Microclimate loggers: A matter of shielding… or wrapping?

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Abstract:

Direct sunlight can heat the sensor, housing, and shield of microclimate loggers overestimating air temperature readings as a result. This raises the question of how loggers should be shielded. We tested whether extra shield layers, ventilation holes inside the shielding and a wrap of aluminium foil around the logger housing reduce the error of one of the most commonly used microclimate loggers, the TOMST TMS-4, in open conditions. We hypothesised that a triple shield with holes combined with a wrapped housing would reduce the error most, and that this effect would be largest under sunny, high-radiation conditions. Over 41 days during summer 2026 in an urban context in Leuven, Belgium, we compared six new setups (single shield, triple shield and triple shield with holes, each with and without aluminium wrap) against an ultrafine-wire thermocouple (SurveyTag), using a mixed model with radiation and wind classes from a nearby weather station. We found that the aluminium wrap lowered the error by 0.33°C on average (95% CI 0.30 to 0.36), and its benefit grew with radiation intensity, from −0.06°C at night to 0.90°C in the very high radiation class. The best setups combined a triple shield (0.12°C to 0.13°C better than a single shield) with the wrap, whereas ventilation holes offered no significant benefit. On sunny afternoons, wrapping reduced the root mean square error by 35 to 40%. Wrapping the housing is therefore a low-effort and cost-efficient way to improve the accuracy of existing loggers in open ecosystems.

1. Introduction

Microclimate shapes where organisms live, how they interact and how they respond to climate change (Kemppinen et al., 2024). Central to the research field of microclimate science are in situ data loggers are central (De Frenne et al., 2025). However, whether to shield these loggers or not has been a pertinent and long-standing debate within the community. In this context, Maclean et al. (2021) showed that commonly used TMS-4 loggers reached maximum hourly measurement errors of about 9 to 12°C close to the ground in open grassland under sunny conditions, whether or not a shield was present. While the largest errors occur when the solar radiation reaches the sensor directly, shields, trying to reduce this error, heat up to and their physical design lowers wind speed and air mixing.

Shielding thus cannot wholly solve this, because the shield itself influences the temperature and the accuracy of the measurement. For open habitats, De Frenne et al. (2025) recommend unshielded ultra fine-wire thermocouples, such as the SurveyTag from Concept Shed (SurveyTag, 2026), and standardised shielding for other logger types. In practice, ecologists balance accuracy against cost and replication (Maclean et al., 2021). The TOMST TMS-4, designed for long-term measurements at ecologically relevant scales (Wild et al., 2019), is one of the most widely used loggers in the SoilTemp database (Lembrechts et al., 2020) and has been applied in multiple ecosystems. With a life span of 10 years, researchers often deploy their set of loggers over a variety of places (Aalto et al., 2022; von Berg et al., 2026; von Büren et al., 2025), raising the question how the accuracy of the measurement can be reduced when switching between open and closed ecosystems.

Here we compared single, triple and ventilated triple shields on TOMST TMS-4 loggers (further referred to as the TMS-4) against SurveyTag thermocouples. We also tested wrapping the logger housing in aluminium foil, a material with low thermal emissivity that reflects most shortwave and longwave radiation (Frolec et al., 2019; Hass and Waylonis, 1961). We hypothesised that a triple shield with holes combined with wrapped housing would reduce the error most, as it acts on two potential sources of error, and that this effect would be largest under sunny, high-radiation conditions.

2. Materials and Methods

2.1. Setup

The experiment was run in the private garden (South-West orientation) of the lead author in Leuven, Belgium, from 1 July to 10 August 2026. Two mortar tubs filled with potting soil (further on referred to as Plot 1 and Plot 2) were placed on the roof of the rear extension of the house.

