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Short communication

Design and evaluation of an inexpensive radiation shield for monitoring surface air temperatures

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ABSTRACT

Inexpensive temperature sensors are widely used in agricultural and forestry research. This paper describes a low-cost (∼3 USD) radiation shield (radshield) designed for monitoring surface air temperatures in harsh outdoor environments. We compared the performance of the radshield paired with low-cost temperature sensors at three sites in western Montana to several types of commercially available instruments. Comparisons included observations made under a tree canopy and in full sun with both passive and mechanically aspirated radiation shields. Beneath a forest canopy, temperature sensors housed within the radshield showed bias of less than 0.5 °C for hourly temperatures when compared with the same sensors housed in an unaspirated Gill-style shield. Sensors and shields mounted on poles in full sun were slightly warmer under low-wind conditions, but overall were cooler than data from an adjacent Remote Automated Weather Station (RAWS). When compared with observations from a high-quality temperature sensor housed in a mechanically aspirated solar radiation shield used in the Automated Surface Observing Systems (ASOS), observations from inexpensive temperature sensors housed within radshields were biased with mean absolute error of 0.99 °C, but performed as well as those housed within a more expensive, commercially available Gill-style radiation shield. Our initial evaluation suggests that the radshield, instrumented with a low-cost sensor is suitable for monitoring surface air temperatures across a range of outdoor environments.

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1. Introduction

Inexpensive temperature sensors are widely used in agricultural and forestry research and management studies. Several inexpensive (20–35 USD) temperature sensors are now commercially available. For example, Maxim's Thermochron® iButtons® are being widely used for outdoor environmental applications including surface air temperature monitoring (Beever et al., 2010; Holden et al., 2011; Holden and Jolly, 2011; Hubbart et al., 2007; Lundquist and Cayan, 2007; Ashcroft and Gollan 2012; Fridley, 2009). However, comparably low-cost radiation shields are needed to make the use of inexpensive sensors cost effective. This paper describes and evaluates an inexpensive, lightweight radiation shield for use in outdoor environments, and reports on its performance in conjunction with ThermoWork's Logtag® data logger.

Accurately recording air temperatures in harsh outdoor environments poses several challenges. Temperature sensors and their surroundings warm when exposed to direct and diffuse solar radiation. In addition, solar radiation reflecting off of snow beneath sensors in the spring can significantly influence temperature measurements if the sensor is not protected from below (Lin et al., 2001; Huwald et al., 2009). Gill radiation shields are commonly used to shield temperature and relative humidity sensors (Gill, 1979). The Gill shield design allows passive natural ventilation, while heat that accumulates in the upper plates dissipates via conduction and radiation. While it is well documented that unaspirated shields may have deviations of up to 10 °C (e.g. Genthon et al., 2011; Maunder et al., 2008), the difficulty of powering fans that perform reliably in harsh, remote locations and without biasing the measurements is not easily achieved without added complexity. For these reasons, unaspirated radiation shields are widely used for a variety of applications. However, commercially available Gill-style shields are relatively expensive in comparison to the cost of modern miniature data loggers (20–50 USD). Shields from Onset Computer Corp.® (the maker of Hobo® products) cost 80 USD while a similar shield from Decagon Devices Inc.® costs around 60 USD. This expense (several times the cost of the temperature sensor) becomes significant when hundreds or thousands of sensors are deployed.

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Fig. 1. Inexpensive solar radiation shield (radshield) mounted on a PVC pole adjacent to the Ninemile RAWS station, Montana.

Several radiation shield designs have been proposed as alternatives to more expensive commercial Gill-style radiation shields (e.g. Clark et al., 2006; Tarara and Hoheisel, 2007). However, these designs all report significant temperature errors relative to standard Gill-style radiation shields. Several previous studies using Thermochron iButtons have used two nested, inverted funnels placed over the sensor (Hubbart et al., 2005; Holden et al., 2011; Holden and Jolly, 2011; Hubbart et al., 2007; Lundquist and Cayan, 2007). However, this design does not shield the sensor from snow albedo effects unless sufficient vegetation is present beneath the sensor. Lundquist and Huggett (2008) propose that vegetation in tree canopies can be used to shield the sensors from direct and reflected radiation. However, in relatively dry areas of the western United States, (e.g. low elevation, south-facing slopes in the northern Rocky Mountains and the southwestern US) where vegetation productivity is relatively low and forest canopies are open, this often is not possible. Additionally, the height at which observations are made will vary using this method. Alternative, inexpensive radiation shielding devices that perform consistently across a range of environments are still needed.

