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More Science with Less: Evaluation of a 3D-Printed Weather Station

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Abstract. A weather station built using 3D-printed parts and low-cost sensors was deployed alongside an Oklahoma Mesonet Station for an eight month study to determine the longevity of these sensors and their performance as compared with standard commercial sensors. The station was built based on plans and guidance provided by the UCAR 3D-PAWS project. While some of the sensors and components did degrade over time and in some cases completely fail, the results show that these low-cost sensors have the potential to perform just as well as the more expensive counterparts.

1 Introduction

Low-cost sensors coupled with 3D-printing can provide researchers with the ability to create tools and instrumentation at a fraction of the cost of commercial counterparts. The 3D-Printed Automatic Weather Station (3D-PAWS) Initiative developed open-source plans and documentation for building low-cost weather stations in an effort to fill gaps in remote, sparsely observed regions (Kucera and Steinson, 2017a). There have been similar efforts to develop low-cost weather stations for small-scale wind farm site selection (Aponte-Roa et al., 2018) and for looking at micro-climate processes (Ham, 2013). Other than the 3D-PAWS experiment, these efforts along with independent ones (Smallwood and Santarsiero, 2019) have focused on relatively short time periods for validation of the sensors and 3D-printed components.

The 3D-PAWS team evaluated their system over a ten month time-frame at two separate facilities, each having commercial grade sensors for comparison (Kucera and Steinson, 2017b). The results showed good agreement between sensors with the relative humidity showing the largest uncertainty (Table: 1). Other than the Smallwood and Santarsiero study, which did not gather enough data for analysis, each effort found that these low-cost sensors can be a viable alternative for data collection. This study was supported by the Cooperative Institute of Mesoscale Meteorological Studies (CIMMS) at the University of Oklahoma with the goal of verifying the 3D-PAWS results, determining the longevity of the sensors and 3D-printed components, and providing undergraduate meteorology students with skills they would not otherwise have learned in the classroom.

2 Station Configuration

The weather station was built based on specifications provided by the 3D-PAWS initiative with some modifications. Due to limitations with anchoring the station in ground, a frame had to be developed to withstand weather conditions in Oklahoma. The frame was built from standard polyvinyl chloride pipe (PVC) and consisted of a central trunk connected to three legs. Each leg was connected to a height adjustable concrete footing (Fig. 1). In order to minimize vibrations on the tipping bucket rain gauge, the support legs were also set in concrete. In place of building a Raspberry Pi tube, an eight by eight by four inch electrical junction box was used to house the Raspberry Pi. Temperature, relative humidity, and atmospheric pressure sensors were installed in the naturally aspirated radiation shield at one-and-a-half meters. Wind direction, wind speed, and ultraviolet (UV) light sensors were installed on the crossbar at approximately two meters. A secondary temperature sensor was installed in the Pi box to monitor internal temperatures. Temperature, relative humidity, atmospheric pressure, and UV sensors were all sealed with conformal coating to help protect against moisture degradation.

Over one hundred parts were 3D-printed using acrylonitrile styrene acrylate (ASA) which has higher ultraviolet radiation, temperature, and impact resistance than regular polylactic acid (PLA) filament. In order to print the parts in a timely manner, the parts were not completely filled in and instead were printed with a grid infill. Initial prints of the funnel using the original design proved problematic with the printer that was being used. The wall thickness was increased to resolve the print issues. The funnel was coated with polyurethane to seal any remaining imperfections in the print. Lab calibrations were performed and the rain gauge was adjusted to ensure that each tip routinely held approximately 0.2 mm of water. The rain gauge screen was created from part of a failed funnel print. Mosquito netting was zip tied to the ring and fit securely inside the funnel. Plans had called for opaque plastic (PTFE) to shield the UV sensor. In order to reduce costs, the opaque plastic tray from a frozen meal was used to create the cover (Fig. 2).

Data were collected every minute for the temperature, pressure, relative humidity, and UV variables. The rain program was constantly listening for tip events and would record minute totals. The wind program was constantly running as well and recorded average, minimum, and maximum wind speed and direction each minute. These programs were set up to automatically start up on any reboot or power loss event to ensure robust operations. Data were uploaded via WiFi connection to a cloud based storage location at the end of every day to ensure minimal data loss in the event of a catastrophic failure.

