Microclimate and radiant energy measurements using a novel device for natural resource monitoring

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ABSTRACT

12   A novel device for microclimate and radiant energy monitoring of natural resources was

13   compared to known reference instruments and sensors to gauge relative performance under field

14   conditions in Nebraska and New Jersey, USA during summer 2016. For all measurements tested,

15   including air temperature, relative humidity, barometric pressure, four component net radiation,

16   and photosynthetically active radiation, the device reported values near or within the accuracy

17   limits as stated by the reference instrument / sensor manufacturer.

INTRODUCTION

19   Plants live within the bounds of a physical environment that is primarily controlled by

20   local atmospheric conditions, radiant energy, and water and nutrient availability (2). The

21   accurate measurement of ambient air temperature (T_a), relative humidity (RH), and barometric

22   pressure (P_a) above the Earth's surface provides insights into the dynamics of near-surface

23   meteorology and the plant status in the ground-plant-atmosphere continuum of matter and

24   energy. The development of heat stress (1), development of water stress (3), and plant

25   productivity (2) are functions of processes that are controlled by these parameters. The radiation

26   budget at a point can be said to be composed of radiation originating from the sun, termed

27   shortwave radiation, and radiation from the organic and inorganic components of the Earth

28   system, termed longwave radiation. Net radiation, or total incoming subtracting total outgoing

29   radiation, is the quantity of energy available to drive natural processes such as sensible heat

30   exchange, latent heat exchange, and photosynthesis (10). Photosynthetically active radiation

31   (PAR) is the total incident radiation within the 400 nm to 700 nm waveband. Radiation, typically

32   expressed as photon flux density (4) within this waveband is available to plants to drive

33   photosynthetic machinery, the process by which carbon dioxide is assimilated into plant biomass

34   (7). Tables 1 - 2 shows a summary of the accuracy of device measurements, relative to

35   references.

MATERIALS AND METHODS

Air Temperature

The Pulsepod measures T_a within a carefully designed chamber that houses ambient air temperature sensors, including a thermistor and a band-gap temperature sensor, within the air stream below the device. This design serves to thermally isolate the device body from the measurement location, ensuring that the measured T_a is representative of the bulk air surrounding the device. The chamber vents allow air to flow freely over the sensor so that stagnant air (10) is not surrounding the temperature sensor. A Pulsepod measured T_a over a soybean canopy (*Glycine max*) alongside a reference Vaisala HMP50 Temperature and Relative Humidity Sensor (*Vaisala Instruments, Vantaa, Finland*) housed within a radiation shield and mounted at the same measurement height over the canopy (Fig. 1 - 2). The Vaisala HMP50 temperature sensor is a 1000 Ω platinum resistance thermometer with a manufacturer stated accuracy of ± 1.5°C across the temperature range -40°C to 60°C (12). Data shown were collected at the University of Nebraska Carbon Sequestration Program (b) Site 3 at Mead, NE in June, 2016. Device measurement height was five meters. Site coordinates are: 41.179665, -96.439336.

Relative Humidity

Relative humidity (*RH*) is defined as "the ratio of actual amount of water vapor in the air compared to the equilibrium (saturation) amount at a given temperature" (8). *RH* is in part a function of the ambient air temperature, so the accuracy of the temperature measurement propagates into the accuracy of the *RH* measurement. The Pulsepod measures relative humidity in the same chamber as it measures air temperature, using a capacitive detection method. The location within the chamber permits ongoing *RH* measurements of free air around the device body. The reference *RH* sensor is the Vaisala INTERCAP capacitive chip (12). Data shown were

[a] Rutgers University Photochemical Assessment Monitoring (PAM) Site
(http://pamsite.rutgers.edu/sub_data_display/met_tower.php)

[b] University of Nebraska Carbon Sequestration Site (UNL CSP) (http://csp.unl.edu/Public/)

59   collected at the University of Nebraska Carbon Sequestration Program (b) Site 3 at Mead, NE in

60   June, 2016 (same as air temperature reference location).

61   *Barometric Pressure*

62   Barometric pressure (*Pa*), or atmospheric pressure, is defined as "the total force per unit

63   area acting isotropically on a body within the atmosphere" (11). It is the resultant force of all

64   atmospheric particles above a sensor location. With an increase in elevation, the total

65   atmospheric pressure is reduced, while the short-term fluctuations in *Pa* are closely tied to

66   changing weather conditions. The Pulsepod measures *Pa* with a compact piezoresistive sensor

67   that responds to changes in local pressure conditions. The *Pa* reported by the Pulsepod is

68   compared to the *Pa* as reported by the reference sensor, RM Young 61302V (*RM Young,*

69   *Traverse City, MI*) with a manufacturer stated accuracy of 0.05% ($\pm$ 1 σ) over the analog

70   pressure range (9). Data shown were collected at the Rutgers University Photochemical

71   Assessment Monitoring Site (a) at New Brunswick, NJ in August, 2016. Device measurement

72   height was two meters. Site coordinates are: 40.462204, -74.429499.