These plots represent harsh environmental conditions: dry, bare soil without the evapotranspirative cooling of vegetation. Each plot contained six TMS-4 loggers, combining three shield types with and without an aluminium (Alu) wrap (Figure 1): a single shield, a triple shield, and a triple shield with ventilation holes (simply referred to as "Holes"). Seven holes of 7 mm were drilled in the middle shield (the shield carrying the attachment structure) and three holes of 5 mm in the top shield. The holes were offset so direct radiation could not reach the top of the logger, and the top shield had fewer and smaller holes to limit the heating of the middle shield. The household aluminium foil was wrapped around the cylindrical part on the body of the logger. The plots received direct sun from approximately 12:00 CEST onwards, since they are shaded earlier in the day by the house. A SurveyTag ultrafine-wire thermocouple logger (beta version; SurveyTag, 2026) was placed in each plot as a reference, averaging its readings over a 1000ms burst length. These loggers do not need shielding and are considered the best practice (De Frenne et al., 2025; Maclean et al., 2021). All sensors, measure at 15 cm above the ground surface. The times mentioned in this study are in UTC (local summer time = UTC + 2 h), unless stated otherwise.

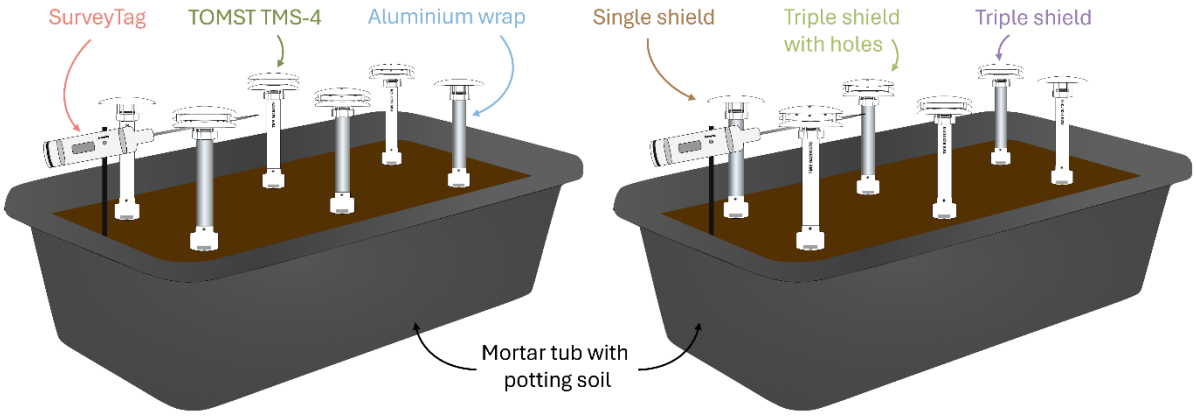


Figure 1. Setup: two mortar tubs filled with potting soil each representing a plot. Each plot contained six TOMST TMS-4 loggers with different shields with and without aluminium foil. Each plot also holds a SurveyTag as reference.

2.2. Preprocessing

All analyses were done in R 4.4.3 (R Core Team, 2025), using the packages dplyr (Wickham et al., 2023) and ggplot2 (Wickham, 2016) for organising and plotting the data. The TMS-4 data were processed with the myClim package (Man et al., 2023), following the procedure described in Metsu et al. (2026) implementing several cleaning procedures including outliers, flatlines and gap detection. From the available TMS-4 sensors, we extracted the temperature at 15 cm height in 15-minute intervals. One SurveyTag per plot, also logging at 15-minute intervals, was used as the reference for that plot.

The SurveyTags were beta versions, and their internal clocks proved somewhat unreliable. At read-out, one was 13 min 20 s ahead of the true time and the other 25 h 6 min 23 s behind. To

88 determine whether these offsets accumulated gradually or resulted from an abrupt shift, we
89 cross-correlated the temperature records of both tags. This showed that the second tag
90 underwent a single abrupt shift around 18 June and remained stable thereafter. Because the shift
91 occurred before the study period, the offset was constant throughout the study and equal to the
92 error measured at read-out. Data recorded after the shift were therefore corrected using the
93 observed offsets (−13 min 20 s and +25 h 6 min 23 s), interpolated to the 15-minute TOMST
94 timestamps, and aggregated to hourly means. This yielded 984 hourly values for each logger.