3 Deployment

The Oklahoma Mesonet (Mcpherson et al., 2007; Brock et al., 1995) deploys meteorological instrumentation (Table: 2) in every county across Oklahoma. Temperature, pressure, and relative humidity sensors are deployed at one-and-a-half meters and the wind speed and direction at ten meters. The Norman station served as an ideal reference point due to the proximity to the University of Oklahoma for routine maintenance visits. The 3D-printed weather station was deployed approximately seventy meters to the West-Northwest of the Mesonet station (Fig. 3). The wind sensor cross-arm was mounted perpendicular to North and the rain gauge was oriented to the West of the station in order to minimize any interference from the station itself or the larger ten meter tower that was nearby. There was a slight slope to the terrain so that the 3D-printed weather station was

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approximately two meters higher than the Mesonet site. Surrounding terrain was mostly native grasses that were mowed on a regular basis.

4 Results

Temperature, relative humidity, atmospheric pressure, wind speed and direction, and UV data collected from the 3D weather station were averaged to five minutes in order to compare with the Mesonet data. The Mesonet does not measure UV index so a one-to-one comparison was not possible. Rainfall from both systems were accumulated to a daily total for comparison. Results across the various sensors are mixed, but overall the station exceeded expectations. The subsequent scatter plots follow the same format, the 3D weather station is on the x-axis, Mesonet on the y-axis, and the points are color-coded by time with dark blue indicating data from the beginning of the deployment and yellow indicating data towards the end of it.

4.1 Air Temperature

The MCP9808 temperature sensor differed from the RM Young probe by an average of 0.81 °C which is within the range of uncertainty of both instruments combined (0.5 °C and 0.4 °C)(Fig. 4). The slight differences could also be attributed to the difference in aspiration, natural vs mechanical. The low-cost sensor did show some signs of degradation at the end of the deployment due to moisture but was otherwise in relatively good shape.

A temperature sensor was also incorporated in the HTU21D sensor used for relative humidity. The HTU21D outperformed the MCP9808 when compared to the Mesonet (Fig. 5), however, the HTU21D failed two-and-a-half months before the end of the deployment. This failure was attributed to corrosion on the board that was not seen with other sensors.

4.2 Relative Humidity

The HTU21D relative humidity sensor had a slight moist bias as compared to the Mesonet's Vaisala HMP155 probe, averaging 4.2 % (Fig. 6). The bias increased with increasing relative humidity. To elaborate on the previously mention failure of the HTU21D sensor, communications problems started roughly five-and-a-half months into the deployment. These communications problems caused readings from other sensors using the same protocol (I2C) to drop out. The HTU21D sensor was removed and not replaced due to the short amount of time remaining in the deployment.

4.3 Atmospheric Pressure

The initial BMP280 pressure sensor that was deployed with the station had large errors when compared to the Mesonet. The replacement sensor suffered from communications problems owing to wire connections and was moved from the radiation shield to inside the Raspberry Pi box. The assumption was that there would be minimal difference owing to the openness of the PVC frame and the connection to the radiation shield which would allow for proper air flow for pressure measurements. The BMP280 sensor also had a temperature sensor, but this move to the logger box invalidated the results. The BMP280 pressure compared well with the Mesonet's Vaisala Barometer with a consistent bias of 2.35 hPa (Fig. 7).

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4.4 Wind Speed and Direction

The 3D-printed anemometer had a slow bias throughout the deployment as compared with the Mesonet's RM Young wind monitor. A portion of this could be attributed to the difference in height, ten meters for the Mesonet and two meters for the 3D printed station, but the method for printing and the bearing used likely had a larger impact. The 3D printed anemometer averaged a difference of 1.6 m/s with a larger shift in the bias occurring six-and-a-half months into the deployment (Fig. 8). The anemometer started to degrade and completely sheared off a month later.

The 3D-printed wind vane was held accurately inline with true North by a 3D-printed clamp and bolt. The clamp and bolt routinely loosened over time causing the direction to drift throughout the entire deployment. The alignment was check and adjusted with each maintenance visit, but was short-lived. While there was good agreement at times (Fig. 9), the majority of the deployment was out of sync with the Mesonet. Additionally, a by-product of 3D printing this piece was small grooves in the wind vane which created a ideal location for insects to lay eggs.

4.5 Solar Radiation

While the SI1145 sensor and the Mesonet's Li-Cor Pyranometer did not measure the same radiative components, the components they did measure were comparable (Fig. 10). It is reasonable that a retrieval could be calculated in order to convert the counts to W/m^2. The plastic disc held up to the elements but the glue used to seal it yellowed. 3D-printed connectors routinely lost connection to the UV sensor and tape had to be applied to hold it together. The tape did not completely fix the issue as their were intermittent outages throughout the deployment.