2. Methods

2.1. Radiation shield design

This inexpensive radiation shield (henceforth referred to as "radshield") was originally designed for measuring air temperatures in forested environments, but may be easily modified to work in a variety of settings (Fig. 1). Paramount to the design of any radiation shield is blocking incoming solar radiation (Fuchs and Tanner, 1965; Gill, 1979; Hubbard et al., 2001). This simple Gill-style shield is constructed by folding white corrugated plastic sheets into a series of plates secured with metal staples. The top of each of the plates are then covered with reflective aluminum foil duct tape, which minimizes absorption of incoming radiation. Because the temperature sensor is housed between three sheets of taped plastic (two above and one below), most incoming and reflected upwelling radiation is blocked. The outer, uppermost plate mounts to the bole of a tree (or to a simple pole or tripod) while smaller plates housing the sensor are suspended beneath it using uv-resistant cable ties. Those ties and air spaces within the walls of each sheet of corrugated plastic (4 mm in both directions) minimize conduction of heat through the shield. In addition, the approximately 3 cm of space between each plate enhance passive air flow within this non-aspirated shield.

In the case of the radshields discussed here, the walls of the radshield were constructed with Coroplast® twin-walled 4 mm white plastic sheets and the foil duct tape was Shurtape® AF-100 tape. The radshield can be constructed in approximately 10 min using materials widely available from home-repair supply stores that cost less than 3 USD per shield. A detailed schematic of the individual pieces and the fully assembled radshield is shown in Fig. 2. A short video detailing construction of the radshield can be found at http://www.youtube.com/watch?v=LkVmJRsw5vs.

2.2. Radiation shield comparison tests

We conducted four field tests of the radshield at sites in western Montana during summer and fall. Comparisons included observations made beneath a forest canopy and in full sun conditions, and using both passive and mechanically aspirated radiation shields. One potential source of concern regarding the materials used in the construction of the radshield is the use of aluminum foil tape. Aluminum is highly reflective, but has a very low emissivity in the infrared range of the electromagnetic spectrum (emissivity = 0.03) compared to other materials with comparable reflectivity. Thus, aluminum could effectively trap heat inside the shield without adequate ventilation. We tested for potential bias resulting from the use of an aluminum surface by coating the exterior surfaces of the radshield plates with higher emissivity materials, including acrylic white paint and aluminum backed mylar tape. The details of each test are described separately below. The data collected in each test, including number and type of sensor and duration of each test are shown in Table 1.

2.2.1. Test 1: radshield and passive radiation shield comparison beneath a forest canopy

Air temperature measurements were compared from ThermoWork's Logtag® TRIX-8 temperature sensors housed in radshields to measurements from the same sensors housed in commercially available 8-plate Gill shields (Model M-SRA, Onset Computer Corp.). Logtags are inexpensive sensors with a temperature range of −40 to 85 °C, and a stated accuracy of 0.5 °C. The test site was a thinned, open-canopy ponderosa pine forest. This site was chosen to represent the extremes of radiation environments that would be encountered during the summer within forests of the US northern Rocky Mountains. Three radshields instrumented with two Logtag temperature sensors each were mounted on three separate ponderosa pine trees at a height of 2 m. For comparison, a commercial 8-plate Gill radiation shield instrumented with 1 Logtag sensor was mounted to each tree. Temperatures were recorded at hourly intervals from 1 July to 31 August 2011.

2.2.2. Test 2: radshield and passive radiation shield comparison in full sun

Three radshields were mounted on Polyvinyl Chloride (PVC) poles and placed next to the Ninemile Remote Automated