Figure 1. Arable Pulsepod deployed at five meter height above soybean canopy.
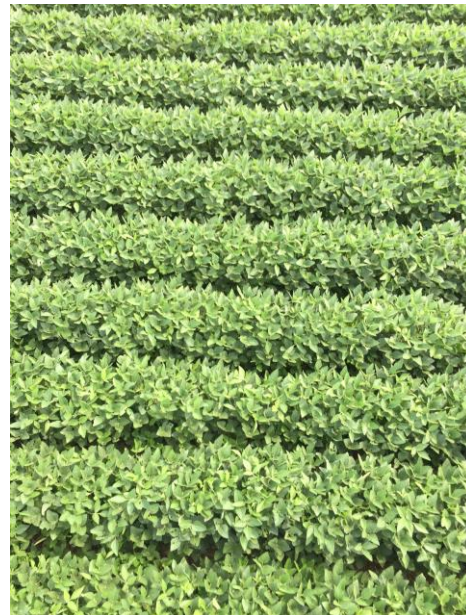
Figure 2. Soybean canopy below measurement location.

73 *Net Radiation*

74   The components of net radiation are shortwave (downwelling and upwelling) and

75 longwave (downwelling and upwelling). The Pulsepod measures these four components

76 separately, using four separate sensors with upward and downward orientations. The upward

77 facing sensors respond to incident radiation from the sun and atmosphere, and provide the

78 downwelling measurements while the downward facing sensors respond to radiation from the

79 Earth - the upwelling components of net radiation. The Pulsepod shortwave sensor response is

80 calibrated against the response of a reference pyranometer, within the Kipp and Zonen CNR4

81 Net Radiometer (*Kipp and Zonen B.V., Delft, The Netherlands*) under field conditions. The

82 longwave sensor responsivities have also undergone a field calibration using a reference object

83 (sky and surface) temperature provided by the blackbody temperature equivalent of the thermal

84 energy as measured by a reference pyrgeometer, within the Kipp and Zonen CNR4 Net

85 Radiometer. The effective blackbody temperature is used to calculate the longwave energy using

86 the emissivity of a blackbody ($\mathcal{E}$=1) and the Stefan-Boltzmann Law (8). The reference longwave

87 measurement was compensated for changes in instrument body temperature prior to performing

88 calibration. The longwave energy as measured by the Pulsepod is a function of a die temperature

89 (*Tdie*) and a voltage generated in response to incident longwave energy (*Vobject*). The spectral

90 response of the reference pyranometer is from 300 nm to 2800 nm and is calibrated according to

91 ISO 9847:1991 and considered ISO First Class (WMO Good quality). Reference manufacturer

92 uncertainty is stated at 5% at the daily total level (95% confidence interval) for shortwave energy

93 and <10% at the daily total level (95% confidence interval) for longwave energy (5). Reference

94 shortwave energy is the total radiant energy between 300 nm and 2800 nm. Reference longwave

95 energy is the total radiant energy between 4.5 µm and 42 µm. Data shown were collected at the

96 University of Nebraska Carbon Sequestration Program (b) Site 3 at Mead, NE in June, 2016.

97 Device measurement height was five meters. Site coordinates are: 41.179665, -96.439336.

98 *Photosynthetically Active Radiation (PAR)*

99   The Pulsepod measures downwelling PAR, which enables an understanding of the

100 instantaneous and daily total PAR available from a source. A Pulsepod was deployed alongside

101 an LI-190 Quantum Sensor (*LI-COR, Inc. Lincoln, NE*), with upward facing orientation. The

102 reference sensor has a manufacturer stated accuracy of ± 5% (6). Data shown were collected at

103 same location as net radiation measurements.