4.6 Precipitation

Efforts to increase the sturdiness of the funnel failed as the funnel had broken off at the neck on the initial installation. A thick layer of silicone caulk was applied to the break, ensuring that opening stayed clear. The funnel was planned to be replaced on failure, however, that failure did not occur. The 3D-printed rain gauge performed surprisingly well in liquid precipitation events as compared with the Mesonet's MET One tipping bucket rain gauge (Fig. 11). The 3D-printed nut holding the rain gauge had come loose at some point towards the end of the deployment and the rain gauge had disconnected and fallen off. Neither the Mesonet nor the 3D-printed rain gauge were heated, so the differences in precipitation measured during solid precipitation events could be attributed to different melt rates between the gauges. The funnel was printed with gray filament due to limited supplies of the white ASA filament and was more exposed to the environment than the Mesonet gauge, both of which could contribute to different melt rates.

4.7 3D-Printed Components

As previously mentioned, some of the 3D-printed components failed (anemometer, rain gauge funnel) or routinely disconnected but overall the components and the frame held up well to the environmental stresses. The decision to reduce the print quality by decreasing the infill and increasing the layer diameter did have a negative impact on some of the components. Issues with the

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wind speed could potentially be attributed to the sturdiness and density not being the same as that of the original design. Water did intrude into the PVC cross-arm, but a few select holes were made to drain the water and no water damage was observed. Holes were initially drilled into the elbow leading into the Raspberry Pi box to prevent water intrusion and worked as expected. In order to account for the additional temperature sensor in the Raspberry Pi box and the eventual relocation of the pressure sensor there as well, block connectors were utilized to simplify connections. These block connectors could easily replace the common rail assemblies in order to reduce the assembly time. The frame and sensor housings that made it to the end of the deployment were donated to the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) education and outreach group.

5 Conclusions

Results showed that many of these low-cost sensors, temperature, pressure, rain gauge, UV, and relative humidity, can be viable options for gathering meteorological datasets when the commercial sensors are too cost prohibitive. The wind sensors did prove problematic, but could be improved with better print quality and different bearings. With the exception of the anemometer shearing off and the rain gauge joint coming lose, the ASA filament did withstand the elements. It is important to note, that while the reduction in print quality did not negatively affect many of the components, there are some where it did to the point of failure. The frame, while not aesthetically pleasing, proved to be extremely sturdy and durable and will continue to serve as mechanism for education and outreach.

Code and data availability. Code and data from the weather station are available at https://github.com/AdamTheisen/3DWxSt

Author contributions. Adam Theisen oversaw the general project, testing sensors, troubleshooting, and performed the final analysis of the data. Max Ungar and Bryan Sheridan were heavily involved throughout the life cycle of the project. They printed the components, developed the frame, built the wiring, assembled the weather station, performed site checks, and resolved problems while in the field. Bradley Illston provided insight and direction for deploying the instrument at the Mesonet site and general recommendations for the project.

Competing interests. The co-PI of the 3D-PAWS initiative, Paul Kucera, was an advisor to Adam Theisen as an undergaduate student at the University of North Dakota.

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The authors also acknowledge Alan Perry for his assistance in the design of the concrete feet to allow for the leveling of the frame.

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Figure 1. 3D-printed weather station initial installation in the field.