95 Hourly global radiation and wind speed were taken from the nearest station of the Leuven.Cool
96 weather station network (Beele et al., 2024), about 200 m from the site. The station differs from
97 the plots in sky view factor and local obstruction, so its data were treated as a proxy for the
98 conditions in the plots, and radiation and wind speed were converted to different interval classes.
99 Radiation was divided into night (0 W m^{-2}) and four daytime classes (low, medium, high, very
100 high), with cut-offs at the 30th, 60th and 90th percentile of the non-zero values (approximately
101 83, 220 and 472 W m^{-2}). These classes contain 310, 200, 204, 202 and 68 hourly time points,
102 respectively. Wind speed was divided into windless conditions (0 m s^{-1}) and three classes (low,
103 medium, high) with cut-offs at the 33rd and 66th percentile of the non-zero values (0.43 and 1.35
104 m s^{-1}).

105 **2.3. Statistical Analysis**

106 The error of each logger was its hourly mean temperature minus the hourly mean of the reference
107 in the same plot, so positive values indicate overestimation. As a descriptive summary, the root
108 mean square error (RMSE), mean absolute error (MAE) and mean bias error (MBE) of the hourly
109 errors between 12:00 and 18:00 local time were calculated for the 10 sunniest and the 10
110 cloudiest afternoons, ranked by the station radiation sum in that window.

111 The effects of the wrap, shield type and weather were tested with a linear mixed-effects model
112 (using REML) on all hourly errors of the study period (glmmTMB; Brooks et al., 2017). Fixed effects
113 were the presence of wrapping, shield type and radiation class (with their three-way interaction),
114 plot, wind class, and the wrap by wind class interaction. Plot was included as a fixed effect
115 because two levels are too few for a random-effect variance. The random part was an intercept
116 for each hourly time point (deviations shared by all loggers) and a first-order autoregressive
117 process over time within each logger (estimated correlation 0.64 per hour) to account for
118 temporal autocorrelation. Effects were tested with Type II Wald chi-square tests (car, Fox &
119 Weisberg, 2019), reported as χ^2(df) with df equal to the number of parameters in the tested term,
120 and explored with estimated marginal means and contrasts (emmeans, Lenth et al., 2026),

averaged with equal weights over the other factors. Wrap effects are reported as the error without minus the error with the wrap, so positive values mean a reduction. Shield types were compared with Tukey adjustment, and the letters in the Figure 3 are based on Sidak-adjusted comparisons of the six setups within each radiation class, displayed as compact letters (multcomp, Hothorn et al., 2008; multcompView, Graves et al., 2024).

3. Results & Discussion

Raw temperatures. Loggers followed the reference closely at night and in the morning, but on sunny afternoons all TMS-4 setups systematically recorded higher temperatures than the reference, up to 4°C for the single-shield loggers (Figure 2). On cloudy days the differences were substantially smaller. Over the entire study period, hourly errors reached maximum values of 5.9°C for the single shield and 3.4 to 3.8°C for the wrapped triple setups (Holes + Alu and Triple + Alu); the 95th percentile of the hourly errors was 3.4°C for Single and 1.8°C to 1.9°C for these two setups.