RESULTS

105 Figures 3 and 4 show Ta as measured by a Pulsepod and by the reference instrument

106 under the same conditions. The range of temperatures measured under the test conditions was

107 from 16.9°C to 30.7°C. Data shown reflect a thirty-minute average of five-minute measurements

108 (Pulsepod) and a thirty-minute average of five-second measurements (reference). The average

109 wind speed, as reported by an anemometer mounted at the same measurement height above the

110 canopy, varied between 0.4 m/s and 4.5 m/s over the course of the comparison with a diurnal

111 pattern represented in Fig. 3.
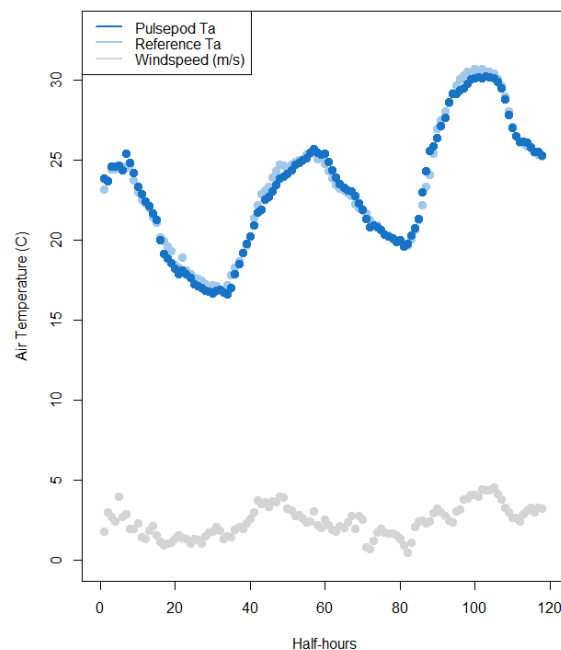
Figure 3. Diurnal time-series of T_a as measured by a Pulsepod (dark blue) and by the reference (light blue). Average windspeed is shown in gray.
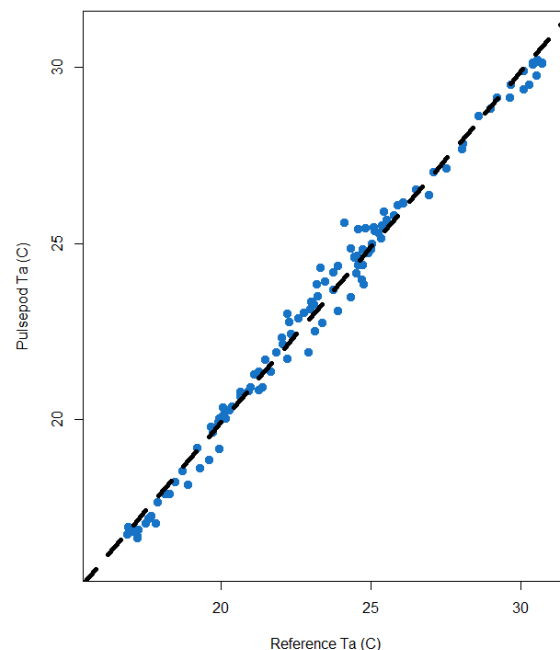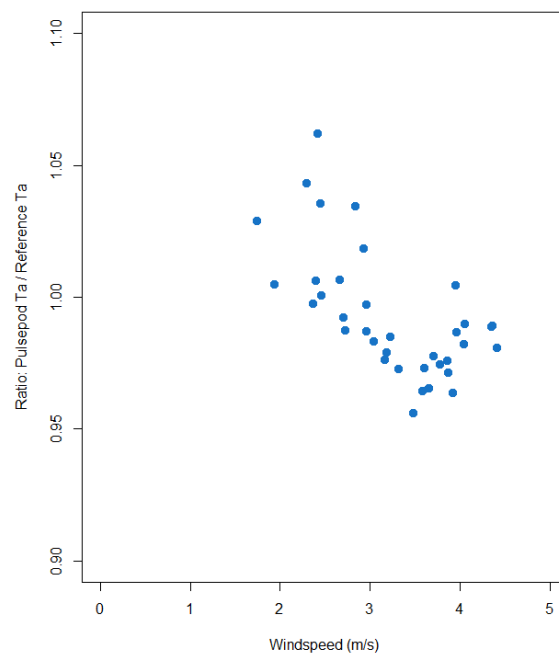
Figure 4. 1:1 of T_a as measured by a Pulsepod and by the reference. R^2: 0.99.