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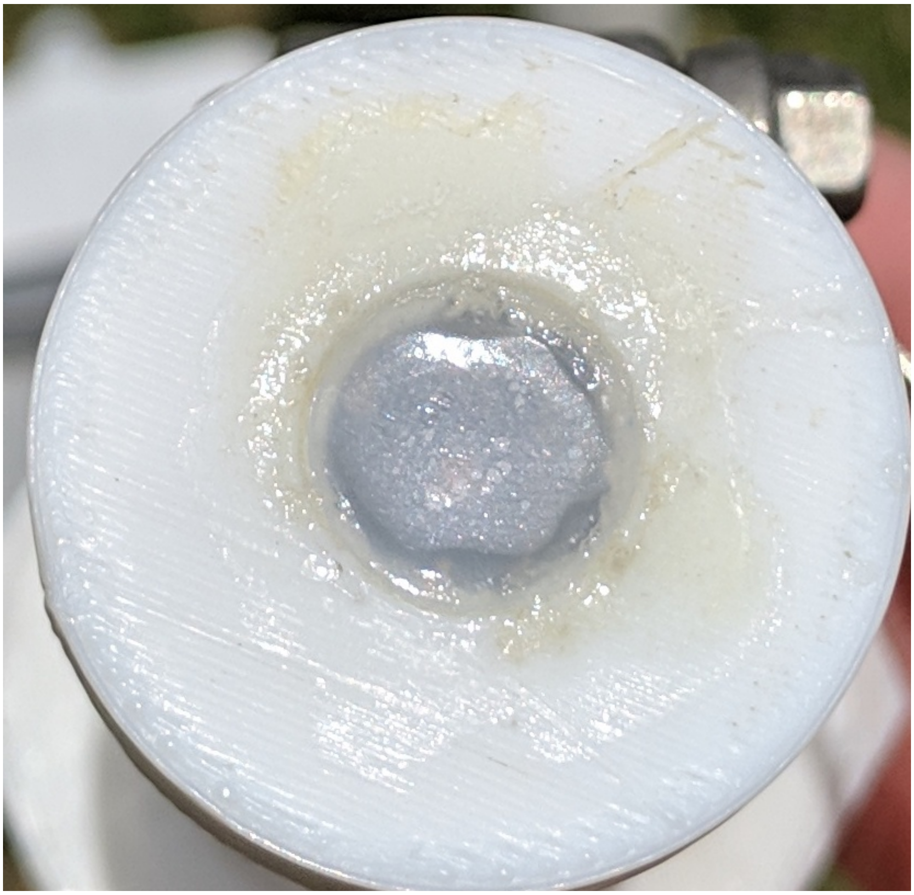

Figure 2. Ultraviolet index sensor using a plastic disc cut from a freezer meal tray. Image taken at the end of campaign shows yellowing of the glue used to seal the edges.

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Figure 3. Location of the 3D-printed weather station relative to the Oklahoma Mesonet (© Google Earth).

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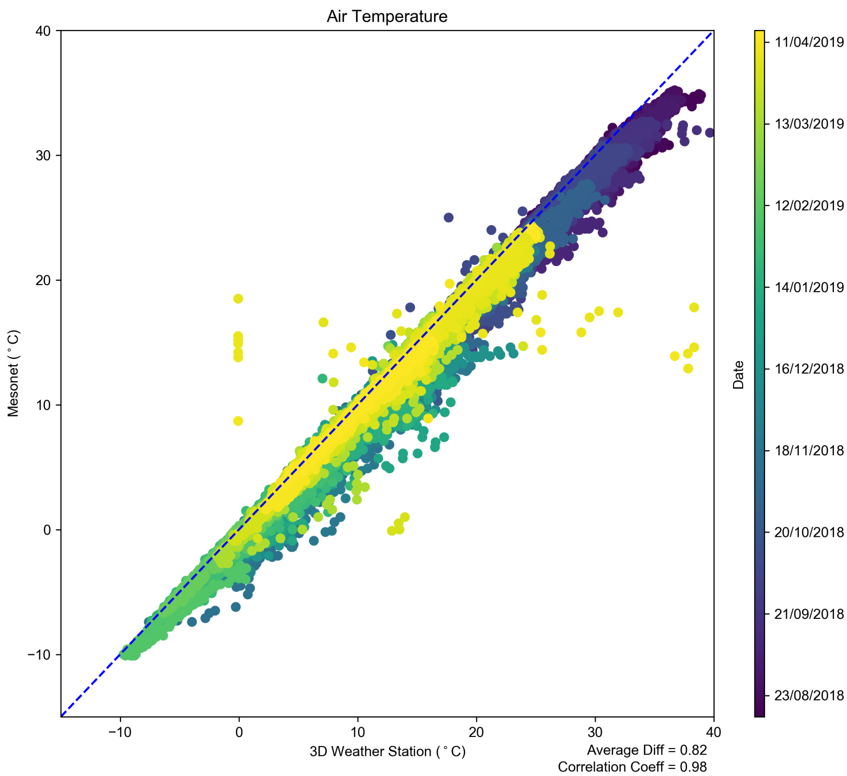

Figure 4. Comparison of the low-cost MCP9808 temperature sensor (x) and the Oklahoma Mesonet (y) for the entire deployment, color-coded by time.