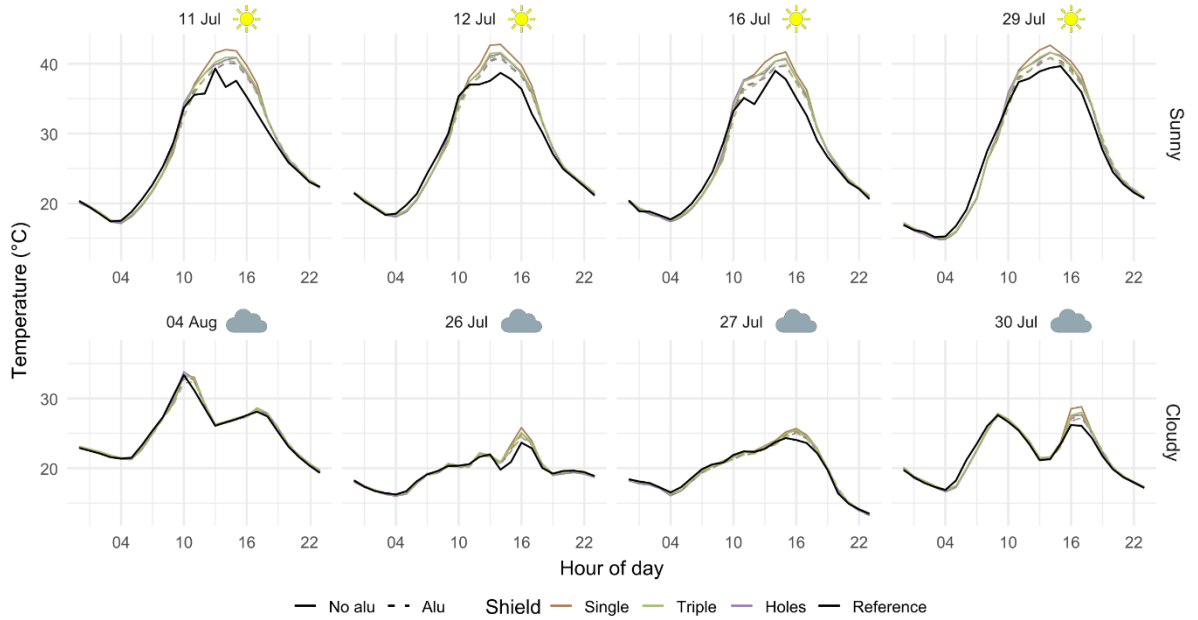


Figure 2. Hourly mean temperatures of the TMS-4 loggers and the SurveyTag reference in Plot 1 on the four sunniest (top row) and four cloudiest (bottom row) days, ranked by the daily radiation sum at the weather station. Solid lines are loggers without aluminium wrap and dashed lines are wrapped loggers. Colours show the shield type. The black line is the reference. Time is in UTC (local time = UTC + 2 h).

Error metrics. On sunny afternoons, errors were largest for every setup (Table 1). RMSE ranged from 2.82°C (Single) to 1.47°C (Holes + Alu). Wrapping with aluminium lowered RMSE by 0.81°C – 1.05°C (35% to 40%) and MBE by about half (for example Triple: 1.94°C to 0.87°C). On cloudy afternoons errors were much smaller, wrapping lowered RMSE by 0.27°C – 0.30°C (30% to 34%). The best setups kept a positive bias of about 0.9°C to 1.0°C on sunny afternoons.

Table 1. Root mean square error (RMSE), mean absolute error (MAE) and mean bias error (MBE) in °C of the hourly mean temperature of each setup relative to the reference, between 12:00 and 18:00 local time. Values are for the 10 sunniest (Sky = Sunny) and the 10 cloudiest (Sky = Cloudy) afternoons, ranked by the radiation sum at the weather station in that window, and pool the two loggers per setup. Positive MBE means the setup overestimated the temperature. Alu refers to the loggers wrapped with aluminium foil. The lowest errors per radiation class are presented in bolt.

Sky	Setup	RMSE	MAE	MBE
Sunny	Single	2.82	2.52	2.47
	Single + Alu	1.77	1.48	1.36
	Triple	2.30	2.00	1.94
	Triple + Alu	1.49	1.23	**0.87**
	Holes	2.45	2.13	2.09
	Holes + Alu	**1.47**	**1.20**	1.01
Cloudy	Single	1.01	0.73	0.67
	Single + Alu	0.71	0.51	0.35
	Triple	0.86	0.62	0.53
	Triple + Alu	**0.59**	**0.44**	**0.16**
	Holes	0.89	0.63	0.52
	Holes + Alu	**0.59**	**0.44**	0.18