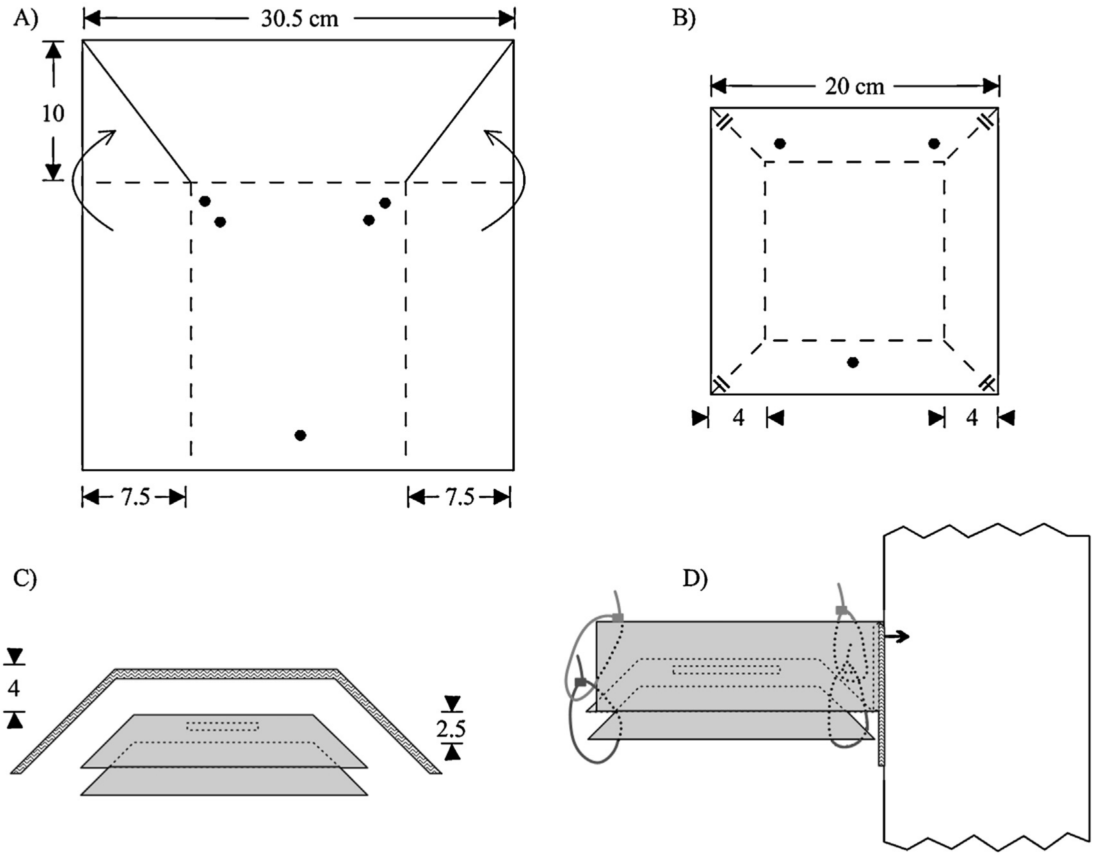

Fig. 2. Diagrams illustrating the construction and installation of the radshield. (A) The top plate of plastic sheeting is cut (solid lines), and scored (dashed lines) to allow the material to bend, and small holes punched (circles; 0.5 cm). Arrows indicate where the material is folded under. (B) The lower plates are smaller squares and two are required for each shield. Hatch marks indicate where the corners are stapled. (C) Front view showing the location of the data logger inside the shield and top of lowest plate as dotted lines. (D) Side view of an installed shield showing cable ties (there are two sets in the rear) holding the plates together and the nails (one on each side) used to secure the two layers of the top plate together and to a tree. In the case of a pole, U-bolts or plastic cable ties can also be used. A video detailing construction of the radshield can be found at: http://www.youtube.com/watch?v=LkVmJRsw5vs.

Weather Station, Montana (RAWS; Lat. = 47.07, Lon. = −114.01, Elevation = 965 m). The RAWS is located in an open field approximately 80 m from any tall vegetation. Each radshield and temperature sensor was positioned at a height of 2.1 m (the height of the Ninemile RAWS temperature sensor). We compared hourly temperatures from these sensors with the RAWS from 2 to 7 September 2011. These days were among the warmest of the summer with no cloud cover. Most RAWS stations, including Ninemile, use a solid-state thermistor housed in a Gill-style multi-plate shield produced by R.M. Young Company (Finklin and Fischer, 1990; Zachariassen et al., 2003).

2.2.3. Test 3: radshield comparison with National Weather Service mechanically aspirated shield

Our final test was conducted at the National Weather Service (NWS) meteorological station in Missoula, MT, which has an Automated Surface Observing Systems (ASOS) site. The Technical Services Laboratory Inc.© model 1088 hygrothermometer used in the ASOS has been used operationally by the NWS since 1983. Temperature is measured using a platinum Resistive Temperature Device (RTD) to measure ambient temperature following specifications laid out in the ASOS manual with a resolution of 0.1 °F and an RMSE of 0.9 °F between −58 and 122 °F (NOAA, 1998). Temperature is measured continuously and an hourly mean is calculated after a series of quality assessment checks. In the hourly reports, the current mean hourly ambient temperature is reported to the nearest 1/10 °C and those temperatures were used here.