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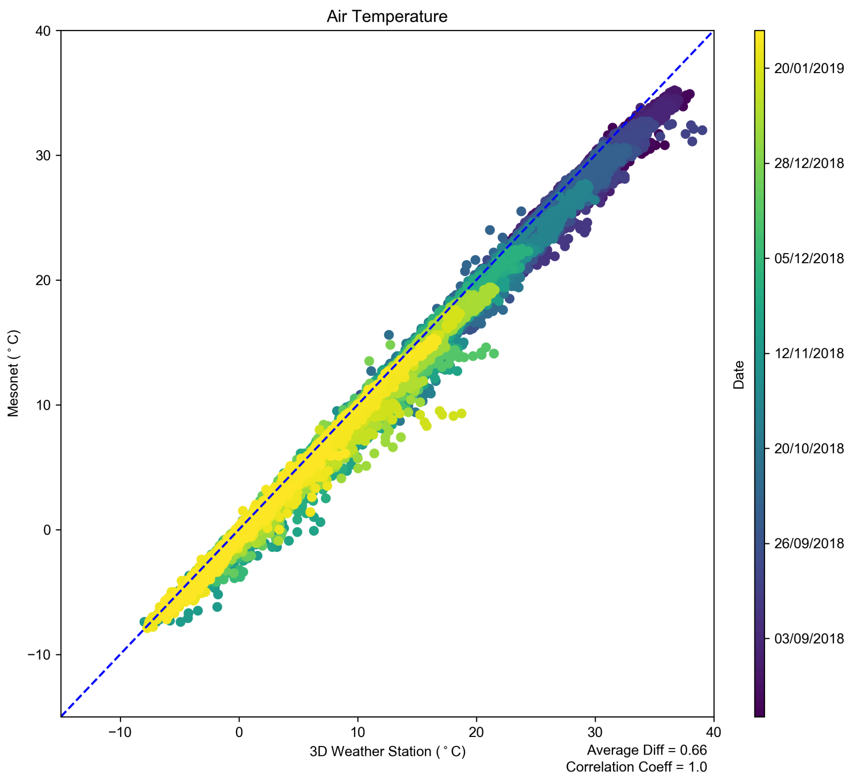

Figure 5. Comparison of the temperature from the low-cost HTU21D sensor (x) and the Oklahoma Mesonet (y) for the entire deployment, color-coded by time.

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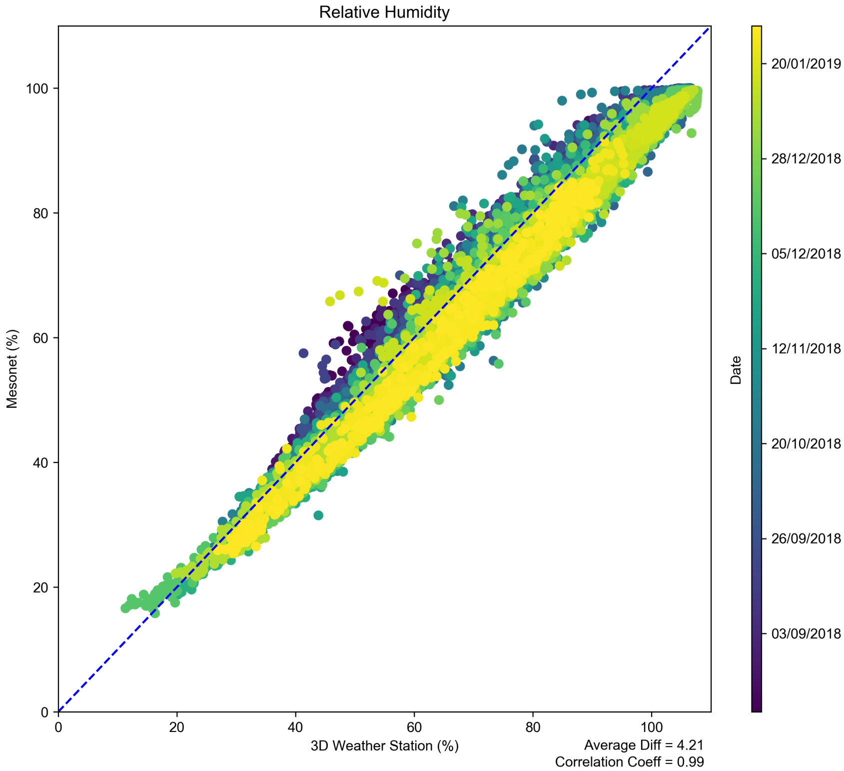

Figure 6. Comparison of the low-cost HTU21D relative humidity sensor (x) and the Oklahoma Mesonet (y) for six-months of the deployment, color-coded by time.