112 The relative error ratio of the Pulsepod temperature to the reference is shown in Fig. 5-6.

113 Fig. 5 shows the ratio of measured air temperature with wind speed from 0 to 5 m/s, during

114   periods with irradiance values less than 300 Wm^{-2}. Figure 6 shows the ratio of measured air

115   temperature during periods with wind speed from 0 to 5 m/s, with irradiance values at or above

116   300 Wm^{-2}. During periods of time with calm conditions (< 2 m/s) and irradiance below 300 Wm^{-}

117   ^{2}, the Pulsepod reports air temperature to within +2% and -4% of the reference instrument.

118   During periods of time with moderate wind speeds (greater than 2 m/s) and low radiative load

119   (less than 300 Wm^{-2}), the Pulsepod reports air temperature to within +3% and -2% of the

120   reference instrument. During periods of time with moderate wind speeds (greater than 2 m/s) and

121   greater radiative load (more than 300 Wm^{-2}), the Pulsepod reports air temperature to within +6%

122   and -4% of the reference instrument. During periods of time with calm winds (less than 2 m/s)

123   and greater radiative load (more than 300 Wm^{-2}), the Pulsepod reported a maximum relative

124   error of +3%. The mean relative error ratio during this comparison, including all wind speed and

125   radiation conditions, is 1.00, with a standard deviation of 0.02.
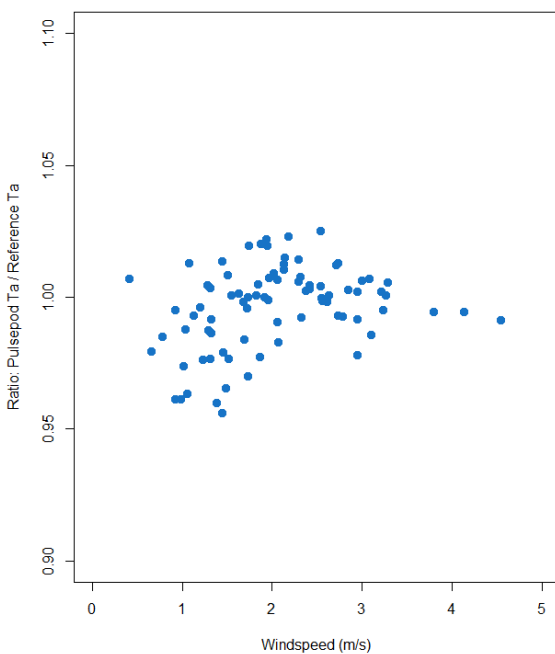
Figure 5. Relative error of Pulsepod *Ta* to reference *Ta* during periods with < 300 Wm^{-2}.

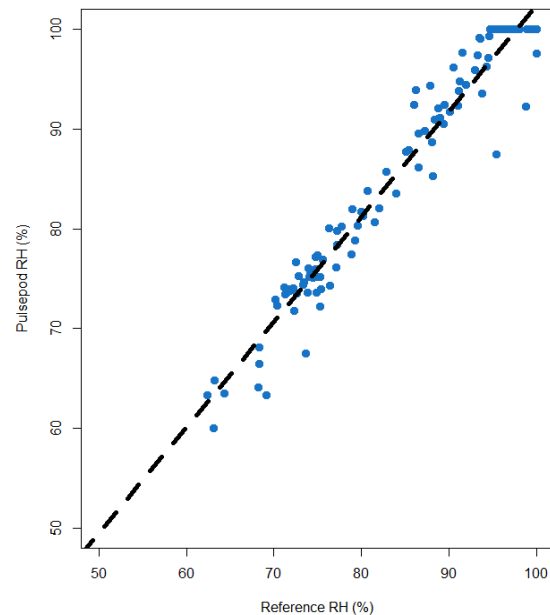**Figure 6.** Relative error of Pulspeod *Ta* to reference *Ta* during periods with ≥ 300 Wm^{-2}.

