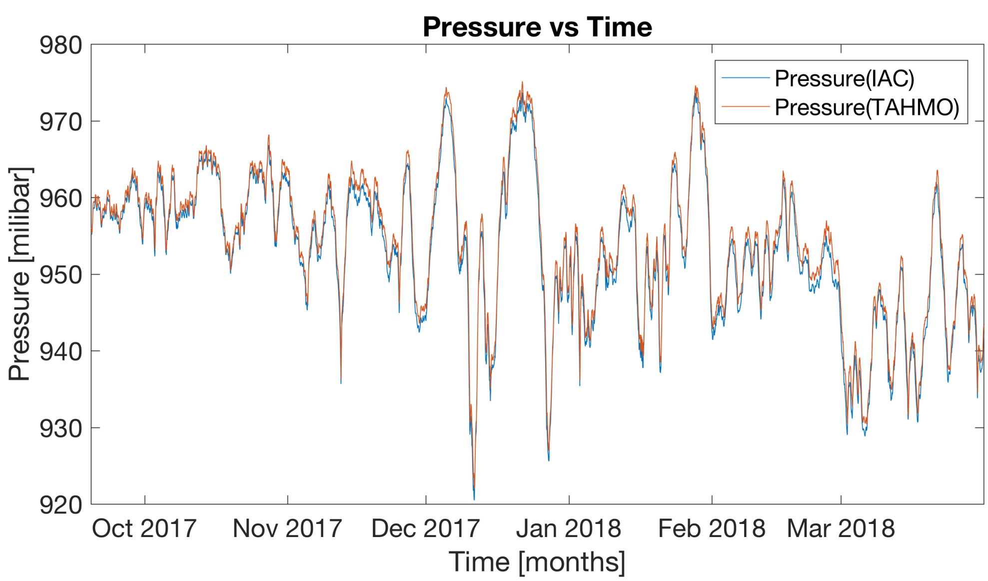

Figure 6.1: Atmospheric pressure timeseries for the two weather stations for the entire testing period.

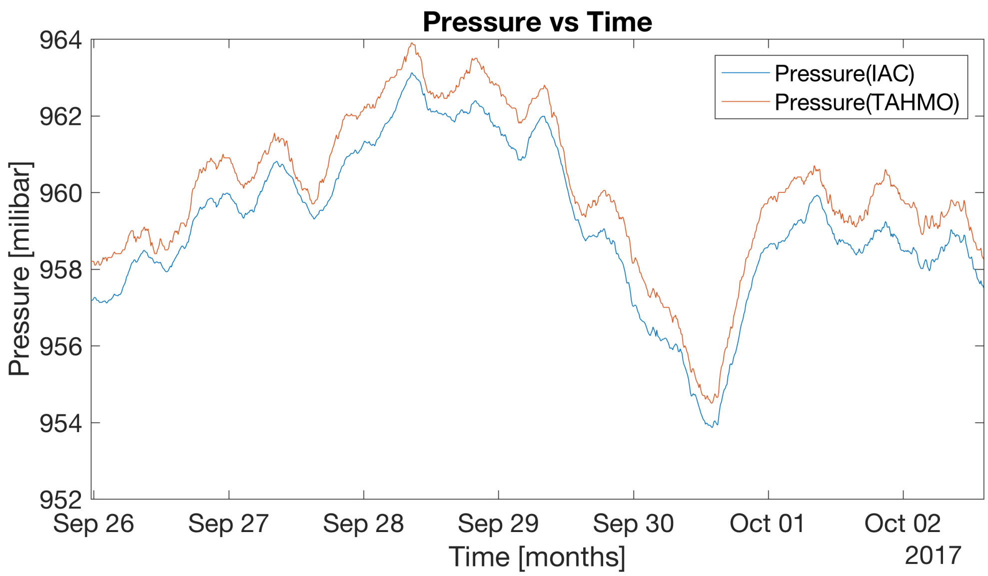

Figure 6.2: Daily variation of atmospheric pressure in the two weather stations for a shorter period 26 September to 2 October 2017.

