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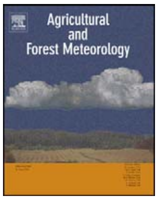

Evaluation of measurement accuracy and comparison of two new and three traditional net radiometers

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ABSTRACT

Net radiation (R_n) is the sum of the radiant energy at the Earth's surface and is a major component of the surface energy balance. However, R_n is difficult to measure accurately, and multiple instruments are available to measure it. Two new instruments (Hukseflux Thermal Sensors B.V., model NR01; Kipp & Zonen B.V., model CNR 2) have been released within the past two years. We compared these models, two less-expensive older models (Kipp & Zonen B.V., model NR-Lite; Radiation and Energy Balance Systems, Inc., model Q*7.1), and a more expensive older model (Kipp & Zonen B.V., model CNR 1) over a uniform turfgrass surface for 33 days in mid-summer. Three replicates of each radiometer were included in the study (except for the CNR 1). The instruments that independently measure the four components of R_n (models CNR 1 and NR01) were typically the most accurate. Incoming shortwave measurements from the four component instruments were compared to a reference pyranometer, and outgoing longwave measurements were compared to infrared measurements of surface temperature. The differences from the reference pyranometer and surface temperature measurements were typically 2% or less. There was a difference of approximately 5% in incoming longwave measurements between these two radiometer models. This is likely due to differences in calibration approaches, which are discussed. This emphasizes the need for standardization of longwave calibration methods and establishment of a world reference for longwave radiation. The instruments that do not separate shortwave and longwave radiation into component measurements (net all-wave radiometers, models NR-Lite and Q*7.1) were generally the least accurate, and had offsetting day and night differences that reduced daily total R_n differences relative to the reference. The CNR 2 measures net shortwave and net longwave, and is an intermediate between a four component instrument and a net all-wave instrument. The R_n measurement accuracy of the CNR 2 typically fell between that of the two groups. Differences among radiometers tended to be larger at night than during the day, indicating higher variability in longwave measurements. An inversion (flip) test in the field showed the NR-Lites and Q*7.1s had well matched detectors, however two of the three replicate CNR 2s had mismatch errors greater than 5%. This becomes important for measurements over non-vegetated surfaces. The data presented here should be helpful in selecting the most cost effective instrument for a given application.

1. Introduction

Radiant energy from the sun and the Earth's atmosphere is the source of energy at the Earth's surface. The difference between incoming and outgoing energy at the surface, net radiation, is used to evaporate water, heat the air and soil, and drive photosynthesis, but it is difficult to measure accurately. Accurate measurements of net radiation are essential in studies of global climate change, where the available energy at the Earth's surface plays a major role in the surface thermal state and energy balance, which has direct controls on atmosphere and ocean circulation, and ultimately, Earth's climate. Foken (2008) summarized surface energy balance closure errors for multiple studies and listed typical closure errors on the order of 10–30%. A potential source of energy balance closure error is net radiation measurement inaccuracy. Foken (2008) listed net radiation measurement uncertainty at 10–20%.

Net radiation (R_n) is comprised of shortwave (SW) and longwave (LW) components and is the sum of net SW and net LW radiation at the Earth's surface, where the net values are the differences between incoming (downwelling) and outgoing

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(upwelling) components:

$$R_n = (SW_i - SW_o) + (LW_i - LW_o) \qquad (1)$$

where SW_i is incoming shortwave, SW_o is outgoing shortwave, LW_i is incoming longwave, LW_o is outgoing longwave, $(SW_i - SW_o)$ is net shortwave (SW_n), $(LW_i - LW_o)$ is net longwave (LW_n), and all terms are generally expressed in units of W m^{-2}.

There are four basic designs of net radiometers. The most sophisticated uses individual upward and downward facing pyranometers (SW sensors) and pyrgeometers (LW sensors) to independently measure the four components of R_n (e.g. Hukseflux Thermal Sensors B.V., Delft, The Netherlands, model NR01; Kipp & Zonen B.V., Delft, The Netherlands, model CNR 1). Four component net radiometers provide the most information, but are the most expensive due to the number of individual radiometers. The second type measures SW_n and LW_n independently with separate SW and LW sensors (transducers) (e.g. Kipp & Zonen B.V., Delft, The Netherlands, model CNR 2). The SW and LW transducers each have upward-facing and downward-facing sensor surfaces (detectors), thus the output from each transducer is dependent on the net difference between the two detectors. The third type measures downwelling (SW_i and LW_i) and upwelling (SW_o and LW_o) radiation independently with an upward-facing transducer and detector combination and a downward-facing transducer and detector combination (e.g. Philipp Schenk GmbH Wien & Company, Vienna, Austria, model 8111). The detectors are sensitive to SW and LW (all-wave) radiation and the transducer outputs are proportional to downwelling or upwelling radiation. The most basic net radiometer design uses a single transducer with upward-facing and downward-facing detectors (e.g. Kipp & Zonen B.V., Delft, The Netherlands, model NR-Lite; Radiation and Energy Balance Systems (REBS), Inc., Seattle, WA, USA, model Q*7.1; CSD Middleton Solar Instruments, Yarraville, Victoria, Australia, model CN1-R). The detectors are sensitive to SW and LW (all-wave) radiation and the single transducer output is proportional to R_n. This type is referred to as a net all-wave radiometer. For a more detailed discussion of net radiometer design and function see Campbell and Diak (2005).