126   Figures 7 and 8 show *RH* as measured by a Pulsepod and the Vaisala HMP50

127   Temperature and Relative Humidity Sensor under the same environmental conditions. The
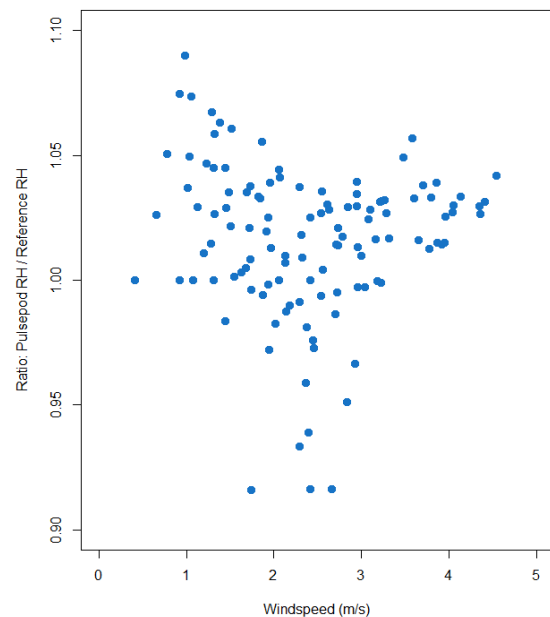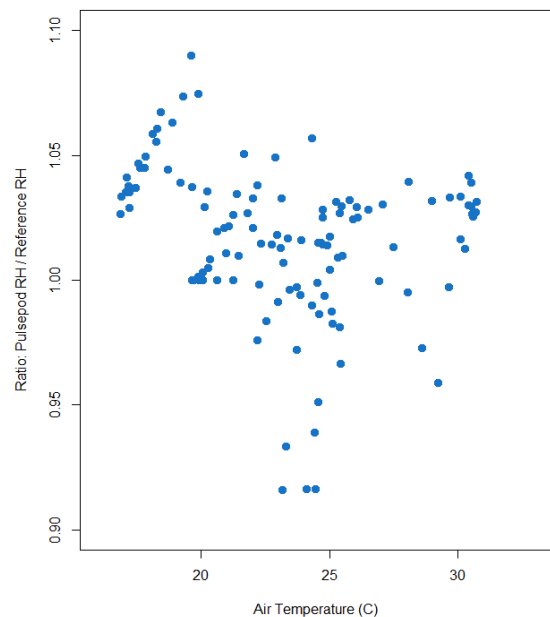
128 reference has a manufacturer stated accuracy of ± 3% over the range 0 to 90% *RH* and ± 5% over

129 the range 90 to 95% *RH* (8).
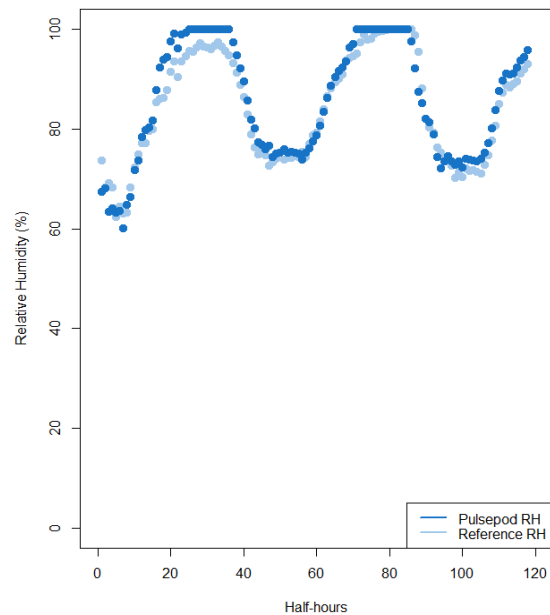
Figure 7. Diurnal plot of *RH* as measured by the Pulsepod and by the reference.

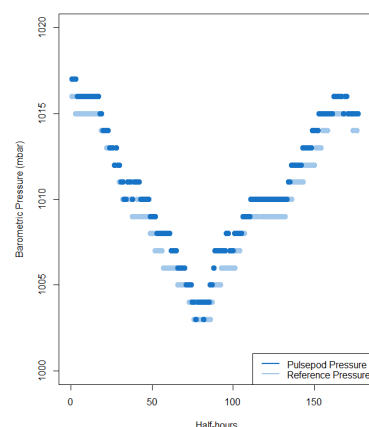**Figure 8.** 1:1 of *RH* as measured by the Pulsepod and the reference. R^2: 0.95.