Figures 6.1 and 6.2 show the timeseries of atmospheric pressure for the testing period and a shorter 1-week period in more detail for the two gauges. Both gauges provide very similar data in terms of timing and variability during the day and in longer (weather type) periods. There is a small bias towards greater values in ATMOS 41 than the IAC gauge, but this is not significant.

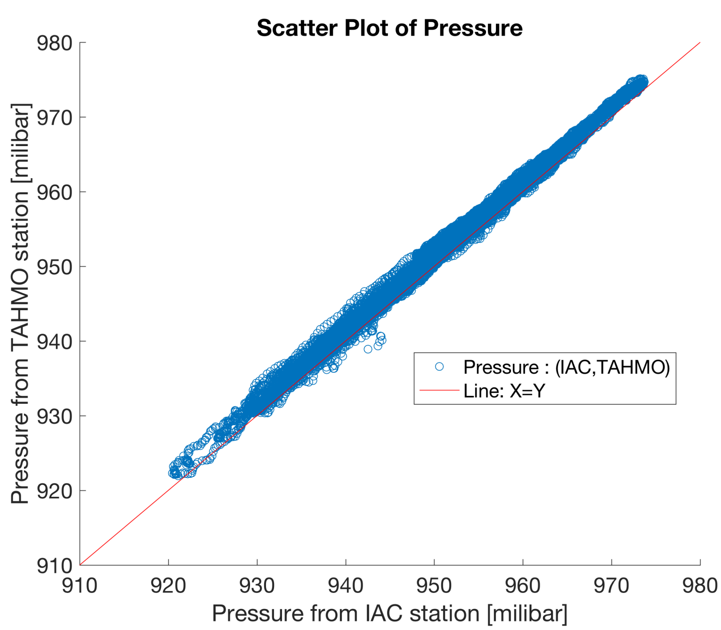

Figure 6.3: Scatterplot of atmospheric pressure from the two weather stations at the $\Delta t = 10$ min sampling resolution.

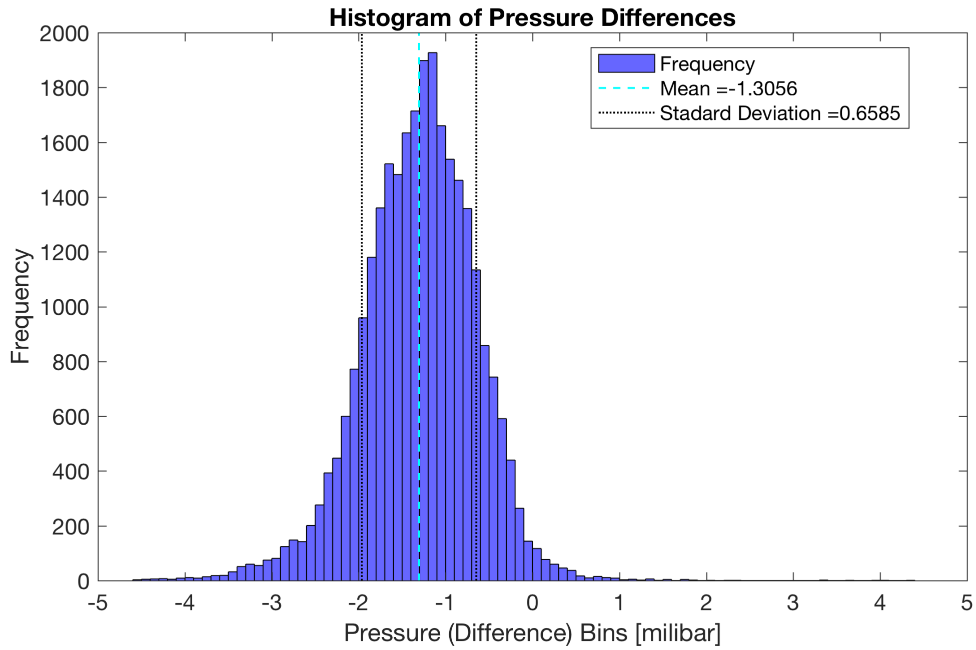

Figure 6.4: Histogram of the differences in atmopsheric pressure between the two weather stations (IAC-ATMOS).