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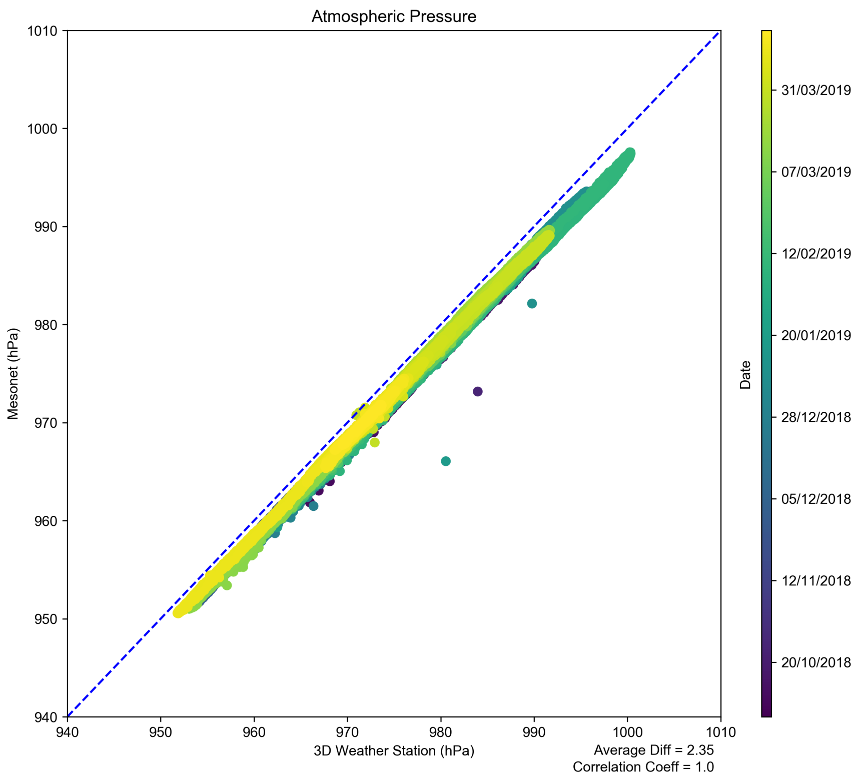

Figure 7. Comparison of the low-cost BMP280 pressure sensor (x) and the Oklahoma Mesonet (y) for the entire deployment, color-coded by time.

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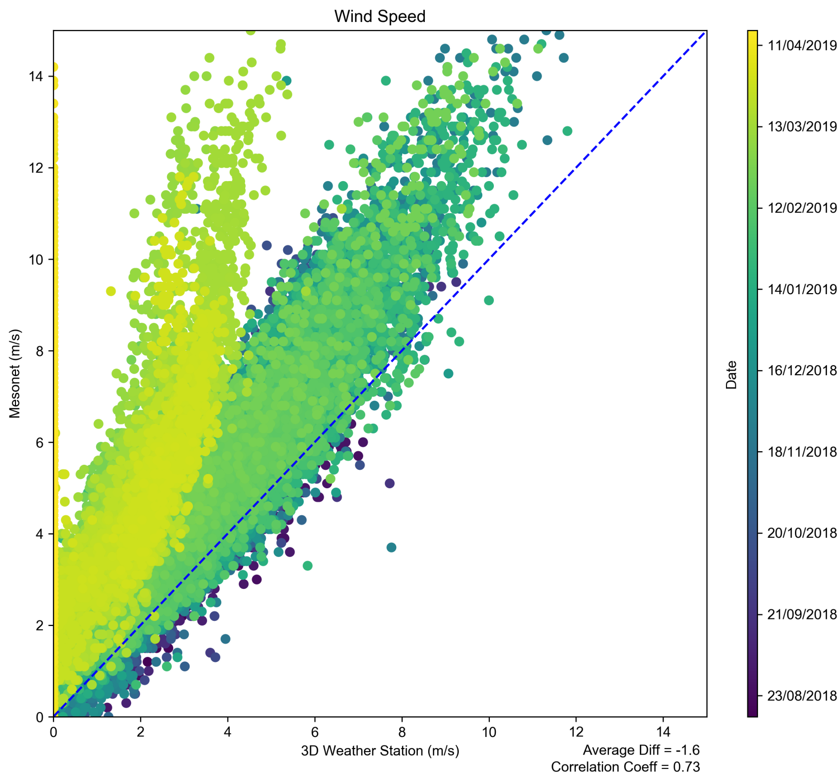

Figure 8. Comparison of the 3D-printed anemometer using a Hall effect sensor (x) and the Oklahoma Mesonet (y) for the entire deployment, color-coded by time.