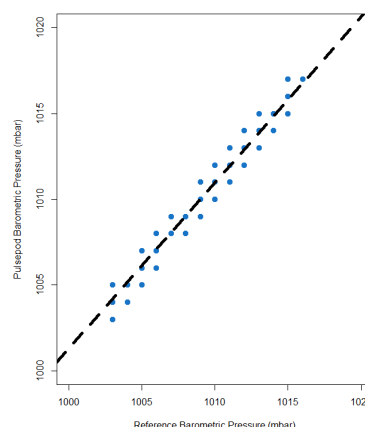**Figure 9.** Relative error of Pulsepod *RH* to reference as a function of air temperature.

Figure 10. Relative error of Pulsepod *RH* to reference as a function of wind speed.

130   Figure 9 shows the ratio of Pulsepod *RH* to reference *RH* as a function of the ambient air

131   temperature, and Fig. 10 shows the ratio as a function of wind speed. The maximum relative

132   error ratio under all conditions was 1.09. The mean relative error ratio during this comparison is

133   1.02 with a standard deviation of 0.03. There is a reduction in relative error when wind speeds

134   exceed 3 m/s.

135   Figure 11 shows the time series of barometric pressure as measured by the Pulsepod and

136   the reference. Figure 12 shows the 1:1 relationship between the Pulsepod and reference, and Fig.

137   13 shows the relative error of pressure as measured by the Pulsepod and the reference. The mean

138   relative error ratio is 1.00 with a standard deviation of .0005.

Figure 11. Barometric pressure as measured by the Pulsepod (dark blue) and by the reference (light blue).

**Figure 12.** 1:1 Barometric pressure as measured by the Pulsepod and reference. R^2: 0.99.
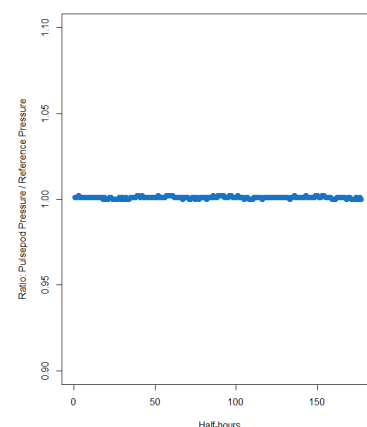
**Figure 13.** Relative error of Pulsepod barometric pressure to reference.

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141   Figure 14 shows the time-series of longwave and shortwave energy as measured by the

142   Pulsepod and the reference net radiometer under field conditions. Each data point represents a

143   thirty-minute average of five-minute measurements (Pulsepod) and a thirty-minute average of

144   five-second measurements (reference). The Pulsepod measured cumulative net radiation over the

145   course of three separate days (Fig. 15), with a mean relative error for each day of 0.94 and

146   standard deviation of 0.04. After 128 half-hour periods, the cumulative relative error for net

147   radiation was also 0.94. The mean relative error at the daily level for shortwave energy (using

148   downwelling sensors for comparison) was 0.97 with a standard deviation of 0.003. The mean

149   relative error at the daily level for longwave energy (using the upwelling sensors for comparison)

150   was 1.00 with a standard deviation of 0.02. Figures 16-18 show the 1:1 relationship between net

151   shortwave energy, net longwave energy, and net radiation as measured by the Pulsepod and the