Three radshields, each instrumented with two Logtag temperature sensors were installed on a plywood board which was then mounted next to the NWS station at approximately the same height as the NWS temperature sensor. For comparison, a single Onset Gill-style 8-plate radiation shield instrumented with three Logtag temperature sensors was mounted next to the ASOS station at the same height as the radshields. In addition, we constructed three inverted funnel shields modified based on the design described by Hubbart (2012). The precise make and model of funnel used by Hubbart (2012) could not be determined. We therefore used 8 oz. (inner) and 16 oz. (outer) funnels distributed by Browne-Halco

Table 1
Characteristics of each radiation shield/sensor comparison.

Test case	Setting	Number of sensors	Number of radshields	Control shield type	Control sensor type	Number of control sensors	Test dates
Test 1	Canopy	6	3	Onset/unaspirated	Logtag	3	07/01/2011–08/31/2011
Test 2	Full sun	3	3	Gill/unaspirated	RAWS	1	09/02/2011–09/07/2011
Test 3	Full sun	6	3	Aspirated	ASOS	1	08/22/2012–10/01/2012

Inc., which were purchased through a kitchen supply company (http://www.kommercialkitchens.com/16-oz-White-Plastic-Funnel.aspx). Each funnel was instrumented with a Thermochron iButton temperature sensor, mounted suspended within the funnels by wooden clothes pins. Prior to testing, all sensors were immersed in an ice water bath for 15 min. Logtag sensors and iButton sensors are not water resistant. Therefore, each sensor was placed in individual snack sized plastic bags. Water was continuously agitated during immersion in the water bath. Temperatures were logged at 1 s intervals. All measured temperatures were found to be within 0.5 °C of the water temperature.

2.2.4. Tests of alternative radshield surface materials

A total of nine radiation shields (three as decribed above, three coated with Krylon® semi-gloss acryclic white paint (emissivity = 0.98) and three coated with 3M® 850R aluminum backed mylar tape (emissivity = 0.60) were instrumented with Logtag sensors and deployed from 21 May 2013 to 2 June 2013, at the Ninemile weather station site described in test 2 logging at 15 min intervals. The goal of this test was to assess whether coating radiation shields with higher emissivity material would improve the radshield performance, or reduce potential bias associated with the low emissivity aluminum.

2.3. Data summary and analysis

For each of the three tests, we compared mean hourly temperatures recorded by Logtag sensors housed in radshields with mean hourly temperatures of the control data. We calculated summary statistics for the radshield data and the control data and then then calculated the Mean Absolute Error (MAE) and root mean squared error (RMSE) for hourly temperatures between shield types. We also separately calculated MAE for daily minimum and maximum temperature between test and control data. For test site 1 (radshields and Onset radiation shields below a tree canopy), mean hourly temperatures recorded by six Logtags and housed in radshields were compared with mean hourly temperatures recorded by six Logtags and housed in Onset Gill radiation shields. At test site 2, (3 Logtags housed in 3 radshields adjacent to a RAWS station in full sun), mean hourly observations from the three sensors adjacent to the RAWS station were compared with hourly observations from the RAWS station for the four day test period (data available at www.raws.dri.edu). MAE and RMSE were calculated between Logtags and the RAWS. At test sites two and three, hourly wind data were also available. The Ninemile RAWS station is equipped with a WindSonic 2-D Sonic Wind Sensor, manufactured by Gill Instruments Inc. The NWS Missoula ASOS station is equipped with a Vaisala WINDCAP® ultrasonic sensor. We compared differences between the radshield and control instrument temperatures at these sites with hourly wind speeds in order to document the potential influences of wind speeds on air temperature bias.

3. Results and discussion

Summary data for temperature observations in each test are shown in Table 2. In all three tests, the radshield performed well compared with more expensive commercially available shields. In test 1, mean hourly temperature differences between the radshield and Onset shields were less than 0.5 °C, and within the 0.5 °C stated precision of the Logtag temperature sensor (Table 2).