The scatterplot in Figure 6.3 shows that the data is in very good agreement between the gauges and highly correlated. It can be seen in Table 6.1 that the correlation coefficient is practically equal to 1. The differences between the gauges are normally distributed with a mean of 1.3 milibar (i.e. 0.1 kPa) as can be seen in the histogram in Figure 6.4, this is a bias of only 0.14% towards higher values by the ATMOS 41 gauge (Table 6.1). This bias is spread across the entire range of measurements. In summary we consider the atmospheric pressure to be measured very well by ATMOS 41.

Table 6.1: **Pressure Statistics and Differences (IAC-ATMOS)**

***Pressure* [milibar]**	**Mean**	**Minimum**	**Maximum**	**Standard Deviation**	**Coefficient of Variation**
IAC	952.73	920.47	973.68	9.48	0.0098
TAHMO	954.03	921.95	975.15	9.36	0.0098
AE [mb]	**PB [%]**	**MAE [mb]**	**RMSE [mb]**	**IoA [-]**	**CC [-]**
-1.31	-0.14	1.32	1.46	0.98	0.99

7. Solar Radiation

7.1 Gauge Description

Solar radiation is measured by a pyranometer that is integrated into the lip of the rain gauge funnel at the top of ATMOS 41. The pyranometer uses a silicon-cell sensor to measure the total incoming (direct and diffuse) solar short-wave radiation. The manufacturers state that the sensor is corrected for sun angle and has excellent sensitivity and response time to changing radiation conditions across the solar wavelength spectrum. The range of the sensor is 0–1750 W/m^2, the resolution is 1 W/m^2 and typical accuracy $\pm 5\%$ of measurement. Measurements are taken every 10 secs and averaged over the desired recording time interval.

7.2 Analysis and Discussion

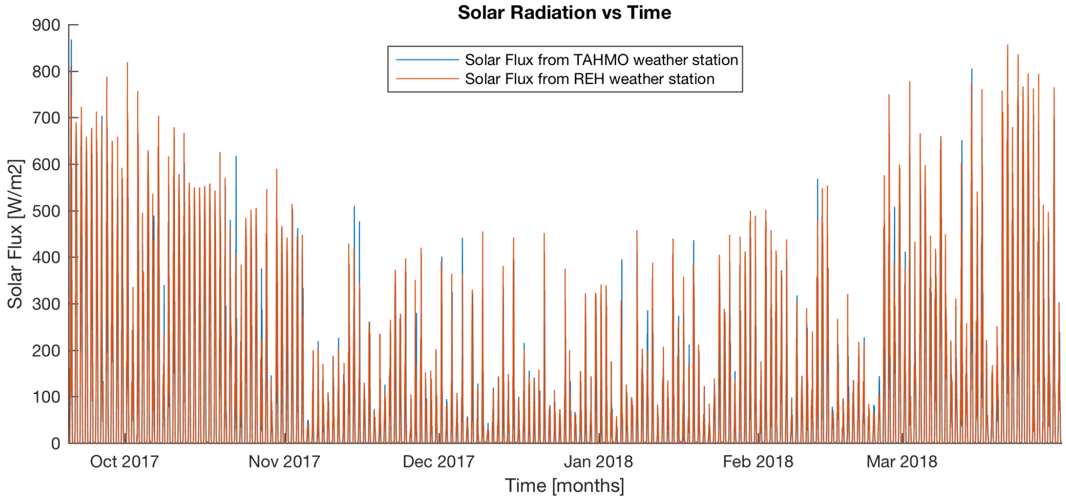

Figure 7.1: Solar radiation timeseries for the two weather stations for the entire testing period.