152   reference net radiometer.
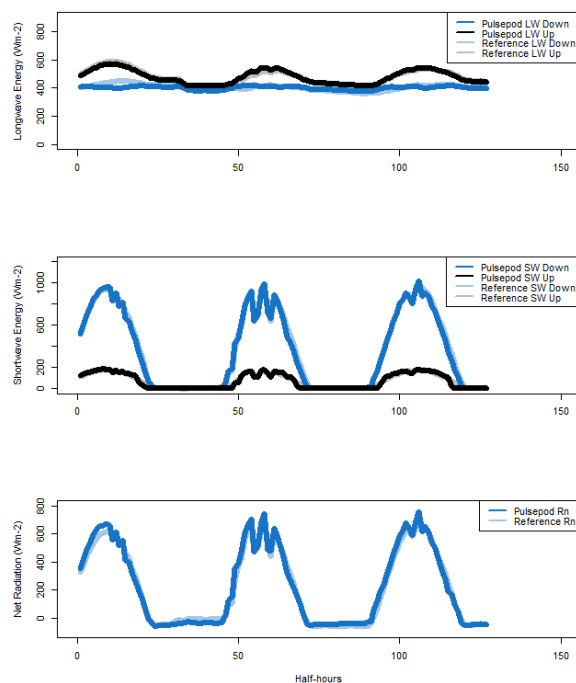
Figure 14. Time-series of longwave, shortwave, and net radiation as measured by the Pulsepod and the reference net radiometer under field conditions.
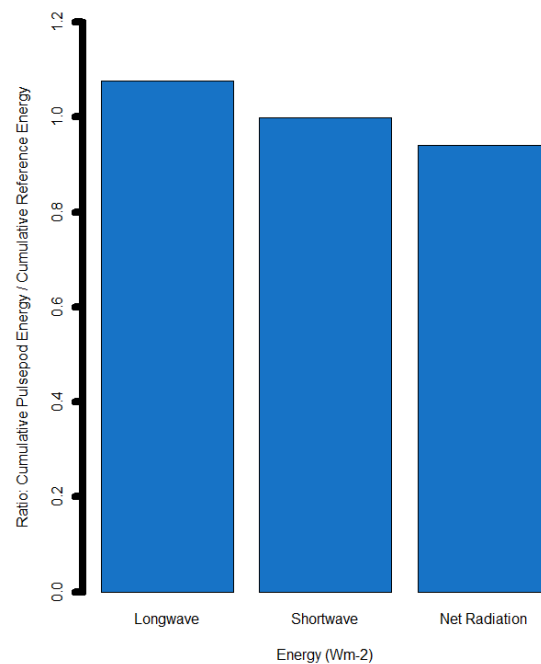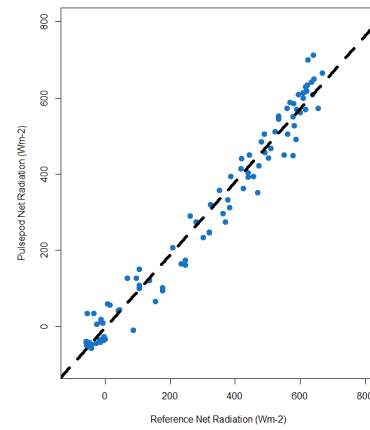
Figure 15. Relative error for cumulative net shortwave radiation, cumulative net longwave radiation, and cumulative net radiation over the course of three days. Cumulative relative error for net radiation after 128 half-hours was 0.94.
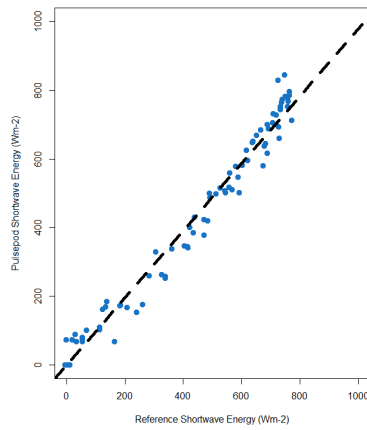
**Figure 16.** Pulsepod and reference net shortwave energy ($R^2 = 0.98$).
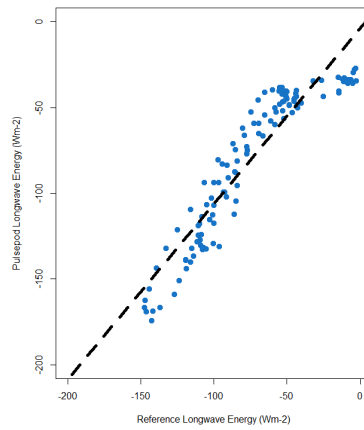
**Figure 17.** Pulsepod and reference net longwave energy ($R^2 = 0.87$).

Figure 18. Pulsepod and reference net radiation ($R^2 = 0.98$).

153   Figure 19 shows the timeseries of PAR as measured by the Pulsepod and the reference

154   sensors. Figure 20 shows the 1:1 relationship between the Pulsepod and reference when

155   measuring downwelling PAR. The Pulsepod measured cumulative downwelling PAR over the

156   course of three separate days (Fig. 19), with a mean relative error for each day of 0.95 and

157   standard deviation of 0.006. After 128 half-hour periods, the cumulative relative error was also

158   0.95.