In test 2, observations from radshields placed in full sun were on average slightly cooler than observations at the RAWS station, but within the stated precision of the Logtag sensor (Table 2; Fig. 3). There was a weak correlation between wind speed and the difference between RAWS and radshield observations and Logtag observations tended to be warmer than RAWS under low wind conditions, with a maximum observed difference of 0.98 °C (Fig. 4).

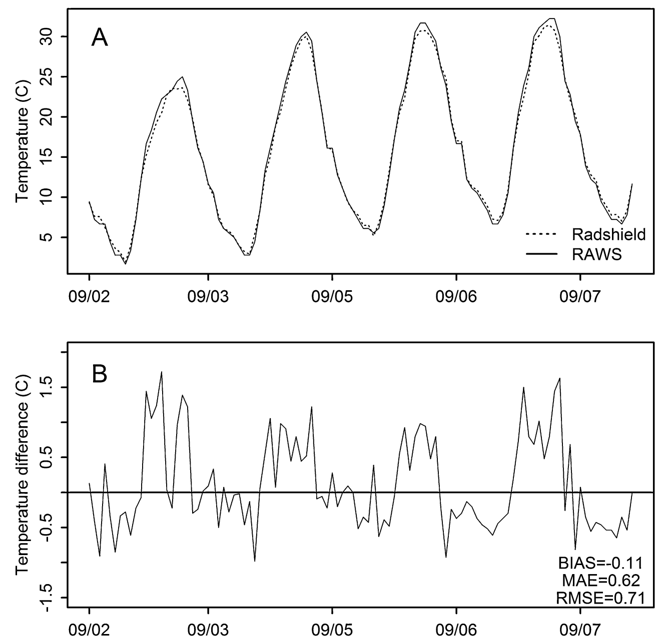

Fig. 3. Hourly temperatures measured at the Ninemile RAWS station and mean hourly temperatures recorded by three radshields and Logtag sensors. (A) Hourly temperature observations. (B) Differences in temperature between the RAWS and radshield (RAWS minus radshield).

In test 3, as expected, temperature measurements made with radshields and Logtags showed a warm bias compared with NWS station observations with a maximum temperature difference of 4.1 °C and a mean temperature bias of 0.24 °C (Table 2; Fig. 5). Overall, the difference in hourly radshield temperature measurements was relatively small (MAE = 0.99, RMSE = 1.27). Differences in daily minimum and maximum temperature were nearly within the precision of the instrument (MAE = 0.45 and 0.56 respectively). The radshield performance was similar to the Onset Gill-style shield (MAE = 1.29; RMSE = 1.56). The NWS station measures temperatures 8 min before the hour, which could partially explain

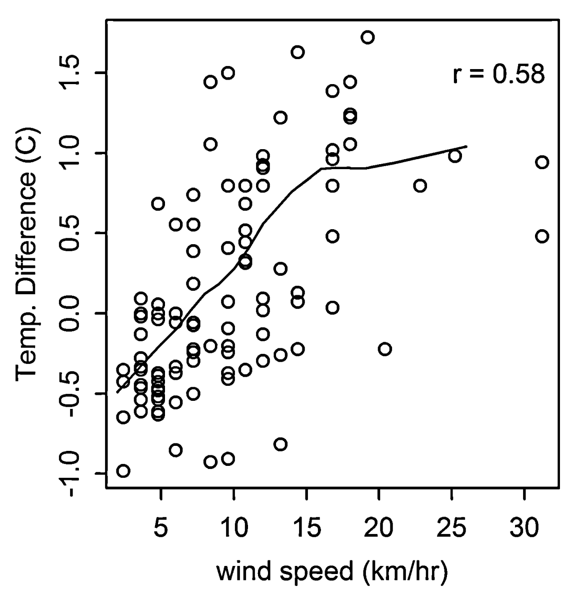

Fig. 4. A scatterplot showing the correlation between wind speed and radshield/Logtag and RAWS temperature observations (RAWS minus radshield).

Table 2
Summary statistics for temperature observations in each of 3 radiation shield/sensor tests.