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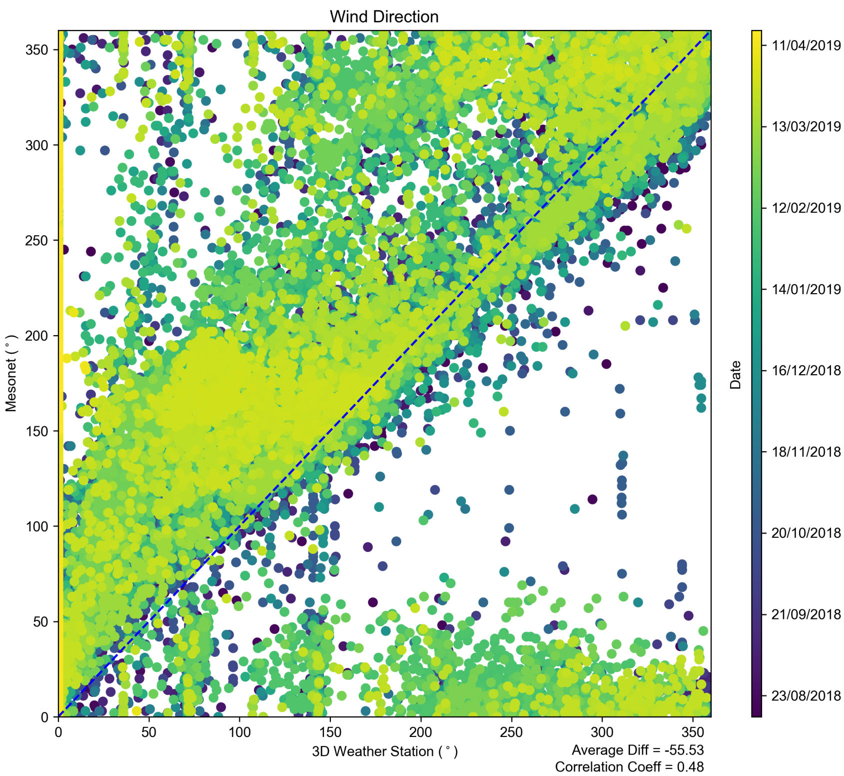

Figure 9. Comparison of the 3D-printed wind vane using a Hall effect rotary sensor (x) and the Oklahoma Mesonet (y) for the entire deployment, color-coded by time.

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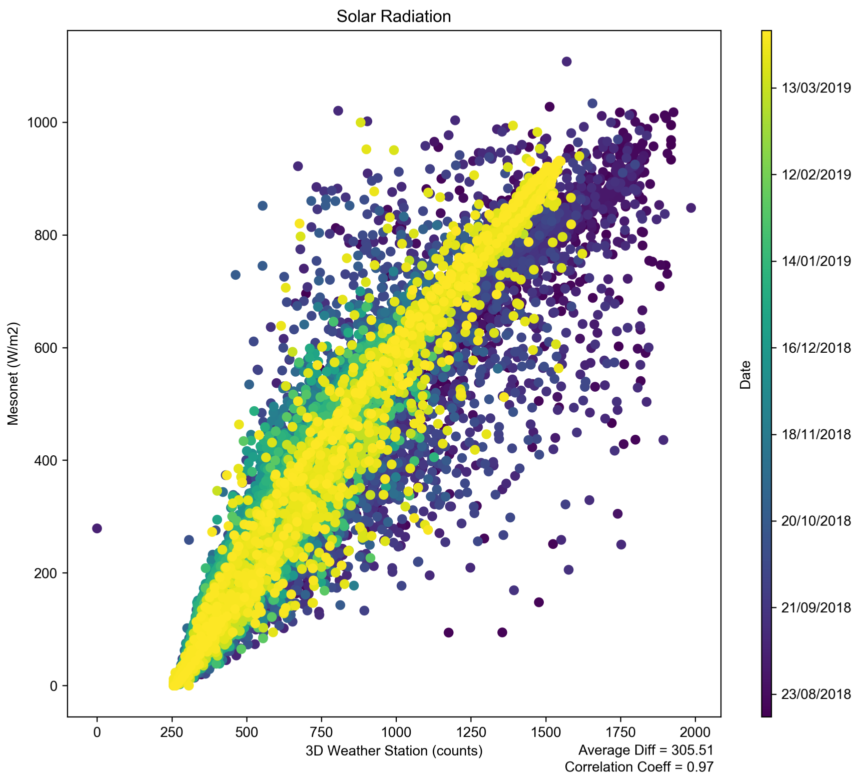