Halldin and Lindroth (1992) investigated six different net radiometer designs and evaluated and compared the measurement errors with each design using a four component Eppley system (The Eppley Laboratory, Inc., Newport, RI, USA) as the R_n reference. The purpose of their study was to evaluate and compare different radiometer designs, not specific radiometer models. They reported differential sensitivity to SW and LW components of R_n for those instruments that use a single detector to measure SW and LW collectively. In all cases, the radiometers were less sensitive to LW compared to SW. They recommended that calibration of pyrgeometers be carried out under field conditions to overcome some of the limitations of laboratory calibration, and they reiterated the need for a reference standard for LW calibration. They recommended exterior ventilation under all conditions to ensure highest measurement accuracy.

Duchon and Wilk (1994) compared a predecessor to the Q*7.1 to a four component Eppley system and found that the net all-wave radiometer was less sensitive to LW radiation compared to SW, introducing errors under variable field conditions, for example, day versus night and cloudy versus sunny.

Kustas et al. (1998) compared one Swissteco (model S-1) and 12 REBS net radiometers (models Q*6, Q*7, and Q*7.1) over wet and dry surfaces in an arid environment. They found significant differences in the measurements from the REBS radiometer models over wet and dry surfaces. When the REBS instruments were cross-calibrated, the differences were greatly reduced. They also found a difference between the REBS instruments and the Swissteco radiometer for dry conditions, and could not cross-calibrate the instruments to match under all conditions. They concluded that spatial distribution of R_n over a variable surface should be measured with cross-calibrated radiometers of the same model. They suggested that energy and water balance studies are often limited by net radiometer accuracy and that there is a need for improved radiometer designs and calibration procedures in order to improve R_n measurement accuracy.

Brotzge and Duchon (2000) compared seven NR-Lites to a four component Eppley system, a CNR 1, and a Q*7.1. They found the replicate NR-Lites matched each other well, but underestimated R_n relative to the measurements from the other radiometers, by 8–13% when compared to the Eppley system. They also measured differences between the Eppley system and CNR 1, where the CNR 1 generally gave low R_n measurements relative to the Eppley system, and attributed the R_n differences to differences in LW measurement. Dome heating and solar radiation interference were reported as the likely cause of the LW measurement differences. They found the presence of precipitation and condensation had a significant impact on the measurements and reliable measurements could only be obtained when all precipitation and condensation had evaporated, particularly for the NR-Lite, due to the lack of shielding domes over the detectors. They reported larger errors for the NR-Lite due to wind as compared to the domed radiometers, and they developed a correction based on measured wind speed. They concluded the NR-Lite was suitable for long-term, remote measurements of R_n.

Cobos and Baker (2003) compared an NR-Lite and Q*7.1 to a four component Eppley system and found the NR-Lite agreed well with the Eppley system under most field conditions, and often agreed better than the Q*7.1. Like Brotzge and Duchon (2000), they found the NR-Lite was very sensitive to precipitation and condensation because of a lack of shielding domes over the radiation detectors, resulting in significant downtime (until all water evaporated) following precipitation and condensation. They also found the NR-Lite was about 15% less sensitive to LW than to SW radiation. They subsequently compared seven NR-Lites to the Eppley system and found good agreement among all seven NR-Lites, but they averaged 14% low relative to the Eppley system. Despite these shortcomings, they concluded the NR-Lite was suitable for a variety of field measurements.

Michel et al. (2008) compared two CNR 1s to a four component Kipp & Zonen system (made up of pyranometers and pyrgeometers calibrated to the radiation references at the World Radiation Center at Davos, Switzerland) over a one-year period in the field. One of the CNR 1s was installed with a heating and ventilation system and the other was not. They found larger uncertainty in SW components versus LW, and larger uncertainty in incoming versus outgoing components. The difference of the heated and ventilated radiometer from the reference measurement was reduced when individual calibration factors were derived from the field data for each component sensor, rather than relying on factory calibration factors. The radiometer that was not heated and ventilated did not show improvement when individual calibration factors were derived from the field data.

Two new net radiometer models have been released within the past two years, the Hukseflux model NR01 and Kipp & Zonen model CNR 2. The objective of this study was to compare the two new models to three existing models (Kipp & Zonen model CNR 1, Kipp & Zonen model NR-Lite, and REBS model Q*7.1) and evaluate the accuracy and performance of all models over a uniform vegetated surface in mid-summer.