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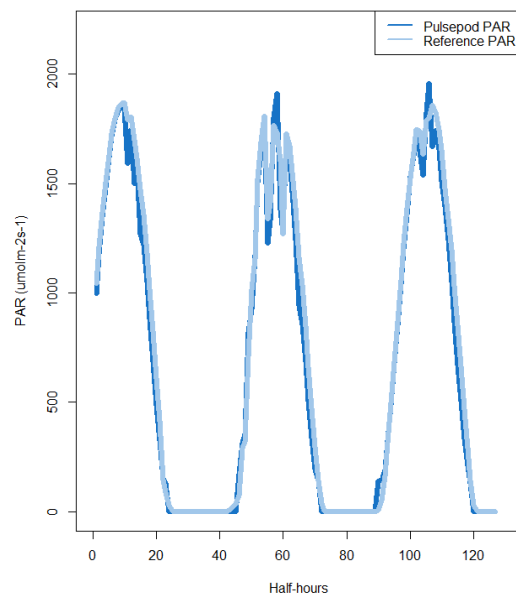
Figure 19. Time-series of downwelling PAR as measured by the Pulsepod and the reference sensor.
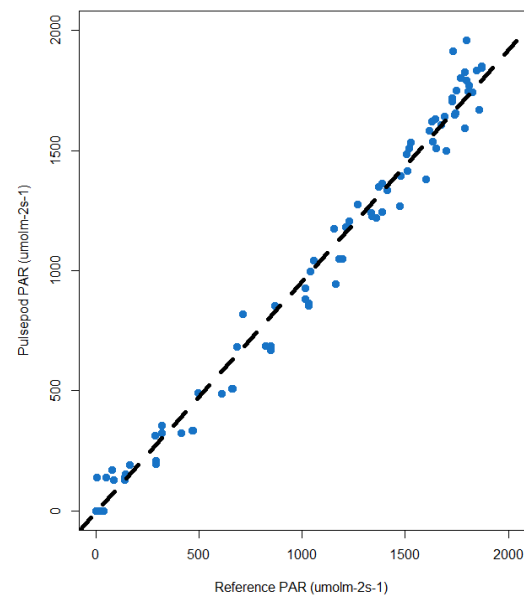
Figure 20. Pulsepod and reference downwelling PAR ($R^2 = 0.98$)

DISCUSSION AND CONCLUSIONS

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163   The device reports the microclimate and radiometric measurements near or within the

164   accuracy limits stated by the reference manufacturers for the measurements shown in this

165   comparison. Standard weather station variables were reported to within 4% of reference (air

166   temperature), 6% of reference (relative humidity) and 0.1% of reference (barometric pressure).

167   The device reported net radiation to within 10% (Table 2) of the reference at the daily total level.

168   The downwelling longwave component of radiation shows the greatest variability (Fig. 17) for

169   net radiation components, which could be due to the changing emissivity of the sky during the

170   course of the study. Further work could identify changing emissivity over time, and incorporate

171   these changing values into the calculation of longwave energy for improved accuracy.

172

173   Table 1. Pulsepod sensor accuracy, relative accuracy, and manufacturer stated accuracy for

174   microclimate measurements.

Measurement	Pulsepod Sensor Accuracy	Pulsepod to Reference Relative Accuracy	Reference Manufacturer Accuracy
Air Temperature	± 0.75°C over the range -40 to 125°C	≤ 4% of measurement (mean relative error ± one σ)	± 1.5°C over the temperature range -40°C to 60°C
Relative Humidity	± 3% *RH* over the range 0 to 100%	≤ 6% of measurement (mean relative error ± one σ)	± 3% *RH* over the range 0 to 90% *RH* and ± 5% over the range 90 to 95% *RH*
Barometric Pressure	± 4 mbar over the pressure range 500 to 1100 mbar	≤ 0.1% of measurement (mean relative error ± one σ)	≤ 0.05% over analog pressure range (± one σ)

175

176   Table 2. Pulsepod measurement accuracy relative to reference and manufacturer stated accuracy

177   for radiant energy measurements.

Measurement	Pulsepod to Reference Relative Accuracy	Reference Manufacturer Accuracy
Shortwave Energy	≤ 4% at the daily total level of downwelling energy (mean error ± one σ)	5% at the daily total level (95% confidence interval)
Longwave Energy	≤ 4% at the daily total level of upwelling energy (mean error ± one σ)	< 10% at the daily total level (95% confidence interval)
Net Radiation	≤ 10% at the daily total level (mean error ± one σ)	Not stated
PAR	≤ 6% at the daily total level (mean error ± one σ)	± 5% traceable to the U.S. National Institute of Standards and Technology

178

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181   Nebraska in facilitating data access and field support over the course of the study.

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184 **REFERENCES**

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186   temperature in higher plants." *Annual Review of Plant Physiology* 31.1 (1980): 491-543.
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