Shield type	Min. temp. (°C)	Max. temp. (°C)	Avg. temp. (°C)	Temp. range (°C) (max–min)	MAE (hourly) (°C)	RMSE (hourly) (°C)	MAE (T_{max}) (°C)	MAE (T_{min}) (°C)
Test 1: radshield/Logtag and Onset/Logtag under forest canopy								
Radshield	2.44	34.66	19.10	32.22	0.34	0.41	0.41	0.44
Onset/Gill	2.25	34.86	18.89	32.41	–	–		
Test 2: radshield/Logtag and RAWS in full sun								
Radshield	1.94	31.43	15.68	29.49	0.52	0.65	0.72	0.28
RAWS	1.66	32.22	15.79	32.05	–	–	–	–
Test 3: radshield/Logtag, Onset/Logtag, funnel/iButton and NWS ASOS in full sun								
Radshield	0.32	33.9	16.25	33.58	0.99	1.27	0.56	0.45
Onset/Gill	0.52	32.63	15.88	32.11	1.29	1.56	0.46	0.44
Funnel	−0.06	38.05	17.40	37.99	1.94	2.52	3.72	0.44
NWS	0.61	33.30	16.10	32.69	–	–	–	–

some of the differences between radshield and the Onset-Gill measurements and the station. We found no correlation between temperature radshield and ASOS temperature measurements and wind speeds (Figure not shown; Pearson's $r = 0.002$; $p = 0.67$). Funnels instrumented with iButton temperature sensors showed relatively large bias compared to the radshield and Onset shields, with maximum temperature differences exceeding 8 °C on several days. This is likely due to the characteristics of the funnel used, which were white and opaque, but appeared slightly transparent when held up to direct sunlight.

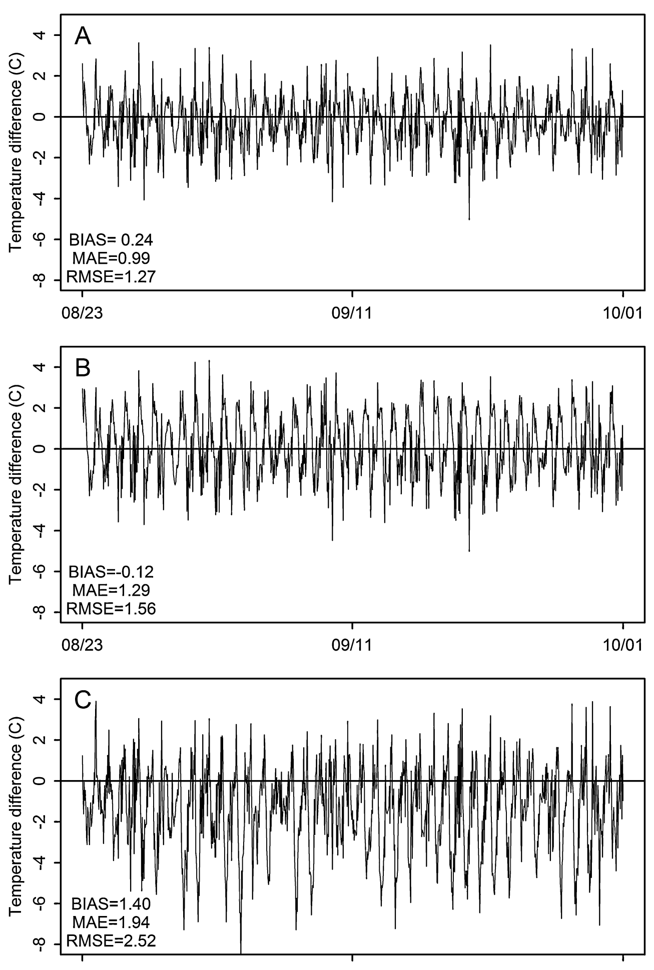

Fig. 5. Mean hourly temperatures differences between inexpensive radiation shield/sensor pairs and the Missoula NWS station. (A) NWS temperature minus radshield/Logtag; (B) NWS temperature minus Onset Gill-style/Logtag; (C) NWS temperature minus funnel/iButton observations.

Temperature measurements from radshields coated with white paint and mylar were slightly warmer than those in the foil-coated shields (Table 3). However, these differences were small, and well within the stated precision (0.5 °C) of the thermistor.

Overall, the results of our comparisons suggest that the radshield design performs well compared with accepted, commercially available unaspirated radiation shields, and better than other previously proposed similarly inexpensive shields. Although the radshield was designed specifically for monitoring air temperatures in forested environments, it also performed reasonably well in open, high radiation conditions. At test site 2 (radshields compared with a RAWS weather station), we observed some bias under conditions with low wind speeds and additional testing is needed to understand the magnitude of error that is possible under extremely calm, sunny conditions. However, because the radshield was primarily designed to be mounted to the bole of a tree for use in forest monitoring applications, the tree bole and canopy would block a substantial portion of incoming solar radiation, particularly during mid-afternoon when sun would be most intense.