Figure 10. Comparison of the low-cost SI1145 UV sensor (x) and the Oklahoma Mesonet downwelling global solar radiation (y) for the entire deployment, color-coded by time.

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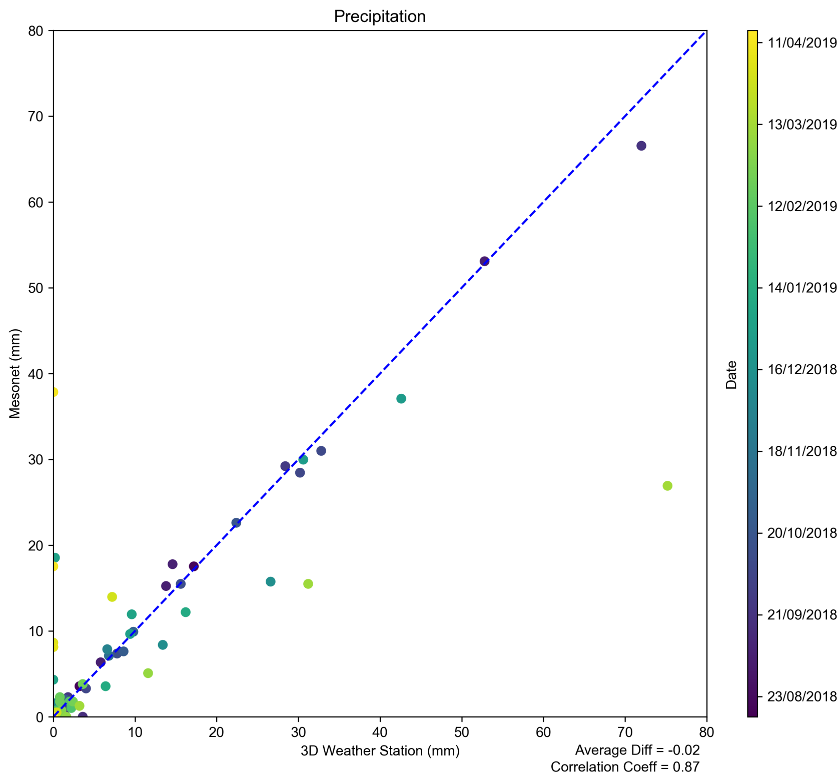

Figure 11. Comparison of the daily precipitation accumulations for the 3D-printed tipping bucket rain gauge using a Hall effect sensor (x) and the Oklahoma Mesonet (y) for the entire deployment, color-coded by time.

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Table 1. 3D-PAWS 10-month sensor evaluation results (Kucera and Steinson, 2017b)

Parameter	Sensor	Resolution	Uncertainty
Air Temperature (°C)	MCP9808	0.1 °C	± 0.4 °C
Atmospheric Pressure (hPa)	BMP280	0.1 hPa	± 0.4 hPa
Relative Humidity (%)	HTU21D	1%	± 5.7%
Wind Speed (m/s)	SS451A	0.1 m/s	± 0.8 m/s
Wind Direction (deg)	Rotary Sensor	1 deg	± 5 deg
UV Index ()	SI1145	0.01	Unknown
Rainfall (mm)	SS451A	0.2 mm	10%

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Table 2. Oklahoma Mesonet Instrumentation

Parameter	Sensor	Accuracy
Air Temperature (°C)	RM Young 41342 RTD Probe	± 0.5 °C
Atmospheric Pressure (mb)	Vaisala Barometer	± 0.4 mb
Relative Humidity (%)	Vaisala HMP155	± 3%
Wind Speed (m/s)	RM Young Wind Monitor	± 0.3 m/s
Wind Direction (deg)	RM Young Wind Monitor	± 3 deg
Solar Radiation	Li-Cor Pyranometer	± 5%
Rainfall (mm)	Met One TBRG	5%