Effect of the aluminium wrap. Averaged over all conditions, wrapped loggers had a 0.33°C lower error (MBE; 95% CI 0.30 to 0.36), with similar magnitude for the three shields (Single 0.29°C, 95% CI 0.24 to 0.33; Triple 0.37, 95% CI 0.32 to 0.41; Holes 0.33, 95% CI 0.29 to 0.38). This benefit depended strongly on radiation ($\chi^2(4) = 578$, $p < 0.001$; Figure 3). It was slightly negative at night (-0.06°C, 95% CI −0.10 to −0.02) and grew from 0.07°C (low; 95% CI 0.04 to 0.11) to 0.24°C (medium; 95% CI 0.20 to 0.28), 0.50°C (high; 95% CI 0.45 to 0.54) and 0.90 °C (95% CI 0.83 to 0.97) in the very high class. This supports our second hypothesis: the benefit of the wrap was largest under high radiation. The afternoon metrics show the same pattern: the absolute RMSE reduction was about 0.8°C to 1.1°C on sunny afternoons but only about 0.3°C on cloudy ones (Table 1), although the relative reduction was similar (35 to 40% vs 30 to 34%).

The increasing benefit of the aluminium wrap with increasing radiation suggests that its primary effect was to reduce radiative heating of the logger housing and sensor. The slightly negative effect during nighttime conditions may reflect reduced longwave radiative cooling. Importantly, the mean effect of 0.33°C masks substantial variation across radiation environments, so the benefit in the field will depend on the local radiation regime. Radiation classes were derived from measurements at a weather station approximately 200 m from the plots and therefore represent only an approximation of the radiation experienced by individual loggers. The wrap effect was also greater at medium and high wind speeds (0.42°C and 0.44°C) than at windless or low-wind conditions (0.21°C and 0.24°C). Because wind speed and radiation were moderately correlated ($r = 0.51$), we mainly focused on the interpretation of the radiation patterns.

Effect of the shield type. The single shield had the highest error. The triple shield and the triple shield with holes had 0.13°C (95% CI 0.10 to 0.17) and 0.12°C (95% CI 0.08 to 0.16) lower errors than the single shield, and these two did not differ from each other (Triple − Holes: −0.01°C, 95% CI −0.05 to 0.02, p = 0.70). The gap between Single and the other shields was larger with the wrap (0.17 and 0.14°C) than without (0.09 and 0.10°C; wrap × shield $\chi^2(2) = 14.9$, $p < 0.001$; Figure 3). The ventilation holes therefore added nothing substantial to the triple shield, and our hypothesis of an additional benefit was not supported. The benefit comes from the extra shield layers and the wrap.