The combined cost of the Logtag sensor and radshield materials is less than 25 USD, excluding time to construct and deploy the shield. This sensor and radiation shield combination appears to be a reasonably inexpensive tool for monitoring outdoor air temperatures. In addition, the radshield is extremely lightweight (<300 g) and can be flattened and assembled in the field for transport into remote outdoor settings. Throughout field testing and extensive field use, we observed fading of the foil tape, even in sensors placed beneath a forest canopy. Whether this degradation affects temperature observations over time is unknown. Further testing of the radshield performance over extended periods should therefore be done. However, for prolonged usage of these shields in the field, we recommend periodic addition of fresh foil tape, particularly in sites with higher exposure to insolation.

Our tests of alternate high-emissivity coatings revealed no discernible differences between shields covered with only aluminum foil tape and shields with an additional layer of higher emissivity white paint or mylar applied to the outer layer of the shield. This finding suggests that design features of the radshield, with

Table 3
Summary statistics for radiation shields coated aluminum foil tape, white paint and mylar tape.

Exterior coating	Min. temp. (°C)	Max. temp. (°C)	Mean temp. (°C)
Foil tape	−0.74	21.39	10.39
White paint	−0.41	21.98	10.66
Mylar	−0.72	21.40	10.44

multiple layers of corrugated plastic and adequate spacing for air flow may overcome any warming that occurs in the foil. The aluminum foil tape has several key advantages over other materials we tested. First, having been designed for use in repair of heating and cooling systems, it maintains its adhesiveness at extreme high and low temperatures. Second, the tape appears to be extremely durable, and the shields we tested were in functional conditional even after more than two years of field use. Additionally, aluminum is malleable. This is important because the radshield is designed out of flexible plastic that often requires some bending and physical manipulation when packing and installing in the field. We found that white paint cracked and degraded relatively rapidly during field use. Despite the apparent advantages of aluminum foil tape, it has physical characteristics that are not ideal for an instrument designed to reduce radiation-induced heating. Further testing with higher precision instrumentation and alternate materials may therefore be warranted. One other drawback of the use of aluminum foil tape is that it makes the radshield shiny and highly visible which may be problematic in some environments. In previous field tests in 2010, bull elk appeared to be disturbed by the light reflecting off the shields and on multiple occasions, removed and stomped on several shields until they were no longer shiny. This visual obtrusiveness could be a problem in non-forested areas with high elk density, where human destruction is likely, or other sites where more discrete coloring is needed (e.g. National Parks or wilderness areas), but could be alleviated with the addition of a layer of white paint.

Forest canopies are highly variable environments, with many factors potentially influencing surface air temperatures. The boles of trees, ground, and nearby vegetation will all absorb and reemit long-wave radiation. This makes direct comparison of measurements made under these conditions with properly sited permanent weather stations potentially problematic. However, many forest management and forest ecology applications (e.g. tree regeneration, soil water balance and fuel moisture predictions) require sub-canopy information. In addition, the need for improved understanding of the magnitude and variability of temperature differences due to topographic effects in complex terrain may outweigh issues of precision and bias to some extent. However, additional testing of this inexpensive temperature device under a range of wind and radiation conditions may be warranted, given the potential for greater bias under low wind conditions. Additional efforts are currently underway to understand fine-scale variation and bias associated with vegetation and ground cover differences.

4. Conclusions

In areas of complex topography with sparse weather stations, it is vital that we start getting better data on climate fields for a variety of biological and other processes that occur at finer scales than is obtained by currently available climate data. The resolution of available gridded daily climate data sources ranges from 1 to 4 km which is insufficient to resolve fine-scale variation in air temperature in regions of complex topography. As the use of inexpensive sensors for environmental monitoring increases, the climatology and ecology community could benefit from the adoption of more consistent standards so that as topoclimatic data accumulate, they can be used in coordinated, longer term analyses. Thoughtful discussions of the role that data from low-cost measurement devices may play in validating or enhancing gridded climatological datasets is also needed. Where more expensive commercially available radiation shields are cost prohibitive, inexpensive alternatives will be needed. The results of preliminary tests suggest that the Gill-style radiation shield described here is suitable alternative to other passively ventilated radiation shields for use in monitoring outdoor temperatures across a range of environments.

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