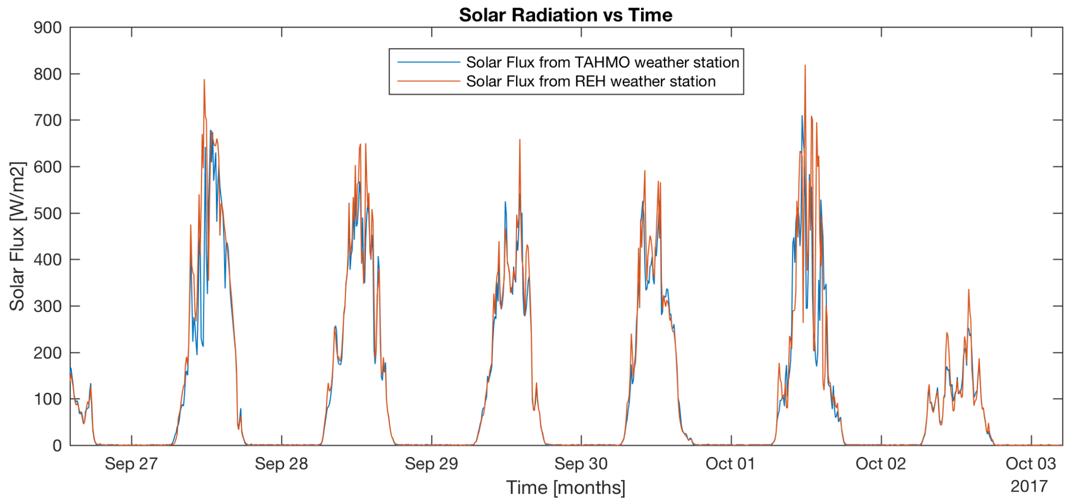

Figure 7.2: Daily variation of solar radiation in the two weather stations for a shorter period 26 September to 2 October 2017.

In the case of solar radiation the IAC weather station did not have an adequate comparable sensor in the meteo field. Instead we chose for comparison short-wave radiation data collected at the closest SwissMetNet station (REH Reckenholz) of the Federal Office of Meteorology and Climatology. This station is 2.5 km straight-line distance from the ATMOS gauge and provides quality-controlled data at $\Delta t = 10$ min resolution.

Figures 7.1 and 7.2 show the timeseries of solar radiation for the testing period and a shorter 1-week period in more detail for the two gauges. The maximum magnitudes at midday are similar at both stations, and the timing agrees perfectly. The actual variability during the day in response to cloud cover is of course not the same, because the 2.5 km distance can lead to differences in cloud cover extent. On overcast days, such as 2 October 2017 (Figure 7.2), the agreement between the two gauges is practically perfect.

Figure 7.3 shows the scatter plot of solar radiation at the two stations. The correlation between the two gauges at the $\Delta t = 10$ min resolution is 0.96. The histogram of the differences at the $\Delta t = 10$ min resolution shows high agreement (zero differences) mainly because of the night-time zero solar radiation agreement. On average during the testing period, the ATMOS 41 gauge measured 5.9 W/m^2 less than the REH gauge, which is a bias of 8.9% (Table 7.1). This is acceptable performance, especially considering that the small pyranometer in ATMOS 41 is only a fraction of the cost of traditional radiation sensors installed in climate stations. In the future it would be desirable to test the solar radiation sensor with another radiation sensor directly in the meteo field. As radiation is an important variable in hydrological studies, it is particularly important to measure accurately.