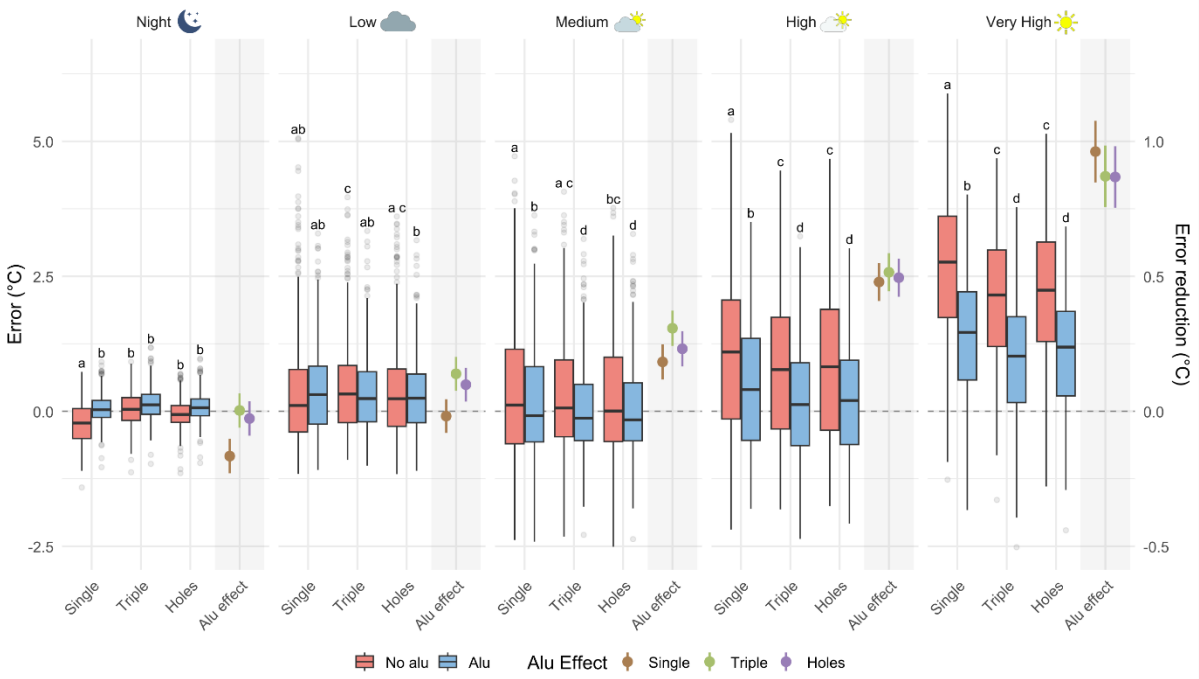


Figure 3. Distribution of hourly errors (logger minus reference, °C; left y-axis) and error reduction by the aluminium wrap (right y-axis) per setup and radiation class over the 41-day study period. Boxes show the median and interquartile range, whiskers extend to 1.5 times the interquartile range, and points are outliers. Box colours indicate without (red) and with (blue) aluminium wrap. Letters give the result of Sidak-adjusted pairwise comparisons of the six setups within each radiation class, based on the mixed model. Setups sharing a letter within a panel do not differ (p > 0.05), and letters cannot be compared between panels. In the shaded area of each panel, points show the error reduction by the wrap (error without minus error with wrap) for each shield type, as model estimates with 95% confidence intervals, averaged over plots and wind classes; positive values mean the wrap reduced the error. The right y-axis is the left y-axis divided by 5, and the zero lines of both axes coincide.

Practical implications. Wrapping the housing with aluminium foil substantially reduced measurement error. With a triple shield, sunny-afternoon RMSE decreased from 2.30°C to 1.49°C, while for a single shield it decreased from 2.82°C to 1.77°C. However, a warm bias of approximately 1°C remained under sunny conditions, indicating that maximum temperatures in open habitats may still be overestimated even with the best-performing configurations. Although aluminium foil wrapping was effective in this proof-of-concept study, we view the main implication as a design recommendation for logger manufacturers, such as TOMST, rather than a recommendation to deploy foil-wrapped loggers in long-term monitoring networks. Reducing

housing absorptivity through reflective materials, coatings, or polished aluminium housings may provide a practical way to improve measurement accuracy without requiring user modifications. Because the housing shape is convex, such reflective surfaces are unlikely to concentrate sunlight and are therefore not expected to increase fire risk.

Future research. This study included only two loggers per treatment monitored for 41 days at a single site. Future studies should increase replication, include logger inter-calibration, and measure radiation and wind directly at logger locations, allowing treatment effects to be quantified across continuous environmental gradients rather than broad radiation classes. Calibration differences are unlikely to explain the observed patterns because treatment effects varied strongly with radiation and time of day, but formal inter-calibration would strengthen inference. Validation across multiple sites, habitats, seasons, and climatic conditions is also needed to determine how broadly the observed benefits apply.

4. Conclusion

The effect of wrapping the housing in aluminium foil is larger than the effect of adding extra shield layers. Averaged over all conditions, the wrap lowered the error by 0.33°C, against 0.13°C for going from a single to a triple shield, and its benefit grew with radiation to 0.90°C in the highest radiation class, as hypothesised. Drilling ventilation holes in the triple shield did not significantly lower the error (0.01°C difference), so our hypothesis that holes would add a benefit was not supported. The best setups, a wrapped triple shield with or without holes, still overestimated the reference by about 1°C on sunny afternoons. Wrapping the housing is therefore a cheap and effective way to reduce radiation error in existing loggers.

Declaration of Generative AI

During the preparation of this work the lead author used Microsoft 365 Copilot in order to improve the readability and language of the manuscript as well as Claude for aiding the coding and data visualisation (ggplot2). After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Data Availability

Data is available on FigShare: https://doi.org/10.6084/m9.figshare.34969102

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