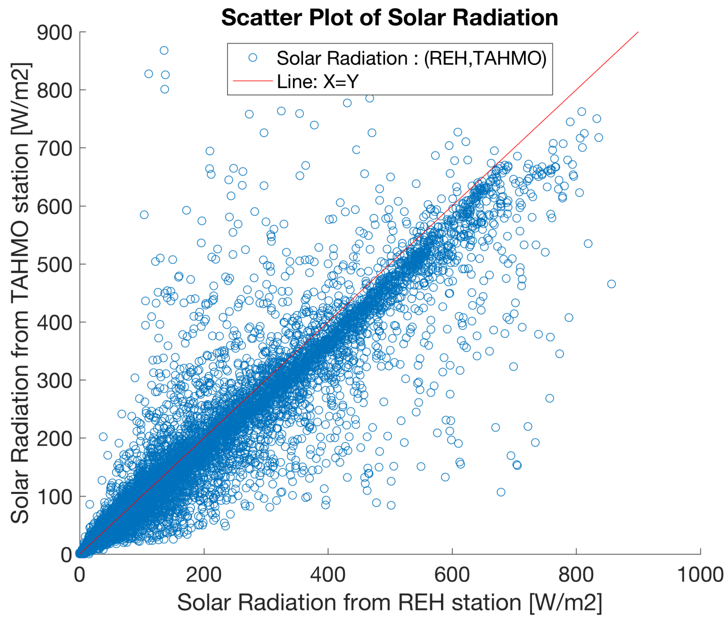

Figure 7.3: Scatterplot of solar radiation from two weather stations at the $\Delta t = 10$ min sampling resolution.

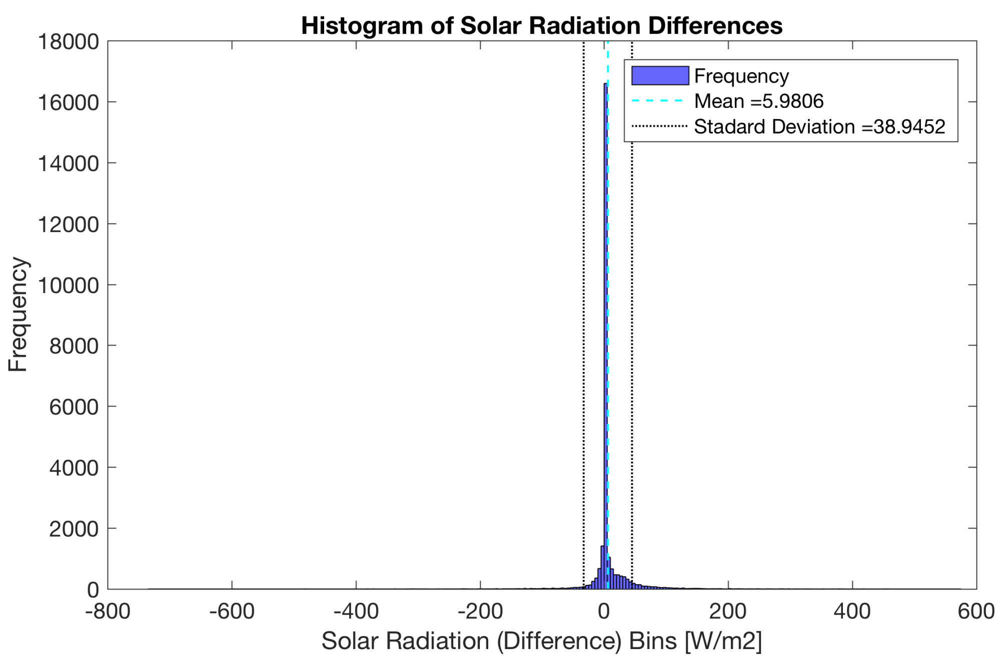

Figure 7.4: Histogram of the differences in solar radiation between the two weather stations (REH-ATMOS).

Table 7.1: **Solar Radiation Statistics and Differences (REH-ATMOS)**

Solar Radiation **[W/m^2]**	**Mean**	**Minimum**	**Maximum**	**Standard Deviation**	**Coefficient of Variation**
REH	73.18	0	857	137.61	1.88
TAHMO	67.20	0	867.9	127.94	1.90
AE [W/m^2]	**PB [%]**	**MAE [W/m^2]**	**RMSE [W/m^2]**	**IoA [-]**	**CC [-]**
5.98	8.90	13.57	39.40	0.90	0.96

8. Conclusions

The comparison of the selected variables for hydrological purposes as measured by the ATMOS 41 weather station and the IAC and REH station sensors over a 193-day period was very satisfactory. The following points summarize the main conclusions and recommendations.

8.1 Summary Remarks

AIR TEMPERATURE. ATMOS 41 performed very similarly to the conventional gauge. The differences at the $\Delta t = 10$ min resolution were on the average 0.16 °C and 3.6% bias, with slightly lower values measured by ATMOS 41. The differences came mainly from cold night-time temperatures. This is a very small difference which can be explained by different sensors and small scale variability in air temperature. Measurement of high temperatures, especially under wind still conditions, should be checked in Africa.

PRECIPITATION. ATMOS 41 performed reasonably similarly to the conventional tipping-bucket gauge. The cumulative difference between the two gauges over the 193-day testing window was about 40 mm which corresponds to a 8.7% bias, with ATMOS 41 measuring less precipitation. Differences were analysed on a $\Delta t = 10$ min basis as well as over individual storms. The main reason for the differences between the gauges is snowfall which is not melted by the ATMOS 41 gauge and is very probably partially blown out of the gauge between storms by wind. At an event scale the coherence between the two precipitation gauges was high (correlation coefficients $r = 0.95$), while at the $\Delta t = 10$ min scale there were more departures caused by the different gauge resolutions and sampling strategies. Importantly, the maxima in 10-mins recorded by both gauges were very similar. Further analysis should focus on the accuracy of these high rain intensity measurement, as this is crucial in the Tropics.

WIND SPEED AND DIRECTION. ATMOS 41 performed reasonably smilarly to the conventional gauge. However it does record on the average higher wind speeds, the difference was on the average 0.5 m/s at the $\Delta t = 10$ min resolution, which corresponds to a bias of 25%. Higher wind speeds were measured especially during less windy conditions, which could be a particularity of the ultrasonic gauge versus the traditional propeller anemometer. This still has to be better understood. Wind direction was measured accurately, probably better than what can be achieved by some moving wind vanes.

R RELATIVE HUMIDITY. ATMOS 41 performed reasonably similarly to the conventional gauge. On the average there was a difference of 5% at the $\Delta t = 10$ min resolution, which corresponds to a bias of 6%, with higher relative humidity measured by ATMOS 41. This was most evident in saturation conditions (RH = 100%) which are reached much more frequently for the ATMOS 41 gauge than the IAC gauge. This can be a calibration issue with the IAC gauge as well. In general the 10-min data were quite well correlated ($r = 0.84$).

R ATMOSPHERIC PRESSURE. ATMOS 41 performed very smilarly to the conventional gauge. On the average there was a difference of only 1.3 milibar at the $\Delta t = 10$ min resolution, which corresponds to a bias of less than 1%, with slightly higher atmospheric pressure measured by ATMOS 41.

R SOLAR RADIATION. ATMOS 41 performed very smilarly to the conventional gauge of MeteoSwiss. Because this gauge was not on the meteo field, but at a distance of 2.5 km, differences in solar radiation were expected, especially during partly cloudy days. During overcast conditions, the gauges agreed very well. On the average there was a difference of 5.39 W/m^2, which corresponds to a bias of 8.85%, with higher solar radiation measured by REH. It has to be remarked that the ATMOS 41 pyranometer is only a fraction of the cost of the MeteoSwiss sensor. Testing of the solar radiation sensor should continue directly in the meteo field.